Issues and SWOT contribution in the coastal zones and estuaries
White Paper

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Background

The Coastal zones are very complex areas with diverse morphology, lithology and hydrodynamic conditions and with important economic and ecological issues. There are several definitions of the coastal zones and according to these defintions, the coast can range from a few hundred meters to several kilometers on either side of the land-sea interface, and can include the shelf, the nearshore zone (a narrow band within ~2 or 5 km of the shoreline), the coastline and estuaries.

These environments are affected by large variations in water levels, controlled by offshore currents, wind-driven shelf circulation and waves, tides, storm surges, sea level rise and inputs from streamflow and groundwater. The combined effects of these complex phenomena on the spatial and temporal variation of water levels are not well known and therefore difficult to model, particularly because of sparse in situ observations of water levels. Despite this, the spatial variability of the hydrodynamics is generally studied by numerical simulations (i.e., modeling), along with dedicated field studies of specific regions and processes.

Remote sensing observations could provide critical information on the spatial variability of water surface elevations under different hydrodynamic conditions. This would allow us to better understand and model the interactions between the different hydrodynamic processes, and their impact on the evolution of these environments. Fine-resolution water level data is also required to calibrate and validate circulation models in the different coastal environments and specifically for the complex interactions between salt water and freshwater in the coastal borders.

Over the last two decades, satellite radar altimeters, measuring sea level variations, have provided major advances in ocean dynamics (Fu and Chelton, 2001; Morrow and Le Traon, 2012), but encountered many problems in the coastal environments, resulting in a rapid degradation of the data accuracy when approaching the coasts. Moreover, nadir altimeter missions, such as TOPEX/Jason, have an inter-track spacing which limits their ability to map smaller-scale features in the coastal zone, such as shelf tides, coastal tides, the effect of winds and storm surges, etc (Arbic et al, 2014).

Nowadays, the physical oceanography and hydrology communities have proposed a new mission named SWOT (Surface Water Ocean Topography) to measure water surface elevations with a high spatial resolution (Alsdorf et al., 2007). The SWOT mission was recommended by the National Research Council decadal review “Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond”, and is in partnership with NASA and CNES, and more recently with the Canadian and UK Space Agencies. The mission design is based on Ka-band wide-swath interferometric altimetry for mesoscale and sub-mesoscale oceanography and land surface hydrology.
SWOT measurements of sea level height and water level in lakes and large rivers will enable us to map and estimate the flux of water globally. Moreover, this new technology will allow a continuum of fine-scale observations from the open ocean to the coasts, estuaries and rivers, allowing us to investigate a number of scientific and technical questions in the coastal domain.

The SWOT Mission Science Document was published in 2012 with the general overview sections written in 2011 (http://swot.jpl.nasa.gov/). In the Science Document, there is already a section on coastal seas and shelf processes which gives a good general overview. However, there is only one paragraph describing the potential of SWOT to observe estuaries and nearshore processes. Thus, the objective of this paper is to provide key elements of the SWOT coastal applications via two papers, the first (Part 1) addressing the estuaries and neashore zones, and the second (Part 2) providing an update for coastal seas and the continental shelves.

The high spatial resolution provided by SWOT measurements will enable regular observations of the complex physical processes in coastal environments and provide new data products for scientists working in these regions. While the SWOT requirements for coastal regions are being finalized, an open dialogue with the user community is necessary to understand their needs and optimize the science return. With this paper, the SWOT Science Definition Team (SDT) aims to communicate its knowledge with the broader coastal science community. As such, the SDT seeks to better understand the potentials and limitations of SWOT's spatially explicit observations of the regional ocean - coast - nearshore - estuaries – rivers with the spatial resolution required to resolve coastal and estuarine processes. It is expected SWOT observations, combined with circulation models and physical equations, will enable us to improve our predictions of tidal dynamics along the coasts as well as capture storm surges and floods.

The SWOT Mission Science Document (Fu et al., 2012 - http://swot.jpl.nasa.gov/) indicates that satellite sampling will provide high spatial resolution (~1.0 km gridding over oceans; 5m x 10-70 m over terrestrial water surfaces) in swaths that are ~120 km wide, with a nadir "gap" of approximately 20 km. An additional conventional altimeter will provide data at the nadir location. The SWOT cycle (repeat period) is ~ 21 days. In the mid-latitude regions, one place will be observed 2-4 times during each 21-day period. In the high latitude regions, the observations will be more frequent (max 7 times in a 21-day cycle), due to the convergence of tracks as the satellite approaches its inclination latitude (78°). The current error budget specifies the cross-swath average rms random error in SSH is 2.4 cm in an area of 1 km^2 in the open ocean and the water height error for rivers is 10 cm for width larger than 100 m over a 10 km reach.

Thus there will be two SWOT products available in the coastal zone, with different spatial resolution and noise levels, to sample scale variations observed in the land-sea interface zones. The dependence between the short term (e.g. surges, tides, flow) and long term (e.g. sea level rise) hydrodynamic factors varies with the interface zones and their distance from the shoreline.
According to the type of physical processes produced in these environments and the spatial resolution required to study them, we distinguish two main interface zones:
- the coastal ocean and shelf domain which is the transition zone between ocean and coastline will have the most precise estimate of sea level height with the 1km ocean data product;
- the nearshore domain (<3 km from the coastline) and estuaries, where SWOT will provide an additional high resolution product but with lower water surface height precision.

Because of the significant differences of these products, we produce two white papers, a first one devoted to the issues, processes and SWOT applications in the estuaries and nearshore, and a second paper addressing coastal seas and shelves.

Issues and SWOT contribution in the coastal zones and estuaries - White Paper
Part I. Nearshore and estuaries processes

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Introduction

The nearshore, coastlines and estuaries, are very complex zones comprising the land-sea interface, with diverse bio-geomorphological environments, and with important economic and ecological issues. The coastlines can be rocky with cliffs, beaches with sand, gravel or pebbles, shingles or mud, but can also exhibit smoother but highly dynamic transitions with fresh water influx from estuaries, coastal marshes, swamps and wetlands.

These environments are affected by large variations in water level, regulated by tides, waves (with runup and overtopping), wind-driven flows, storm surges, sea level rise, and discharge from streamflow and groundwater. However, the combined effects of these phenomena on the spatial and temporal variations of water levels, and their impacts on inundations patterns and morphological evolution,of coastal and estuarine regions are not well known and difficult to model..Given the punctual and sparse coverage offered by gauges, the spatial variability of the hydrodynamics is generally studied with poorly calibrated models. In addition, the models used by the hydrologists and oceanographers are often developed separately, using different equations, and may not be adapted to the coastal and estuarine zones, failing to simulate relevant phenomena.

Therefore, the interest of satellite radar altimetry in these environments is to provide spatially explicit measurements of the water level variations under different energy conditions. The 2-D SWOT water level data will enable us to better understand and model the interactions between tides, waves, storm surges, sea level rise, streamflows and groundwater discharge, and their impact on inundations, morphosedimentary evolution (coastal erosion and accretion), water quality and on the biodiversity of these environments.

Recent algorithm developments extended traditional nadir altimeters measurements closer to the coast (Cipollini et al., 2010), but the presence of land within the relatively large nadir altimetry footprint (few km in diameter) still contribute to large errors. Even with the smaller altimetry footprints available from new missions such as SARAL/AltiKa in Ka-band, or Cryosat-2 in SAR mode, the improved coastal altimetry processing only provides reliable data up to 5-10 km from the coast (Picot et al., 2014), not covering the nearshore of estuarine regions.

With the new SWOT altimeter mission, sea surface heights over a 120 km wide swath with a 20 km gap at the nadir track are provided. An additional conventional altimeter will provide data at the nadir location. Using the interferometric processing, 1 km gridded data will be available over the entire continuum from the regional ocean - coast - nearshore - estuaries – rivers. In addition, the high-resolution terrestrial surface water data will also be available over the rivers, estuaries and nearshore zone, up to 3 km from the coast. This higher resolution will have a higher noise, but offers the opportunity to average the data in variable coordinates to reduce the noise, and to explore the spatial and temporal variability in locally-adapted coordinates.

In fact, SWOT applications in the coastal zones and in estuaries represent an exciting challenge that was recently addressed by the SWOT science definition team. Some results have shown the potential of SWOT in the Seine Estuary (Laignel et al., 2014a; 2014b; 2015), the San Francisco Bay (Chao, 2015) and the English Channel (Turki et al., 2015a; 2015b; Turki and Laignel 2014; Turki and Laignel 2015). Simulations in these regions advanced our understanding of the hydrological variability in different environments and enabled us to derive the SWOT measurement requirements.

The nominal SWOT mission will provide global coverage of coastal zones with fine-resolution coverage every few to 10 days (with an exact repeat of 21 days) for a minimum period of 3 years. The unprecedented SWOT water surface height observations, will reveal the complexity of the estuarine and coastal processes, providing useful information for scientists and users to understand the hydrodynamic variability in the coastal zones. It is important for the SWOT teams to open the dialogue with the interested communities to determine their needs, and refine the requirement on SWOT observational capabilities.

SWOT will provide absolute global spatial coverage of all nearshore and estuarine zones up to 78°North and South, with revisit every few to 10 days depending on latitude. The nominal orbit repeat is 21 days. One focus of the SWOT Science team members is to assess the impact of SWOT's spatial and temporal sampling on our ability to resolve different physical processes, such as tides and extreme events (storm surges, floods). For example, the orbits have been specifically chosen to be able to separate and observe the main tidal constituents after the 3-years of observation – although the more complex non-linear tides in the nearshore and estuarine zones will be more challenging (see the accompanying White Paper on Tides, also on http://swot.jpl.nasa.gov/). Highly dynamic coastal processes, we need to characterize their spatial response under the different forcing conditions occurring during the 3-year mission. The sensitivity of SWOT's observation strategy needs to be considered within different geophysical contexts and hydrodynamic conditions in order to specify the altimeter requirements given specific geophysical features and forcing.

In this paper, the estuary and the coast are separated because the interactions between the dominant physical processes are not exactly the same and the spatial resolution required to study them can also vary : (1) the nearshore coast can be define as the areas where the tides, waves, storm surges and sea level rise act, sometimes with tidal flooding and ebbing, and counter currents from freshwater channels and sheetflows within wetlands and, (2) estuaries include impacts from the coastal marine dynamics but are dominated by inputs from the rivers, tributaries and groundwater discharge.

Therefore, this paper concerns the issues and the potential contribution of SWOT in estuaries and the coastal zone. The objectives are to:

- propose an overview of the issues in these environments (section 1),
- describe the SWOT use and contribution within each environment (estuaries: section 2, nearshore: section 3),
- discuss the potential applications of SWOT in these environments (section 4),
- propose recommendations for future studies on the use of SWOT altimeter in the nearshore/coastline and estuarine zones (conclusion and recommendations).

1. Overview of the issues in estuaries and nearshore

Coasts and estuaries are dynamic areas and of great economic and environmental importance. Coastal areas are used for fishing, aquaculture, mineral extraction, industrial development, energy generation, tourism and recreation, and for waste disposal. Estuaries are partially enclosed areas of water on the coast where saltwater from the sea mixes with fresh water from rivers and streams. These transitional waters are highly biologically productive ecosystems providing many other important ecological functions.

Coastal ecosystems are critical to maintaining human livelihood and biodiversity. Ecosystems such as mangroves, salt marshes, and sea grasses provide essential ecosystem services, such as supporting fisheries by providing important spawning grounds, filtering pollutants and contaminants from coastal waters, and protecting coastal development and communities against storms, floods and erosion. Additionally, recent research indicates that these vegetated coastal ecosystems are highly efficient carbon sinks (i.e. "Blue Carbon") and can potentially play a significant role in ameliorating the effect of increasing global climate change by capturing significant amounts of carbon into sediments and plant biomass. The term blue carbon indicates the carbon stored in coastal vegetated wetlands (i.e., mangroves, intertidal marshes, and seagrass meadows). This organic carbon is fixed in aboveground (leaves, branches, stems) and belowground biomass (roots), non-living biomass (e.g., litter and dead wood), and in sediments, which store most of the blue carbon. The role of tidal wetlands in regulating water flow and mass (i.e., nutrient, carbon, salt) exchange at the coastal boundary at regional scales remains unknown.

These systems are subject to widespread human use with high population density, and extensive harbor, industrial, and tourism activities. In fact, few of the world's coastlines are now beyond the influence of human pressures, although not all coasts are inhabited (Buddemeier et al., 2002). Use of the coast increased dramatically during the 20th century, a trend that seems certain to continue through the 21st century. Coastal population growth in many of the world's deltas, barrier islands and estuaries has led to widespread conversion of natural costal landscapes to agriculture, aquaculture, silviculture, as well as industrial and residential uses (Valiela, 2006). It has been estimated that 23% of the world's population lives both within 100 km distance of the coast and <100 m above sea level, and population densities in coastal regions are about three times higher than the global average (Small and Nicholls, 2003). The direct impacts of human activities on the coastal zones and estuaries have been more significant over the past century than impacts that can be directly attributed to observed climate change (Scavia et al., 2002). Direct impacts include drainage of coastal wetlands, deforestation and reclamation, and discharge of sewage, fertilizers and contaminants into coastal waters. Engineering structures, such as damming, channelization and diversions of coastal waterways, harden the coast, change circulation patterns and alter freshwater, sediment and nutrient delivery. Natural systems are often directly or indirectly altered, even by soft engineering solutions, such as beach nourishment and foredune construction (Hamm and Stive, 2002). Thus, ecosystem services on the coast are often disrupted by human activities.

Moreover, the coastlines and estuaries are strongly impacted by climate change, including sea level rise and an increase in extreme events (such as floods, storm surges) in some regions (IPCC, 2007, 2013). Large waves generated by ocean storms also cause elevated water levels (setup) and generating large runup (e.g., Senechal et al., 2011) which can lead to significant flooding. Under such conditions, erosion has increased river sediment load; for example, suspended loads in the Huanghe River have increased 2 to 10 times over the past 2000 years (Jiongxin et al., 2003). In contrast, damming and channelization have greatly reduced the supply of sediments to the coast on other rivers through retention of sediment in dams (Syvitski et al., 2005). In Europe, approximately 75 % of the shorelines retreat. These effects will likely dominate during the 21st century. In addition to erosion and inundation damage, these environments are subject of significant changes in water quality in particular during extreme floods, with increased turbidity from the river to the sea; this creates a turbidity plume affecting the hydrodynamic conditions of tidal currents and waves in coastal zones.

In estuaries, the water quality depends on pollution from human activities (agriculture, industry, urbanization), but is also strongly linked to the position of the high turbidity zone and the salinity gradient, which are related to hydrodynamics (water level). These evolve an increasing of seasonal storm surges, annual responses of estuaries to sea level rise and more frequent extreme events (floods and storm surges).This may cause a change in the estuary zonation, having a strong impact on ecosystems: changes in water levels, wetlands, salinity, temperature, turbidity and sedimentation, morphology, etc... The example of Gironde estuary shows the importance of interaction between anthropogenic inputs (pollutants), high turbidity zone and hydrodynamics on the water quality. This creates a significant decrease in oxygen during periods of low flows, with adverse consequences on wildlife, particularly fish (Etcheber et al., 2010).

In summary, the consequences of human impact and climate change in these environments are numerous and significant: inundation, morphological and sedimentary change, erosion, water quality change, property damage, reduction in the beach surface and on tourism… In consequence, the design and management of coastal infrastructures (harbours, dikes ...) as protection against the sea need to be reviewed, which leads to considerable costs. According to the OCDE, property damage at the coast affected by hydro-meteo-marine phenomena in 2005 was estimated at 3000 billion (5% of annual global PIB) and could be multiplied by 10 in 2070.

These issues require the monitoring and forecasting of changes in hydrodynamic conditions in the coastal zones (coastline and nearshore) and estuaries at different spatial and temporal scales. Interactions between tides, waves, storm surge, river flows, groundwater and sea level rise need to be observed and modeled to resolve the variability of sea level. These complex interactions are difficult to model and require specific tools and big computational costs.
SWOT measurements with their high spatial resolution will provide unprecedented observations of the river, estuary and nearshore regions, allowing us to understand the interactions and changes in the hydrodynamic conditions in these environments, and to better model these phenomena.

2. Estuarine processes and SWOT contributions

Estuaries are complex ecosystems which can include wetlands and mangrove swamps along their intertidal shores, areas of saltmarsh, fen or peatlands, tidal floodplains, and/or island areas with complex channel networks. They serve as a meeting point between land and sea, exhibit high primary productivity, and occupy ecological niches of considerable importance. They are often an important source of food for coastal aquaculture, whereby they act as natural filters for suspended material and pollutants, and offer effective flood protection for low-lying areas (Falconer and Lin, 1997).

Estuarine hydrodynamics are very complex because there are interactions between different water bodies: the sea with the same phenomena that the coast experiences (tide, wave, surges, sea level rise) but also the river, tributaries, and groundwater. Furthermore, estuaries are complicated by the fact that their boundaries move in response to the hydrodynamics and thus are difficult to define. Generally, the upstream limit is defined as the limit of tidal influence and the downstream limit (more difficult to define), is sometimes defined as the estuary mouth or the extent of the river plume emanating from the mouth. Additionally, estuaries span a wide variety of sizes and types ranging from large (e.g., the Amazon ~1000 km) to small, (e.g., the Seine estuary ~160 km long with width from 150 m to 8 km) and from well-mixed to highly stratified (see Valle-Levinson et al. 2010 for various classification schemes). The estuarine ecosystem is dependent on both natural physical and chemical processes (e.g., tide, current, bathymetry, nutrient influx, etc.) as well as anthropogenic activities (e.g., agriculture, industrial operations, fishing, dredging, etc.).

The circulation patterns within an estuary respond to tides, freshwater inflow, winds, offshore sea level, offshore density, vertical mixing, stratification, basin topography and bathymetry, air-water exchanges, water-sediment exchanges, the rotational effects of the earth, etc. Efforts to classify estuarine hydrodynamics based on simple observational parameters have been extensive and remain under investigation (e.g., Geyer and MacCready 2014). While water level alone cannot classify an estuary, it is an important parameter in understanding estuarine hydrodynamics and ecosystem function.

In-situ measurements provided by tide gauges are important to improve our knowledge of estuarine water elevations and then monitor the water quality and the possible changes in zonation (for example: movement of the salinity fronts and high turbidity zones within the estuary). The number of gauges needed to survey an estuary varies in relation to its size, but only a few estuaries in the world have enough gauges to allow this calibration/validation (ex: the Seine estuary, with a length of 160 km, has 17 tide gauges). A good survey requires a lot of instrumentation and field techniques which is very expensive and not always possible in some areas with complex topography characteristics.

Due to the complex physical processes occurring in an estuary, numerical models have been increasingly used to predict flow, water quality and sediment and contaminant transport processes. Depending on the type of estuary, several types of models can be used: (1) Simple 1D models for water levels and salt intrusion in well-mixed estuaries of regular and symmetrical geometries, (2) 2D height models for well-mixed estuaries with irregular geometries and 2D velocity models for stratified estuaries with symmetrical geometries, (3) 3D models for more complex geometries and physical processes. The choice of the most appropriate model to reproduce the variability in the estuary depends on the physical complexity of the hydrodynamic regime and the irregularities of the geometry. In fact, estuaries pose a particularly interesting set of problems for modeling, as they comprise a number of disparate systems that respond to hydrodynamic forcing in different ways, and also interact with each other in complex ways. The tidal forcing, the key parameter in the estuary, was studied by Flather and Heaps (1975) for the Morecambe Bay (UK), Oey et al (1985a, b and c) for the Hudson-Raritan Estuary (USA) and in Galperin & Mellor (1990a and b) for the Delaware Bay (USA), among others.

In reality, estuaries depend on both hydrologic and oceanic conditions. However, often estuarine models use the river and ocean as relatively static boundary conditions. Similarly, hydrologic models often ignore the estuary and the coast while oceanographic models either ignore or crudely model estuarine and groundwater inputs. Thus for accurate estuarine models, we need to work towards more integrated models across these boundaries. Moreover, accurate estuarine models require accurate high resolution bathymetry, coastal topography, fine spatial resolution, accurate bottom-generated vertical mixing, and data to calibrate/validate the model. Sometimes it is difficult to obtain accurate bathymetry because there are many data sources (National Institutes, Universities, Harbor, etc.) or because there is no data in some areas. Recently, the scheme in estuaries employs a raster-based approach based on LiDAR-derived digital elevation models (DEMs), which can have a high spatial resolution. The DEMs (and other ancillary data) can be used to classify the estuary into its component landforms, (e.g. tidal flats, salt marshes, channels), so that sub-models can be applied to the different landforms at an appropriate level of complexity, although this can be complicated by boundary movements under varying hydrodynamic conditions. To properly incorporate high resolution bathymetry and ensure accurate tidal propagation, grids are either nested or increase in resolution from the sea to the estuary. Often bottom drag coefficients also require modifications along the estuary. Finally, numerical models need to be validated with data which are generally provided by gauges and/or satellites, which are unfortunately limited.

The interest of using satellite data for estuaries is to provide information on the hydrodynamic spatial variability. Until now, within estuaries, the contribution of satellites has mainly focused on the monitoring of water color and its relation to suspended sediment and chlorophyll by measuring the amount of solar radiation at different wavelengths correlated to water quality parameters (e.g. total suspended solids, TSS). In terms of water level, satellite radar altimetry has had limited applications in estuaries due to the land perturbations within the radar footprint. Even so, the Topex/Poseidon altimeter has been used to measure wetland water level changes over the Louisiana wetlands (Lee et al., 2009). Most of the waveforms are specular (narrow-peaked), and need to be retracked using threshold algorithms. Several sites were chosen to generate decadal (1992-2002) time series of relative water level changes which show a clear seasonal and interannual variation, and agree well with the river stage data which was measured at one of study sites. A combination of models and satellite data have been used to study the sediment dynamics of estuarine environments; in particular, both show that turbidity distribution varies considerably with tidal and river flow conditions, fluctuating on a variety of timescales, and are heavily influenced by bottom topography.

To overcome these problems, the more precise SWOT SAR-interferometric altimeter will provide higher spatial resolution, which is fundamental in order to improve our knowledge of the complexity of the physical processes in these systems, validate and calibrate our models and improve the data assimilation by coupling physical models to altimetry measurements.

In the framework of SWOT project, high resolution modeling has been initiated in a number of estuaries. In the Seine estuary, the spatial variability of the water elevation was investigated with the barotropic TUGO model, including hydrodynamics and tides (Chevalier, 2014; presented by Laignel et al. (2014) . For this finite-element model, the meshgrid varies from 25 meters in the estuary to 4 kilometers in the Channel, with 66482 nodes. Boundary conditions include water level data from upstream of the estuary, and for the marine conditions (tide, surges), we use tidal constituents or altimetric data (Topex/Poséidon), associated with a global barotropic surge model (ex: Dynamic Atmospheric Correction, ERA-Interim).

The hydrodynamic modeling of the Seine estuary showed the importance of an accurate bathymetry, and varying bottom coefficients along the estuary. Two modeling studies were carried out, with : (1) a constant bottom coefficient and a bathymetry accuracy of 10 m, (2) several bottom coefficients along the estuary and a bathymetry accuracy of 3 m. In the first case, the error of the M2 tide amplitude varied from 10 to 70 cm although the temporal variability was reproduced quite well ; in the second case, the error of the M2 amplitude is less than 10 cm and both the temporal variability and the water level amplitude were reproduced well. The water level maps obtained by modeling (TUGO) in the Seine estuary (Chevalier, 2014), and in the Amazon estuary (Lion, 2013), show that the water levels are spatially highly variable in different hydrodynamic conditions.. In the example of the Seine estuary, this high spatial variation can be observed over distances of less than one kilometer. This shows the importance of the high spatial resolution of SWOT to observe these transitions and to study and better understand and model these spatial variations. Moreover, if we want to study hydrodynamics in the upstream part of the estuary, with widths of less than or equal to 100 m, we require the highest resolution of 100 m.

Regarding the temporal variability of the water elevation, a wavelet analysis of in situ data and simulated SWOT data (based on realistic SWOT orbits but without instrumental error) shows that SWOT reproduce well the variability of water levels in the river and in the upstream estuary, but less well in the downstream estuary and in the English Channel. Indeed, the wavelet coherence between the SWOT simulated data (without error) and the observed data decreases from 99% upstream to 53% downstream. Indeed, in the river and upstream estuary, the simulated SWOT data reproduces very well the 2 y variability mode which corresponds to the NAO (North Atlantic Oscillation), the annual modes of 1 y and 6 months which correspond to the dominant hydrological cycle modes, and also a winter mode of 1,5 to 3 months which corresponds to the flood period. In the downstream estuary and the Channel, SWOT sampling reproduces less well the 1 year variability modes while the 2-4 month winter mode is overexpressed by SWOT. Several simulations of harmonic component combinations have shown that the 2-4 month mode has a tidal origin; it is generated by the non-linear interaction between ter-diurnal components. Such mode, being observed by in-situ measurements, was also identified by SWOT with an over-expression of the energy power which is caused by the combination between the aliasing tide effects and the aliasing in SWOT altimeter (Turki and Laignel., 2015). Removing the ter-diurnal interaction from the tide signal, the over-expression of the 2-4 month band is not observed.

The accuracy of the SWOT measurements in estuarine regions will also be impacted by the inability of the low-frequency radiometer to provide accurate wet tropospheric path delay measurements near or over land. Several approaches exist to overcome this problem, including the use of numerical weather prediction model outputs and also estimates from near-by ground based Global Navigation Satellite System stations. Previous work has shown that correction methods depend on the GNSS network density and the atmospheric variability which may condition the meteorological model accuracy and the geography knowledge. Moreover and regarding the SWOT altimeter, it is also important to consider the two-dimensional variability of water vapor over the 120-km swath. The variability over the swath would manifest as coherent error structures in the SWOT imagery. Different correction methods must be compared to understand the error structure in each. Errors from different sources are expected to be on the order of 2-5 cm, but could exceed 10 cm in some cases and it is important to understand the nature of the errors in both time and space. Specifically, understanding the diurnal and seasonal correlation of the error is important for understanding the impact on tide estimates and understanding regional systematic biases is important for inland water level mapping. Additionally, a discontinuity will exist in the coastal zone between the accurate wet path delay provided by the radiometer over the ocean (> 50km from land) and the wet path delay derived from ancillary sources over land. This will introduce an error in the estimated slope of water heigh from ocean to land. Methods to optimally combine the ocean product with the derived products over land are needed.

3. Nearshore processes and SWOT contributions

The nearshore regions are subject to large hydrodynamic variability at different time and spatial scales due to the complexity of the physical processes resulting from non-linear interaction between tides, waves, storms and currents. This complexity, responsible for the coastal morphological evolution, should be examined in detail for coastal prevention from flooding and shoreline retreat. In fact, during storms, waves and currents in the surf-zone move sand and rapidly change the shape of the seafloor and the location of the shoreline. Understanding the coupling of waves, currents, and the seafloor so that changes to the morphology (e.g., beach erosion) can be modeled is important for coastal infrastructure, ecosystems, and recreation. A detailed survey of the hydrodynamic conditions in coasts is needed to understand the main changes occurring in these zones. While physical exposure is an important aspect of the coastal vulnerability for both human populations and natural systems to both present and future climate variability and change, a lack of knowledge of the variability near to the shoreline and in the nearshore zones is often the most important factor that creates hotspots of human vulnerability in these populated areas. The nearshore zones have high biodiversity, where data collection is an expensive activity, and very sensitive to the large nearshore perturbations and the bottom topography. For example, in the case of French coasts, the national network of tidal gauge (see REFMAR website) has 63 tidal gauges for 3427 km of coastline. Moreover, tide gauges are located in sheltered areas (such as harbours) and confined to coastal zones. To overcome the lack of measurements, the use of nearshore models is important in this case, but their spatial variability is difficult to validate.

An enigmatic aspect of the numerical modeling of waves and currents is that they are almost always undertaken independently even though wind is a primary forcing generating both (e.g. Pond and Pickard, 1983). This is principally because the characteristic time scales of waves are much shorter than most other processes generating near-shore circulations (winds, tides, internal waves, coastal trapped waves, tsunamis, large-scale ocean currents; Cathers and Peirson, 1992). In near-shore regions, direct interactions between currents and breaking waves are well established (Phillips, 1977) and modeled (Taebi et al., 2012). The characteristically short time scales of storm waves (0.5 to 20s) means that very small time steps (and therefore substantial computation effort) are required to represent waves on a wave-by-wave basis (so-called phase resolved models).

Spectral models are often used to increase the computational time step to the order of the temporal change in the forcing wind field or the evolving wave groups. A contrast can also be drawn between wave and circulation models in terms of their treatment of turbulence. The diffusion of momentum is a fundamental aspect of circulation models which must incorporate some representation of the Reynolds stresses (with appropriate boundary conditions) in their formulation (e.g. Craig and Banner, 1994). The success of the irrotational approximation In the characterization of ocean waves has led to wave models being formulated with any Reynolds stresses being neglected except implicitly in terms of energy losses due to breaking (e.g. Banner and Morison, 2010) or interactions with the bed during shoaling (e.g. Smith et al., 2010). Spectral models have had long acceptance in coastal design (Resio, 1988) and phase-resolved models have been slowly gaining acceptance although their most computationally efficient forms (Boussinesq models, e.g. Kirby et al., 1998) although they struggle to adequately represent waves in deeper water (e.g. Peirson et al., 2011). Phase-resolved modelling of wind-forced seas to date has remained a research activity (Xue et al., 2001). Circulation models have been applied to study the water quality (Cathers and Peirson, 1991) and determine the impacts of cyclone landfall (e.g. Harper et al., 2011). The models normally solve stratified 3D forms of the Reynolds equations employing the shallow water approximation. If the flows are shallow and resolution of the wind drift layer is not required, depth-averaged forms may be used. However, there is little doubt that numerical model capability will continue to improve substantially over the coming decades primarily due to improved capabilities in computational power, improved physics and model integration. Also, modeling tools need high resolution bathymetry field and detailed meshgrid to accurately model coastal zones. Providing these dataset is costly in zones with complex geometry and large changes in morphology.

Consequently, there is a pressing need for sea level observations with short space and time scales, required to validate and calibrate these numerical models. The limited coastal gauges can be coupled to satellite altimeter measurements to improve the coverage of the sea level variability in these environments. Historically, satellite altimetry has the potential of measuring sea level variations, geostrophic currents and the surface waves in the coastal zones, but has been limited to regions > 10-25 km from the coast, due to perturbations of the radar waveforms. Offshore, altimetry and has been used to assess climatological variability of the historical wave climate over the last 25-30 years (Young et al., 2012). While altimeters provide regular samples of waves over most of the globe, the sampling frequency is low (~10-35 days) and statistics of storm events, which have duration of a few days, are compromised. Capturing long records of individual storm events are essential for designing nearshore structures to resist to storms (Shand et al., 2011). Offshore altimetry wave height statistics are presently being used to validate operational wave models, and are also assimilated in some operational schemes (Skandrani et al., 2004).

Nearshore geostrophic currents are difficult to derive from nadir altimetry. The assimilation of offshore altimetry data, as frequently used in models, is problematic since (1) it leaves an unconstrained nearshore band and (2) the principal errors on the shelf may lie in the wind forced currents (**Gorman** and Stephens, 2003). Models with assimilation that combine all available in-situ tide gauges, HF radar, glider lines and satellite data including offshore altimetry are being developed (Chao et al. 2009; Wilkin and Hunter, 2013), but the absence of spatially coherent sea level observations in the nearshore zone remains a problem.

In addition to validation and calibration, altimeter data in coastal zones are needed as input parameters to supply the morphological models which should be coupled to the hydrodynamic ones in order to determine the evolution of the coastal features (Gallop et al. 2006; Turki et al., 2012; 2013). Since the previous nadir altimeters have a large inter-track spacing which limited their ability to map smaller-scale features, as well as missing data in the nearshore band from 10-25 km from the coast (Cipollini et al., 2010; Arbic et al., 2014), the use of SWOT will provide unprecedented high resolution data coverage in the nearshore band. This will be necessary to map the sea level and wave height variability during different energy conditions and a series of hydrodynamic scenarios by combining the different parameters of neap/spring tides, high/low tides and stormy/moderate events. In the nearshore zone < 3 km from the coast, two products will be available : the most accurate standard open ocean product on a 1 km^2 fixed grid (2 cm error in SSH), but also the higher spatial resolution hydrology "HR" product on a finer scale grid (5m alongtrack and 10-70 m crosstrack) with larger errors (45 cm error in SSH at 100 m^2). Although spatial averaging will be required to reduce the errors and use this HR product in the nearshore zone, the averaging can be done in alongshore or dynamical co-ordinates, to improve the restitution of nearshore dynamics.

The global SWOT coverage will allow nearshore studies on: (1) regional scale with contrasting climate, hydrodynamic (macrotidal, microtidal, etc) and morphological conditions, in many key sectors of economic and/or ecological interest and/or potential hazards of flooding, sea level rise and shoreline retreat; (2) the global scale from the comparison between different hydrodynamic systems with different geographical coordinates which is strongly related to SWOT sampling.

Some preliminary studies in the nearshore zone using simulated SWOT data have been used to help us investigate: the continuum from regional ocean – nearshore – coasts and the sensitivity of the satellite sampling to record tides and storm surges. The resolution needed by the altimeter to capture the variability in the nearshore zones and close the shoreline will be also discussed. Turki et al., (2015a) have subsampled a series of tide gauge records in the English Channel and the Atlantic sea (French coasts) to simulate the SWOT satellite orbit and to investigate the capacity of SWOT to reproduce the temporal variability of water level. This only tests the SWOT sampling conditions, since the errors generated by the satellite interferograms and meteorological conditions were not considered. We note that the SWOT orbit has been chosen to observe well the principal 8 tidal constituents, and to help observe the more complex non-linear constituents in the coastal zones (see the accompanying SWOT White Paper on tides, Arbic et al., 2015). Turki et al (2015a) demonstrate the sensibility of the SWOT sampling to the aliased harmonic tides, in this region of strong coastal tides.

Several investigations have shown that the main findings are that the virtual SWOT measurements are able to reproduce the non-tidal residual of the sea level variability during the maximum lifetime of the future mission (Turki et al., 2015a, In press). The SWOT capabilities were checked for different time scales and frequency modes. The different frequency components, investigated by a wavelet analysis, characterize the annual, inter-seasonal and inter-monthly and monthly scales. These frequencies are well reproduced by SWOT although the distribution is biased with an over-expression and a spreading of the energy spectrum as the number of overpasses increases per repeat cycle. Also, the reconstructed bands of the non-tidal sea level have shown that the high frequency components related to the extreme surges in the English Channel are detected by SWOT samples. The 2D structure of the storm surges, studied by Turki et al (2015b) along the French coasts, will be clearly reproduced by SWOT if the sampling coincides, although their temporal evolution cannot be monitored.

Concerning the nearshore spatial scales, the small-scale variability near the coasts requires a detailed resolution to be well mapped and the question is: What is the resolution needed in coastal zone and what is the limit of this resolution from the coastline to the nearshore zones and the shelf ?
Chao (2015) simulated High Resolution SWOT Data in the San Francisco Bay/Estuary, and showed that the total error height as a function of grid size and is : (1) 45 cm for a grid of 100 m x 100 m, (2) 20 cm for a grid of 250 m x 250 m, (3) 10 cm for a grid of 1 km x 1 km. A meshgrid of 100 m x 100 m with a vertical precision of 45 cm is not adapted for the variability at the coasts since most processes under moderate and averaged extreme conditions vary between 12 and 22 cm (Carter et al.,1993).

Generally, most of the cross-shore variability of coastal features varies from the shoreline position to the closure depth, which is the depth where the bathymetry becomes stable in time, with less sediment movement. According to previous literature, analyses in many Australian beaches with different characteristics and energy conditions have shown that the closure depth varies between 0,5-2,5 km from the shoreline position. In the case of the English Channel, modeled results by Delft3D, presented by Turki and Laignel (2014; 2015), have shown a large variability of the hydrodynamic conditions from the shelf to the nearshore zone and along the coast. This work confirms also the difficulty to simulate some specific environments when the energy transformation (convergence and divergence of the wave crests) close to some topography structures is very complex.

With the aim to investigate this challenge, a series of simulation of the English Channel by Delft3D were performed by combining different scenarios (stormy/moderate events, neap/spring tide cycle and low/high tides) and using several meshgrids, from 250m; 500 m to 1Km. The last biggest storms recorded in the English Channel, such as Xavier and Joachim, were also considered in our simulations. Results have shown that the 1 km grid is not enough to capture the main variability in coasts and nearshore zones since the wave gradient and changes in the sea level are not adequately mapped. Using 10000 simulations, the 500 m grid can capture 50% of the variability in the nearshore zones during stormy events and 20% for averaged conditions. More than 80% of this variability is captured using the 250 m grid where the forms of wave gradients are more structured, and extend between 300 and 400 m. The position where the transition between the 1 km ocean resolution and the 250 m coastal zone resolution is needed will vary, depending on wind/wave conditions: it ranges from 800 m, during high energy conditions in stormy events, to 2 km for average conditions. This range (800m-2km) represents the limit separating the HR variability at the coast and the nearshore zones from the shelves and oceans. Similar work has been carried out in the Biscay Bay of the Cantabria Sea (eg. Turki and Medina., 2010) and in the Mediterranean sea (Turki et al., 2007; Turki et al., 2011). The findings emphasized that the large variability in the nearshore zones requires a meshgrid of less than ~300 m.

Such mode, being observed by in-situ measurements, was also identified by SWOT with an over-expression of the energy power caused by the combination between the aliasing tide effects and the aliasing in SWOT altimeter (*Turki and Laignel., 2015*). Removing the ter-diurnal interaction from the tide signal, the over-expression of the 2-4 month band is not observed.

Therefore, the SWOT resolution in the nearshore zones for macrotidal systems, which is the case of the English Channel, should be probably be around 250 m in order to map most of the hydrodynamic variability. For this horizontal resolution, the SWOT precision will be around 20 cm. The trade-off between the spatial resolution and the vertical precision seems to be appropriate to resolve the full variability of the hydrodynamic changes (wave breaking, energy dissipation) in coastal macrotidal systems with high energy conditions. More investigations are needed in other coastal systems with different energy conditions of tides and waves to confirm these results.

Regarding the wet tropospheric path delay, the same issues exist in the near-shore region as in estuarine regions. It is particularly important to understand the temporal and spatial correlation of the errors in the near-shore region and the correlations with the SSH signal. Land-sea interactions play an important role in the variability of the wet path delay in this region. Sea/Land breezes could create a systematic diurnal variability which would also have seasonal components. Localized topography can create regional systematic biases as the air transitions from land to sea. A collaboration between atmospheric and coastal modelers is required. In parallel to the proposition of these new processing strategies, it may be a necessity to think about an enhanced high resolution radiometer (with much smaller land impact

4. SWOT applications

With most of the World's population living along the coasts, the societal benefits of the SWOT mission range from improving our understanding of the water cycle and its role in maintaining ecosystem services, to assessing population vulnerability to hazards and natural disasters. In addition, the data products and derived models will provide a new tool for decision makers for informed practices on sustainable development.

Indeed, the high spatial resolution of SWOT will allow us to propose many applications in coastal and estuarine environments. The monitoring and mapping of water levels and the associated morphological changes is an essential support for the implementation of strategies for navigation and economic development and for the security of property and people (inundations, coastal retreat).

Some examples can be mentioned:
- the identification, survey & mapping of seasonal & interannual variability of water level and inundations (flood & storm surge), including support for modeling the propagation of inundations (providing elements for understanding the limits of inundation extensions),
- the understanding of the interactions between different water bodies and their impact on the water level & changes in the estuary zonation related to the sea level rise,
- monitoring & mapping the seasonal & interannual changes of water areas in wetlands (natural and artificial lakes) for a better management of water levels for different usage (agriculture, nature reserves, leisure centers…),
- monitoring & mapping of the changes in island positions and channels,
- monitoring the water quality in relation with these hydrodynamic conditions: salinity gradient, turbidity, oxygen,
- prevention of flooding and the low water thresholds which are responsible for the turbidity plumes and the decrease of the oxygen in estuaries,
- monitoring of water level changes in the main big harbours,
- ecological conservation & restoration, because the evolution of fauna and flora and their habitats is related to the water level,
- role of the estuaries and vegetated coastal ecosystems as sink or emitter of CO2, according to the temperature, salinity, turbidity and hydrodynamic conditions.

5. Conclusions and Recommendations

Coastal and estuarine areas are environments with economic and ecological issues and with complex hydrodynamics. The hydrodynamics is difficult to study and to model because there are many interactions between water bodies and different dynamics (tides, waves, storm surges, sea level, flow, groundwater). The SWOT mission, due to its high spatial resolution, will hopefully provide insight into these complex dynamics and represents a significant advance for coastal estuarine oceanography and hydrology.

To answer these issues, we propose several recommendations.
Studies conducted in the macrotidal environments should be continued because they present high water level variability (& slope inversion in estuaries).
Studies should be conducted in other coastal environments with contrasting climate, hydrodynamics (eg microtidal ...) and morphological conditions to :
- study SWOT's ability to reproduce the temporal and spatial hydrodynamic variability in a range of regional environments, and consequently to better estimate SWOT coastal parameters and approaches at the global scale (from the comparison of the regional studies).
- define whether the coverage of the high-rate data from the coastline to the nearshore of 2 km with a grid of 250 m x 250 m proposed for the macrotidal coastal environments such as the Channel coasts can be validated in other coastal environments.

In consequence, regional modeling of shelf/coastal areas and estuaries should be encouraged. Studies should be focused on different dynamical regimes:
- tide propagation, relation between the tide and flow in estuaries,
- storm surges, relation between storm surges & tides (the highest surges are linked to the combination of storms and high tides),
- run-up amplifications during extreme conditions in coastal zones and estuaries.

More interest should be focused on SWOT measurements of barotropic gradients in estuaries. Changes in hydro-dynamical and morpho-dynamic from wet vs. dry cells also need to be considered to study SWOT capabilities.

Coupling between tide and flow suggests that interpretation of SWOT data in estuaries require collaboration between hydrologists/oceanographers, modelers & geodesists (since a precise knowledge of the bathymetry & the coastal marine geoid are required).
Investigations should consider the transition of spatial scales, from the mesoscale (ocean) to the

smaller scale (coast), in the different dynamical regimes.

Comparisons should be performed with other altimeter measurements and other satellites.

Determine regions where the high resolution (land-mode) will be preferred and which dynamics can be extracted. NB. The lower resolution (ocean-mode) will be available globally, over all surfaces).

Collaboration between atmospheric and coastal modelers is required to improve the knowledge of the wet tropospheric path delay in the neashore and estuary.

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