A Coordinated International Satellite Altimetry Virtual Constellation: Towards 2050

White Paper prepared

by the CEOS OST-VC (Ocean Surface Topography Virtual Constellation)
and the satellite altimetry community

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2 Executive Summary

The "Assmannshausen Report" (Escudier and Fellous, 2009) stood for 15 years as the CEOS reference document for the international altimetry community, gathering user requirements for the altimetry satellite constellation for the years 2010 to 2025. It is encouraging to see that all the high-level requirements from that document have since been implemented in the various recent satellite missions, their products, or dissemination strategies.

This new report builds on the progress made over those 15 years, in terms of satellite instrumentation as well as the user uptake, new and developing applications, and the outlook of user needs for the next decades. The Ocean Surface Topography Virtual Constellation (OST-VC) working group, co-chaired by CNES and EUMETSAT, took on the task, incorporating contributions from all involved space agencies and a wide range of experts and end users, to build the new reference for a better international coordination of the altimeter constellation for the years 2025-2050. After some preliminary context about altimetry and its community, the report lists the user needs including emerging ones, then focus on the gaps in the current international space constellation, gaps that space agencies must consider in their future program prospectives.

This report highlights the importance to continue the ocean observation including waves and currents. Considering the climate change impact on the evolution of the water cycle, the monitoring of inland waters, coastal waters and ice is crucial and must be elevated as key objective. Swath altimetry, successfully demonstrated by SWOT mission, will benefit numerous applications and is on good track to be implemented on future space missions (such as the Sentinel-3-Next Generation Topography mission). The interest in smaller scale and rapidly evolving phenomena, justify the recurring user need to improve both the revisiting times and the spatial sampling. On the global and basin scale, it remains imperative to continue and to improve the climate time series of sea level change with missions such as Sentinel-6.

The report further emphasizes the importance to create higher level thematic products by collocating high-resolution altimetry with other satellite data (ocean color, wind speed, salinity, or others). It is also essential to continue the open and free data policy, to support and develop user uptake and to take advantage of the future computing capacities.

Thanks to a huge implication of the altimetry community (International Altimetry Team, 2021), the current altimetry constellation is currently consolidated by Copernicus missions until 2040, with still some enhancements to be done. Open data polices, widespread collaboration and support from multiple agencies and nations will be necessary for the continued success of these missions and especially if the enhancements are to be realized.

3 Introduction Purpose and scope

3.1 Purpose and scope

In 2006 CEOS initiated the gathering of user requirements for a satellite constellation in support of ocean surface topography monitoring for the years 2010 to 2025. Under leadership of EUMETSAT and NOAA this led to what is generally known as the Assmannshausen report (Escudier and Fellous, 2009). It is encouraging to see that all the high-level requirements from that document have since been implemented in the various recent satellite missions, their products, or dissemination strategies.

The report that you are now reading is intended as an update to the Assmannshausen report and was initiated by the CEOS Ocean Surface Topography Virtual Constellation (OST-VC) working group, co-chaired by CNES and EUMETSAT, and incorporates contributions from all involved space agencies and a wide range of experts and end users.

This update naturally includes the various innovative technologies implemented on-board recent altimeter missions:

- The use of Ka-band as implemented in SARAL/AltiKa and planned for the CRISTAL mission.
- Synthetic Aperture Radar (SAR, also known as delay-Doppler) altimetry as implemented on CryoSat-2, Sentinel-3, and Sentinel-6.
- Wide-swath altimetry as implemented on SWOT and planned for Sentinel-3 Topography Next Generation.

Beyond the satellite technology, also the ground segments have greatly improved due to:

- Improved access to the data through the internet, with free data access policies implemented by most space agencies.
- High-performance computing capacities to process even the high-rate SAR data in near real time.
- Capacity building and outreach to emerging users.

As was already envisioned in the Assmannshausen document, new emerging applications start to set their specific requirements on what were historically “ocean missions”. Such applications include:

- Applications near the coast, relating to sea level, marine meteorology, waves and currents.
- Polar monitoring of sea level, ice thickness and glaciers.
- Hydrological applications such as lake, river and wetland levels, slopes, volumes and discharges.
- Climate monitoring, through the assessment of global and regional sea level change, its trend and acceleration.

Lastly, with large and sustainable programs like Copernicus and the Chinese Haiyang 2 constellation, a long-term operational perspective has become feasible, supporting ocean observations and forecast from the large scale for climate to the mesoscale, as well as inland water monitoring.

This document is not a formal update of the detailed requirements of the Assmannshausen report. Instead, you will find an inventory of user needs including emerging ones, followed by an identification of gaps in the current international space constellation, for better international coordination of the altimeter constellation.

It is up to agencies, once the coordinated space programs are decided, to set up mission requirement documents.

3.2 The satellite altimeter measurement concept

Altimetry satellites determine the distance from the satellite to a target surface by measuring the satellite-to-surface round-trip time of a radar pulse. Combined with precise satellite location data, after accurate correction of a lot of external perturbations to the signal, the altimeter measurements can provide an estimation of the height of the target surface, as well as additional information related to the surface.

Indeed, the magnitude and shape of the echoes (or waveforms) also contain information about the characteristics of the surface which caused the reflection. The best results are obtained over the ocean, which is spatially homogeneous and has a surface that conforms to known statistics. Surfaces that are not homogeneous, that contain discontinuities or significant slopes, such as some ice, rivers, or land surfaces, make accurate interpretation more difficult.

3.3 The success story of satellite altimetry

Since the onset of satellite altimetry, this remote sensing tool has been instrumental in observing the global oceans as had never been feasible before. While land-based instrumentation has been able to sense the ocean in coastal areas and ships, drifters and buoys could only take localized measurements, altimeter measurements opened access to the global oceans, sampled at regular intervals and to regions where these kinds of deployments are difficult or even impossible.

The applications, originally focusing on wave height and wind speed (Geos-3, 1968), soon expanded to mapping of the ocean topography (Seasat, 1978) and bottom topography (Geosat, 1985-1989), while large-scale ocean variations were also targeted. The realm of applications exploded particularly when a series of reference missions, starting with TOPEX/Poseidon (1992-2006), focused on the global mean sea level and large-scale ocean circulation, while another set of sun-synchronous missions, starting with ERS-1 (1991-2000) applied itself to higher latitudes and mesoscale ocean circulation. This paradigm has basically continued until today with the Copernicus missions Sentinel-6 Michael Freilich (since 2020) as reference mission and Sentinel-3A and -3B (since 2016 and 2018) providing the meso-scale and higher latitude observations. Together with the traditional measurements of sea level, wind speed and wave height, upper ocean heat content has become an essential altimetry-derived variable, providing an indispensable link between the ocean and atmosphere in coupled models.

Recent developments of SAR (delay-Doppler) altimetry, from CryoSat-2 in 2010 through Sentinel-3A, -3B, and -6 Michael Freilich (MF), thanks to a step change of spatial resolution, have allowed the transition into coastal areas and thus much better validation with coastal instrumentation and capturing the unique ocean features there. Also, the observation of inland waters has been facilitated by this novel technique.

Finally, in 2022 the first wide swath altimeter satellite (SWOT) was launched as an experimental mission, allowing the 2D observation of sea level at a much higher (cross-track) resolution than was ever feasible before from a single satellite. Thanks to its wide swath and rich spatial density, SWOT observations have enabled continuous global monitoring of inland waters for the first time, providing simultaneous measurements of water level and extent. This dual information paved the way for new satellite-based products on water volume and discharge at a global scale. Undoubtedly, this will set a trend for future operational missions as well. In fact, swath altimeters are planned to be carried on board both Sentinel-3 Next Generation Topography (S3-NGT) satellites.

In addition, it is worth noting that for decades now, the success of the satellite altimetry mission has been made possible primarily through widespread collaborations between nations and agencies. The broad groups of scientists and engineers (both in terms of disciplines and countries of origin) have ensured widespread use and continued improvements and innovations. Likewise support from a growing number of agencies have vastly expanded the scope and capabilities of the constellation of altimetry missions. It is also expected that meeting the goals and closing the gaps laid out in this document will continue to require open access to data, widespread collaboration and support from many agencies and nations to be successful.

3.4 The importance of satellite altimetry in earth observation

Spatial data play an essential role in studying major climate cycles, monitoring the effectiveness of mitigation policies, and implementing measures to adapt to climate change.

Space-based altimetry is the only technique able to provide the Essential Climate Variable named sea level, a key indicator of climate change and anthropogenic impact on climate. The closure of the sea level budget confirms the significant acceleration in its rise on a global scale since the beginning of the altimetry era and shows that this acceleration is essentially due to accelerated mass loss to the ocean from the Greenland and Antarctic ice caps (Hugonnet et al. 2021) and thermosteric expansion of the ocean due to warming. Moreover, altimetry data combined with spatial gravimetry data are also used to assess the amount of heat stored in the ocean in response to climate change, and now enable geodetic measurements of the temporal evolution of the Earth's energy imbalance on interannual and longer time scales.

Moreover, altimetry (sea level, waves and wind) data are of major importance as an input to ocean models, and atmosphere/ocean coupled models.

Altimetry data are also crucial with other spatial and in situ data to better anticipate extreme events affecting coastal areas, where most of the economic activities take place and half of humanity is currently living.

In addition, altimetry observations play a crucial role in monitoring water levels in rivers, lakes, and reservoirs, providing key data for hydrological and climate studies. When combined with water extent measurements, from SWOT or satellite imagery, these observations allow estimating river discharge, which is an Essential Climate Variable. River discharge is fundamental for understanding the global water cycle, managing water resources, and predicting floods and droughts. It supports various applications, including climate modeling, agriculture, and disaster risk management.

3.5 CEOS OST-VC and OSTST

The CEOS Virtual Constellations coordinate space-based, ground-based, and/or data delivery systems to meet a common set of needs within a specific domain. They leverage inter-Agency collaboration and partnerships to address observational gaps, sustain the routine collection of critical observations, and minimize duplication and overlaps, while maintaining the independence of individual CEOS Agency contributions.

The goal of the CEOS Ocean Surface Topography Virtual Constellation (OST-VC) is to implement a sustained, systematic capability to observe the surface topography of global oceans and to guarantee the continuity of the reference altimetry series called the climate series. OST-VC links CEOS Agencies, the Ocean Surface Topography Science Team (OSTST), and the altimetry user community. It is suited to discuss constellation-wide programmatic issues related to altimetry missions and high-level constellation user needs.

The work done by the OSTST is fundamental to feed IPCC experts reports and is a significant contribution to the seven UN Ocean Decade major objectives (https://ozeandekade.de/en/un-ozeandekade/), mainly “An accessible ocean”, “A predicted ocean” and “A safe ocean” objectives.

OST-VC also interacts with the other CEOS virtual constellations, mainly linked to ocean (SST-VC for Sea Surface Temperature, OC-VC for Ocean Color, COAST-VC for The Coastal Observations

Applications Services and Tools and OSVW-VC for Ocean Surface Vector Wind). OST-VC is also involved in other CEOS initiatives (i.e., in 2023, The Coastal Observations Applications Services and Tools (COAST) Ad Hoc Team, e.g., CEOS Analysis Ready Data Oversight Group, the Working Group on Capacity Building and Data Democracy).

The OSTST is renewed every 4 years by a ROSES call managed by NASA-HQ/NOAA for the US (only addressed to PIs fundable by NASA) and a TOSCA call managed by CNES/EUMETSAT (addressed to the others worldwide PIs). There is a strong interaction with other mission science or validation teams (i.e.: SWOT, Sentinel-6, Sentinel-3, CryoSat-2, CFOSAT, or SARAL teams often have dedicated splinter meetings during OSTST meetings). The OSTST science Team will be renewed in 2025. In parallel, a SWOT Science Team has been set up in 2015, and renewed in 2020 and 2024, to address the specific scientific objectives of this innovative mission. In particular, SWOT is bringing together, for the first time, a global hydrology community to collaboratively advance the understanding of altimetry observations for inland water monitoring. By enhancing our ability to study rivers, lakes, reservoirs, and wetlands, wide swath altimetry is paving the way for groundbreaking hydrological science from space. This community will continue to grow, as SWOT marks the beginning of a new era in satellite-based hydrology.

Due to this rich context, with the increase of space missions embarking altimeters and the relevant multi-sensor science studies utilizing altimetry data, and due especially to the carbon footprint of travel and the new science travel ethic recommendations, a strategy has to be put in place in the coming years to optimize the synergies of all the dedicated altimetry teams and associated meetings.

4 User Needs

As indicated above, the altimetry missions and applications have evolved over time as their capabilities, precision, and number increased. The landscape now includes a wide span of realms: large-scale and mesoscale ocean circulation, ocean-atmosphere interactions, global and regional sea level change, geodesy and geophysics, coastal sea level and circulation, extreme events, sea ice and land ice observation, river basin monitoring, inland water volume changes, river runoff to the ocean, global and local hydrology.

This Section breaks down the user needs for the various applications, whereas Section 6 summarizes the ‘gaps’ (what has not been achieved by the current constellation).

4.1 High level thematic user needs

4.1.1 Ocean

Ocean surface topography plays a central role in supporting the study of oceanic processes across the globe. It meets operational needs that depend on knowing the ocean state, and it supports investigations of oceanic processes over a range of length scales from tens to hundreds of kilometers. Here we summarize key applications and you will find recommendations for future research in Section 6.

4.1.1.1 Ocean Dynamics

Sea surface height carries the fingerprints of shifting mass, heat, and freshwater throughout the water column, making it a strong constraint for ocean observing systems (e.g. Morrow et al. 2017). Satellite-based ocean surface topography measurements (along with winds and sea surface temperature) are instrumental in estimating ocean surface currents (Bonjean & Lagerloef 2002). Gradients in sea surface height variability indicate the time-varying geostrophic velocity at the ocean surface, often referred to as “balanced flow”. Since geostrophic flow extends into the ocean interior, sea surface height provides key information about ocean transport throughout the upper ocean. Geostrophic eddies (meandering jets and vortices, 30-200 km in diameter) dominate oceanic kinetic energy (Ferrari & Wunsch 2009). On eddy scales, altimetric observations indicate the ocean's distribution of heat, salt, nutrients, and other chemical properties, through processes that include frontogenesis, stirring, and mixing.

Ocean surface topography also relays information about tides, surface waves (see Section 4.1.2), and internal waves. In polar regions, altimetry measures ocean, ice, and snow height, providing information about the changing cryosphere and ice-ocean interactions (see Section 4.1.5). In addition, sea surface topography returns signals over rivers and large lakes, measuring the rise and fall of freshwater storage outside the ocean (see Section 4.1.3).

On top of that, the small-scale surface ripple, reflected in the surface backscatter, gives us measurements of surface winds (see Section 4.1.2).

4.1.1.2 Operational oceanography

Satellite altimetry plays a fundamental role in operational oceanography (Le Traon et al. 2017), providing data needed to constrain the 4D mesoscale circulation in ocean models. Assimilation of sea level anomaly observations helps to generate better ocean analysis (Agarwal et al. 2022), which is used to initialize models for an accurate forecast. Since the sea surface height reflects processes throughout the water column, altimetry provides information needed to make adjustments to the vertical thermohaline structure. Near real time global and high-resolution altimeter measurements serve a wide range of applications: maritime transport, marine safety, search and rescue operations, combating marine pollution events, offshore operations and coastal hazard forecasting (see Section 4.3). Both Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs) (e.g., Hamon et al. 2019) have demonstrated the major contribution of altimetry to ocean modeling and data assimilation.

4.1.1.3 Biology

Marine ecology and biogeochemistry strongly depend on 10-100 km processes that are in large part detected by altimetry (McGillicuddy 2016). Many ecological processes, such as phytoplankton demography or the duration of foraging trips for marine predators, vary on time scales of days to months that also characterize variability of this regime. The eddy circulation advects phytoplankton, modulates nutrient pathways in the horizontal and in the vertical, and mediates the distribution, encounter rates and behavior of phytoplankton consumers and higher trophic levels (Lehahn et al. 2018). Key elements of the Earth system, such as the biological component of the oceanic carbon pump, are strongly dependent on the geostrophic components of ocean circulation detected by altimetry.

Fish, mesopelagic species, and top predators are also found to respond to eddy dynamics. These findings are important for managing marine resources (e.g., fish bycatch reduction), for correctly choosing the location of marine protected areas, and for anticipating how large-scale climate change will ultimately impact marine ecosystems and their diversity.

4.1.2 Sea state and surface currents

Global oceans play an important role in regulating the Earth's climate as they redistribute heat, freshwater, carbon, nutrients around. Global oceans are also extremely important for the sustainable economic developments of various coastal countries. Tourism, naval operations, fisheries, green energy, shipping are major industries that are impacted by changes in ocean state. Hence it is mandatory to monitor ocean state for operational oceanography. Since 1993, altimeters allow us to retrieve geostrophic currents from sea surface height measurements allowing us to understand better how the water moves around the planet but also to trace debris, aid in navigation, etc. Ocean state is largely dependent on wind conditions. Winds are major drivers for ocean waves and currents. Apart from tides and other unusual events like earthquakes, ocean waves are largely generated by the wind and consume much of the kinetic energy of the winds. The majority of ocean related activities is impacted by these wind-generated ocean waves. At any given time, the ocean surface is a combination of wide ranges of waves of varying amplitudes. In deep water, wave growth depends on the wind velocity, wind duration, and fetch conditions. Their dissipation is predominantly due to white capping, bottom friction, and depth-induced breaking.

Nadir altimeters provide the along-track significant wave height and the normalized radar backscatter which is closely related to wind speed and mean square slopes of the waves.

Sea state forecasting has been improved significantly during the last decade, thanks to significant wave height provided from multi-mission altimetry covering all ocean basins with a good spatial and temporal sampling, as illustrated by Figure 1. It was also shown by Aouf et al (2021) that adding information on wave direction and wave number as provided by the CFOSAT/SWIM near-nadir beam has a positive impact on the wave forecast. As a result, the monitoring of high waves during storms and cyclones is becoming increasingly reliable for wave submersion warnings, for ship routing, and for the safety of the population in coastal areas. However, there is still room for improvement in terms of revisit and coverage for specific seas that may be exposed to dramatic changes as a result of rising sea levels, such as the islands of the Pacific Ocean. And in the coming years, it will be necessary to ensure better monitoring of sea state in polar oceans and marginal ice zones, in order to better understand the evolutions in the different ice-wave-ocean components, and the consequences on ocean circulation.

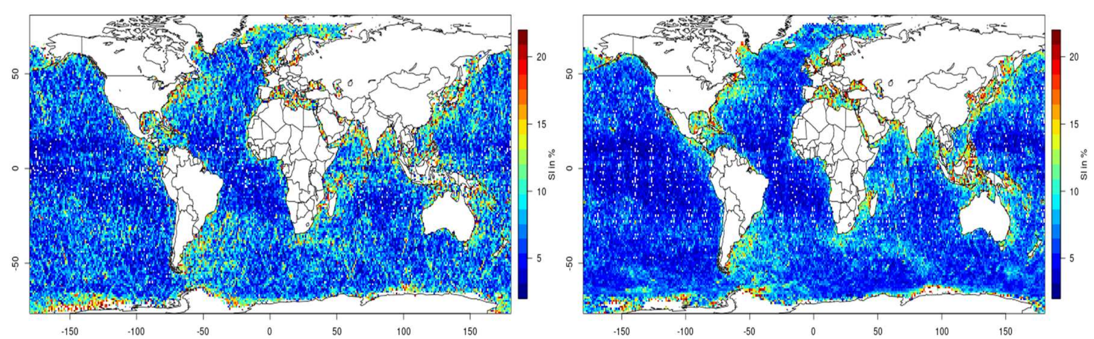

Figure 1. Map of Scatter index (in %) of Significant Wave Height (SWH) from Copernicus Marine Service (MFWAM model) for January-February-March, in comparison with HY-2 independent SWH data. (left) stands for 2017, and (right) for 2023. The global average scatter index of SWH decreases to roughly ~8 % in 2023 in comparison with ~10% in 2017, thanks to additional altimetry missions (Sentinel-3A and -3B, Sentinel-6 MF and CFOSAT) in the assimilation system. The smaller scatter index is, the better for wave system performance.

Another very important topic for monitoring of sea level is the strong dependency between sea state and surface elevation retrieval (Putnam et al. 2023). Better spatial data coverage in coastal areas will improve sea level retrieval and better estimate of sea state dependent uncertainties. Recently, the use of SAR mode (delay-Doppler) altimetry opens up the capacity of retrieving directional wave spectrum with a cut-off limitation about 200 m of wavelength (Altiparmaki et al. 2022). This could enable better correction of sea-state bias for sea surface height retrieval. Also, denoising processing such as EMD (Empirical Mode Decomposition) on wave data from altimetry has proved its interest for a better representation of wave-current interactions in ocean regions dominated by extreme waves, such as the Agulhas retroflection region (Quilfen et al. 2019).

The use of altimetry data for wave climate analysis in different ocean regions (Echevarria et al. 2019) is necessary to better understand the evolutions affected by climate change. The need for data continuity and better density in oceanic zones of interest remains a priority to prepare for the impact on beach erosion and sediment transport in coastal areas where all the population's economic activity is concentrated.

In other respects, better understanding of wave variability at large and small scales plays a key role for accounting wave-coupled physical processes such as Stokes drift and wave-induced surface stress in ocean circulation (Law-Chune et al. 2018). Coupling experiments between waves and ocean models with improved sea state by wave data assimilation has revealed a significant impact on surface currents, particularly in the tropics, western boundary currents and Southern Ocean (Aouf et al. OSTST 2022, see

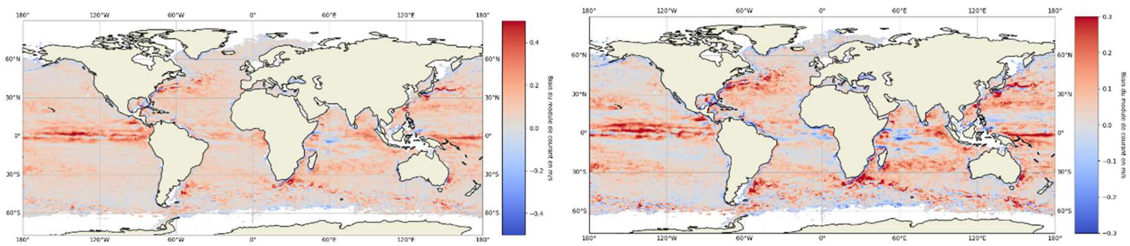

Figure 2.

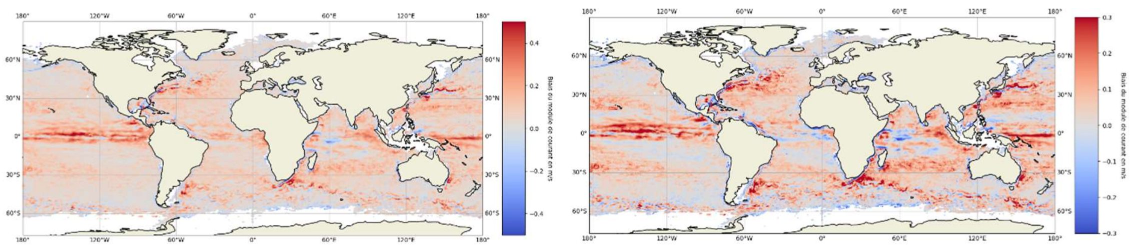

Figure 2. Average bias of surface current intensity from coupled simulations of wave model MFWAM (left) and ocean model NEMO (right) during the period from January to June 2020. The comparison is performed with AOML monthly mean currents from drifters.

Wind-generated waves interact with ocean surface currents at all scales, so that wave properties, in particular their phase speeds and varying amplitudes, can be a unique source of information on surface currents (Barrick 1977, Kudryavtsev et al. 2005). The normalized radar backscatter measured by the altimeters is closely connected to the variance of the surface slopes as indicated by Nouguier et al. (2016). As a result, at scales larger than a few kilometers the radar backscatter is closely related to the wind speed (Munk 2009), while its smaller scale variation also follows current gradients (Kudryavtsev et al. 2005). Delay-Doppler altimetry should also be able to provide a measure of the surface velocity variance (Buchhaupt et al. 2021).

An increasing body of evidence recognizes the importance of wave-current interactions in coastal processes and correct prediction of both coastal flood hazards (Lewis et al. 2019, Lyddon et al. 2019) and hazards to navigation. Refraction of waves in the near coastal zone may be enhanced by combined effects of bathymetry and strong levels of shear in the current field. Observing these phenomena via Earth Observations requires both an improvement in retrievals from the near coastal zone and colocation of wave and current measurements across and downstream of regions of high current shear.

4.1.3 Inland waters

Continental surface water plays a crucial role in the global water cycle, which is the transport of water between ocean, atmosphere, continent and subsurface (Getirana et al. 2017, Papa et al. 2008, Dorigo et al. 2021). Continental surface waters (lakes, rivers and floodplains) are also intimately linked to global climate change. They are indicators of climate changes, they store and re-emit greenhouse gases, and their bed sediments can be used as an archive of past climate. Indeed, although the increasing concentration of greenhouse gases in the atmosphere is mostly due to land use and fossil fuels, it has also been demonstrated in several studies that lakes and wetlands store carbon dioxide and methane and re-emit them to the atmosphere (Raymond et al. 2013, Pi et al. 2022). This led Williamson et al. (2009) to define lakes, for example, as sentinels, regulators and integrators of climate change. The same applies to rivers and floodplains.

It is therefore essential to quantify these different elements and to understand their linkage with the overall climate system, in order to understand the global water cycle and its evolution from short to long time scales. Climate change is leading to an increase in the frequency and severity of devastating floods (Hirabayashi et al. 2013, IPCC 2021), while also exacerbating droughts in arid regions such as the Central Asia (Li et al. 2017). As a consequence, the intensification of precipitation in some regions, for example, increases surface runoff, the expansion of floodplains or lakes, and also intensifies the hydrological cycle (Durack et al. 2012, Huntington 2005). A large literature based on modeling and remote sensing data has shown that increased precipitation on the one hand and glacier melt on the other have led to a strong increase in area (and water level and storage) over the Tibetan Plateau since 2000 (Zhang et al. 2021). In East Africa, a strong intensification of precipitation has also been observed since the end of 2020, leading to extremely high floods, for example in South Sudan, and to lake level increases in the region (Herrnegger et al. 2021). On a global scale, Syed et al. (2010) showed that river discharge increased by 540 km^3/year between 1994 and 2006. The water cycle is therefore strongly affected by this variability, which also poses a risk to the security of water supply (Eekhout et al. 2018). On a global scale, Yao et al. (2023) have shown that over the last 40 years, more than half of the 2000 largest lakes and reservoirs have shrunk due to climate change as a result of water consumption for human uses. They show that endorheic lakes are more affected by this trend than exorheic lakes, and that inter-annual variability in lake and reservoir water storage is also significant, although the long-term trend still dominates. Continental waters are also a driving component of the global sea level rise, as increasing (or decreasing) discharge in large river basins and retention (or release) of water in artificial reservoirs and natural lakes also contribute positively (or negatively) to global sea level rise. Wada et al. (2017) and Frederikse et al. (2020) have shown that the development of water infrastructure over the last century has had a profound impact on the hydrological cycle, including the construction of dams, which either impound rivers to create artificial reservoirs, or raise the water level of natural lakes, which have gradually reduced continental runoff to the ocean.

Compared to the total amount of water on Earth, continental waters represent a very small fraction, but they have a critical impact and role for terrestrial life and the environment (Kundzewicz et al. 2007). Moreover, increased human water use is an additional factor of vulnerability for water resources, which in turn exposes the world population to water scarcity due to increasing water withdrawals for agriculture, industry and human consumption (Vörösmarty et al. 2010, Wada et al., 2017).

Several ECVs are related to the water cycle, and among them some are directly related to lakes and rivers: water height, area, volume changes, river discharge.

However, it is currently a challenge to provide such datasets with high accuracy and consistency over long time periods and in an automatic manner, which is required not only by GCOS for climate change studies, but also by some core services (such as those defined by the European Union within the Copernicus program) for various applications in hydrology.

Water level of lakes and rivers can be derived from satellite altimetry and altimeters are therefore a key tool to meet the GCOS requirements. For example, lake water levels are directly derived from satellite altimetry measurements from a historical constellation of several missions, starting with the US/French TOPEX/Poseidon (1992-2003), followed by Jason series (2003-2020) and continuing with the current Copernicus Sentinel-6 mission. Today, this technology can monitor several hundred lakes

(Cretaux et al. 2023), with the potential addition of many more as processing techniques improve (e.g. Biancamaria et al. 2018). The accuracy of the measurements ranges from a few centimeters in large lakes to a few decimeters in narrow lakes. The temporal resolution varies from near daily for the largest lakes to monthly for the smallest. In general, for large lakes there are no significant challenges to operational water level monitoring at high spatio-temporal resolution. Over the past 25 years, a large number of published studies have demonstrated the ability of this technique to determine water height along rivers. Although satellite altimetry was initially used over large rivers such as the Amazon (Birkett 2002, Getirana & Peters-Lidard. 2013, Paiva et al. 2013a, Paris et al. 2016 and many others), improvements in the retracking algorithm and the development of SAR (Synthetic Aperture Radar) with some of the latest altimeters (on board Sentinel-3 and Sentinel-6), smaller rivers such as the Danube or the Po (Nielsen et al. 2022) or the Garonne (Biancamaria et al. 2018) can now be monitored with high accuracy. After more than 20 years of research and development in both hardware and software, the accuracy has gone from 50-80 cm with the historical missions (Calmant et al. 2013) to 10-20 cm today with the SAR missions (Kittel et al. 2021). Thanks to these performances, satellite altimetry data have been assimilated into hydrological models to improve their parametrization for the determination of river discharge over ungauged rivers (Garambois et al. 2017, Kittel et al. 2020). Some other authors have also developed new methods, that combine the water level above the river, derived from satellite altimetry, with optical satellite imagery to measure the river discharge, which in turn allows the development of operational flood forecasting algorithms in ungauged basins (Tarpanelli et al. 2017, 2022, Scherer et al., 2020).

With the advent of wide-swath altimetry observations, hydrology has entered a new frontier. For the first time, we can simultaneously monitor water levels and extents with unprecedented spatial density. This capability, made possible by SWOT, enables the estimation of river discharge and lake storage on a global scale, allowing continuous monitoring of water levels and volumes in previously ungauged basins. Several studies have leveraged SWOT observations alongside hydraulic modeling and data assimilation techniques to generate global river discharge estimates (Durand et al, 2023, Oubanas et al., 2018, Frasson et al 2021, Larnier et al., 2021). These derived products are essential for various hydrological applications and require precise and accurate measurements of the water elevation, slope and width for rivers as well as surface area for lakes. Despite SWOT's exceptional spatial coverage, its temporal frequency remains insufficient for comprehensive and continuous river monitoring. To address this limitation, high-frequency observations are needed as a complement to wide-swath dual measurements of water level and extent, in an operational framework. This integration would enable the monitoring of rapidly changing dynamics and enhance flood-monitoring capabilities from space.

The SWOT mission, providing direct, high-resolution measurements of the water height and volume of nearly all water on the Earth's surface is now allowing for a new understanding of how the Earth water's storage and movements change in a warming climate (Vinogradova et al., 2025).

4.1.4 Coastal and continental shelf waters

Since the user needs for land-based observations and those within 3 km of the land are very different from needs of mariners in the open ocean, we discuss here the coastal waters (Sections 4.1.4.1 through 4.1.4.4) separately from the continental shelf waters (Section 4.1.4.5).

4.1.4.1 Long-term coastal sea level rise and impacts on humans

One of the severe long-term impacts that climate change will have on human society is the rise of sea level (see Section 4.1.9). Accurately monitoring this process in order to make accurate, regional, model-based predictions of sea level rise is essential to mitigate this consequence of climate change. As altimetry is the only observational technique capable of monitoring sea level globally (tide gauges cannot be installed everywhere), the societal demand for altimetric estimates of coastal sea level is increasing.

Thus, we see a need for accurate, precise, drift-free measurement of coastal sea level (relative to the land, as well as to the reference ellipsoid). The present collection of existing and past altimetry missions, however, is not ideally suited to measuring coastal sea level (because the footprint of most radars is large and several of the corrections, such as for the wet troposphere, have larger errors near the coast than in the open ocean). Hence, there is an unmet need to measure sea level close enough to the coast for direct applicability to coastal infrastructure and habitation.

4.1.4.2 Short-term, extreme sea level variation and impacts on humans

Similarly, but on shorter time scales, coastal inundation (see Section 4.1.7) associated with extreme weather events or earthquake-triggered tsunamis is one of the greatest impacts that high-frequency (time scale of days or shorter) ocean variability has on human society. Here, the role of altimetry is to reduce the human and economic losses by increasing the accuracy of the warning system. This can be achieved, for example, by using altimetry to monitor the Tropical Cyclone Heat Potential, which influences the track and intensity of a tropical cyclone, or the sea level near where the earthquake occurred, which can be used directly for initializing a tsunami prediction.

The main limitation today is due to the fact that weather systems move quickly compared with the repeat-times of nadir-sampling altimeters, so many storm centers are not sampled. A better temporal sampling is required for this application.

4.1.4.3 Coastal tides and tidal currents

Coastal sea level is also influenced by other less-extreme processes. The dominant one of these is the barotropic tide, which is still inadequately predictable at locations away from where a tide gauge has been in place for a sufficient period. The currents associated with the tide are even less predictable. Improved tidal models continue to be released, made possible by the increasing length of the altimetry time series.

Internal tides, generated where tides interact with sills and the continental shelf, have been blamed for the loss of an Indonesian submarine as well as damage to numerous pieces of marine infrastructure (pipes, cables, etc) in the coastal zone. Sampling is also key for advancing our observation and knowledge of internal tides.

4.1.4.4 Non-tidal coastal sea level and currents

Increasing the accuracy of the predicted tides and tidal currents will not completely satisfy all users, because much of the uncertainty of any sea level and currents forecasting service is due to processes not associated with tidal forcing. The non-tidal component of coastal sea level and currents depends on many things (wind, atmospheric pressure, waves, etc), not all of which are adequately sampled. Coastal ocean forecasting systems are becoming more widespread to meet the needs of stakeholders at or near the coast but it is fair to say that it will be quite some time before user demands for accuracy will be met. One reason for this is that nadir-sensing altimeters sample the ocean too sparsely and too infrequently for the needs of coastal ocean forecasting where the time scales of importance are often less than a day, and spatial scales of importance are ~km. Wide-swath altimeters (such as SWOT), by sensing sea level as a 2D field, will improve the skill of coastal ocean forecasting systems once a constellation of such missions becomes operational, better serving societal needs in marine safety and security, ecosystem management, environmental protection, and so on.

4.1.4.5 Continental Shelf Waters (between 3km from the shore and the shelf-break)

Although representing only a fraction of the ocean's surface area and volume, the oceanic regions over the continental shelves support marine ecosystems that supply an oversized portion of the global fisheries catch. These regions also provide other important economic, ecological, and cultural benefits (and threats) to the growing human populations in coastal communities. Examples include recreation and tourism, transportation, CO_2 absorption and heat transport, energy generation, preservation of biodiversity, increases in hypoxia and ocean acidity, pollutant transport, indigenous practices, etc. Given the fluid nature of the ocean, better explanations for, and predictions of, changes in these systems require improved understanding of the physical processes that control regional ocean currents and sea levels.

Although satellite altimeter data have contributed greatly to our understanding of continental shelf ocean processes over the past three decades, in situ observations demonstrate that traditional altimeter data miss much of the variance in currents and sea levels over the shelves. This limitation is due to: (i) the low spatio-temporal frequency of altimeter sampling, as compared to the spatio-temporal process that dominate continental shelf seas; and (ii) the fact that the rapid and small-scale ageostrophic components of the currents often contribute more to the velocity variance than the geostrophic currents derived from altimeter sea levels. Increasing the spatial resolution of the altimeter height data by using swath altimeters will help narrow the gap with the in-situ observations. Likewise, directly measuring surface currents by the proposed high-resolution swath sensors would provide spatial resolution of ageostrophic currents. However, denser temporal sampling is also required to resolve the high-frequency currents that occur over continental shelves, geostrophic and ageostrophic. Thus, the need is for denser spatial and temporal sampling of surface currents and sea level, which will both increase the accuracy of our observed variability over the shelves and improve the models that predict future changes in these systems.

Two examples show the ecological importance of currents over continental shelves. Over the wide Patagonian shelf, satellite altimetry currents explain 53% of the interannual variability of the squid abundance (a 1800M USD annual fishery during favorable years (Figure 3)). Over the mostly narrow shelf next to the western U.S., altimeter-derived currents covary with the presence of cold-water zooplankton along the Oregon coast (high in fats, good for juvenile salmon survival and advected from the north), as opposed to the presence of warm-water zooplankton (low in fats, poor for juvenile salmon survival and advected from the south (Strub et al. 2022 OSTST meeting). Other authors would undoubtedly present different examples of the impact of currents and sea level over the continental shelves. The point is that these examples are numerous, occur everywhere over continental shelves and affect both regional and global human populations.

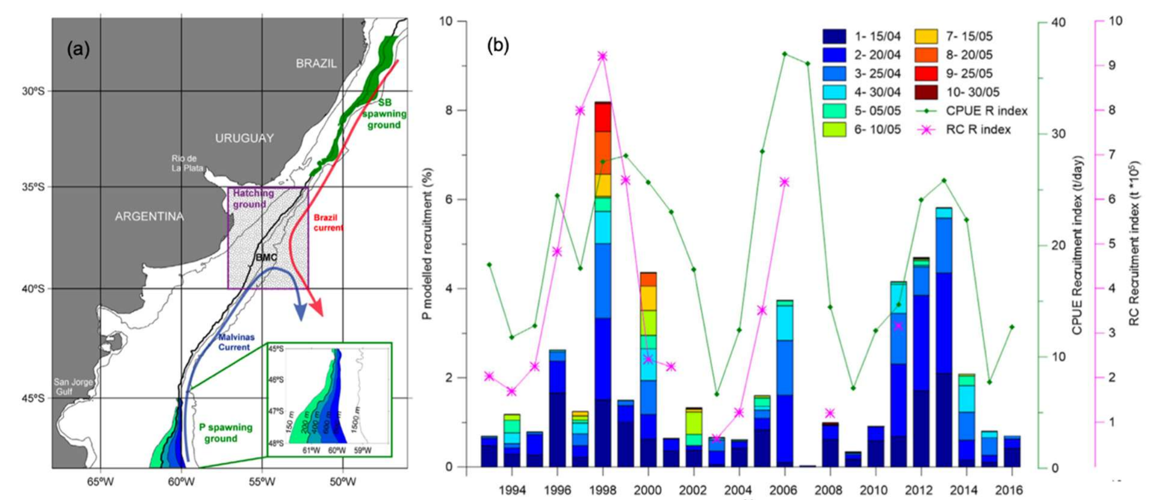

Figure 3. (a) Study area: the two spawning grounds (Southern Brazil, SB and Patagonia, P) of the Argentine shortfin squid (Illex argentinus) and the inferred hatching ground. Different colors of the P spawning ground refer to different sectors where particles were released and then tracked considering satellite altimetry currents. The Brazil/ Malvinas Confluence region is marked by BMC. Black lines are isobaths 50 m, 200 m (bold line), 800 m and 1,500 m. (b) Recruitment index versus modeled recruitment for the Patagonian spawning grounds. Color bars represent the percentage of successful particles (left axis), and green and magenta line the recruitment

indexes, respectively (right axis). Different colors in the bars indicate the success of different eggs batches (particles) set free along the spawning season. The legend indicates the releasing period represented by each color. For more details see Figure 1 in Torres Alberto et al. (2021) Adapted with permission from Wiley.

4.1.5 Ice

Altimetric observations of ice topography play a central role in understanding rapid climate change and support the study of important feedback processes in the cryosphere. Here we summarize the key applications of polar altimetry.

4.1.5.1 Role of Polar Altimetry in Understanding Climate Change

Ice at Earth's high latitudes exerts strong controls on the climate system, influencing global atmospheric patterns, ocean thermohaline circulation and planetary energy balance (Barry & Gan 2022). Floating ice provides a vibrant marine habitat, and in the Northern Hemisphere it sustains indigenous communities. Diminishing sea ice is exacerbating the rise in global temperatures while mass loss from Earth's ice sheets is accelerating sea level rise (Fox-Kemper et al. 2021). Due to their scale and inaccessibility, complete observation of Earth's polar regions requires a suite of remote sensing techniques. Although ice extent has been monitored successfully for over four decades with two-dimensional microwave and optical imagery, much less is known about ice thickness which is needed to calculate mass balance, an important metric in climate modeling (Edwards et al. 2021). Altimeters provide less dense, but complementary measurements of ice in the vertical dimension, i.e., measurements of ice surface height, from which land ice mass variations (Shepherd et al. 2019) and sea ice thickness, and hence volume (Laxon et al. 2013), are derived. Modified reprocessing techniques in ice-covered waters also provide measurements of polar sea level anomalies and geostrophic circulation (Doglioni et al. 2023). Moreover, because we can track ice sheet elevation change in higher spatial resolution with altimetry than with gravimetry, it can be used to understand the mechanisms of mass loss. A long-term altimetry plan to monitor Earth's polar ice, snow and ocean topography is therefore of interest to both operational and scientific users of Arctic and Antarctic observations.

4.1.5.2 Opportunities and Needs in Polar Altimetry

Newly identified risks and increasing end-user needs necessitate the evolution of altimetry techniques and comprehensive observations are essential at both poles. The Arctic is emerging as a more viable area of commercial maritime activity, offering new opportunities but also challenges in term of geohazards, geopolitics, global security, environmental protection and safety at sea.

Applications: Since the early 2000s, ICESat (2003-2009), CryoSat-2 (2010-present) and ICESat-2 (2018-present) have measured changes in ice surface topography. Their orbital inclinations were designed to provide extensive coverage of the poles and they are the only altimeters capable of sampling poleward of 81.5° latitude. Observations from these missions have revealed a decline in Arctic sea ice thickness and volume over the last two decades (Kwok 2018), thinning and volume loss from Antarctica's ice shelves (Paolo et al. 2015), accelerating ice loss from the West Antarctic Ice Sheet (Shepherd et al. 2019) and mass loss from Greenland which now dominates ice sheet contributions to global sea level rise, yielding ~9 mm between 2003 and 2019 (Smith et al. 2020).

As Arctic sea ice declines, the capability to track the thickest multiyear ice floes in the high Arctic (above 81.5°, the latitudinal limit of most oceanographic altimeters) is important, as shown in Figure 4. In the Southern Hemisphere, increasing global temperatures are expected to lead to more snow deposition across the East Antarctic Plateau and limiting coverage to 81.5° latitude would miss ~20% of the area. To capture both abrupt changes and separate interannual variability from long-term trends, such as distinguishing between a transient evolution versus an instability in the West Antarctic Ice Sheet, continuous records of elevation change from altimetry are critical. Other pressing needs include monitoring melt rates on the Greenland Ice Sheet and at the base of ice shelves and floating ice tongues in Antarctica, which depend on measurements of surface elevation change obtained with adequate spatial resolution and high temporal fidelity.

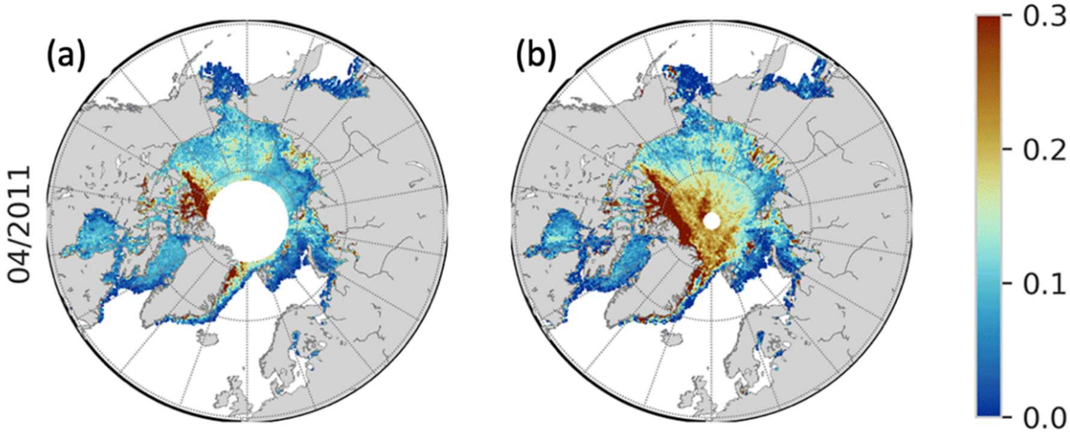

Figure 4. Arctic sea ice freeboard (the portion of an ice floe above sea level) in April 2011 from (a) Envisat and (b) CryoSat-2, illustrating that the thickest region of ice is north of the Envisat latitudinal limit at 81.5° and the necessity of avoiding a "pole hole". From: Bocquet et al. (2023).

The Arctic Ocean has been seeing drastic changes, it has warmed faster than any other part of the Earth. Sea level has been rising rapidly in the Arctic region but polar oceans are often not included in the estimations of global mean sea level (Rose et al., 2019). It is therefore important to monitor sea level in these fast-changing polar regions. Dynamic Ocean Topography up to 81.5° can be retrieved from altimeters such as CryoSat-2 (Armitage et al., 2016) and CRISTAL mission in the future.

Forecasts, climate modeling and ice services: Inverse modeling of ice sheet surface elevation for optimizing the otherwise inaccessible physical parameters of the ice sheet base have the potential to improve forward modeling of ice sheets. This newly evolving field would benefit from satellites in short repeat orbits. Similarly, improved knowledge of sea ice thickness is an important priority for climate modeling (Massonnet et al. 2018). Assimilation of sea ice thickness observations into forecasting systems can have a considerable impact for forecasting across a range of timescales. Although not yet fully operational, studies have shown that ice thickness information improves sea ice forecasts from a few days to several months (Allard et al. 2018). Correct initialization of models with sea ice thickness is important for long-range forecasting applications (Blockley and Peterson 2018) since sea ice volume changes on much longer timescales than ice concentration, and anomalies can persist for several years (Day et al. 2014). On the other hand, sea ice thickness forecasts on sub-daily timescales have many maritime applications particularly for ship routing (Wagner et al. 2020). Short-range operational models, that forecast conditions out to ~1 week, require daily sea ice thickness with high spatial coverage at low latency (not more than 72 hours and ideally less than 24 hours) to complement assimilation of ice concentration. Sea ice and snow thickness are also important for constraining ocean-atmosphere energy transfer in coupled models as errors in their specification can have large implications for atmospheric forecasts (Blockley & Peterson 2018). For ice mass balance studies over sea ice, year-round observations of ice thickness, even during summer melt, are needed.

Advanced observation techniques: Since individual nadir satellite altimeters survey a relatively small area along their orbits due to their footprint size, fusion of data from different sensors can reduce retrieval errors (Ricker et al. 2017) or be used to obtain improved spatial coverage from complementary orbits (Gregory et al. 2021), both important factors for data assimilation. Snow depth on sea ice remains challenging and advanced observation techniques are needed such as dual-band altimetric methods that combine data from two altimeters operating at different frequencies (Guerreiro et al. 2016). The Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL), scheduled for launch in 2028, will embark a high-resolution dual-band radar on a single platform to reduce errors in ice thickness retrievals by measuring overlying snow depth simultaneously with ice freeboard (Kern et al. 2020) and to continue the monitoring of sea level in the polar oceans, at latitudes not sampled by the TOPEX-Jason-Sentinel-6 series. A satellite constellation with polar coverage at multiple bands (radar and laser wavelengths) would provide better spatial sampling of the vast polar regions, lowering the revisit interval. This would offer higher temporal frequency in observations, benefiting forecasters, modelers, ice services and other operational maritime activities. Gaps in coverage should be avoided (for further discussion on risks, see Section 6).

4.1.6 Geodesy

Satellite altimetry provides foundational data for various geodetic reference surfaces like the gravity field, the mean sea surface, and the geoid (Rummel et al. 1990). The mean sea surface is the geodetic reference for mapping sea surface topography and sea level change. In the era of climate change, accurate mapping of sea level related to cyclones, surges, and hurricanes is vital for coastal protection. The geoid is vital to map as it reflect the gravity field of the Earth. The fine scales of the geoid and mean sea surface is related to bathymetry and the surfaces will have small dips and bumps mimicking seafloor features (Wessel 2001).

Satellite altimetry is today the primary tool for studying and mapping bathymetry for more than two-thirds of the ocean basins that have not yet been surveyed by ship sonar. While shipboard surveys are the only means for high-resolution (200 m wavelength) seafloor mapping, moderate resolution (15-25 km wavelength) can be achieved using satellite radar altimetry at a fraction of the cost of bathymetric survey. Scientist still expect that there are more than 30000 seamounts with a height between 1-2 km still uncharted. Gevorgian et al. (2023) demonstrated the importance of recent improvements in satellite technology and how many of these could be recovered by increasing the spatial resolution and accuracy of satellite observations by a factor of two. The following Figure 5 from Sandwell et al. (2014) shows how new tectonic structures can be revealed over the Gulf of Mexico by mapping Vertical Gravity Gradients (VGG) from CryoSat-2 and Jason-1 altimeter missions.

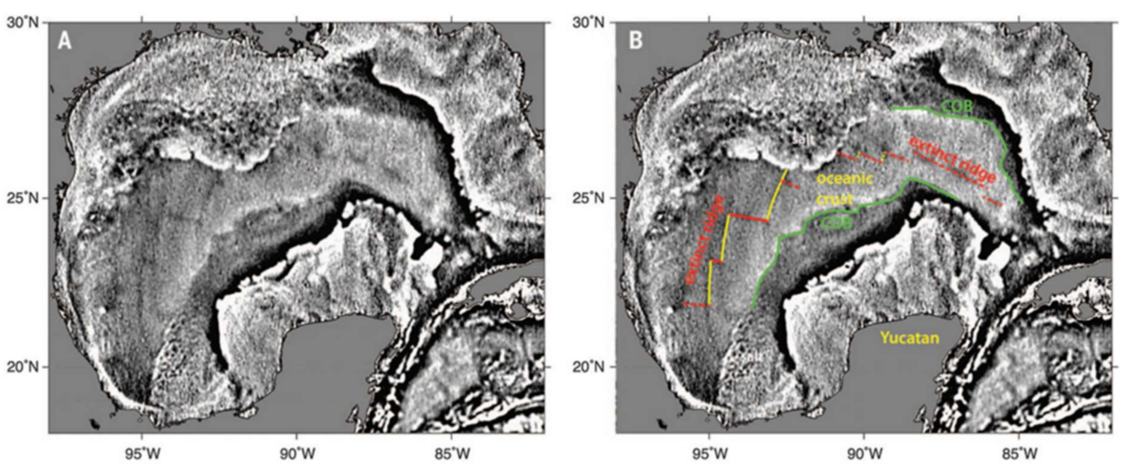

Figure 5. Gulf of Mexico VGG. (A) Uninterpreted. (B) The VGG reveals subtle signatures of the extinct spreading ridges and fracture zones as well as a significant change in amplitude across the boundary between continental and oceanic crust (COBs).

There is a globally coordinated effort to improve the mapping of the oceans called Seabed2030 (Mayer et al. 2018, https://seabed2030.org) aimed at providing a complete map of the seabed. Improved bathymetry mapping is important to a variety of oceanographic fields like ocean circulation and climate models, ecological and biological models, tide models, tsunami warning and geological knowledge about the sea floor and subsurface tectonic structures.

4.1.7 Extreme events

Extreme events have variable definitions depending on the phenomenon of interest; however a consistent aspect is the need to detect a significant deviation away from a known baseline or average set of conditions. The growing record of climate quality data records from altimetry, combined with the provision of near-real-time data, allows for the analysis of such phenomena. From the perspective of altimetry-derived variables, extreme events can include severe storms and their associated surges, winds, and waves conditions, tsunamis, and rogue waves. Understanding the occurrence of extreme winds, waves, and storm surges is essential for promoting marine safety, informing maritime operations, determining the positioning of coastal defenses and marine spatial planning. Altimetry can also provide important information towards understanding other extreme events, and their drivers, such as floods and droughts, through contribution to measuring water levels, and understanding changes in ocean heat content influences on storm formation.

4.1.8 Weather monitoring and forecast

Numerical Weather Prediction (NWP) has made significant progress with the use of coupled ocean-atmosphere systems and the assimilation of innovative observations. Recently, the assimilation of wind field provided by the Doppler lidar of AEOLUS mission, has revealed an improvement of the representation of large-scale winds in the atmospheric column, leading to better forecasting, particularly in the tropics and high latitudes of the southern hemisphere. However, coupled systems still face significant uncertainties concerning the estimate of momentum and heat fluxes at the air-sea interface, and also misfit or lack in the description of wave feedback in the Marine Atmospheric Boundary Layer (MABL). This clearly requires the availability of additional observations at ocean surface such as wave properties represented by energy (SWH from altimeters) and directionality of different wavelength scale of waves (from Sentinel-1 and CFOSAT). Moreover, the tropical ocean has one of the most energetic flux exchanges that drive the atmospheric seasonal variability. One can mention the example of the Atlantic Marine Intertropical Convergence Zone (AMI), which is a core engine of the tropical Atlantic climate system. The term AMI denotes the climatological envelope of tropical convective rain systems across the Atlantic Ocean between West Africa and South America. It is still difficult to describe accurately what controls the location and intensity of the AMI. Recently Giordani and Peyrillé (2022) demonstrated that upward motions represented by vertical velocity can be induced by wind convergence and by differential heating associated with the turbulent heat fluxes (Figure 6). Reliable sea level and surface currents from a constellation of altimetry data would be of utmost interest in order to account such frontogenesis processes in NWP models. This could have significant impact on the production of the vertical velocity and consequently on induced precipitation.

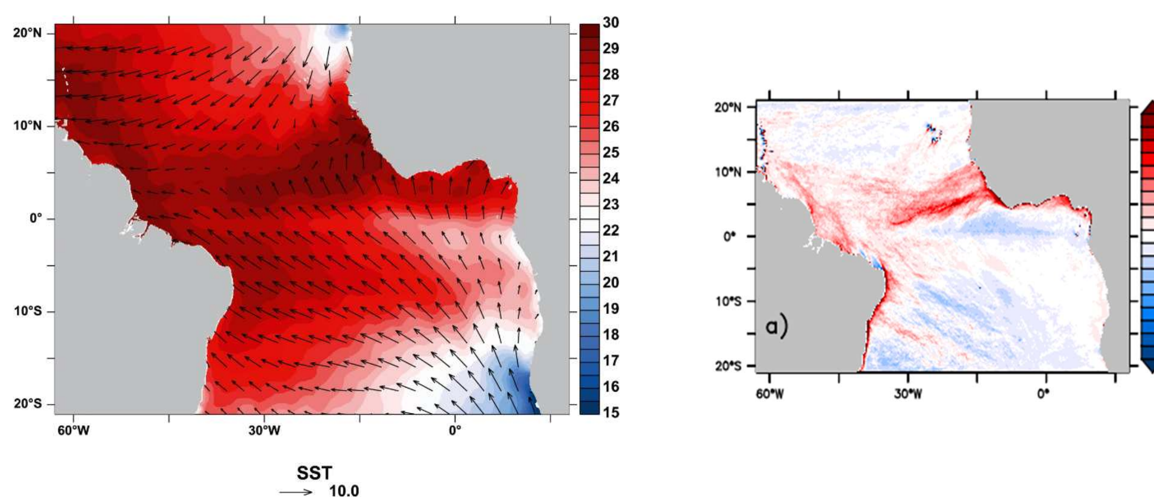

Figure 6. (left) average Sea Surface Temperature (SST) from high resolution MESONH atmospheric model in June 2010 (Giordani et al. 2022), which is one the largest SST anomaly in the recent years. Arrows shows the wind variability in the ocean zone. (right) average vertical velocity in the marine atmospheric boundary layer from model simulation (Giordani et al. 2022).

The assimilation of ocean surface wind field from various spaceborne scatterometers (ASCAT, HY-2B, HY-2C, HY-2D) into atmospheric models has significantly improved surface wind vectors in the recent years, enabling better wave forecasting and an accurate description of mesoscale and submesoscale ocean circulations. Verification of the quality of winds from atmospheric model involves comparisons with buoys and altimetry data, as performed by ECMWF in the frame of WMO Lead Centre-Wave Forecast Verification project (Figure 7). The along track wind intensity from altimeters has a good accuracy in comparison with buoys and model observations as given by Quartly et al. (2020). A constellation of altimeters would enhance the quality of surface wind in all ocean basins, both in deep water and particularly coastal zones where rapid changes can occur regarding to tides and orographic conditions. We also highlight the role of altimetry constellation in the frame of development of coupled assimilation at the air-sea interface in the future NWP models.

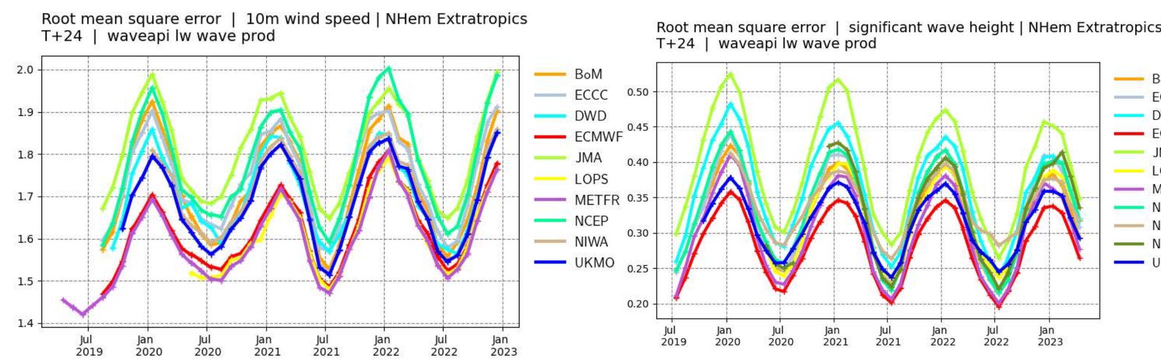

Figure 7. Root Mean Square errors from WMO/LC-WFV intercomparison of wind speed (left) and Significant wave height (right) from operational centers.

Surface wind observations are crucial relevance for waves and ocean forecasting. The altimetry missions provide along track surface wind speed based on retrieval model using normalized backscattered coefficient sigma0, representing the surface roughness. Several works have been dedicated to the calibration of wind and wave data (Ribal and Young 2019) from altimetry in order to analyse climate trends (over 30 years) of such parameters. Strong regional variations have been noticed by Young and Ribal (2019), and the area with the most significant increase in terms of mean wind speed is the Antarctic Ocean. Additional works on global trends in wave climate have been implemented in the frame of the CCI Sea State project. The Copernicus Marine Environmental Service has also been recommended to add altimeter wind speed in the multi-year products to allow users to implement their own wind and waves applications.

The intensification of tropical cyclones involves a combination of different atmospheric and oceanic conditions. Ocean heat plays a critical role in hurricane intensification as hurricanes are fueled from heat stored in the ocean and can intensify over warmer water. As water expands when it warms up, there's a strong correlation between sea surface height observations and the thermal structure of the upper ocean (Willis et al., 2004). Therefore, NOAA's National Hurricane Center is now using sea surface height measurements along with sea surface temperature to provide estimates of tropical cyclone heat potential to help better hurricane intensification forecasts in seven tropical basins where storms occur on a regular basis (Goni et al., 2009).

4.1.9 Climate Monitoring and Research

After 30 years of research and development, the sea level estimates derived from satellite altimetry measurements have reached a level of maturity that is unprecedented. Among the ECVs measured from space, sea level is arguably one of the most advanced with a quasi-global coverage, a very low ratio of missing or corrupted data, an advanced estimate of the uncertainties which accounts for the time-correlation in errors, a robust validation (through both the comparison with tide gauge records and the closure of the sea level budget) and a high accuracy (point-to-point accuracy of a few cm, Global Mean Sea Level accuracy of a few mm for a 10-day average).

This high level of accuracy and precision that exceeds early expectations, has enabled the detection of global mean sea level rise and acceleration (Figure 8) and the attribution to greenhouse gas emissions. These results are essential to validate current projections of sea level rise for the future decades (Figure 9). It has also enabled the closure of the sea level budget at the level of less than 1mm/yr, which confirms the drivers to be mostly ice melt and thermal expansion. The continuity of satellite altimetry measurements with the same level of accuracy and precision is absolutely essential to monitor sea level rise, sea level acceleration and to evaluate the associated impacts on the coast. However, there is still room for improving further the performance of satellite altimetry, predominantly by improving spatial resolution, polar coverage, and coastal measurements. Reduced uncertainties would enable the regionalization of the detection and attribution problem for sea level change. With regional detection and attribution of sea level change, sea level projections could be validated at the coast, and impact studies could be refined regionally helping coastal communities to better adapt to local sea level rise. Improvement in regional projections also require a longer record, meaning that several more decades of such observations are needed. Reduced uncertainties would also provide new observational constraints on the water-energy cycle response to greenhouse gas emissions by improving the estimate of the ocean heat uptake and the Earth Energy Imbalance, particularly in the deep parts of the ocean where direct temperature observations remain sparse. This is essential to better understand and predict the physics of current climate change. Altimetry has been also useful at documenting ice sheet changes since the 1990s and more so with the advent of laser altimetry missions since 2003. These studies have been integrated in the International Mass Balance Intercomparison Exercise (IMBIE), now in its phase 3, with other methods including time-variable gravity from GRACE/GRACE-FO and the mass budget method combining ice motion, ice thickness and reconstructions of surface mass balance. These products are very mature and extended in time on a monthly basis at present. As a result, we have a very deep understanding of the contribution of ice sheets to sea level.

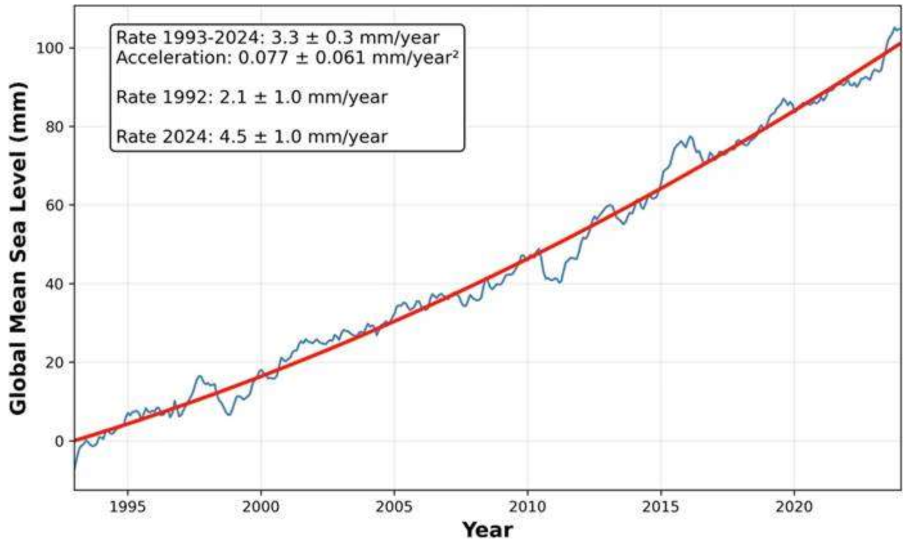

Figure 8. Rates and acceleration in global mean sea level from 1993 to 2024 (Hamlington et al., 2024).

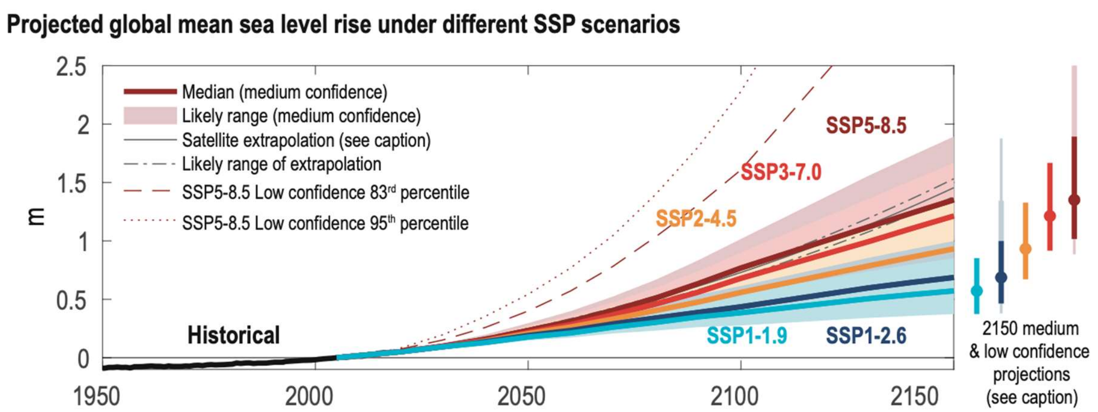

Figure 9.27 | Projected global mean sea level rise under different Shared Socio-economic Pathway (SSP) scenarios. *Likely* global mean sea level (GMSL) change for SSP scenarios resulting from processes in whose projection there is *medium confidence*. Projections and *likely* ranges at 2150 are shown on right. Lightly shaded ranges and thinner lightly shaded ranges on the right show the 17th–83rd and 5th–95th percentile ranges for projections including *low confidence* processes for SSP1-2.6 and SSP5-8.5 only, derived from a p-box including structured expert judgement and marine ice-cliff instability projections. Black lines show historical GMSL change, and thick solid and dash-dotted black lines show the mean and *likely* range extrapolating the 1993–2018 satellite altimeter trend and acceleration. Further details on data sources and processing are available in the chapter data table (Table 9.SM.9).

Figure 9. Figure 9.26 from IPCC AR6, Chapter 9, Page 1303 (IPCC 2021).

4.2 Calibration and validation needs

4.2.1 Calibration

The calibration of the altimetry reference missions mainly relies on the intercalibration phase when two satellites are flying in tandem configuration (Ablain et al. 2010). For this configuration, the two satellites are flying over the same area with a time difference limited to around 1 minute and even reduced to around 30 seconds for the latest missions. The measurements from the two satellites can be, therefore, directly compared and allow to neglect any differences in terms of ocean surface and atmospheric propagation delays. The duration of the tandem phase is typically around six months. From the global data set, the inter-mission bias can be estimated with an accuracy of better than 1 mm for the reference altimetry missions.

When two satellites are not flying on a tandem phase (after the tandem phase or for satellites on different orbits), a statistical approach can be used to compute the intermission bias. Comparing estimates from the two missions at crossovers generally offers the most accurate estimation for this configuration. However, as the time of sensing is different for the two satellites and the number of measurements compared is dramatically reduced compared to a tandem configuration, the accuracy for the intermission bias is then degraded. In their study, Zawadzki and Ablain (2016) mention an accuracy of 0.9 mm for the Jason-3 vs Jason-2 inter-mission bias estimation (derived from the tandem phase) but degraded up to 2.5 mm for the Sentinel-3 vs Jason-2 intermission bias estimation (in the absence of tandem phase). These numbers map into, respectively, uncertainties of 0.1 mm/year and 0.4 mm/year over 10 years for the Global Mean Sea Level (GMSL). The requirement from the climate users (GCOS) in 2011 was an accuracy for the GMSL trend of no worse than 0.3 mm over 10 years. Having a tandem phase is therefore critical to satisfy the needs of this community. In addition, as the climate experts are now also focusing on the acceleration component of the sea level rise, the demands on accuracy will likely become even more stringent.

Once the tandem phase is completed, the two missions rely on their instruments' long term calibration systems and in-situ monitoring to provide a stable altimetry time series. More specifically, the altimeters are usually calibrated using dedicated on-board calibration modes (Dinardo et al. 2022) while the radiometers can be calibrated using a combination of on-board and external calibration systems (Islam et al. 2017) and can necessitate special satellite maneuvers (cold sky maneuvers). Sentinel-6 MF has been the first altimetry satellite with a radiometer equipped with a dedicated on-board calibrator system (Supplemental Calibration System or SCS) for long term stability (Maiwald et al. 2020).

As an independent capability to control and calibrate altimetry mission estimates, in-situ measurements capabilities have been developed and deployed to support operational altimetry. Several dedicated sites have been equipped with tide gauges and buoys as close as possible to the altimetry ground tracks. In particular, it includes for the reference altimetry ground track, the Harvest platform in California, USA (Haines et al. 2021), the Senetosa site in Corsica, France (Bonnefond et al. 2021), the Bass Strait site in Tasmania, Australia (Watson et al. 2011) and the Gavdos site in Greece (Mertikas et al. 2015). It should be mentioned that the Harvest platform was decommissioned in 2022 and replaced by a tide gauge in Vandenberg in 2023 under the same track and 12 km away from the platform. The connection between the two time series has been supported with the deployment of buoys around Harvest with mostly continuous occupation since 2020. These sites provide a comparison between the Sea Surface Height (SSH) estimated from the satellites data and measured locally with on-ground equipment. They provide additional measurements as the tropospheric and ionospheric refraction corrections or estimates of the Sea Surface Height. This allows to monitor separately the different components of the satellite altimetry measurement. The data from the dedicated in-situ sites are very carefully checked and processed. They have offered long term records covering several satellites with continuous improvements in the calibration accuracy. Having several sites is also critical to address potential mission systematic geographical errors and experts have been intercomparing their results to improve the consistency in their respective calibration results.

In addition to the dedicated in-situ calibration sites, non-dedicated instrumentation from the global network of tide gauges is also being used (Mitchum et al. 2000) to calibrate satellite SSH estimates. Such a method presents some challenges as the tide gauge instruments are not consistently managed and calibrated. A major flaw is the lack of GNSS receivers for some gauges to accurately provide their position over time. However, this technique has proven to be valuable and efficient to detect potential jumps in the satellites' time series.

The previous techniques are based on the comparison of the SSH. A different calibration approach has been developed with the use of transponders (Denys et al. 1995). Transponders are active on-ground instruments that basically receive and transmit back the altimeter signal with a significant amplification. The estimations are independent from the sensed surface and present a low level of noise compared to the SSH comparisons. This calibration is therefore more closely related to altimeter instrument itself and is complementary with the calibration through SSH measurement. Transponders have been already used long in the past to support the ERS and the TOPEX missions for example. However, it is only more recently that they have become a significant component of the operational altimetry calibration. For the Sentinel-6 MF satellite calibration, currently two Ku-band transponders are being operated by the Technical University in Greece (Hausleitner et al. 2012 and Mertikas et al. 2020) and a dual Ku/C-band transponder is being operated by the NASA Jet Propulsion Laboratory on Santa Catalina Island in California. Lately, corner reflectors (Gibert et al. 2023) have been deployed and are currently being evaluated to support altimetry missions. Unlike transponders, corner reflectors are passive instruments. It was not possible to use them for non-SAR altimeters as the required instrument size to obtain a seemly Signal to Noise Ratio (SNR) would have been prohibitive. For altimeters with a SAR capability, thanks to the improved SNR from processing, a corner reflector with a typical length of the order of 2 m could offer suitable performances. Such instruments are lower cost, reliable and do not require any power supply. They could therefore become an interesting option in the future.

Today there is no in-situ calibration tool capable of calibrating relative SSH with the same accuracy as obtained through a tandem phase. However, they provide monitoring of absolute SSH bias and potential drifts and changes in the system measurements over the mission lifetime. They have been instrumental in the past to detect processing anomalies and drifts at satellite level. In case of any mission failure, the dedicated calibration sites would be pivotal to mitigate the impact on the altimetry GMSL time series, providing a connection trough the corresponding data gap. Notably, because of the switch of altimeter sides on TOPEX, such a support has been necessary to align the two corresponding time series.

The development of the dedicated in-situ calibration sites and the deployment of several instruments has required significant efforts from the space and research agencies in terms of funding, time, and logistical resources. For future missions, the orbit selection and phasing should consider optimizing the use of the current sites to take benefit first of their availability and second of the long history of measurements. For the reference altimetry missions, a tandem phase with the previous satellite is, today, still critical to meet the requirements in terms of GMSL.

4.2.2 Validation

4.2.2.1 Validation objectives

Validation activities address several objectives summarized as: verification of mission requirements, quality metrics monitoring, characterization of sensors/payload errors or in the ground processing and calibration scheme, uncertainties assessment, inter calibration for different purposes (assess biases between several missions, harmonize the products from different missions, build homogenous long time series for climate change studies), documentation and traceability of the validation results.

4.2.2.2 Who are the users targeted by validation?

Altimetry has evolved towards an operational era. In this perspective, validation activities address two different communities and needs: they serve operational applications (Copernicus programme services, NOAA operational services, meteorological services, etc.) and support more research-oriented activities. It is critical to fulfill these two needs which might trigger to some extent different approaches (methods and data sources), dedicated activities organization and go through different decision processes.

4.2.2.3 Validation needs

Validation activities address the mission performance and product data quality for different surfaces on which user needs are derived: open, coastal and polar ocean, inland waters, sea ice and inland ice.

The needs for validation activities must be considered through the perspective of the existing validation means for each of these surfaces. They can be gathered in four categories: in situ data, model outputs, satellite data sets and finally alternative data processing of the same satellite.

When referring to validation activities (or calibration), the definition for a Fiducial Reference Measurement (FRM) (Zibordi et al. 2014) arises naturally along with the principles of the Quality Assurance framework for Earth Observation (QA4EO 2010). In altimetry, the FRM label has been initially restricted to transponder sites, but we shall also consider all the different independent means such as wave buoys, tide gauges, radiosondes, GNSS, on-ground radiometer, drifters, micro stations over rivers, etc. Absolute calibration sites have been used in altimetry since 1992 (see Section 4.2.1). In addition to these permanent networks, there are some dedicated campaigns deployed for validation purposes such as the ones set-up for SWOT commissioning phase or CryoVex campaign over land ice or campaigns of opportunity, which target a scientific objective, can be still of interest for product validation.

There are specific needs related to the validation of full mission reprocessing datasets that request long time series of FRM data to check the mission performance and data quality (Jettou et al. 2023). Not only, should the FRM have an uncertainty low enough to allow measuring the improvements brought by the reprocessing compared to the previous version, they should also comply to a set of community-agreed criteria. To guide the process in assessing maturity and compliance of reference measurements to these criteria, the CEOS Working Group on Cal/Val (WGCV) set up the CEOS-FRM assessment framework (https://calvalportal.ceos.org/web/guest/frms-assessment-framework).

The community is encouraged to work towards CEOS-FRM compliant data for each of the altimetry-derived variables, with a traceable uncertainty, low enough to be compared against the requirements and to allow discriminating between two different data processing, with a continuous, homogeneous and long data record and of course with a global sampling to observe all the different conditions over ocean, coastal, inland waters, sea ice and land ice. Such a need is not affordable and FRM data can only address today part of it, that is why satellite and model data have extended the use of FRM-based Level-2 validation to areas, ranges, sampling, sensitivities and features not accessible to ground-based instrumentation.

Each of the validation means has assets and drawbacks and the strength of altimetry validation has been the combination of all these validation methods and data sources to provide a powerful validation framework. This is a key element to secure validation efficiency and continue improving the methods in the coming years.

Over the two past decades, dramatic progress has been made in validation thanks to key approaches recommended by the OSTST community and set-up by the Agencies. The most important one was the decision to conduct a tandem phase between TOPEX/Poseidon and Jason-1 missions in 2001, with a time lag between the two satellites small enough to measure the same topography under the same sea state and atmospheric conditions. It revealed errors on both missions that would have been impossible to detect with classical validation approaches. The exercise has been repeated since then for, at least, each new altimetry mission during commissioning phase of new launched satellites (Jason-1/Jason-2/Jason-3/Sentinel-6 MF, Sentinel-3A and -3B). It allowed a quicker and more precise validation of the mission, both for sensors and products (Ablain 2010, Taburet 2020). For the reference altimetry missions, a tandem phase with the previous satellite is, today, still critical to meet the requirements in terms of GMSL.

Finally, a significant need has emerged regarding the assessment of uncertainties associated to the different altimetry-derived variables. The emblematic one is indeed the uncertainty associated to sea level rise which concentrated a lot of efforts and progress made by the validation community (Ablain et al. 2019, Prandi et al. 2021, Guerou et al. 2023). On top of that, there is also the need for assessing the uncertainty associated with the validation methods.

4.3 End-user Application needs

Altimetry has a wide range of maritime applications and plays a significant role in understanding and managing various aspects of the world's oceans. It provides valuable data for oceanographic research, climate research, and ocean modeling, marine biology and fisheries, marine navigation and sailing race, oil and gas industry and spill mitigation, making it an essential tool for maritime professionals and scientists.

Maritime applications of altimetry include:

- Physical oceanography and oceanographic research: Altimetry provides valuable data for studying ocean currents, sea surface height, and variations in sea level. This data is critical for understanding ocean circulation patterns, which impact climate, weather, and marine ecosystems. Altimetry measurements help scientists monitor changes in sea level rise, which is important for studying climate change and its effects on coastal areas.
- Climate Research: Altimetry data is used to study the impact of climate change on the world's oceans. By measuring changes in sea level, researchers can monitor the rate of sea level rise and its impact on coastal areas, which are vulnerable to flooding and erosion. Altimetry data also helps scientists study the ocean's heat content, which is a critical component of the global climate system.
- Ocean Modeling and Forecasting: Altimetry data is used to improve oceanographic models and forecast ocean conditions such as currents, eddies, and sea level anomalies. These models are used by marine scientists, meteorologists, and oceanographers to understand and predict ocean behavior, which has practical applications in marine transportation, offshore operations, and ecosystem management.
- Marine biology and fisheries: Altimetry data helps marine biologists and fisheries scientists track and study oceanographic features such as eddies, fronts, and upwelling areas. These features can affect the distribution of nutrients, temperature, and productivity in the ocean, which in turn influence the distribution and behavior of marine species, including fisheries ones. Altimetry data provides valuable information on the location, strength, and movement of these oceanographic features, allowing researchers to better understand their impact on marine ecosystems and fisheries.
- Marine Navigation and Sailing race: Altimetry is used in maritime navigation to determine the height of the sea surface above a reference level and the ocean currents, which helps ships and boats determine their plan safe routes. Moreover, adding wave height data is becoming more and more interesting to detect rogue waves and to better prevent ship captains.
- Oil and gas industry: Altimetry data can also aid in the knowledge of sea state, wave height, ocean surface current and other marine weather conditions, providing valuable information for oil and gas industry for design, commissioning phase, operation at sea and decommissioning phase.
- Spill mitigation: By providing real-time information on sea state, wave heights, sea surface currents, altimetry helps decision-makers to fight against drifts due to spill accidents at sea (oil rig leaks, shipwrecks...).
- Coastal areas: From high-resolution wave forecast models that assimilate satellite data, it is possible to know the conditions that are conducive for small scale features like rip currents generation. This helps to generate probabilistic rip current forecast maps for various beaches, which is quite useful information for tourists and the authorities.
- Hydrological modeling, flood and drought forecasting: altimetry data is crucial for a wide range of hydrological applications, including flood and drought forecasting, water resource

management, and climate impact assessments. By offering continuous monitoring of rivers and lakes, satellite altimetry derived products support scientific research on water uses and human intervention, sediment transport, and land-ocean-atmosphere interactions, enhancing our understanding of the global water cycle and strengthening resilience to climate change.

4.4 Summary of user needs

A summary of the user needs in terms of spatial and temporal data sampling, spatial and temporal resolution, timeliness, uncertainty and stability is provided in the table below (Table 1). It is to be noted that these needs are in general agreement with the requirements set by GCOS (https://gcos.wmo.int/site/global-climate-observing-system-gcos/essential-climate-variables) and GOOS (the Global Ocean Observing System, https://goosocean.org/what-we-do/framework/essential-ocean-variables).

Application	Horizontal Resolution	Temporal Resolution	Delivery Timeliness	Uncertainty (2-sigma)	Stability
open ocean mesoscale topography	1-10 km	1-5 days	few hours (for operational purposes)	1 cm	
open ocean wind speed	< 10 km	< 1 day	< 3 hour	< 1 m/s	
open ocean SWH	< 10 km	< 1 day	< 3 hour	< 10%	
open ocean currents	< 10 km	1 day	< 3 hour	5 cm/s	
open ocean directional wave spectra	60-1000m < 20km	1 day	< 3 hour	< 15%	
coastal waters (topography)	< 100 m	< 1 hour	<1 hour	1 cm	
inland waters topography	< 50m	1 day	few hours (for operational purposes)	10 cm	
land ice topography	< 1 km	< 1 month	< 1 month	< 50 cm	1 cm/yr
sea ice thickness	< 1 km	< 1 day	< 1 day	< 10 cm	
geodesy	< 1 km	< 1 month	< 12 months	< 1 µrad	
extreme events	meters to kilometers	minutes to days	minutes (for events), months for baseline	phenomenon dependent	
global mean sea level	< 100km	< 30 days	< 12 months	< 4 mm	< 0.1 mm/yr (90% CL) over 10-year and longer periods,

					and an uncertainty of the GMSL acceleration of 0.5 mm/yr/decade (90% CL) over 20-year and longer periods
Regional Mean Sea Level	< 100km	< 7 days	< 12 months	< 1 cm	0.3 mm/yr (90% CL) over 20-year and longer periods.

Table 1. Key user needs in terms of spatial and temporal data sampling, spatial and temporal resolution, timeliness, uncertainty and stability. Uncertainties are assumed to be Gaussian distributed with zero mean; the 2-sigma value is given.

5 The current Altimetry Virtual Constellation

5.1 Present Altimetry Virtual Constellation

Modern-day altimeter measurements have come a long way in the past 30 years (beginning early 1990's with TOPEX/Poseidon and ERS-1/2), providing global sea level observations along with wind and wave data with unprecedented accuracy and coverage, helping operational oceanography and climate change studies. And, in all this, constellation became the key, principally to enhance the coverage. The timeline of the altimetry satellites constellation, which includes present and future missions, as planned by various space agencies, is shown in Figure 10. Following the recommendation of GCOS Implementation Plan Satellite Supplement (2006), the requirement of two lower precision but high-resolution altimeter missions along with one high-precision altimeter in the constellation to meet the various applications has mainly been fulfilled in the past, as seen from the Figure. Constellation comprises exploration missions (e.g., Cryosat-2, SARAL/AltiKa, CFOSAT, SWOT) and operational missions developed within long-term programs with a commitment of 20+ years (Copernicus or HY-2 programs, for example). In 2024, the constellation comprises 11 satellites: Cryosat-2, SARAL, Jason-3, Sentinel-3A/3B, CFOSAT, HY-2B/C/D, Sentinel-6 MF, and recently launched SWOT, offering measurements from 12 altimeters (including for SWOT Poseidon-3C for nadir altimetry and KaRIn for swath altimetry).

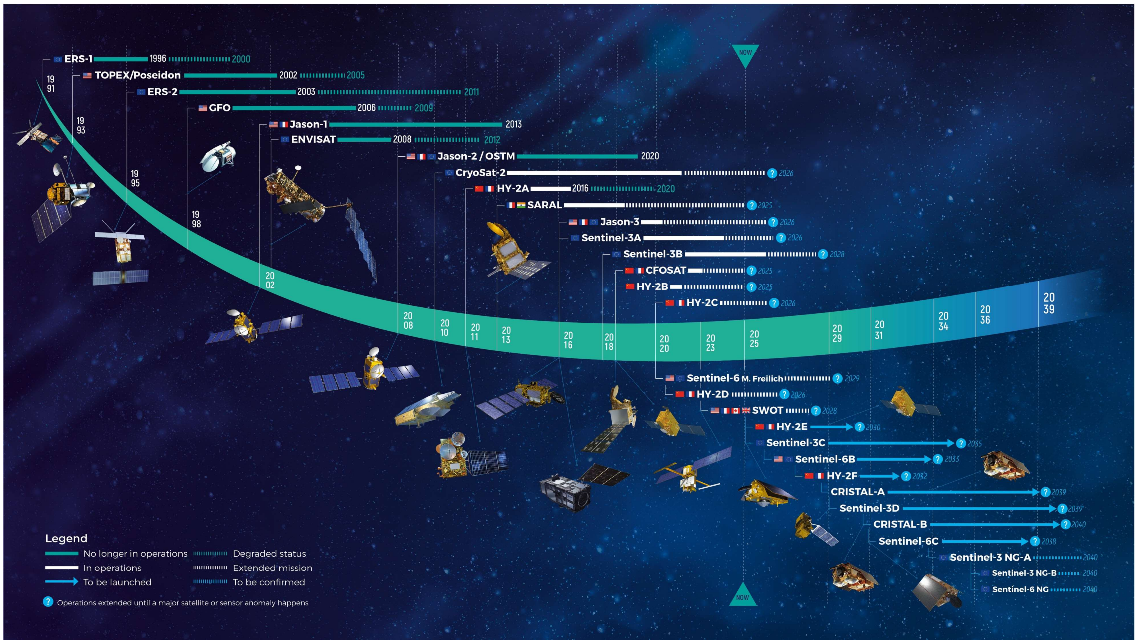

Figure 10. Timeline of modern radar altimetry missions. Courtesy of CLS. doi:10.24400/527896/A02-2022.001

5.2 Performance and complementarity of the current virtual constellation

This Section presents a brief overview of the performance of the current virtual constellation of satellite altimeters, along with some recent updates on each of these altimeters.

The “reference missions” have ensured the long-term continuity of sea level observations over the same orbit for estimating GMSL, providing sea level rise information to decision-makers of climate policies. Reference missions initiated by the French-US TOPEX/Poseidon satellite in 1992 continued with the Jason series (Jason-1, Jason-2 and Jason-3), and followed by the Copernicus Sentinel-6 MF mission have successfully completed 32 years of reference mission in the year 2024. These altimeters are inter-calibrated during the tandem flight phase to ensure persistence/constant biases among each other. Sentinel-6 MF mission completed cross-calibration with Jason -3 during tandem flight and CEOS-OST-VC, taking into account the OSTST project scientists’ recommendation, has declared this satellite as the next reference altimeter from 7th April 2022. In doing this, Jason-3 was relocated into an interleaved orbit with Sentinel-6 to maximize the temporal and spatial sampling the two altimetry missions provided. All other altimetry missions make cross-validation with the reference mission to better access their own performance. The reference missions will continue with Sentinel-6B and -6C that are already approved to fly in 2025 and 2030, respectively.

Launched in 2013, SARAL/AltiKa first high-frequency (Ka-band) microwave altimeter completed ten years of operations in orbit. In this decade-long operation, it has catered to a vast number of applications related to operational oceanography, climate sciences, hydrology and cryosphere. From the exact 35-day repeat orbit, it moved to a drifting orbit in the year 2016. However, since Feb 2019, SARAL has moved from the drifting phase to the mispointing phase due to the malfunctioning of the star sensor of the spacecraft. SARAL/AltiKa continues to deliver quality data for operational oceanography, so it has been recommended to extend its functioning until Dec 2025, allowing also 3 years of cross-validation with the new Ka wide-swath altimeter of SWOT.

The Sentinel-3 Copernicus dual-constellation is fully operational since April 2018. Both satellites, A and B, embark an altimeter, combined with a radiometer and provide key contribution to the virtual constellation, with SAR mode for high resolution and a complementary orbit to the reference one to improve sampling and coverage of high latitudes. This first generation constellation will be extended with Sentinel-3C and -3D (to be launched respectively in 2026 and 2028) allowing a unique consistent series until at least 2035 when the new generation will take over.

CFOSAT, the first of its kind mission with Ku-band Doppler scatterometers (SWIM and SCAT) providing the surface ocean waves directional spectrum and associated wave parameters along with winds, has completed six years in orbit. This mission continues to provide valuable parameters for oceanographic applications. Considering its innovative design and the array of parameters it provides, CFOSAT is highly desirable from a user perspective, and hence the extension of its lifetime is one of the crucial aspects that is being considered apart from the renewal of the dedicated science team for 2023-2026.

The SWOT mission launched by NASA and CNES on 16 Dec 2022, is the first wide-swath altimeter to provide data over ocean and continental waters. The main objective of SWOT is to measure the heights of Sea surface and freshwater reserves over the earth to assess the impact of warming earth on our oceans and freshwater resources. With 21 days of revisit, SWOT measures water level along a roughly 120 km wide swath. SWOT has achieved its Cal/Val phase (1-day repeat orbit) of its mission operation and entered its Science phase (21-day repeat orbit) since July 2023.

5.3 Assessing the performance of the reference mission from the global mean sea level rise perspective

Sea level record from satellite altimetry is now a reference for climate scientists to support their decisions and for stakeholders to formulate strategies on climate change-induced sea level rise (IPCC SROCC chap 4, IPCC AR6 chap 9). Satellite altimeters have precisely provided global sea level observations with the launch of TOPEX/Poseidon (T/P) in 1992. T/P and its successor missions like Jason-1, Jason-2, Jason-3 and Sentinel-6, referred to as "reference missions", have provided estimates of global mean sea level (GMSL) rise at 10-day intervals over fixed tracks for more than 30 years. The long-term reference altimeter data analysis shows the GMSL is rising by 3.3 mm/year in average, increasing to 4.4 mm/year over the last ten years. Observing system calibration reveals that the uncertainty in GMSL rise is approximately 0.3 mm/yr at a 90% confidence level (Guerou et al. 2023). One of the significant concerns in estimating GMSL is how to minimize this uncertainty. And there are several factors responsible for this uncertainty, e.g., determining fixed and time-variable systematic errors within and between each reference mission is challenging. Several corrections, such as bias drift corrections (drift of sea surface height system), require constant comparison of altimeter and tide gauges. GNSS-based vertical Land Movement (VLM) estimates must be carefully incorporated into GMSL estimates. While the altimeters provide the best possible measurements of GMSL, they do not provide direct observations of the causes of rise, namely increase in ocean volume (primarily from the absorption of heat) or increase in ocean mass. Another limitation of altimeter-based GMSL rise estimate is its inability to measure the mass component of GMSL. These missions measure the combined effect of ocean warming and mass changes on ocean volume. Only missions like Gravity Recovery and Climate Experiment (GRACE) can directly estimate the mass component of GMSL. Hence optimizing the satellite configuration with existing reference missions and GRACE-type instruments is another challenge. And lastly, the fixed reference mission orbits only allow measurements up to ±66°N latitudes. This limits the coverage of the polar areas. Other altimeters can measure up to ±82°N latitudes but are less precise and stable than reference missions. However, combining observations from reference mission satellites with those from high latitudes have proven effective at extending regional sea level records into higher latitudes and such techniques hold promise for improving GMSL records as well.

6 Overview of gap analysis

Whereas Chapter 4 was dedicated to the user needs, this chapter is highlighting the gaps identified for each thematic application.

6.1 High level thematic user needs

6.1.1 Ocean

The present constellation of satellite altimeters observes variability of ocean surface topography on a global scale using multiple nadir-looking satellite altimeters. Today's gridded multi-mission maps monitor ocean dynamics at scales larger than 150 km and 10 days. The SWOT mission provides 2x2 km^2 (or 250x250 m^2 at the highest resolution) sea surface height measurements across a 120-km-wide swath below the satellite, using a 21-day repeat orbit cycle (Morrow et al. 2019). Together with nadir-looking altimeters using synthetic aperture radar (SAR) capabilities, SWOT is ushering in a new era of high-resolution satellite altimetry that offers the promise of refined spatial resolution (Figure 11, from Chaudhary et al. 2021).

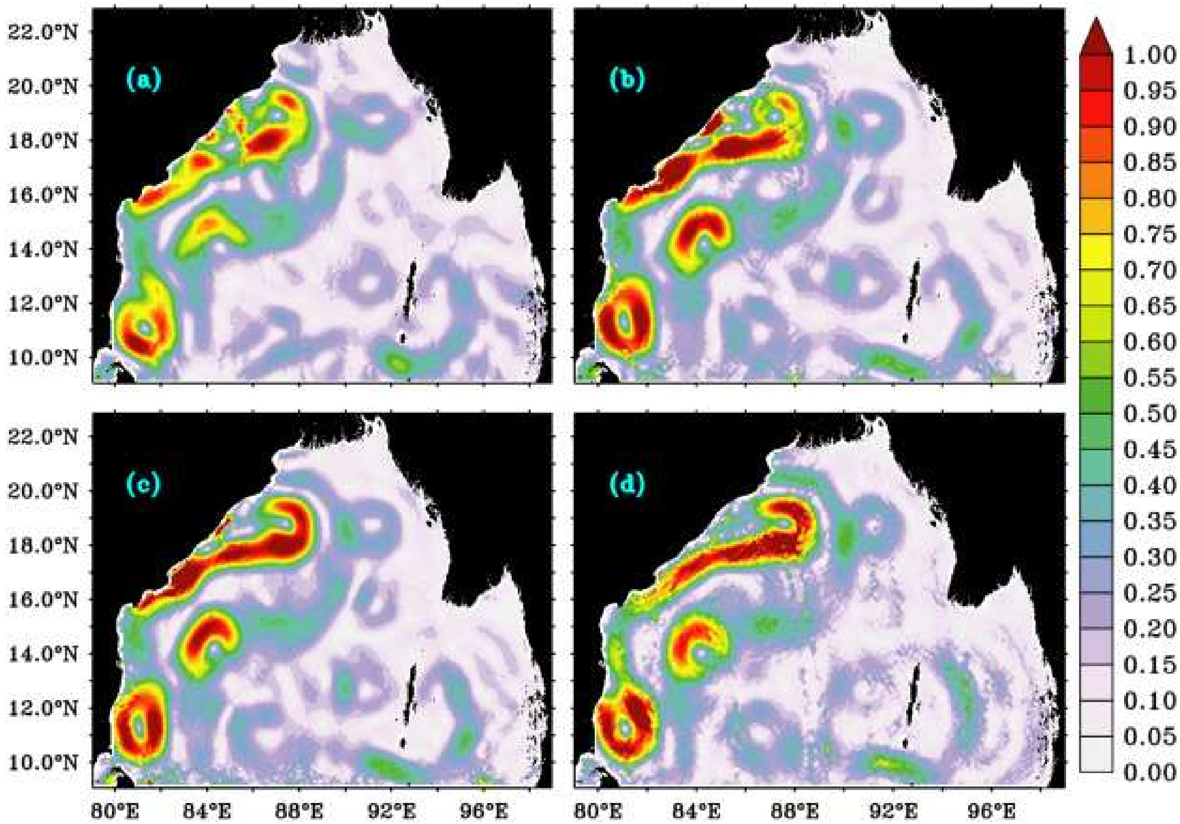

Figure 11. Better altimeter satellite coverage resolves smaller-scale structures in geostrophic current magnitude (in m s-1). Here model-simulated sea surface height data are mapped for 11 January 2015, using (a) one nadir altimeter only (Jason-2) (b) two nadir altimeters (Jason-2 + SARAL/AltiKa) (c) three nadir altimeters (Jason-2+ SARAL/AltiKa+ CryoSat-2) (d) SWOT. (From Chaudhary et al 2021).

In the coming decades key priorities for ocean dynamic topography will enable new research and applications:

High-resolution altimetry. Smaller scale ocean circulation studies, as well as geoid and tidal studies require global scale altimetry with about 2 km resolution and rapid sampling on scales of 1-5 days.

High-resolution measurements will allow investigators to better detect ocean dynamics and to investigate interactions between balanced and unbalanced flow, particularly if wide-swath and nadir altimetry can be used in tandem with total surface current measurements from a Doppler scatterometer (as proposed by SKIM, STREAM and ODYSEA concepts proposed to ESA or NASA calls).

Extended coverage to coastal and regional seas and into polar regions. Full global coverage with high-resolution capabilities to extend into coastal zones (see Section 4.1.4) and polar regions (see Section 4.1.5) will expose the evolving dynamics in regions near coastlines and ice edges, with small-scale, rapidly varying sea surface height features that have not previously been detectable.

Collocation of high-resolution altimetry with other satellite fields. Sea surface topography in combination with sea surface temperature, ocean color, sea surface salinity and ocean winds, will enable new understanding of a host of surface processes that are critical to upper-ocean interactions with the atmosphere and biosphere, including mixed-layer interactions, marine heat waves, the impact of ocean eddies on air-sea interactions (with analogous processes for tides and surface gravity waves.)

Synergies Between Argo, GRACE and Altimetry. Sea level is an extremely important climate indicator. Since the beginning of the 1990s, altimeter satellites have measured sea level globally with high precision and a revisit time of about a week. Global sea level rise is primarily caused by melting ice sheets and glaciers, and by the expansion of seawater as it warms. Measuring these contributing processes of ocean mass changes (by the GRACE-series satellites since 2002) and steric expansion (by the Argo network since 2006) provides key insights into the mechanisms of net water exchange between the oceans, land and atmosphere, and heat uptake and redistribution. It is also essential for realizing closure of the sea level budget. Regional sea level changes reflect the integrated global change plus wind, steric and gravity effects.

Upper ocean heat content and impacts on regional weather and climate. Sea surface height, when coupled with knowledge of sea surface temperature and background vertical temperature profiles, provides a strong measure of upper ocean heat content that can show how much heat is available to be released to the atmosphere and can also show when major heat exchange events occur. This provides key information that will improve our understanding of the coupled ocean-atmosphere system and ultimately lead to improved weather forecasts and refined climate projections.

Future high-resolution operational advances: To better serve applications, model resolutions will soon reach a few kilometers at the global scale and 1 km or less at regional and coastal scales. The user community is now preparing for operational tests of swath altimetry from the SWOT mission. OSSEs for SWOT (Tchonang et al. 2021) and for a future Sentinel 3NG swath altimetry constellation (Figure 12, from Benkiran et al. 2022) have demonstrated that this new generation of sensors, complemented by the improved performances of the nadir-looking altimeters operating in SAR mode, is expected to provide the information needed to constrain future high-resolution ocean and coastal models and downstream applications.

Eco-biogeochemical perspectives: Bio-physical interactions are particularly dependent on exchanges between coasts and the open ocean, which contribute to off-shore export of organic matter. Preliminary results of the SWOT observations, show that these coast-to-open-ocean transport processes, which are not well resolved by nadir altimetry, are well captured by the wide-swath capability of SWOT. The improvement of altimetric spatial resolution is needed for co-locating marine biological data, like biologging and genomics, and to provide their physical environment.

Challenges ahead: While data from high-resolution altimeters offer a wealth of opportunity, two challenges remain: (1) small-scale surface circulation requires higher temporal resolution, and (2) at small scales, ageostrophic (or unbalanced) motions are potentially important and will require additional measurement or modeling capabilities. These challenges are important considerations for the coming decade.

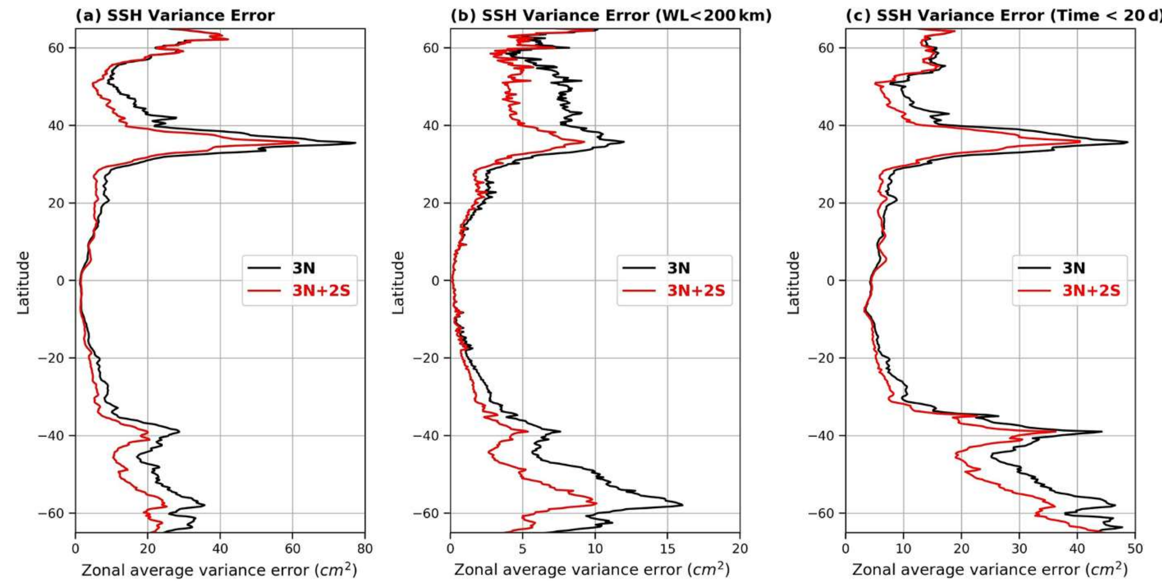

Figure 12. Assimilation of simulated sea surface height (SSH) from 3 nadir (black lines) vs 3 nadir + 2 swath (red lines) altimeters in the Mercator Ocean international global 1/12° data assimilation system. Zonal averaged error variance of SSH: (A) for full scales, (B) for scales less than 200 km and (C) for time scales less than 20 days. (Benkiran et al., 2022).

6.1.2 Sea state and surface currents

The wave spectra provided by CFOSAT are unique and already assimilated in marine predictive models, increasing, for instance, the reliability of wave submersion warnings. The continuity of the wave spectra series is of first importance and should be quickly supported.

Future efforts to investigate wave-current interactions would benefit from large swath measurements that will allow better characterization of the non-local wave-current interactions. For this, adding off-nadir beams to classical nadir beams has been demonstrated to be a cost-effective method to map both spectral information on waves and current parameters across a 300 km wide swath (Ardhuin et al. 2019), building on the heritage of CFOSAT (Hauser et al. 2021). High-quality sea surface height data to provide rotational velocities is possible from swath altimeters such as SWOT (Morrow et al 2019), and total surface currents can be provided by Doppler scatterometry (e.g. ODYSEA (Rodriguez et al 2019)) or multi-look SAR systems (e.g. Harmony (Lopez-Dekker et al 2019); or SeaSTAR (Gommenginger et al 2019)).

Recent detailed analyses of pulse-limited and delay Doppler altimeter datasets at short spatial scales of less than 50 km have helped to identify and measure inherent variability in the sea state due processes such as wave-current interaction and wave groupiness. Future satellite missions should strive to detect and quantify these sea state variations in order to improve their representation and impacts within global wave models, but also in order to capture and account for their impacts on nadir and swath altimeter range corrections (e.g. sea state bias) needed to accurately measure sea level at these short scales.

6.1.3 Inland waters

Some of the largest lakes on the Earth are monitored from in-situ ground observations, with regular update and publication of water level changes in time. This is usually done by national hydrological networks. For large rivers, water level and discharge are also available from the Global Runoff Data

Center (GRDC). However, long-term sampling is mostly concentrated in a limited number of countries, while in-situ networks in the rest of the world are very scarce.

This is even more true for publicly available data, as data from many national stream gauge networks are not shared with the international scientific community. Moreover, for lakes, it is practically impossible to maintain an operational network in densely covered regions such as Canada, Alaska, and Siberia. For rivers, many regions are no longer monitored by ground-based instruments. However, in the context of extreme events, mostly related to the effects of climate change and economic and social reliance on regular access to surface water resources, reliable data are urgently needed to maintain a continuous, accurate and near real-time observation system. Currently, only satellite technology offers a realistic and efficient solution. As mentioned above, for water height on lakes, rivers and floodplains, satellite altimetry allows measurement of these Essential Climate Variables. However, after three decades of using satellite altimetry to measure inland water levels, recording a large number of applications in water cycle studies, the role of lakes and rivers in climate or flood detection, some limitations have been identified. The main limitations of nadir altimeters are their coarse spatial and temporal sampling. They measure only at their nadir along the satellite's ground track (the cross-track distance at the equator depends on the orbit, but can vary from 52 km for the two Sentinel-3A/B satellites to 315 km for Jason-3/Sentinel-6) and miss all water bodies that are not directly overflown. Their time sampling is at best 10 days (Jason-3 and Sentinel-6), but could be coarser (27 days for Sentinel-3 and 35 days for the discontinued Envisat mission). Another limitation of satellite altimetry for monitoring ECVs related to lakes and rivers is that current satellite altimeters only measure a one-dimensional variable, the water height. ECVs such as lake volume changes or river discharge are not directly accessible from satellite altimetry data. For this purpose, it is necessary to combine nadir altimetry products with satellite imagery and/or models (e.g. Paris et al. 2016, Tarpanelli et al. 2018).

To increase the temporal sampling of river discharge at virtual stations, various approaches have been published to combine data from multiple altimetry missions operating simultaneously (e.g. Hossain et al. 2014; Tourian et al. 2016; Bogning et al. 2018) or to combine multi-satellite information from radar altimetry and optical imagery (Tarpanelli et al. 2015, 2018). Altimetry water elevations or altimetry-based discharge have also been assimilated in hydrological models to improve the modeled discharge at the basin scale (e.g. Emery et al. 2018, 2020, Michailovsky et al. 2013, Paiva et al. 2013b) or in hydraulic models to improve the representation of local phenomena (Garambois et al. 2017, Malou et al. 2021). The inherent limitation related to the temporal revisit time and spatial resolution for hydrological applications on smaller basins has recently been overcome thanks to the development of different multi-mission merging approaches (Tourian et al. 2016, 2017, Schwatke et al. 2015, Nielsen et al. 2022). These approaches make it possible to obtain data with improved temporal and spatial resolution by combining different altimetry missions, thus overcoming the limitation of poor resolution provided by a single altimeter, especially at high latitudes.

The situation is different for lakes. Temporal resolution on large lakes can be improved by combining several satellites with different repeat cycles and in some cases (Caspian Sea or Great lakes of North America) it may reach daily time sampling (Lahijany et al. 2023). But for an extremely large number of lakes, there is no way to measure water levels even with monthly time sampling. There are nearly 6 million lakes larger than 1 ha, and only a few thousands are currently covered by satellite altimetry but many of them are not included in current databases. Some missions, such as ICESat-2 or CryoSat-2, have a very dense coverage, allowing this number to increase dramatically, but with very coarse timing (annual for small lakes: Cooley et al. 2021). For lake volumes, it is necessary to combine satellite altimetry with imagery, building so-called hypsometry and applying it to determine lake area and volume changes (Gao et al. 2012, Crétaux et al. 2016, Busker et al. 2019). Again, to date this work is limited to a few hundred lakes.

To overcome the current gaps, the NASA-CNES SWOT mission was launched in December 2022. It carries a Ka-band radar interferometer, called KaRIn, which measures the slope, height and width globally, for all rivers wider than 100 m, with a goal of measuring rivers as narrow as 50 m. These measurements allow river discharge to be estimated using a range of algorithms on average twice every 21 days along reaches of 10 km (Durand et al., 2023; Frasson et al. ,2021; Oubanas et al., 2018; Larnier et al., 2021). These data are intended to be assimilated into hydrodynamic and hydrological models. This will allow the calculation of river discharge on a global scale in a fully consistent manner. An a priori river database containing the distribution and location of more than 210,000 river reaches worldwide has been created (Altenau et al. 2021, https://swordexplorer.com), called SWORD, on which the SWOT river discharge product is operationally distributed. SWOT is not designed to replace in situ data, which are more accurate and temporally dense, but it will fill the gap on a very large number of rivers where it is impossible to measure discharge from ground instruments, such as tropical rivers, arctic rivers, and braided rivers. SWOT will therefore improve understanding of the connectivity between river discharge and surrounding lakes and floodplains, and their role in the water cycle at local, regional and global scales (Biancamaria et al. 2016).

For volume changes, once satellite altimetry has been acquired on a given lake (or floodplain), the method for volume calculation is entirely dependent on the availability of satellite imagery, with enough samples to cover a sufficient range of height variation and to adjust for realistic hypsometry. Moreover, if the number of images is too small, it is not possible to sample the full hypsometric curve from very low to very high elevations. SWOT is helping to overcome this issue. The KaRIn instrument measures water height and water extent at each pass over a given lake (or floodplain). This allows a single instrument to simultaneously calculate changes in the lake height, area and volume. In addition, the KaRIn instrument and processing have been designed to measure all lake surfaces larger than 1 ha, representing ~6,000,000 lakes, for which the three variables will therefore be measured. This includes nearly all human-constructed reservoirs globally, which will allow SWOT to provide a global inventory of available water resources, which will be particularly important in transboundary river basins where such data are often not shared among affected countries.

For hydrological operational applications, the new generation of altimetry missions such as Sentinel-3 Next Generation or the concept of Small Altimetry Satellite for Hydrology (SMASH) constellation of 10 nano-satellites (Blumstein et al. 2019) have the potential to fill the gap of the temporal and spatial limitation of current altimetry missions. Daily (or sub-daily) and high-resolution monitoring of water level for rivers and lakes will not only strongly support water resource management and hydraulic risk mitigation activities, but it will also be extremely useful for monitoring extreme events such as floods and droughts for small to large basins and, more importantly, for flood forecasting activities where accurate and timely information is needed in real-time. The availability of water levels at a daily (or sub-daily) resolution, will facilitate the early warning system to advise people to evacuate and reduce property damage with an important impact on the operational level.

6.1.4 Coastal and continental shelf waters

Coastal waters are in the blind spot of the existing altimetry data set (with some exceptions), creating a significant gap between the locations of available altimetric observations of sea level and the majority of the potential users of sea level information. Removing the need to extrapolate across this gap is vitally important for altimetry to realize its potential. Priority must therefore be given to designing sensors that can accurately measure sea level and its gradients in the coastal zone.

The second major deficiency, for both coastal and continental shelf applications, of the existing altimetry data set is the long intervals between observations at any one point – a consequence of altimeters not being imaging instruments. A constellation of SWOT-like missions will mitigate this deficiency but the spatio-temporal coverage will still be short of what is possible for sea surface temperature (clouds permitting), ocean color, etc., because the swath width is still relatively narrow, with low overlap fraction. Thus, the rapid variations of sea level and coastal currents (that are prevalent across all the continental shelf) are likely to remain under-sampled, even with a constellation of swath altimeters. However, these high-frequency motions can be estimated by assimilating the data from the altimeter constellations into high-resolution, realistic ocean circulation models, at least partially addressing this problem.

6.1.5 Ice

Accelerating mass loss in West Antarctica, mass accumulation on the East Antarctic plateau, an ice-free Arctic Ocean in summer, and the continuing decline of sea ice along the northeast passages, with the simultaneous rapid expansion of commercial activities, even in winter, are just a few examples of the widespread changes anticipated for the polar regions in the next two decades. Maintaining altimetric observations of elevation change poleward of 81.5° is therefore a critical task (Figure 13). With the launch of CRISTAL not expected until 2028, and considering that CryoSat-2 is well beyond its nominal mission lifetime, there are legitimate concerns that all-weather, high-latitude radar altimetry capabilities may fail at any time. Loss of polar coverage would be a regression in recent progress, not only in the observation of ice sheet, ice shelf and glacier elevation, but also in monitoring sea ice thickness, sea level, dynamic polar ocean circulation and linkages to global thermohaline circulation. Moreover, any gaps would disrupt the continuity of the climate record during a period of accelerating change at both poles, limiting our capacity to assess and improve climate models. The international community should seek solutions to avoid or minimize any gaps in polar altimetry while simultaneously improving the delivery of open-access, low latency polar altimetry data products to advance domain awareness for operational and forecasting activities. A multipronged approach is needed. Recent examples of successful international coordination to obtain targeted altimetric observations in areas of rapid change using multi-instrumented aircraft include ESA's CryoVex campaigns and NASA's Operation IceBridge (MacGregor et al. 2021). But such surveys lack temporal continuity and are often limited in scope due to geopolitical challenges. Emerging capabilities, including the use of drones and unmanned aircraft flying dual-frequency radar and laser altimeters, can help to establish long-term, year-round observatories in the Arctic that will also provide useful validation of satellite retrievals, but ultimately, they will not replace satellite observations in terms of spatio-temporal coverage.

The extension of current polar altimeter missions, acceleration of the development of future polar altimetry missions, modification in the orbital coverage of current/planned oceanographic missions, and a long-term commitment to the deployment of state-of-the-art altimeters on manned and unmanned airborne assets are all viable avenues for consideration to achieve a constellation that provides truly global coverage.

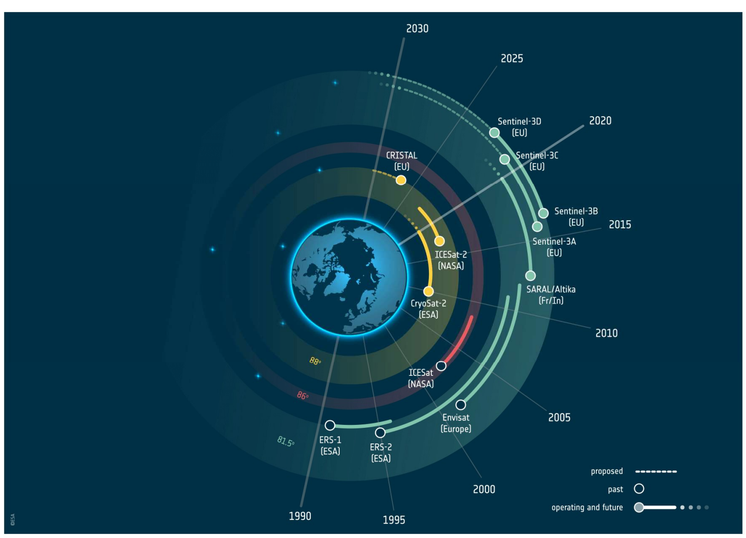

Figure 13. Past, operating, approved, and proposed polar altimeter missions. CRISTAL will continue to acquire climate-critical data over ice poleward of 81.5° latitude extending the time series obtained by ICESat, CryoSat-2 and ICESat-2. From: Kern et al. (2020).

6.1.6 Geodesy

Global gravity field maps, mean sea surface models and geoid (hereinafter called geodetic reference surfaces) have vastly improved over the past 3 decades to a level where sea surface slopes can be mapped with an accuracy approaching 1 cm over 1 km corresponding to 1 mGal gravity field accuracy.

Satellite altimetry is the primary tool for studying and mapping bathymetry for the 75% of the ocean basins that have not been surveyed by sonar. Present-day nadir altimetry measures sea surface topography along track with high precision. Unfortunately, cross-track topography gradients are less well determined and related to the track-to-track distance. Today the spatial resolution of most geodetic maps is limited to around 15 km because of the track-to-track distance. Consequently, satellite-derived bathymetry will be limited to the same spatial resolution, causing a deficit in mapping smaller seafloor features like seamounts limiting the accuracy.

Recent improvements in satellite technology with emerging swath altimetry, laser altimetry from ICESAT-2, interferometric imaging radar and the recently launched SWOT satellite will improve the accuracy and resolution of geodetic reference fields over the next decade. It is expected that SWOT will increase the spatial resolution and accuracy of satellite observations by a factor of two revealing a wealth of seamounts between 1-2 km height.

Despite improved knowledge about ocean bathymetry from recent satellites and the Seabed2030 initiative detailed knowledge about bathymetry will still require scientists to continuously improve spatial resolution and accuracy of satellite observations to efficiently reveal finer and finer scales with higher and higher precision for future mean sea surfaces, geoids and bathymetry models.

6.1.7 Extreme events

As mentioned in Section 5.1.4, coastal inundation events are rarely sampled by altimetry because the revisit time is long (10 to 30 days) compared to the duration (~6h) of these events. It is also true that if sampled, many such events are at risk of being flagged as being erroneous measurements because some of the corrections applied to the range data are subject to contamination near land. A constellation of wide-swath altimeters would go a long way towards filling this gap in the temporal and spatial coverage of altimetry, thus becoming a more valuable data set that could be used for validating coastal ocean forecasting (and hindcasting) systems.

6.1.8 Weather monitoring and forecast

In the future, the development of coupled earth systems will need a better coverage of satellite observations in order to improve parameterizations of surface processes connected to modulations of wind-waves and surface currents. With the constellation of altimetry, the exploitation of wind intensity and significant wave heights will contribute to a better understanding of the momentum and heat fluxes transfer between the atmosphere and the ocean. In addition, the use of geostrophic currents with a detailed description of submesoscale ocean circulation will quantitatively improve the feedback of waves and currents on the marine atmospheric boundary layer. These altimetry-based observational efforts will also play a key role to better prediction of surface winds and fast-weather changes near the coasts, and the monitoring of extreme events. Big effort is ongoing on the implementation of coupled assimilation, and the assimilation of surface roughness in NWP models. This is a very good opportunity to rely on nadir and swath altimetry sensors. The major advantage is therefore to provide more spatially resolved altimetry observations and a precise description of the physical processes that impacts the exchange of heat and momentum fluxes between ocean/waves/ice/atmosphere.

6.1.9 Climate monitoring and research

The interferometer of SWOT yields 2D topography images with unprecedented precision with the objective to observe small mesoscale or geoid features. This is an important advance that helps monitoring sea level at fine scales close to the coast. However, the interferometer uncertainty budget is specified only for scales ranging from 15 to 1000 km and the instrument has no accuracy requirement for large scale and stability at seasonal and longer scales. An important effort is needed in the coming years to evaluate the stability of SWOT measurement and the uncertainty budget on seasonal to longer time scales as we did with TOPEX/Poseidon and Jason satellites in the early years. This effort will enable to assess if/how SWOT measurements are affected by instrumental and geophysical errors and to which extent it can be used or should be improved for climate studies.

In contrast, the Sentinel-6 topography next generation mission should be designed to provide continuity of sea level measurements with the same space and time resolution and the same accuracy and precision as current topography missions (including at large spatial scales and at climate time scales). This will ensure the continuity of measurements but it will not reduce significantly the uncertainty because, after 20 years of record, the time correlation between uncertainties vanishes and the uncertainty budget is dominated by systematic errors such as the wet tropospheric correction drift and the ITRF geocenter realization, which do not decrease with time. Some of these systematic errors are intrinsic to the measurement strategy. For example, the wet tropospheric correction stability could be reduced with improved microwave radiometer capabilities (e.g. more spectral channels, enhanced performance) or with new calibration strategy to reduce the wet tropospheric correction drift although that would reduce the frequency of sea level measurements. Other systematic errors are simply due to ancillary data errors such as the ITRF realization errors. These error sources can be reduced in the mid-term to long term with new satellite missions like GENESIS (Delva et al. 2023) or by increasing the number of satellite laser ranging stations around the world to improve the ITRF realization. In the short term, it is also possible to reduce the uncertainties in sea level measurement in particular by improving the characterization of uncertainties because they are often overestimated. The characterization of uncertainties could be improved by cross validating more often the data (from the radiometer for example) against independent climate data records or by deriving all uncertainties and their spatio-temporal correlation from a propagation of the low level instrumental errors down to the sea level measurement.

Altimetry on ice sheet would benefit from denser coverage, i.e., go beyond track spacing to swath mapping, as done for ocean altimetry with SWOT. Dense coverage of the ice sheets would help better constrain estimates of ice shelf melt, refine the altimetry results at the glacier level, especially in Greenland, and reduce data noise through spatial averaging. There is also interest for future research in finding out whether high resolution (1 km) altimetry along the ice sheets could help constrain the pathways of ocean heat at flowing onto the continental shelf and toward the glaciers, as this process is one of the most important vector of ice sheet change at present, but observations are very sparse. Over the ice sheet interior, altimetry remains difficult to use because of the very weak signal (possibly close to zero) and the challenges of compensating the data for firn compaction (which is larger than the long-term trend). In this situation, it is essential to extend the data collection for many more years, if not decades to come. Generally speaking, it has been well illustrated that continuous data, improved calibration, and improved measurement precision have considerably helped our understanding of the evolution of polar ice sheets in recent decades. Such progress should still be actively pursued. Data continuity is fundamental to climate change studies. Improvements in spatial resolution and temporal revisit are critical to understand the fundamental processes of heat and mass exchanges around the periphery of the ice sheets, and their global impacts on sea level rise. The next generation instrument needs to address phenomena at the km scale, sub-monthly, and with improved precision to detect seasonal to sub-seasonal mass changes in polar regions at the Gigaton per year level as well as interannual to longer-time trends.

6.1.10 Calibration

There are only a small number of dedicated, high-quality, in-situ calibration sites and the frequency of the comparisons with satellite measurements is quite poor and limited to one or two flyovers per site and per satellite cycles. Each of these comparisons are affected by a significant noise and potential geographical systematic errors. It therefore necessitates a large number of cycles to obtain a statistically meaningful trend. It is, then, critical to maintain capabilities at each site over long period of time and with a high availability ratio. Another objective is to reduce the noise of the comparisons. Transponders are one option to achieve this goal, but the global network is still very sparse and today, only one transponder offers a dual frequencies calibration capability. Systematic errors can also affect the calibration. Tide gauges instruments are mostly installed on the coast where direct comparison with satellite altimetry is not possible, and their measurements can be affected by local sea conditions but also local vertical land motions. It highlights the need to accurately being able to connect the tide gauge estimates and the satellites observations measured offshore. SAR altimetry will also be helpful to improve this discrepancy offering both measurements closer to the coast and SSH estimates with a reduced noise. However, to ensure continuity in the tide gauge comparison time series, it requires to further improve the consistency between SAR and conventional LRM altimetry.

Swath altimetry will present a new challenge. The Cal/Val high precision network has been originally developed to support nadir altimetry missions. Relatively to the surface covered by swath altimeters, the number of potential comparisons is even scarcer and moreover even not necessarily possible with the location of the current dedicated sites. It requires deploying in-situ instruments at additional locations in particular to study the potential correlated errors as a function of the distance to the nadir. Tandem phase assessment is also becoming more complex compared to the nadir-to-nadir cross-calibration.

6.1.11 Validation

These last years, several initiatives have been conducted to identify gaps in the validation of altimetry products (dedicated Copernicus activities supported by validation teams, St3TART (Da Silva et al. 2023) or ASELSU projects (https://earthobservation.magellium.com/project/aselsu/).

A major recommendation is to systematize the use of tandem phases for commissioning of future altimetry missions. The concept of tandem approach is currently further explored with the set-up of a second tandem phase between the same satellites that would occur several years after the first one done during commissioning phase (OSTST 2022 recommendation, will be implemented in 2025 for Jason-3/Sentinel-6 MF). Such configuration will provide a precious data set for validation experts to better understand the effect of respective aging of the two satellites (platforms and instruments). This will indeed serve the needs of assessing the stability and associated uncertainty of topography observations (Ablain et al. 2020). We might also discover unexpected added value from such exercise and more important, validation teams will be in a position to provide recommendations to maximize the benefits of such configuration for future second tandem phase operation.

With respect to the sea level rise uncertainty budget, there is clearly a gap in our capability to detect drift at the requested level and validate the proposed uncertainty budget with sources independent from altimetry (Watson 2021). This further strengthen the need for considering a specific FRM network and/or system dedicated to this purpose with increased accuracy and precision. Additionally, design upgrades to the satellite system to ensure long-term stability are warranted. As an example, prior to the launch of Sentinel-6, the wet tropospheric correction component provided by on-board microwave radiometers had been one of the largest sources of uncertainty in the global mean sea level trend derived from satellite altimetry (Ablain et al. 2009). Drift detection and validation have relied on model data and Fundamental Climate Data Records derived from other spaceborne radiometers (Brown et al. 2009; Brown et al. 2012; Barnoud et al. 2023). However, the microwave radiometer deployed on the Sentinel-6 mission includes a dedicated calibration system to stabilize the radiometer to < 1mm/yr on decadal time scales. After 5 years in flight, this calibration system has demonstrated 0.02+/- 0.07 mm/year level stability (Brown et al. OSTST 2024). Future designs for the altimeter constellation should ensure that at least one reference missions embarks instruments of similar or improved stability. It is also important to maintain and improve methods to validate these stabilized systems which requires reducing uncertainties associated with their method (Jugier et al. 2022; Meyssignac et al. 2023).

The emergence of swath altimetry is one of the major challenges for validation activities for the next decade or more.

Considering the variety of observations measured by spaceborne missions, altimetry validation should consider more systemically the benefits from satellite observations not dedicated to altimetry, especially for waves, sea ice and of course laser technology for altimetry such as ICESAT mission observations (Scherer et al. 2023). In that respect, there should be some synergy and bridges to be set-up with the validation approaches carried out by the downstream services.

6.2 End-user applications

End-user applications rely on accurate measurements for a range of purposes, including mapping, navigation, weather forecasting, and scientific research. While specific gaps in altimetry for end users may vary depending on a particular application and user requirements, common gaps can be identified.

- Accuracy Gap: End-users require access to sea level measurements and ocean currents derived from altimetry (geostrophic component). They expect a sea level accuracy of approximately 1 cm in near real-time. Additionally, they anticipate an accuracy of 0.1 knots (that is ~5 cm/s) for ocean currents in near real-time (a few hours of delay).
- Spatial Resolution Gap: The spatial resolution of nadir satellite altimetry is limited due to its measurement geometry, which focuses on providing information only in the nadir direction beneath the satellite's orbit. As a result, the coverage and detailed spatial representation of the data are constrained. However, the introduction of wide-swath altimetry has the potential to enhance the resolution by capturing smaller features in the open ocean (~10 km to access submesoscale features). Additionally, it can provide improved resolution in coastal areas, where oceanographic phenomena tend to be more complex and require finer spatial detail (below a few kilometers).
- Temporal Resolution Gap: The impact of the current temporal resolution on capturing and analyzing dynamic changes over time, including oceanographic, climatic, or hydrological phenomena, can be complex and dependent on end-users' specific needs. For open ocean mesoscale activity, the classical 10-day satellite repeat cycle is considered adequate. However, capturing submesoscale activity may require higher frequency data acquisition, which can be addressed by combining multiple altimeters. In coastal areas, where high-frequency ocean features are present, a higher frequency of data acquisition may be sufficient. Wide-swath altimetry holds promise in addressing the temporal resolution gaps observed in traditional altimetry measurements. With its capability to capture a larger coverage area during a single pass, wide-swath altimetry enables more frequent and continuous data collection. This fills the temporal gaps that exist between conventional altimetry measurements, resulting in a more comprehensive and continuous temporal coverage.

- Parameter Gap: Today end-users are interested in sea surface height and ocean currents, limited today to the geostrophic component but also in wave heights, eddies, and circulation patterns.

Within the known limits of nadir-viewing only, the altimetry mission seems in good shape, especially if altimetry program is provided with long-term continuity. The important potential of large-swath altimetry is being explored with SWOT and once operational with Sentinel-3 NG should enable a step change in the development of operational applications using altimetry data.

7 Evolution of data and service components

7.1 Standardization

Through the efforts of community organizations and operating agencies, much has been achieved towards the standardization of altimeter data in terms of data formats, product contents, and algorithms used.

Due to popular demand of users and multi-satellite services like RADS and SSALTO-DUACS, the last two decades already saw a transition from each mission having their own binary format to the use of self-documented NetCDF files, which certainly facilitated the data uptake. On the other hand, BUFR formats are also still supported for dissemination to WMO.

Beyond the formats, agencies are now coordinating on setting some standards with regards to processing and corrections. These efforts including coordination in schedules for implementing change, must continue and be strengthened in the years to come, as this is an important key to optimizing the use of the constellation and satisfying the end users, and allowing the development of new applications. we cannot state that standardization has been achieved. OST-VC will be instrumental to this process.

There will be challenges relating to the diversifying needs among users of ocean, coastal and inland data, which are being increasingly better served by new missions. Challenges in future will come from maintaining continuity in products, formats, and algorithms whilst missions advance, and playing the synergy between instruments, missions and programs.

Continuity is essential for some applications (particularly those at the global ocean and climate scale). A concern that largely impacts the use of altimeter data for climate purposes is the lack of reprocessing capabilities for past missions, thus complicating the standardization over all altimeter missions that contribute to the 3-decade long time series. This is essential work towards the contribution of altimetry data to essential climate variables.

Advances can also be taken advantage of to bring online new application possibilities, particularly in coastal and transitional waters. This means that the desirability of continuity and enhancement may lead to clashing requirements. For example, newer measurement types like high resolution altimetry (Sentinel-3 and Sentinel-6) facilitate newer methodologies (such as fully focused synthetic aperture radar, or FFSAR processing) which can still be captured as small additions to existing product type. Whereas swath altimetry (SWOT and Sentinel-3 NG) requires entirely new types of products and (because of their size) distribution types altogether. In these cases, users may need to be served by alternative file formats, such as the provision of shape files for river and lakes data as already in place for SWOT. This may also be useful in the coastal domain, facilitating greater usage by downstream users, and further interoperability with other data sources.

In general, this diversity of needs, alongside the growing volumes of data, may motivate moves from the classical process-centric approach (i.e. data download and local processing) to a data-centric approach (i.e., working remotely on HPC/cloud infrastructures). In terms of data formats, this would necessitate careful consideration of the use of catalogs (e.g. Spatial Temporal Asset Catalogs (STAC)) containing interoperable, cloud optimized formats (e.g. ZARR) and/or facilitation of data conversions.

7.2 Data management and distribution

With the scale of data availability increasing rapidly, a concurrent shift in how data is served and processed has occurred and will continue to occur as more missions with even higher data resolutions are launched.

In the last 25 years, two major data distribution methods have developed. Operational, near-real time data delivery has been well served by 'push' methods, where data is sent to users via either satellite multicast (e.g. EUMETCast Satellite) or, more recently, through National Research and Education Networks (NRENs) (e.g. EUMETCast Terrestrial). These are likely to remain preferable services for users requiring data as fast as possible, without dependence on individual internet connections.

Online, "pull" data services where users can request data for download have also developed substantially in recent years (e.g. via AVISO, EUMETSAT Data Store, Copernicus Marine Service, and NASA PO.DAAC). These services have historically been based of File Transfer Protocol (FTP), with further advances towards other data servers (e.g. THREDDS Data Server (OPeNDAP, WMS, FileServer)) and more modern Application Programming Interfaces (APIs) based on open standards.

Although it would be a new way of working for a lot of altimetry users, we strongly encourage the move from file based services like FTP/SFTP to APIs with the capability of search on location and time as well as subsetting; the ever growing volume of data products (particularly with the expectation of swath altimetry) will require this.

Simultaneously, due to the volume and complexity of data and its applications across the Earth Observation sector, there is likely to be a shift towards the data-centric approaches described in the previous Section. Alongside the requirements for cloud optimized data formats, are the need for these to be directly accessible in cloud computing environments where users can deploy their processing proximate to the data itself. These are seen as the most promising development for future altimeter data services. Developments of tools and services will need to be cognizant of the cloud provider landscape, facilitating users working across multiple cloud environments. Appropriate user support and training would be needed to support users in this transition (see following Section).

It speaks without mention that open and free access to altimeter data, as has been the standard from many of the past missions, should continue to be adopted for future missions. Open science principles could be further integrated into working practices across the altimetry value chain e.g. promoting use and sharing of open source software for data processing, facilitation of open environments for validation, algorithm development etc. such as that offered in ESA's EarthConsole® Altimetry Virtual Lab.

Ensuring traceability in downstream products and usage is an ongoing challenge. The use of Digital Object Identifiers can help towards tracing and citing data when used, and trusted provenance techniques may offer more dynamic solutions in future.

7.3 User support

User support activities are key to maintaining and increasing uptake and impact of data. The growth of the Earth Observation sector has seen an increasing number of user engagement roles, tools, and programs established, supporting users from across the value chain.

At the expert level (users working with data at level-1 or 2, and/or creating downstream products) improvements have been made in providing necessary technical information online (e.g. relating to processing baselines and algorithms). Documentation should be dynamic, searchable, updateable, versionable, open (and community engaging if desirable). Ideally it can be integrated with functionality such as example code or processing tools, where appropriate. Formats for documentation that support comments, questions, or the raising of issues can allow users to engage more with content, creating bodies of knowledge, and informing data producers of challenges faced.

Expert users will likely need support in regards to the shifts in data access and processing discussed above. There is also a need to ensure that training is provided for future experts in the field to continue to the development of new mission products and applications. This can be achieved through coordination of training courses with representatives from across the community, and integration of reusable training material into university programs. Modern pedagogical approaches (e.g. participant led, interactive practicums etc) and platforms for training (online, synchronous and asynchronous) should be exploited for maximum uptake. Training will also need to be increasingly 'cloud-native' to support the transition to this more data-centric approach to working.

One cross-sector challenge is supporting users in the selection of the right product for the right application. This is particularly challenging with multiple satellite operators and data providers (necessarily) producing data, products, and services. Fitness for purpose information is increasingly provided in data catalogues, via uncertainty products and technical validation reports, and through example workflows and case studies. Collaboration across agencies to provide products and training in context can help users navigate the available product portfolio.

Outreach can promote the value of the altimetry data to wider society, generating interest in both the method and its applications for societal and environmental benefit. Ongoing outreach should show the contributions of altimetry to understanding and forecasting of extreme weather events and climate change, as well as its role in understanding the physical oceanographic environment, cryosphere, and impacts of these on marine ecosystems. Translation of research findings into relevant simplified yet still accurate public interest stories is needed for communicating the importance of altimetry data. It is inevitable that altimetry data will be present in discussions of risks related to climate change, and clear communication will be essential to ensure the public receive accurate information. The community should seek to develop communication points, and communication as a skill amongst its members, to facilitate this. To improve reach, modern forms of media such as short form videos and 'ask me anything' events held on social media platforms, could be embraced.

8 Summary

During the intervening years since the "Assmannshausen Report" (Escudier and Fellous, 2009), a number of new applications and new technologies have emerged in satellite altimetry that warrant a follow-up in the form of this White Paper, covering the user needs and expectations up to 2050:

- The availability of SAR altimetry globally from Sentinel-3 and Sentinel-6 created the capability to observe Ocean and Coastal areas with unprecedented accuracy and resolution. In addition, it now allows to collect data for tens of thousands of hydrology targets, over smaller and larger rivers and lakes alike.
- The understanding of our changing climate is aided by the unprecedented precision, accuracy and stability of the reference altimeter missions, developing new science and setting the requirements and expectations for the next decades;
- The increased capacity of assimilation in ocean models in terms of resolution and sampling is guiding a much more challenging requirement on spatio-temporal sampling;
- Through new long-term sustainable operational programs like Copernicus in Europe and HaiYang in China, we are now able to envision and develop cross-cutting and complementary missions far into the future;
- The emerging technologies associated with smaller Ka-band or swath altimeters allow a much better spatio-temporal sampling than could be had a decade ago;

- The capabilities of new IT technologies, in processing power and in storage capacity but also in accessibility to general users outside the traditional government agencies and academics, bring the data now closer to home than ever before.

The CEOS Ocean Surface Topography Virtual Constellation (OST-VC) working group, co-chaired by CNES and EUMETSAT, took on the task to build this new reference document for a better international coordination of the altimeter constellation for the years 2025-2050, with the aim to include all the above mentioned aspects of the changing of times. Thanks to the contribution of the OST-VC agencies and of key experts and end users in our community, we provide in this report the progress made over the 15 years since the previous version, and the need in terms of programs, payloads, products and user services for the decades to come.

This report highlights the importance to continue and to improve the observation by satellite altimetry of some key components of the earth system: the open ocean including sea state and currents and by extension into the coastal waters, inland waters, ice, geodesy, extreme events, weather monitoring and forecasting, and climate monitoring. Major transverse activities like calibration and validation as well as the overall service to a wide range of users are also covered.

After some preliminary context about satellite altimetry and its community, the report lists the user needs, including emerging ones, and then identifies the gaps in the current and expected international space constellation, gaps that space agencies must consider in their future program prospectives in order not to miss out on valuable observations, applications, and science to be extracted from a well-designed constellation.

For most of the applications related to water level, both over sea and inland, there is a need to overcome the main limitation of our current altimetry missions, the relatively poor spatio-temporal sampling, i.e. either lack in coverage or revisit time, or both. To overcome that, the expectation is to fly satellites with swath altimeters and/or nadir altimeters, that cover a significant part of the polar areas as well, and to fly them in coordination with highly accurate climate-quality reference missions. Towards this goal, the successful demonstration of the experimental SWOT mission has already resulted in the formulation of the Sentinel-3 Next Generation as operational swath altimeters in the Copernicus programme. The gain in spatial and temporal resolution will principally boost coastal management applications where length and time scales are significantly shorter than in the open ocean, but also allow much better ocean and weather forecasting through coupled modeling and uptake for the monitoring of inland waters for applications like flood warning and water management.

Sea state and surface currents are considered a still underdeveloped domain of satellite altimetry. SAR and swath altimetry as well as a combined use with other sensors are expected to aid the disentangling wind driven waves from swell as well as surface and geostrophic currents. Particularly an advance in the understanding of the sea state is expected to further enhance sea level estimation.

A better coverage of polar areas is key to climate change monitoring. The need is therefore expressed to avoid the gaps between “polar” missions in the future, the likely upcoming gap between the Cryosat-2 and CRISTAL missions being the exception.

For the monitoring and understanding of climate change and its contributors, we need to continually improve the stability of the observing system —not only the satellite altimeter component— and ensure the continuation of the now three decades long time series of reference altimeter missions, preferably maintaining the same ground track to ensure uninterrupted continuity. This is considered critical to comply to the stringent constraints on the stability of the observing system as a whole and specifically to the quality of global and regional mean sea level trends requested by GCOS. En passant, a network of in-situ stations for calibration and validation (transponders, corner reflectors, and tide gauges) need to be maintained and further developed.

There is a current gap and opportunity in developing higher level products in synergy with other satellite-borne sensors (SAR, scatterometers, radiometers, visible or infrared imagers, etc.) and/or other geophysical parameters (ocean color, sea surface temperature, ocean salinity, etc.).

To serve more applications and to reach a broader user community, the agencies need to further improve the service to users, follow the data distribution technologies for a larger user uptake, maintain open and free data policies, provide adequate and accessible documentation, and cloud/hosted processing.

The international collaboration across continents has been key to the success story that is satellite altimetry (e.g. OSTST). This holds at the agency level, as most of the altimeter missions have been multi-national and multi-institutional. But it applies maybe even stronger at the level of the user community that has historically been very open and collaborative, spanning an immense array of disciplines: oceanography, geodesy, weather monitoring and forecast, hydrology, space technology, and many more. The expectation is that such transnational and transformative collaboration continues for the coming decades.

A. Altimetry key contributing factors

A.1 Families of instruments

Altimeter technologies encompass nadir-looking altimeters, including radar and laser altimeters, as well as swath altimeters. Nadir-looking altimeters offer precise measurements along a narrow track and are useful for studying sea surface height, ocean dynamics, and inland waters elevation. Laser altimeters provide high precision and vertical resolution, making them suitable for complex topography and polar studies. Swath altimeters have wider coverage, enabling comprehensive mapping of water bodies and coastal regions, and also improve the revisit time in the open ocean. The diverse capabilities of altimeter technologies contribute to our understanding of Earth's surface, including the oceans, cryosphere, and terrestrial environments. The following list provides an overview of satellite altimetry technologies currently in use.

Nadir-looking altimeters

Radar Altimeters use microwave or radar pulses to measure surface elevation. These altimeters emit short pulses towards the surface and measure the time it takes for the signals to return. One can differentiate between conventional (low-resolution) and synthetic aperture radar (SAR) (high-resolution) altimeters.

- Conventional pulse-limited altimeters, such as those onboard the TOPEX/Poseidon and Jason series of satellites, and SARAL/AltiKa, emit short pulses of radar or microwave signals towards the Earth's surface. The altimeter measures the time it takes for the pulse to return after bouncing off the surface, which provides the range or distance between the satellite and the surface. The width of the footprint is determined by the pulse length and the antenna characteristics of the altimeter. For example, the TOPEX/Poseidon and Jason series altimeters have a ground footprint of a few kilometers.
- Synthetic Aperture Radar (SAR) altimeters, like those on board CryoSat-2, Sentinel-3 and Sentinel-6, use synthetic aperture radar techniques to generate high-resolution measurements of the Earth's surface. SAR altimeters transmit a series of radar pulses and use advanced processing techniques to synthesize a long aperture, resulting in a narrower footprint and improved along-track resolution compared to conventional altimeters.

Laser altimeters (lidars) use laser pulses to measure surface elevation. They emit short laser pulses and measure the time it takes for the pulses to return. Laser altimeters, like ICESat-2, provide highly precise measurements and have a high vertical resolution. They are especially valuable for studying complex topography and the polar regions, offering insights into changes in ice sheets and land surfaces, but have also demonstrated the ability to measure ocean, lake, and river levels

Swath altimeters

Swath altimeters have a wide-swath coverage capability. They employ a combination of radar interferometry and wide-beam altimetry to obtain measurements over a broader area. Swath altimeters are designed to capture the topography of both terrestrial surfaces (land and water) and ocean surfaces simultaneously, enabling detailed mapping of coastal regions, rivers, lakes, and other water bodies. The wide coverage of swath altimeters allows for more comprehensive monitoring of dynamic features like ocean currents and river discharges. The first mission of this kind is the Surface Water and Ocean Topography (SWOT) mission, a collaboration between NASA and CNES with contributions from the Canadian Space Agency (CSA) and United Kingdom Space Agency (UKSA), launched in December 2022. With a swath of 120 km across-track, the SWOT mission provides high revisit observations over the open ocean, coastal zones, and hydrology targets with high measurement accuracy. The Sentinel-3 Next Generation Topography mission (S3-NGT), expected launch date 2032, will be composed of two companion satellites that incorporate both a nadir-looking SAR altimeter (to ensure measurement continuity with the predecessor Sentinel-3 constellation) and swath altimeters to enhance the revisit time and spatial coverage of the mission.

A.2 Retracking

By means of inversion techniques satellite altimetry allows for deriving key ocean geophysical estimates. A theoretical waveform model dependent on geophysical variables is fitted to the measured satellite data leading to the derivation of sea surface height (from which we derive global mean sea level), significant wave height and backscatter coefficient (the last two allow for derivation of wind speed).

Existing models are analytical, semi-analytical or empirical. Regardless of the form, all account for a minimum of three physical components: the Flat Sea Surface Response (FSSR), the Radar Point Target Response (PTR), and the probability function of the surface elevation (PDF). The convolution of the three results in a mathematical function which shape is similar to the real backscatter of an ocean surface topography system. This allows for comparing real versus theoretical in an iterative mode by changing the geophysical values of the theoretical model until achieving a perfect fit of the two.

In most operational missions until present, the reference models are in analytical form. For conventional pulse-limited altimeters (low resolution) the theoretical model of reference for ocean surfaces is the Brown model (Brown 1977). This model evolved in different forms leading to the MLE4 (Amarouche et al. 2004) nowadays available in all operational missions and considered as reference model for conventional altimetry.

For high resolution as available in delay-Doppler altimeters (a.k.a SAR altimeters or high-resolution altimeters), the reference mode is the SAMOSA mode (Ray et al. 2015). SAMOSA is the reference for high resolution in all existing high-resolution operational altimetry missions.

Clearly, all operational reference models for ocean surfaces are analytical. The advantage of analytical models is that they are computationally efficient, in turn they allow for near real time processing (products are available 3 hours after acquisition time). However, although allowing for achieving requirements the main disadvantages of these models are the introduction of a series of approximations. From all the approximation it is worth highlighting that these models do not account for the real instrumental behavior. This introduces irreversible patterns in the measurements.

The evolution of science has allowed numerical models to become operational and computational efficient. This is the case of the more recent model (Buchhaupt et al. 2021). This model opens a new generation of topography products that allow for exploiting all the instrument calibrations without assumptions, in turn a perfectly calibrated real data that will certainly allow for understanding better our historical data record. Numerical retracking is available since 2023 operationally in the Sentinel-6 mission for the first time in history.

A.3 Orbit

New climate-driven needs have now to be considered when thinking about the future of altimetry. Probably the most stringent aspect lies in that regional sea-level patterns driven by anthropogenic forcing are within 0.5 mm/y over a decade (Fasullo and Nerem 2018, Meyssignac et al. 2023). This means that assessing the current status of climate change and how much will local sea-level rise over the next decade and beyond will require highly stable orbits of better than 0.5 mm/y decade at regional scales. Meeting this challenge for satellite altimetry implies that we should tackle a variety of limitations that affect both the current dynamic and measurement models used in Precision Orbit Determination (POD).

In terms of orbit, because of the difficulty to model Solar Radiation Pressure perturbations, spurious signatures linked to the satellite beta (or draconitic) period will impact the satellite-based mean sea level observations, as well as the North-South centering of the orbit. For the reference missions, a draconitic period close to one solar year (365.25 days and its harmonics, associated with the seasonal component of geophysical interest) should be avoided to reduce aliased draconitic signatures into the annual signals measured by satellite altimetry. In addition, alternating forward and backward flying (like on Jason and Sentinel-6 satellites) facilitates observation of satellite modeling errors, even though the radial component of the orbit is generally not sensitive to these characteristics.

For the satellite, one should improve Center-of-Mass knowledge and the stability of the average radial acceleration due to surface forces (e.g., properties of the satellite surface oriented towards the Earth, thermal fluxes). A spacecraft design that introduces self-shadowing of different elements w.r.t to incoming radiation increases the complexity and thus reduces the reliability of the modeling of forces acting on the surface of the satellite. Embarking accelerometers to directly observe the surface force accelerations could improve the overall performances.

Satellite tracking systems should also evolve accordingly. Their systematic errors should be better understood, as well as their impact on orbit stability (or their ability to observe it). Including multiple independent tracking techniques (SLR, DORIS, GNSS) on board the altimeter satellite is essential, and we strongly encourage improvements in the quality of the tracking techniques and the data that they provide. In particular, the densification of the SLR network, especially in the Southern Hemisphere, is key to the calibration/validation of satellite altimetry orbits.

When integrating the equations of motion, background measurement and dynamic model uncertainties will have to be incorporated into POD for altimeter satellites. This should not only improve the orbit determination results but also provide more accurate orbit-related error bars. It would be useful if these uncertainties were provided with the different models, which is not always the case.

Independently of the satellite altimetry missions, reference frames play an important role with respect to this goal. For instance, inter-technique inconsistencies between the reference frame-defining parameters should be resolved by that time. This an important objective of the GENESIS mission. The same goes for mass change observations by satellite, for which there are a lot of interplay with satellite altimetry. As a consequence, the support of next generation gravity missions (Mass Change, MAGIC) to assure continuous observations is mandatory. We need continuous observations of time-variable gravity provided by GRACE-FO like missions as an input for precise POD modeling.

Satellite altimetry missions are not independent of each other; a single altimetry mission will in the end be included in a global constellation solution, and this specificity should be considered during the design of the mission. Thus, reaching these new targets for climate-driven goals for altimetry means that we should consider the requirements of complementary altimeter missions (other than the reference missions).

A.4 Geophysical corrections

The computation of accurate sea surface heights (SSH) from satellite altimetry requires the observed range to be corrected for the path delays caused by the interaction of the radar signal with the atmosphere and with the sea surface (the so-called range corrections) and for geophysical phenomena that introduce variability in the SSH other than that due to the pure oceanic signal and therefore must be accounted for prior to sea level studies. The range corrections include the effects of the atmosphere (dry, wet, and ionospheric effects) and the sea state bias. The most relevant geophysical corrections are the tides and the dynamic atmospheric correction.

A review of the various range and geophysical corrections, including the specificities related with coastal zones and inland waters, can be found in e.g., Andersen and Scharroo (2011), Escudier et al. (2017), and Fernandes et al. (2014, 2021).

Dry tropospheric correction

The Dry Tropospheric Correction (DTC) accounts for the path delay due to the interaction of the altimeter signal with the dry gases in the atmosphere (mostly nitrogen and oxygen) and is proportional to the surface atmospheric pressure, i.e., it has the spatial and temporal pattern of the atmospheric pressure. With an absolute mean value of 2.3 m at sea level, it can be modeled with high accuracy and the corresponding state-of-the-art methodologies are well established. Within a few millimeters, the DTC can be derived from sea level pressure provided by one of the ECMWF models, further reduced to surface height. Governed by the height variation of atmospheric pressure, the DTC has a very strong variation with height (1 cm per 40 m), which can induce very significant errors in case wrong surface heights are used in its computation. While over the ocean the DTC is one of the most precisely computed range corrections, systematic errors of several centimeters may still exist in some current altimeter products over some coastal and inland water regions, causing significant errors in coastal water surface heights and mean river profiles (Fernandes et al. 2014, 2021). For future developments, the DTC estimation for satellite altimetry would benefit from finer DEM and/or accurate altimetry-derived heights over these regions.

Wet tropospheric correction

The Wet Tropospheric Correction (WTC) refers to the path delay that is mostly due to the presence of water vapor in the atmosphere. Due to the water cycle, the amount of atmospheric water vapor is constantly changing both in space and time, making this correction highly variable and one of the major sources of uncertainties in satellite altimetry. With an absolute value less than 0.5 m, the most accurate way to compute this correction over the ocean is using the observations acquired by dedicated MicroWave Radiometers (MWR) on board the altimetric missions (Brown 2010, Hermozo et al. 2019, Obligis et al., 2009, Vieira et al. 2022) or e.g., from GNSS over continental waters. The spatial resolution of the current 2-band and 3-band MWR is coarse compared to the altimeter one, leading to large uncertainty in the WTC retrievals over coastal and inland waters. Methods such as the Mixed Pixel Algorithm (MPA) (Brown 2010), and the GNSS-derived Path Delay Plus (GPD+) methodology (Fernandes & Lázaro 2016; Lázaro et al. 2020) have been developed to improve the WTC over these regions, where the MWR estimations are invalid. The first method is applied to the reference missions while the second is applied to all altimetric missions, with major impacts in the missions possessing 2-band MWR. In the absence of observations, WTC from NWM can be used. Currently, the best NWM-derived WTC are the ECMWF Op. model, after 2004, and the most recent reanalysis, ERA5, before that date (Fernandes et al. 2014, 2021).

The MWR spatial resolution is being improved with a new generation of radiometers providing observations at higher frequencies (>37 GHz), currently on board the Sentinel-6 MF satellite. This will be supported by dedicated processing to better characterize the water vapor variability over open ocean and to improve the WTC retrieval over coastal waters. In the near future, it is expected that these technological developments, together with better retrieval algorithms, will reduce the estimation errors in the WTC, therefore meeting the requirements for coastal altimetry applications.

Ionospheric correction

The Ionospheric Correction (IC) accounts for the path delay due to the interaction of the altimeter signal with the ions and electrons in the atmosphere. It is function of the electron density in the ionosphere and, for the frequencies and altitudes at which the altimeters operate, it has absolute values in the range of 1 to 20 cm, maximum over periods of high solar activity. Unlike the tropospheric corrections, this path delay is strongly dependent on the frequency and the most accurate way to determine the IC is by combining the altimeter measurements in two frequencies. For single frequency altimeters or for measurements over non-ocean surfaces, models based on GNSS observations such as the JPL Global Ionosphere Maps (GIM) of Total Electron Content (TEC), properly scaled for the height of each mission, can be adopted (Fernandes et al. 2014). Due to the smoothing applied to reduce the high frequency noise and to the larger retracking errors, the dual-frequency IC has larger errors in coastal and inland water regions. This may be improved by tuned filtering methods, possibly combining dual-frequency and JPL-GIM estimates.

Sea state bias

The Sea State Bias (SSB) refers to the net altimeter range correction (Chelton et al. 2001) applied to account for added range delay due to surface gravity wave effects on the intrinsic radar range estimate; this be it a conventional pulse-limited altimeter (e.g., Jason-1, -2 and -3) or a delay-Doppler altimeter (e.g., Sentinel-3). The first SSB component is due the fact that scattering elements across the km-scale radar surface footprint do not contribute equally to the radar return; troughs of waves tend to reflect radar energy better than crests. Thus, the range centroid is shifted below mean sea level towards the troughs of the waves. This cm-level shift is referred to as the electromagnetic (EM) bias. A smaller wave elevation skewness bias adjusts for the assumption that the wave elevation probability density function (pdf) is symmetric, whereas the true pdf is nominally skewed towards the troughs. The final component is the return waveform tracker bias, an effect that accounts for any sensor-specific combination of range errors due to instrumental and signal processing considerations.

These three terms are not separately estimated using independent surface wave measurements because approaches to do so are not yet available. Instead, the net SSB correction is determined empirically (Labroue et al. 2004) from each altimeter's on-orbit data. The resulting model, including tracker bias specifics, applies only to that altimeter. These empirical models predict the SSB using 1 Hz altimeter measurements of both the significant wave height (SWH) and wind speed, with the former largely controlling the correction. Several studies have shown that a slightly improved SSB correction estimate results when adding a third input variable (i.e., a 3D SSB model), the mean wave period (Pires et al. 2019, Tran et al. 2010). The SSB correction is applied using a bi(tri)linear interpolation of a table of sea state bias vs. significant wave height and wind speed (and wave period). For a typical SWH of 2 meters, the correction is about 10 cm (+/- 1-2 cm). SSB estimate noise depends mainly on sensor and geophysical noise in altimeter SWH estimates, where recent research shows that SWH noise at length scales of 5-100 km can factor into undesired artifacts in altimeter SSH spectra (Tran et al. 2019).These SSB models are for global application under all wave conditions to include both coastal and open ocean locations. They represent a least-squares type of solution built using at least one year of global data. No algorithms specific to coastal areas are yet proposed even though coastal and inland water may differ in their SSB. This is in part due to limitations in the empirical SSB modeling approaches used to date. Ongoing evaluation of the delay-Doppler altimeter suggests that sea state bias correction models will be similar to that for conventional altimeters, but these altimeters require additional precision when working with the SWH and range measurements because of intrinsic non-SSB impacts due to wave period variability.

Dynamic atmospheric correction

The Dynamic Atmospheric Correction (DAC) accounts for the sea surface height variations due to the time varying loading of atmospheric pressure. With values ranging from -50 cm to 50 cm, the modeling of this effect includes a static component (inverse barometer), accounting for low frequency effects (time scales less than 20 days) and a high frequency part (HF), accounting for SSH variations shorter than 20 days, which may be aliased into lower frequency signals of periods larger than twice the satellite sampling interval (~10 days for the reference missions). Currently, the DAC is best modeled by MOG2D-G (two-dimensional Gravity Waves model), which includes the low frequency inverse barometer effect and the high frequencies of the MOG2D-G (Carrere 2003).

Compared to the operational product, the DAC estimated from the ECMWF reanalysis ERA Interim shows a great interest for the first decade of altimetry (Carrere et al. 2016). Further improvements can be obtained from the most recent ECMWF reanalysis, ERA5, particularly relevant for climate studies.

Tides

The ocean tides generally account for the largest variance in open-ocean sea-surface height. Mean tidal amplitudes in deep water are of order 70 cm, and potentially many times that along certain high-tide coastlines. Because they are of periods one day and faster, the tides are aliased to low frequencies in all altimeter measurements. The signals must generally be removed by use of prior models. For an extended discussion of present-day modeling methods and their accuracies, for both barotropic and (the much smaller) baroclinic tides (Ray & Egbert 2017). In the deep ocean, between latitudes ±66°, the barotropic tide is predictable with an accuracy now approaching 1 cm, and this is continuing to improve as smaller constituents are better accounted for (e.g., recent models such as FES2014 (Lyard et al. 2021) now include a number of nonlinear tides, which are generated in shallow water but can propagate into the deep). Coastal tide prediction is much worse, and locations can be found where errors easily exceed 10 cm. Models of shallow-water tides are slow to improve, because progress often depends on the availability of accurate, fine-scale bathymetry, but the community expects significant progress in coastal tides after several years of SWOT wide-swath data have been collected. Tide models in polar regions are also problematic, with major difficulties being those under Antarctic ice shelves, on the Siberian Shelf, and in the Canadian Archipelago. A lack of high-quality observations is a major impediment to mapping polar tides, although retracking of CryoSat-2 data and the newly collected laser data from ICESat-2 are proving invaluable and should result in improvements over the next few years. Polar tides can typically have significant seasonal variability, reflecting changes in dissipation from seasonal ice cover and stratification, and this needs to be better accounted for in predictive models. Finally, for missions such as SWOT that are designed to map the oceanic submesoscale, the prediction of baroclinic tides and their separation from non-tidal motions of similar wavenumber are challenging problems. Current models (Carrere et al. 2021) of the phase-locked baroclinic tide (at least for M2), constructed from historical altimetry and from deep-ocean drifters, appear to be a good first step at removing baroclinic tidal variance from observations. However, the non-phase-locked tide is thought to be a significant part of the variance, and progress with that will require new approaches and better understanding of the interactions between tides and ocean circulation. New measurements and new studies based on SWOT data will begin to attack this problem in the near future.

In addition to ocean tides, satellite altimetry must also be corrected for solid-earth tides, both the body tide and the load tide. The load tide, which is the deformation of the crust by the weight of the overlying ocean tide, is calculated from the adopted model of ocean tides. The solid body tide is the response of the solid Earth to gravitational forces of the Moon and the Sun. The tidal elevation is proportional to the tidal potential, and this proportionality is defined by the Love numbers. With values ranging up to ±30 cm, this correction is computed with high accuracy from the accurately known tidal potential (Cartwright & Edden 1973), although small errors arise from uncertainties in a diurnal-band resonance of the Love numbers.

The pole tide is generated by small perturbations to the Earth's axis of rotation with respect to its mean geographic pole, with main periods of ~14 months (the Chandler wobble) and 12 months. It is a small correction, with values in the range ±2 cm. Recent improvements have occurred in the pole tide correction by means of a more accurate mean pole location and updated Love numbers (Desai et al. 2015).

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C. Acronyms

AGU	American Geophysical Union
AOML	Atlantic Oceanographic and Meteorological Laboratory
Argo	A program of freedrifting profiling floats that measures temperature and salinity
ASCAT	Advanced SCATterometer
AVISO	CNES data center for Altimetry and DORIS products
BUFR	Binary Universal Form for the Representation
CCI	Climate Change Initiative (https://tinyurl.com/ESACCI)
CEOS	Committee on Earth Observation Satellites
CFOSAT	China France Oceanography SATellite
Copernicus	European Union's Earth observation program (previously known as GMES, Global Monitoring for Environment and Security)
CL	Confidence Level
CNES	Centre National d'Etudes Spatiales, French space agency
COB	Continental Ocean Boundary
CRISTAL	Copernicus polaR Ice and Snow Topography ALtimeter
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CryoSat2	ESA's Earth Explorer for Cryospheric studies (Launched in April 2010)
CryoVex	CryoSat Validation Experiment
CSA	Canadian Space Agency

SDEM	Digital Elevation Model
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DUACS	Data Unification and Altimeter Combination System
ECMWF	European Centre for Medium range Weather Forecasts
ECV	Essential Climate Variable
Envisat	ESA Environmental Satellite (March 2002 - May 2012)
ERA	European ReAnalysis
ERS	ESA European Remote-Sensing Satellite
- ERS-1	(July 1991 March 2000; Altimetry mission ended in June 1996)
- ERS-2	(April 1995 Sept. 2011)
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites (Australia)
FFSAR	Fully Focused SAR
FIO	First Institute of Oceanography (China)
FRM	Fiducial Reference Measurements
GCOS	Global Climate Observing System
GDR	Geophysical Data Records
Geosat	GEOdetic SATellite
GMSL	Global Mean Sea Level
GNSS	Global Navigation Satellite Systems
GOOS	the Global Ocean Observing System
GRACE	Gravity Recovery And Climate Experiment, NASA/DLR missions, (March 2002 - Oct. 2017)
- GRACE-FO	GRACE-Follow On (since May 2018)
HPC	High Performance Computing
HY-2 (Haiyang2)	Second generation ocean observation/monitoring satellite series by CNSA (China National Space Administration)
- HY-2A	(August 2011 - September 2020)
- HY-2B	(since October 2018)
- HY-2C	(since September 2020)
ICESat	NASA's Ice, Cloud and land Elevation Satellite
IPCC	Intergovernmental Panel on Climate Change
ISRO	Indian Space Research Organisation, Indian space agency
ITRF	International Terrestrial Reference Frame
Jason-1/2/3	NASA/CNES/NOAA/EUMETSAT Franco-American satellite, altimetry reference missions
KaRIn	Ka band Radar Interferometer onboard the SWOT mission
LRM	Low Resolution Mode
MAGIC	MAss Change and Geoscience International Constellation
NASA	National Aeronautical and Space Administration, US space agency
NetCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
NWM	Numerical Weather Model
ODYSEA	Ocean Dynamics and Surface Exchange with the Atmosphere
OSSE	Observing System Simulation Experiment
OST-VC	Ocean Surface Topography Virtual Constellation
OSTST	Ocean Surface Topography Science Team
PI	Principal Investigator
POD	Precision Orbit Determination
PO.DAAC	Physical Oceanography Distributed Active Archive Center
RADS	Radar Altimetry Database System
ROSES	Research Opportunities in Space and Earth Sciences (NASA)
SAR	Synthetic Aperture Radar (SARM for SAR mode)
SARAL/AltiKa	Satellite with Argos and AltiKa, ISRO/CNES Ka-band altimetry satellite (Feb. 2013)
SCAT	wind scatterometer (fan beam concept) on board CFOSAT
SEASTAR	SEA Squinted Three Azimuth Radar
Sentinel	European Copernicus Programme operational satellites
Sentinel-3	Four Copernicus operational altimetry missions (includes color and temperature sensors)

- Sentinel-3A launched on 16 February 2016
- Sentinel-3B launched on 25 April 2018

Sentinel-6	Copernicus operational successors to the Jason series
- Sentinel-6A/Michael Freilich	First of series of three Sentinel-6 satellites, launched 21 Nov 2020
SKIM	Sea surface KInematics Multiscale monitoring, preselected for Earth Explorer 9
SLR	Satellite Laser Ranging or Sea Level Rise (depending on the context)
SMASH	The SMall Altimetry Satellites for Hydrology
SSALTO	Segment Sol multimissions d'ALTimétrie, Orbitographie et localisation précise
SSH	Sea Surface Height
SST	Sea Surface Temperature
STREAM	ocean Surface TRansport, mechanical Energy, Airsea fluxes and Mixing" satellite mission
SWH	Significant Wave Height
SWIM	Surface Waves Investigation and Monitoring on board CFOSAT
SWOT	Surface Water Ocean Topography, NASA/CNES satellite mission (launched in 2022)
SWORD	SWOT River Database
TOSCA	French committee on “Terre, Océan, Surfaces Continentales et Atmosphère”
UKSA	UK Space Agency
TOPEX/Poseidon	NASA/CNES first satellite altimetry reference mission (Aug 1992 - Jan 2005)
WMO	World Meteorological Organization