Title
Altimetry for the future: Building on 25 years of progress

Journal
Advances in Space Research, 68(2)

ISSN
0273-1177

Authors
Team, International Altimetry
Abdalla, Saleh
Kolahchi, Abdolnabi Abdeh
et al.

Publication Date
2021-07-01

DOI
10.1016/j.asr.2021.01.022

Peer reviewed

ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research xxx (xxxx) xxx

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Altimetry for the future: Building on 25 years of progress

International Altimetry Team[‡]

Received 16 August 2020; received in revised form 11 January 2021; accepted 13 January 2021

Abstract

In 2018 we celebrated 25 years of development of radar altimetry, and the progress achieved by this methodology in the fields of global and coastal oceanography, hydrology, geodesy and cryospheric sciences. Many symbolic major events have celebrated these developments, e.g., in Venice, Italy, the 15th (2006) and 20th (2012) years of progress and more recently, in 2018, in Ponta Delgada, Portugal, 25 Years of Progress in Radar Altimetry. On this latter occasion it was decided to collect contributions of scientists, engineers and managers involved in the worldwide altimetry community to depict the state of altimetry and propose recommendations for the altimetry of the future. This paper summarizes contributions and recommendations that were collected and provides guidance for future mission design, research activities, and sustainable operational radar altimetry data exploitation. Recommendations provided are fundamental for optimizing further scientific and operational advances of oceanographic observations by altimetry, including requirements for spatial and temporal resolution of altimetric measurements, their accuracy and continuity. There are also new challenges and new openings mentioned in the paper that are particularly crucial for observations at higher latitudes, for coastal oceanography, for cryospheric studies and for hydrology.

The paper starts with a general introduction followed by a section on Earth System Science including Ocean Dynamics, Sea Level, the Coastal Ocean, Hydrology, the Cryosphere and Polar Oceans and the "Green" Ocean, extending the frontier from biogeochemistry to marine ecology. Applications are described in a subsequent section, which covers Operational Oceanography, Weather, Hurricane Wave and Wind Forecasting, Climate projection. Instruments' development and satellite missions' evolutions are described in a fourth section. A fifth section covers the key observations that altimeters provide and their potential complements, from other Earth observation measurements to in situ data. Section 6 identifies the data and methods and provides some accuracy and resolution requirements for the wet tropospheric correction, the orbit and other geodetic requirements, the Mean Sea Surface, Geoid and Mean Dynamic Topography, Calibration and Validation, data accuracy, data access and handling (including the DUACS system). Section 7 brings a transversal view on scales, integration, artificial intelligence, and capacity building (education and training). Section 8 reviews the programmatic issues followed by a conclusion.

Keywords: Satellite altimetry; Oceanography; Sea level; Coastal oceanography; Cryospheric sciences; Hydrology

1. Introduction

The conclusions and recommendations presented in this paper are based on an analysis of the history of altimetry and its achievements, an analysis of the current situation, of the evolution of scientific issues, and of the technological perspectives. The construction of the satellite radar altimetry constellation (Fig. 1), its well-established successes and contributions to scientific advances in ocean dynamics are unique in the history of Earth observation from space. A real ambition was originally posed and was finally able to be accomplished. Many references (e.g. Koblinsky et al., 1992; Fellous et al., 2006; Escudier and Fellous, 2009; Simmons et al., 2016) were seminal in the attempt to drive

‡ List of co-authors[1] at the end of the paper.

[1] The following four individuals have assembled this document after receiving and reviewing comments from all authors: Jacques Verron (jacques.verron@univ-grenoble-alpes.fr), Barbara Ryan (bjrgeneva@gmail.com), Pascal Bonnefond (Pascal.Bonnefond@obspm.fr) and Jérôme Benveniste (Jerome.Benveniste@esa.int).

https://doi.org/10.1016/j.asr.2021.01.022
0273-1177/© 2021 COSPAR. Published by Elsevier B.V.

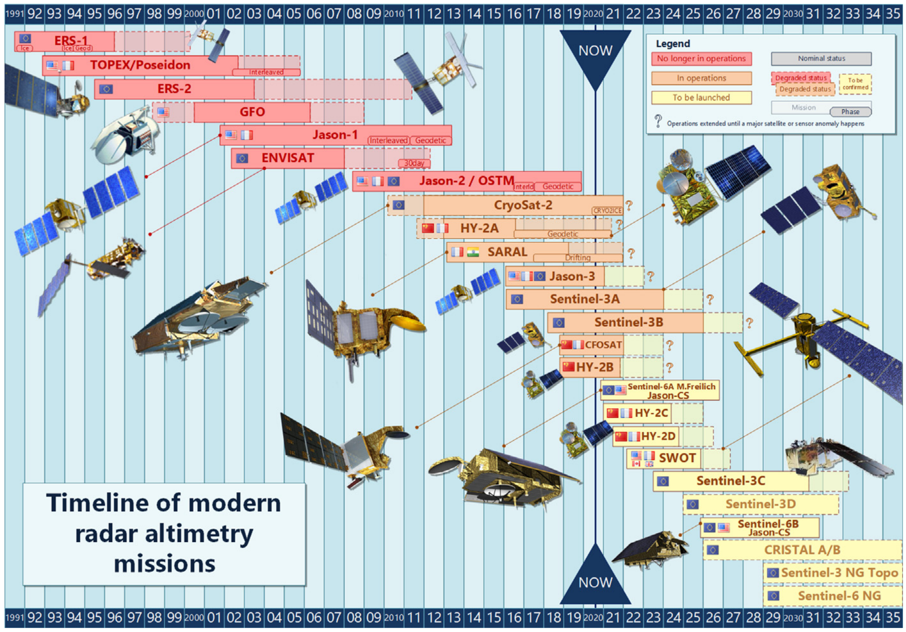

Fig. 1. Altimetry Satellites Timeline.

the requirements for an observing system exploiting radar altimetry. They marked milestones in requirements for progresses of Radar Altimetry and advised on a roadmap for future progresses. This paper is written in the same spirit with the same goals. The present altimetric system has exceeded expectations not only for monitoring and understanding ocean circulation at mesoscales and larger, but for the fulfillment of stringent requirements of observing global sea level rise and its acceleration. It has even proved to be a valuable observational tool for other components of the hydrosphere (ice, rivers, lakes and wetlands) as well as for other variables (e.g. wind, sea state) and components. The level of accuracy and precision needed have largely evolved from the early beginning until now and strongly depends on the type of scientific studies. As an example, for the mean sea level rise, Nerem (1995) recommended at least 1 mm/yr and now Ablain et al. (2019) recommend 0.3 mm/yr (over a decade) and even begin to give an estimation of the current uncertainty on the acceleration. Another example, in terms of spatial resolution, while TOPEX/Poseidon mission (Stammer and Wunsch, 1994) was focusing on circulation of large scale (more than 100 km) the SWOT mission will resolve small spatial scales down to 15–30 km (Morrow et al., 2019). And last but not least is the level of improvement from Smith and Sandwell (1994) to Sandwell et al. (2019), which is related to the geophysics and impacts the dynamic topography determination. In this paper we have chosen to not give exact numbers for the requirements but have preferred to cite recent publications that deal with such numbers.

The international constellation of satellite altimetry thus became a key element of the global ocean observing system (Fu and Cazenave, 2001; Stammer and Cazenave, 2018). The instrumental performances and the orbital reference accuracy have improved very significantly over time and, with the new missions, the instrumental error is now higher (<20 mm) than the radial orbit error (<10 mm) (Fig. 2). Satellite altimetry has provided the foundation for products of many marine service programs, for monitoring the cryosphere and, with more difficulty but still tangible achievements, for inland water and coastal zones, altogether benefiting society and science. In addition to providing data that have enabled scientific advances, altimetry is also distinguished by a mode of organization in the design and distribution of data, and by outstanding international cooperation through the development of applications, particularly related to operational oceanography, coastal ocean and hydrology monitoring and in several cases ice sheet and sea-ice monitoring. The excellent cooperation between the European and US scientific communities has been a key factor, and the long-running Ocean Surface Topography Science Team (OSTST) (https://sealevel.jpl.nasa.gov/science/ostscienceteam/) is testimony to this cooperation as well as the Mission Advisory Groups (MAG) and the Calibration/Validation teams. In the more recent years, very fruitful cooperations with India and China through the development and exploitation of satellite missions (SARAL/AltiKa, HY-2A&B, CFOSAT) have enabled and increased fruitful exchanges in our scientific communities.

Every five years the community celebrates the advancement of radar altimetry with an international symposium that extends the yearly OSTST meetings. They took place in Venice, Italy, for the 15th (2006) and 20th (2012) years of progress and in 2018, the 25 Years of Progress in Radar Altimetry Symposium was held in Ponta Delgada, Azores, Portugal. The community is large and thematically very broad. For example, at the last symposium, nearly 500 sci-

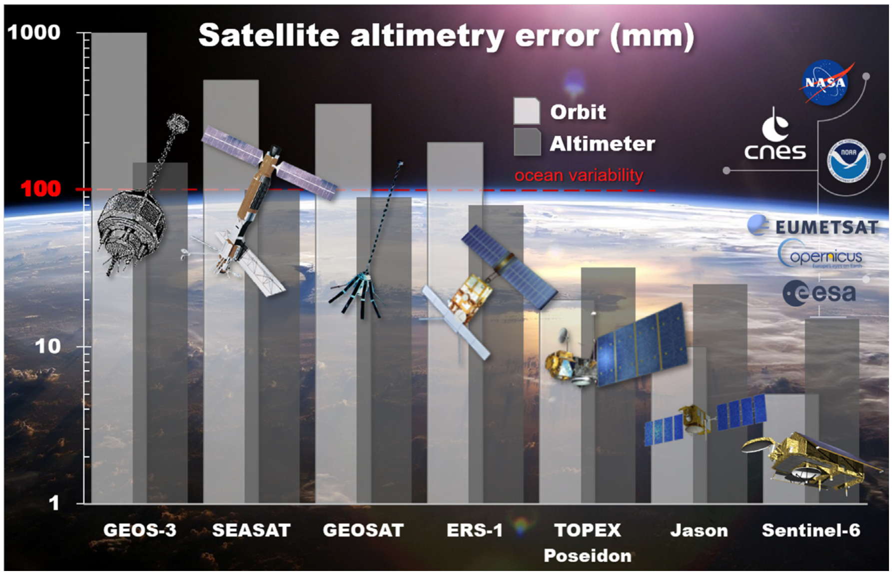

Fig. 2. Time evolution of the altimetry errors: (light grey) radial orbit error and (dark grey) instrumental error (including corrections). The red line illustrates the average level of ocean variability.

entists, engineers and managers came to Ponta Delgada from 28 countries worldwide, submitting papers with more than 1000 authors and co-authors. On this occasion it was decided to collect all the contributions of the scientists, engineers and managers to give the state of altimetry and to propose recommendations for the altimetry of the future.

This paper summarizes those contributions and recommendations, and provides guidance for future mission design, research activities and sustainable operational radar altimetry data exploitation. The paper is organized as follows. Firstly in Section 2, the various scientific fields are discussed with their own objectives and priorities for the development of satellite altimetry. In Section 3, recommendations are proposed with regard to the main operational fields of altimetry applications. Section 4 discusses instrumental developments and technological evolutions. Section 5 provides detailed discussion of the data obtained from altimetry, the processing of these data and Section 6 focuses on the additional observation data necessary for the processing and/or corrections of altimetric data. In Section 7 the interdisciplinary activities between the different fields of scientific and operational applications are discussed. Section 8 discusses the programmatic dimension of altimetry satellite missions as it relates to space agencies and operators. Finally a conclusion is offered in Section 9.

2. Earth system science

Altimetry was first used for open ocean observations. With time, interest in altimetric data expanded to other areas of science. The so-called "New frontiers of altimetry" (https://tinyurl.com/NewFrontiersAltimetry) today encompass coastal oceanography, the cryosphere, inland water hydrology, and climate – all beyond the initial and traditional mission objectives of open ocean investigations. As climate underlies and motivates many scientific studies in the field of Earth Sciences, more and more attention is being devoted to studying Essential Climate Variables (ECVs). The surface ocean ECVs, as identified by the Global Climate Observing System (GCOS), are listed in Annex A. Altimetry underpins five of them: Sea level, Sea state, Sea ice, Ice sheets, Surface current as well as Lake and River level changes. Moreover, the altimetric measurement reflects internal adjustments of the ocean, and as such, provides observations of processes beyond just the surface. Viewing the Earth as a system of integrated processes, and thinking in both multi- and cross-disciplinary ways are important steps for the evolution of altimetry and its future applications.

2.1. Ocean dynamics

One general issue for oceanography is to improve our knowledge of the role of the ocean in the Earth climate system. To reach this objective it is needed to monitor, understand and predict the ocean's evolution in order to analyze the impact of mitigation measures and to implement appropriate adaptation policies. Satellite altimetry has substantially advanced understanding of the oceans by providing unprecedented observations of the surface topography at scales larger than ~200 km, thus, increasing our knowledge of global ocean circulation (Fig. 3), from the role of mesoscale eddies in shaping this ocean circulation, up to global sea level rise (Fig. 4) (Cazenave et al., 2018; Fu and Le Traon, 2006; Morrow and Le Traon, 2012). One of the challenges for modern oceanography is to facilitate observations of ocean dynamics at smaller, faster scales (Klein et al., 2019). Recognizing the essential role of small scales (from mesoscales to submesoscales) on ocean

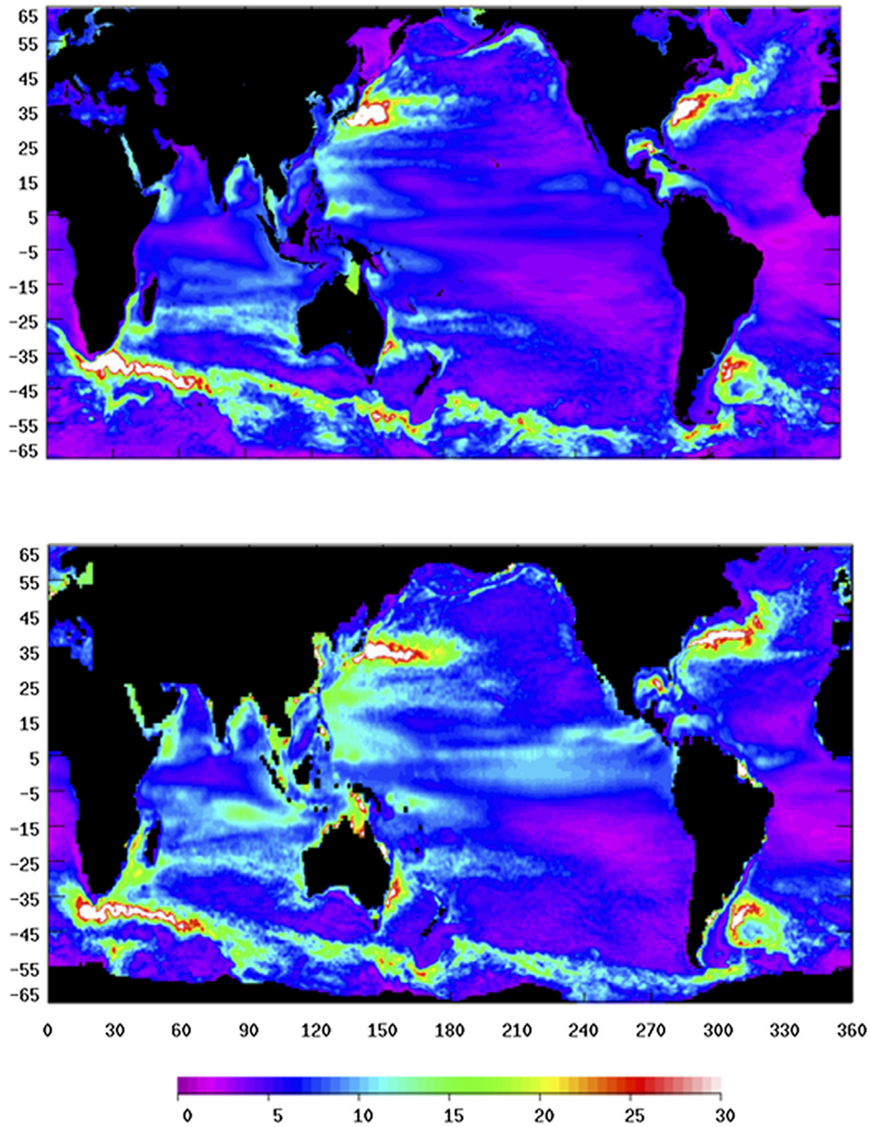

Fig. 3. Comparison of the standard deviation (in cm) of the sea surface height derived from the simulation of an ocean general circulation model (upper panel) and altimeter data (lower panel). The model was developed by a group at the MIT with eddy-permitting horizontal resolution of 18 km. The simulation was performed for the period of 1992–2006. The altimeter data were taken from the same period of time. See Fu (2009).

dynamics, as well as their impact on biological productivity of marine ecosystems, is one of the major advances of recent years in oceanography. It goes hand in hand with the development of global and regional models with a kilometric resolution and their coupling with coastal models (Siegel et al., 1999; Guo et al., 2019).

Among the various scientific priorities put forward by the oceanographic scientific community, there is a lot of interest in using altimetry to observe the ocean mesoscale and submesoscale circulation at spatial resolutions of 15 km and larger, providing the missing link for ocean dynamics between 15 and 200 km for climate studies. Resolving two-dimensional details of the ocean circulation is essential for improving the understanding of the ocean circulation, since these smaller scales are critical in driving the vertical transfer of heat, carbon, and nutrients and many other properties of the ocean (Mahadevan et al., 2020; Ruiz et al., 2019). It is not just that global observations at these scales are lacking: these smaller processes are only parameterized in climate models, which in turn need validation with observations for both parameterizations and model output. Resolving finer scales was already a goal of several altimetric missions, such as the Jason and Sentinel-3 series and SARAL/AltiKa, and this is even more crucial with the future wide-swath SWOT mission (Morrow et al., 2018; Morrow et al., 2019). There is a strong interest in the community for a better understanding of the ocean's vertical and horizontal structure and velocities, to address not only the high resolution satellite and in situ observations, but also their relationship to the climate record (Mulet et al., 2020; Knudsen et al., 2019). Observing the small scales is also crucial for understanding the ocean's energy budget, and the exchange of energy occurring between the large scale circulation, the mesoscales, down

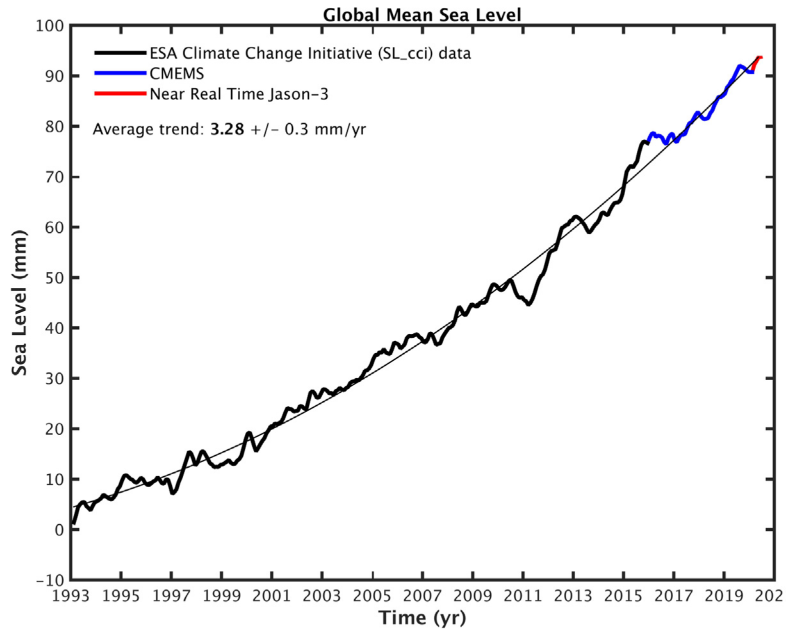

Fig. 4. Global mean sea level from satellite altimetry over 1993–2020. Data from the ESA Climate Change Initiative Sea Level Project until December 2015 (black curve, Legeais et al., 2018), extended by the Copernicus C3S data until 9 March 2020 (blue curve) and Near Real Time data from Jason-3 until 16 June 2020 (red curve). The thin black curve is a quadratic function fitted to the data to represent the acceleration (+0.10 +/- 0.02 mm/yr2). The TOPEX-A drift and GIA (Glacial Isostatic Adjustment) corrections have been applied.

to the smallest scales of ocean mixing and dissipation for the global ocean. Satellite altimetry does not provide a direct observation of these dissipative scales, but can observe regions of rapid change in energy where mixing may be important and, therefore these are ideal target sites for intense studies and parameterization development. Clearly dissipation and mixing are not only an open ocean consideration, but includes observing the coastal and regional seas and high latitude oceans. Recent altimetric observations and high-resolution models have also revealed that "unbalanced" dynamics such as internal tides and waves can mask the sea surface height signature of "balanced" motions such as eddies and currents, especially at high wavenumbers (Richman et al., 2012; Rocha et al., 2016; Tchilibou et al., 2018). This dynamical interaction has important implications for the ocean's energy budget, and will be a key subject of research in the coming years.

Overall, the scientific priorities are to better understand the dynamical interactions between motions of different horizontal scales and vertical structures, and of different dynamical origins (e.g., balanced vs. unbalanced motions) and how they impact on the ocean energy budget, on the oceanic transport of mass and tracers, on mixing and dissipation, on the ecosystem and on water mass evolution.

The most general recommendations by the ocean sciences community for the future of altimetry are (i) to continue current capabilities but also to sustain and improve existing observations, and (ii) to better observe the global open ocean at finer space and time scales, but also extend observations into the coastal and high-latitude oceans, including the capacity to observe the tides and internal tides. Beyond these general recommendations, the usefulness of long ocean reanalyses which provide insight to interannual variations (Artana et al., 2019a) must be mentioned. The 25-year-long GLORYS12 reanalysis has shown definite skills when compared to non-assimilated in situ mooring data in Drake Passage for example (Artana et al., 2019b). The necessary evaluation of operational models and reanalyses with non-assimilated data should be stressed. Many of these recommendations will be supported in other areas of this paper.

Some specific statements and recommendations for the open ocean dynamics concern the good coverage of all scales and their interactions:

- As interests range from large to smaller mesoscales and submesoscale, no single measurement is likely to be sufficient. Multi-platform in situ measurements, multi-satellite and SAR and SAR-interferometry altimetry are all required. As much as possible, for these observational efforts, in situ and remote should be coordinated;
- In the smaller mesoscale and submesoscale range, balanced and unbalanced motions co-exist. Theoretical, statistical and numerical model-based approaches are synergetically needed to disentangle them. However, these must be supported by well designed field experiments for in situ data collection, and those guided by remote data;
- As the horizontal length-scales decrease, the vertical circulation becomes increasingly important. Evaluating the vertical circulation that is constrained by in situ and

high-resolution Sea Surface Height (SSH) measurements is important for ocean dynamics, climate (heat and carbon uptake) and biology.

2.2. Sea level

The present space observation system has, in all likelihood, exceeded the expectations for not only ocean circulation at mesoscales and greater, but also the more stringent requirements for determining global sea level rise and its acceleration (Fig. 4). The present rate of acceleration is detected with 99% confidence (Cazenave et al., 2018; Ablain et al., 2017; Nerem et al., 2018; Veng and Andersen, 2020). This is a good indication that the present observing system has reached maturity and exceeded its performance requirements. Another good indication is that the sea level budget is now closed on decadal and longer time scales with an uncertainty $< \pm 0.3$ mm/yr ((Ablain et al., 2019), The WCRP sea level budget group). This accuracy in closing the sea level budget has opened recently new science perspectives for altimetry. Indeed, it is now possible to combine satellite altimetry with space gravimetry data from GRACE to estimate the ocean steric sea level and further derive estimates of the ocean heat content changes with an uncertainty < 0.4 W/m^2 (Meyssignac et al., 2019). This new estimate of the global ocean heat content place a strong constraint on the Earth energy imbalance estimate on interannual and longer timescales. This is because 91% of the heat excess caused by the Earth Energy Imbalance (EEI) is accumulated in the ocean in the form of ocean heat content changes (von Schuckmann et al., 2020). With this new constraint it is now possible to use satellite altimetry data to study the Earth energy budget and analyse the Earth energy cycle at annual and longer time scales (e.g. Meyssignac et al., 2019; L'Ecuyer et al., 2015).

Current global mean sea level (GMSL) rise is accelerating in accordance with the acceleration of land-ice melt, and is very likely a consequence of anthropogenic global warming, due to increased atmospheric levels of greenhouse gases. Global mean sea level will continue to rise during the 21st century and beyond, in response to global warming (global mean rise of more than 1 m by 2100 not unlikely). The regional variability will amplify the global mean rise by about 20% in the tropics and some other regions, such as the eastern coast of North America (Oppenheimer et al., 2019). In some cases, this regional sea level rise can be up to 3 times the global mean, for instance in the western tropical Pacific (Ablain et al., 2017). Even if greenhouse gas emissions stop tomorrow, sea level will continue to rise for several centuries. There are also, however, several remaining unknowns like: How quickly the ice sheets will melt? Whether abrupt and irreversible ice sheet mass loss will occur? And whether sea level at the coast is rising at the same rate as in open oceans (Marti et al., 2019)? The accuracy of GMSL estimates also depends on the satellite constellations used for the calculation as well as on the calculation method itself (Scharffenberg and Stammer, 2019). Meridional sampling limitations due to the satellite orbit inclination are a fundamental constraint on the accuracy level of GMSL estimates. Best GMSL estimates can be derived by a multimission satellite constellation with complete meridional extend.

Three key challenges in sea level science for the next decade are: (i) to determine the response of the Greenland and Antarctic ice sheets to continuing global warming and their contributions to future sea level rise (Ludwigsen and Andersen, 2020), (ii) to estimate absolute, but most importantly relative coastal sea level changes, worldwide, and study impacts of sea level rise in highly vulnerable coastal zones and (iii) improve the accuracy in sea level and the consistency with space gravimetry data to derive more precise constraints on the EEI estimates and on the global energy budget. Indeed, the level of the ocean can also change because the underlying land is rising or falling with respect to the ocean surface. Such relative sea level change usually affects a local or regional area, and in numerous cases, is actually outpacing the rate of sea level change.

The primary requirements that are advocated for sea level science are:

- A long and accurate global and regional sea level record for climate studies which implies sustained altimetry missions, and continuing Research and Development (R&D) activities to feed operational production of sea level (e.g., the Copernicus Marine and Climate Change Services in Europe, https://www.copernicus.eu/en). Extending the ocean altimetry data record beyond 4 decades should be an objective. A key aspect is to maintain a high accuracy reference mission following Jason-3 and Sentinel-6;
- The continuity of the measurements is essential, not only the continuity of altimetry but also of the other observing systems that accompany altimetry (Argo, deep Argo, GRACE, etc.) and all geodetic data (DORIS, SLR or GNSS data) needed to improve the orbit of altimeter satellites and the geophysical corrections applied to altimeter measurements;
- The regular assessments of closure of the sea level budget at global and regional scales. Uncertainty estimates on regional sea level and on regional sea level trends are still lacking to improve this closure. It includes the uncertainties that are estimated through comparison with other observing systems such as tide gauges (Watson et al., 2019). Improving the comparison between tide gauges and altimetry likely requires equipping more tide gauges with GNSS positioning, in order to achieve higher accuracy, and to improve the relative sea level trends estimations;

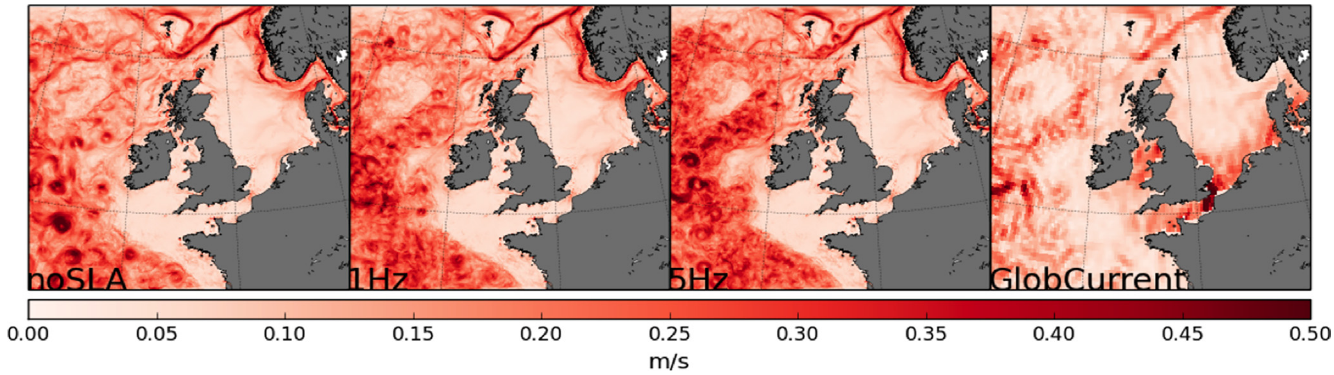

Fig. 5. Monthly mean surface current speed (m/s, March 2015) from the Met Office 1.5 km resolution North-West European Shelf operational ocean forecasting system (AMM15, Tonani et al., 2019). The impact of assimilating the standard 1 Hz SLA product is shown (middle-left) compared to no altimeter assimilation (left) and using the experimental 5 Hz product (middle-right), along with the lower-resolution (0.25°) GlobCurrent v3.0 (Rio et al., 2014) observation-derived current products (right). The resolution of the 5 Hz data is better matched to the model resolution and further development of the assimilation system should allow better use of these observations.

– It is also essential to improve the sea level record at the coast using different techniques to study coastal impacts (see also Section 2.3). This is essential to check whether sea level change at the coast is different from the open ocean and understand underlying processes. For this purpose, systematic monitoring of sea level in the world coastal zones from high-resolution SAR altimetry (e.g. Sentinel-3 and Sentinel-6 missions) and retracked LRM altimetry missions is highly recommended. Besides, increasing the coastal coverage of tide gauges equipped with GNSS is another important goal for two reasons: (i) validation of altimetry-based coastal sea level trends and (ii) production of sea level change measurements in coastal portions not covered by satellite altimetry tracks. Finally, further development of GNSS reflectometry is also recommended. This is a very promising technique that can provide sea level change measurements right at the coast (Larson et al., 2017). It will definitely complement altimetry and tide gauge measurement of sea level at the coast;
– The development of modeling efforts is essential for many sea level studies and also for other related scientific objectives. Eddying ocean model simulations are also mandatory to characterize in the open and coastal oceans the imprint of the multi-scale chaotic ocean variability on sea level, which may hinder the detection and attribution of interannual-to-decadal fluctuations and regional trends of observed sea level (Penduff et al., 2019). For a review of recent advances in modeling and assimilation, see Chassignet et al. (2018).

2.3. Coastal ocean

The coastal ocean is a growing and multifaceted priority given the links with societal needs such as coastal hazards monitoring (e.g. Vignudelli et al., 2011; Passaro et al., 2018; Benveniste et al., 2019; Gómez-Enri et al., 2019; Quartly et al., 2019). Dedicated workshops have held since 2008 (ESA Coastal Altimetry Workshop series, http://www.coastalt.eu/). Better understanding of the dynamics of coastal areas (land-sea continuum including coupling with watersheds) is needed. And monitoring and predicting their evolution are high priorities for the next decade (Fig. 5).

As discussed earlier, there is a need to monitor Sea Level and Sea State (both ECVs) up to the coast. This monitoring is increasingly possible thanks to the development of customised reprocessing algorithms for the retrieval of both sea level (Marti et al., 2019; Dieng et al., 2019) and significant wave height (Schlembach et al., 2020), which have brought the validity of dedicated altimetry dataset to the last 0–5 km to the coast, compared to the traditional limit of 30 km of proximity. It is necessary to understand how the spatial and temporal variabilities (i.e., annual, interannual and decadal) near the coast are linked to the measured off shore change and how small-scale dynamics impact measured variability near the coast (Woodworth et al., 2019; Ponte et al., 2019). A global multi-mission coastal altimetry data set, with vertical land motion, is needed (requiring reference against tide gauges with GNSS and InSAR). A high-resolution geoid, Mean Sea Surface and other range correction fields are similarly required (Kumar et al., 2003).

Coastal currents are a major priority, with many research activities measuring and interpreting seasonal and inter-annual variability. The issue here is how to better understand non-geostrophic flows near the coast, and how best to use altimetry data with models. In respect to the former, studies that combine available in situ records with numerical modeling may provide clues on how best to approach this issue.

There are significant challenges to improve coastal ocean current estimations, and an open discussion on the best way to achieve this objective is necessary (e.g. by integrating altimeter data with other measurements, and/or assimilation into coastal models (Levin et al., 2019)).

Some requirements for the coastal oceans are therefore:

– Development of a global sea level product recognized by the community that will enable all regional studies;
– A Sea State Bias (SSB) correction at high rate (e.g. 20 Hz or 40 Hz) (Passaro et al., 2018; Tran et al., 2019) and a specific SSB for each retracker is needed. The SSB could be split into a retracker correction (Quartly et al., 2019) (surely to be applied at high rate) and a geophysical one that can be smoother (even if not completely true for SAR altimetry due to its high resolution along track) (Badulin et al., 2019);
– Internal wave corrections (not only for coastal ocean) are needed although identified methodology must be developed to address this issue and is not obvious at the moment. High-resolution data must be distributed with all corrections;
– In regional or local studies, the adoption of a global Mean Sea Surface (MSS) to investigate the Sea Level Anomalies (SLA) might hide some of the sea level variability compromising the oceanographic interpretation (Gómez-Enri et al., 2019). The exploitation of dedicated high-resolution coastal altimetry reprocessed data to generate a local MSS (Ophaug et al., 2019) is recommended as it gives a more realistic indication of the oceanographic processes in the area; and
– A general important requirement is to be able to link the signal at the coast with the offshore signal.

2.4. Hydrology

Hydrology encompasses lakes and reservoirs as well as rivers, estuaries and flood plains. For these inland waters, there are many applications under development and also an increasing range and sophistication of remote sensing capabilities. The challenge with applications and services related to inland waters is that the introduction of altimetry data requires a great deal of transdisciplinary knowledge. So it is very important to ensure that users understand the products, including uncertainties, how the data were acquired and processed, what can actually be expected from the data products, and what in their content might be valuable for different applications. In hydrology the use of satellite altimetry is not new (Brooks, 1982; Birkett, 1994; Birkett, 1995), though it did start after its application to oceanography. Currently the satellite altimetry missions by construction (i.e. repeat cycle orbit, size of footprint) only allow monitoring water level changes on a limited number of lakes and rivers. But for the near future, it will considerably change, with new technological approaches: generalization of the SAR and evolution towards interferometry on large swath (SWOT, WiSA). The recent development of onboard DEM for current missions (e.g. Jason-3) as well the SAR technology (CryoSat-2, Sentinel-3) or LIDAR (ICESat, ICESat-2) help to provide better measurements and SWOT will be a major step forward to improve the global coverage and high resolution (Biancamaria et al., 2016).

Altimetry over inland water requires specific processing ((Birkett, 1995; Birkett, 1998; Abileah et al., 2017), Fig. 6), that is different from open ocean altimetry. Several processors and databases have been developed in the past 20 years. At the beginning of the 21st century three systems (in France, U.K. and USA) have emerged. These systems are “River&Lake” (Berry and Wheeler, 2009), “Hydroweb” (Crétaux et al., 2011) and “USDA Lake database” (Birkett et al., 2011). Subsequent to these three pioneers another has been launched in Germany at the Technical University of Munich: “DAHITI” (Schwatke et al., 2015). Most recently, the ESA CCI “Lakes” ECV (http://cci.esa.int/lakes, (Woolway et al., 2020) as well as other R&D initiatives, available online have been started. A further step forward has also been achieved by integrating altimetry products in the Water and Cryosphere component of the Copernicus Global Land Operational Service. Lake and River Water Levels are operationally produced on several thousands of targets spread worldwide, using the advanced capabilities of onboard tracking offered by Jason-3 and Sentinel-3A&B missions (https://land.copernicus.eu/global/products/wl). Freely available radar altimetry data through these databases has led to an increasing number of studies focusing on the monitoring of lake and reservoir water level (e.g. Crétaux et al., 2011; Okeowo et al., 2017; Thakur et al., 2020), storage (e.g. Gao et al., 2012; Van Den Hoek et al., 2019; Zhou et al., 2015), outflow (e.g. Getirana et al., 2020; Hossain et al., 2014) and bathymetry (e.g. Zhou et al., 2015; Getirana et al., 2018; Li et al., 2020).

Beyond supplying inland water level and volume variation, the current challenge is to derive river discharge, which is not directly observable from space independently from in situ data. Several studies have proposed algorithms merging radar altimetry with in situ observations (Thakur et al., 2020; Kouraev et al., 2004; Papa et al., 2012; Dubey et al., 2015; Gleason and Durand, 2020), model outputs (e.g. Getirana et al., 2009; Leon et al., 2006; Tarpanelli et al., 2013) and optical sensors or other data (e.g. GRACE data in Carabajal and Boy, 2020) in order to increase discharge space-time sampling (Tarpanelli et al., 2019), required by hydrologists. Radar altimetry data has also been used in the calibration and evaluation of hydrological models (Coe et al., 2002; Getirana et al., 2013; Dhote et al., 2020), as well as in data assimilation frameworks (Michailovsky et al., 2013; Paiva et al., 2013; Pedinotti et al., 2014). Other studies have also used radar altimetry data to understand surface water storage and variability in rivers and floodplains (Frappart et al., 2012; Melo, 2019).

Even though the hydrology remote sensing community makes a broad use of radar altimetry data, one of the main challenges still remains to convince hydrologists, a community with a long history, that satellite altimetry, notably through dedicated products in the above databases, can

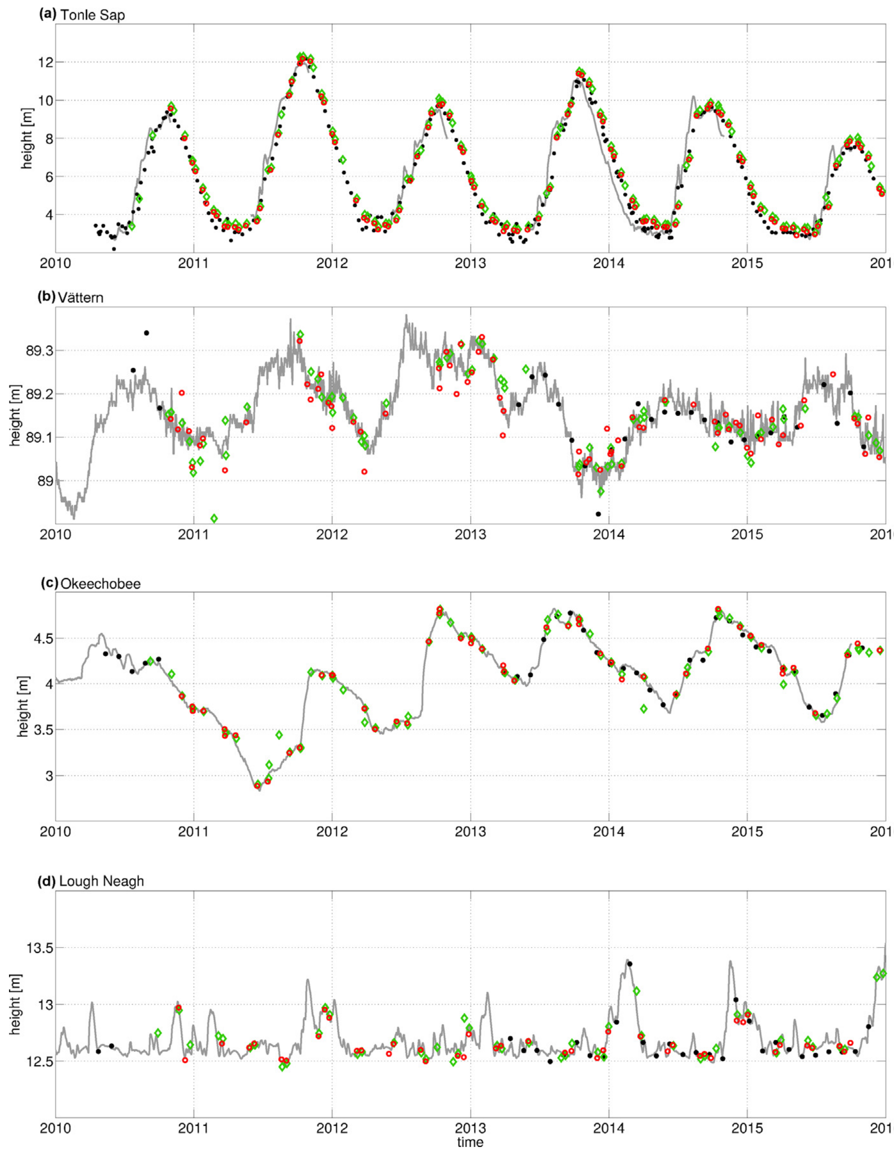

Fig. 6. Water level time series solutions for the lakes (a) Tonle Sap, (b) Vättern, (c) Okeechobee and (d) Lough Neagh: DGFI-TUM (red), gauging stations (grey), DAHITI (black) and DTU (green) (from Göttl et al., 2016).

be usefully applied to their work, particularly in operational hydrological monitoring systems. This requires an understanding of the main challenges that can be tackled with satellite altimetry (for example understanding long term evolution of lake or river level linked to climate change and/or water resources uses). Data access is a big part of encouraging hydrologists to use more remote sensing, including altimetry. Although data are easily accessible, it is difficult for hydrologists who are not remote sensing experts to access the data as they become available in quasi near-real-time (NRT) from the providing agencies. It can also be difficult to process altimetry data and to understand which software to use. This is a challenge in the education, training, and advancement of researchers and their capabilities (see Section 7.4).

Other critical points for the use of altimetry in hydrology are in providing tools useful for modelers (Paiva et al., 2013; Papa et al., 2012; Paris et al., 2016). While funds are invested to improve the instruments in orbit, much less is available for scientific support and establishing synergy between different actors. This relates partially to knowledge (or lack thereof) of the quality of products: there is a strong need for systematic, transparent work on calibrating and validating altimetry products, which requires supporting in situ networks. Initiatives in this direction are often limited in space and time: individual researchers develop capacity (often via cooperating with local authorities (Crétaux et al., 2015)) to retrieve data in situ, but there is no strong coordination at high level as is the case in oceanography. Sustained improvement in validation requires the development of a network of multi-sensor observatories on lakes and rivers, so that there is a consistent set of validated reference data over a long time span, of known accuracy, so that the use of altimetric data is recognized and adopted by a greater number of researchers in the field. In hydrology, each basin is special case, and so it is not easy to globalize and standardize expert systems for full annual cycles. There are initiatives in this direction (CCI/ESA, SCO/CNES) but these are not well-known in the hydrology community.

In short, as for other disciplines, the continuity of data services, standardization of information, characterization of errors and accuracy are necessary and will provide strong arguments for convincing hydrologists to use these data products. Finally, there should be a pilot initiative for the development of a prototype for an operational hydrological system, including altimetry, building on the 25 years of efforts mentioned above.

2.5. Cryosphere and polar oceans

The polar regions are experiencing major changes due to global warming (Pörtner et al., in press), and this is much more apparent than in the global ocean. These are key regions that are difficult to observe either directly or with existing remote sensing platforms, and which present many geostrategic issues (e.g. Naylor et al., 2008). Also, of particular interest to the climate community is the contribution to sea level rise associated with melting ice sheets (Shepherd et al., 2018; Shepherd et al., 2020), the projected disappearance of summer ice cover in the Arctic ocean (Stroeve et al., 2012), the behavior of the Antarctic sea ice cover (Shepherd et al., 2018), and the circulation of the polar oceans. “Polar oceans” is a collective term for the Arctic Ocean (about 4–5% of Earth’s oceans) and the southern part of the Southern Ocean (south of Antarctic Convergence, about 10% of Earth’s oceans).

Altimetry has a major role for measuring mass changes of the ice sheets and the glaciers of the world, in synergy with GRACE and GRACE-FO. There is a 26-year record of altimetry since ERS-1 which has played a key role in measuring mass changes of the ice sheets (Shepherd et al., 2019) and glaciers (Gardner et al., 2013) of the world. ERS-1 and its ESA successors, ERS-2, Envisat and CryoSat, have a very different approach concerning the selection of their orbit inclination compared to the TOPEX/Poseidon and Jason series. The inclination of the orbit of altimetry missions (i.e., the latitudinal coverage) is optimized either for having a homogenous observation of the dynamic topography, with ascending and descending tracks crossing nearly perpendicular, to derive geostrophic currents (the 66° inclination orbit of TOPEX/Poseidon) or reaching the poles as close as possible with a very high inclination to observe the Polar Ocean, sea-ice and ice sheets. Further to the 26-year record initiated by ERS-1, if the coverage of the southern part of Greenland by Seasat and Geosat is included, this record extends to 40 years (Zwally et al., 1989). Most recently, CryoSat-2 has demonstrated the utility of the altimetric data in high latitudes for observing both the polar oceans (Armitage et al., 2016), the sea ice (Laxon et al., 2013) and land ice (McMillan et al., 2014; McMillan et al., 2016). Eighteen years of sea ice volume variations has already been reconstituted thanks to CryoSat-2 (10 years) and a recalibration of Envisat with CryoSat-2 during their common flight period (Guerreiro et al., 2017). This time series need to be extended and cover up to near the pole where the sea ice remains.

Importantly, CryoSat-2 is near the end of its operational life (after 10 years) and ICESat-2 has a mission design life of only 3 years, though with an expectation to operate for longer (Wingham et al., 2006). The continued monitoring of the polar regions in the coming decade is to be addressed. As a baseline, the recommendation is to continue our current capabilities to measure and monitor variability of Arctic and Southern Ocean sea-ice thickness, which requires satellites that provide complete polar coverage to at least 88° inclination.

Exploiting existing altimetry datasets, with new advanced techniques such as SARIn-based “swath mode” processing (Gourmelen et al., 2018), and fully focused SAR (Egido and Smith, 2017), should be prioritized, to increase the spatial resolution of altimetry products to beyond the boundaries of the original mission design. Knowledge of snow loading (snow depth and density) has been a major challenge in the accurate retrieval of sea ice thickness and ice sheet elevation changes (Tilling et al., 2015). To address this issue instrumentally, dual frequency altimeter systems (e.g. Ka/Ku band) and/or altimeters in tandem/complementary orbits are undergoing preparation (Kern et al., 2020; Guerreiro et al., 2016). To implement this approach, it is crucial to understand the quantitative differences in penetration of radar waves into the snow/ice/ocean medium at Ku/Ka wavelengths, in particular taking the benefit of SARAL/AltiKa (Verron et al., 2020).

Currently, there are clearly new opportunities for improved understanding afforded by the complementary observations from multiple altimeters over polar oceans (CryoSat-2, ICESat-2) or part of it (Sentinel-3, SARAL/AltiKa up to 81.5° of latitude). Of course, supporting field campaigns should be integral part in the validation of potential retrieval approaches. Maximizing the utility of satellite sea ice thickness and polar ocean dynamics observations for the user community (including weather and forecasts) requires an end-to-end solution. Provision of the higher-level data products to the end users requires appropriate consideration of space scales of measurement (resolution of gridded and along-track products), frequency of updates (e.g., daily to weekly), and latency of data delivery (e.g., NRT/within 6 h and STC/within 36 h). Realistic and traceable uncertainty estimates/quality flags for all sea ice (freeboard and thickness) and polar ocean (ocean surface topography) variables should be adopted to enhance confidence in usage.

Apart from monitoring long time-series, refining our understanding of the geophysical processes driving change across the cryosphere and polar ocean, is crucial for improvement, development and validation of models as a first step toward data assimilation into a coupled ice-ocean operational system.

Satellite missions also serve to broaden our knowledge. A good example is the pattern of Antarctic ice sheet elevation change since 1992 (Fig. 7) (Shepherd et al., 2019; Hogg et al., 2020). CryoSat-2 in synergy with ICESat permitted the discovery of subsurface lakes and interconnected drainage systems beneath Antarctica. For glaciers in the margins of Greenland ice sheet and Antarctica, there are glacial surges in the temperate zones. Glaciers are suddenly changing their speed, their velocity and their mass properties.

A mission for mapping the polar oceans and land ice elevations has been approved for development by ESA as a Copernicus High Priority Candidate Mission (CRISTAL, Kern et al., 2020), but as this mission is not yet fully funded, pending confirmation of the 2021–2027 EU Space budget, the community recommends maintaining CryoSat-2 in operation as long as possible and an expedited commissioning of the new mission as a priority to ensure that there is no gap in our observational record. Observations of the open ocean in polar regions are also essential. In addition to sea ice observations, continuity of CryoSat-2 altimeter high-latitude observations of the ocean are required to improve the coverage of sea level estimates in the leads as emphasized for example by Johannessen and Andersen (2018) and Lawrence et al. (2019) and would maximize the use of CryoSat-2 data (Armitage et al., 2018).

2.6. Green ocean

In recent years there has been an increase in the application of altimetry to the so-called "Green Ocean", in particular extending the frontier from biogeochemistry to marine ecology. Altimetry by itself does not directly measure biological parameters, but it does provide information on key physical drivers of primary production and other ocean biotic processes. Historically, the association of mesoscale activity to the spatial variability of bulk phytoplankton production has been recognized since the beginning of spatial oceanography (Yoder et al., 1987). This type of observations has contributed to our comprehension of the biogeochemical budget and in particular to the carbon cycle by demonstrating how mesoscale circulation variability can redistribute primary production, nutrients, and modulate downward particle export either laterally or vertically (Gaube et al., 2013; McGillicuddy, 2016). Biogeochemical experiments have also greatly benefited from NRT altimetry for targeting and more timely tracking specific features of interest (Lehahn et al., 2018).

More recently, it has been acknowledged that the term "Green Ocean" means much more than chlorophyll concentration. Chlorophyll is not diluted in the ocean, but rather contained in organisms which belong to different taxa, each with specific characteristics in terms of growing and mortality factors, nutrient uptake, carbon export, responses to climatic and environmental variability, and

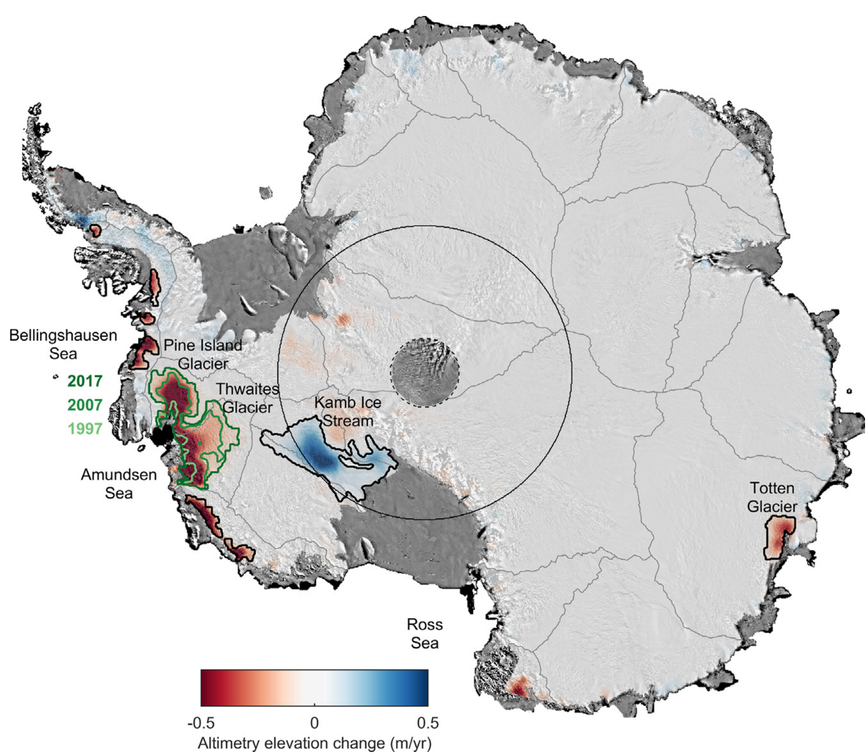

Fig. 7. Average rate of Antarctic ice sheet elevation change between 1992 and 2017 determined from ERS-1, ERS-2, Envisat, and CryoSat-2 satellite radar altimetry. Black circles around the pole indicate the southern limit of the CryoSat-2 (dashed) and other (solid) satellite orbits. Grey boundaries show glacier drainage basins. Black boundaries show areas of dynamical imbalance, and green boundaries show those that have evolved over time (adapted from Shepherd et al., 2019).

roles inside the trophic chain. Understanding the physical drivers behind phytoplankton and to a larger extent, marine life, is of interest on its own, but it is also one of the big challenges for reducing uncertainties in the biogeochemical budgets, for conservation and for managing the complex interactions between human populations and the marine environment (Olascoaga, 2010). In terms of ocean biogeochemistry and ecology, altimetry increasingly plays a key role bridging models and observations.

Recent advances in coupled physical-ecological models reveal that the fine scale physical dynamics (1–100 km) is a key regime for preconditioning plankton diversity and community structure (see a review in Lévy et al., 2018). In fact, the fine scales largely control frontogenetic processes. On the horizontal, the enhanced physical gradients induced by the fine scales create in turn a patchwork of physico-chemical niches, which - in some cases - can be inferred from altimetry and which are causally related to the spatial heterogeneity of phytoplankton communities. Recent studies have shown however that the entire range of the fine scales can have an important control on phytoplankton community as well as on the exchanges of the photic layer with the atmosphere and the deep ocean, driving important vertical biotic processes such as the upwelling of nutrients and the export of organic matter (e.g. Zhang et al., 2019).

Today, altimetry remains unsurpassed for the ‘‘large mesoscale” component of the balanced motion in terms of coverage as well as temporal and global variability. For the fine scales which are not yet resolved by conventional altimeters (roughly <70–100 km), great expectations are for future satellite missions with enhanced resolution (e.g., SWOT, WiSA, SKIM) which will provide unprecedented ground truth on the role of fine scale circulation on biophysical processes, in particular when paired with emerging high throughput biological methods for microbial analysis like flow cytometry, automated pattern recognition, and DNA and RNA sequencing (Villar et al., 2015; Marrec et al., 2018). While not strictly speaking of the ‘‘Green Ocean”, but dependent upon it, are mentioned here applications to higher trophic levels, due to the surge of marine animal telemetry and availability of fishing data. Many examples have been reported on the association between tracks of marine megafauna and features extracted from altimetry, in particular fine scale frontal regions or transport features detected by so-called Lagrangian methods (see e.g. Lehahn et al., 2018, for a review and Fig. 8). The integration of altimetry analyses with marine management tools for supporting the definition of marine protected areas (Della Penna et al., 2017), for managing commercial fisheries (Watson et al., 2018) and for reducing by-catches of endangered species (Scales et al., 2018) has been recently proposed. However, these applications are currently critically limited by the resolution constraints of altimetry maps, coarser than the geolocation of biological data.

Recommendations are therefore as follows:

– Higher spatial resolution. Biological data like animal telemetry, fish catches, or acoustic densities demand ideally kilometric resolution, which is not achieved by altimetry observations available today. This is especially relevant for Lagrangian features derived from altimetry, which capture transport properties and seem to play a

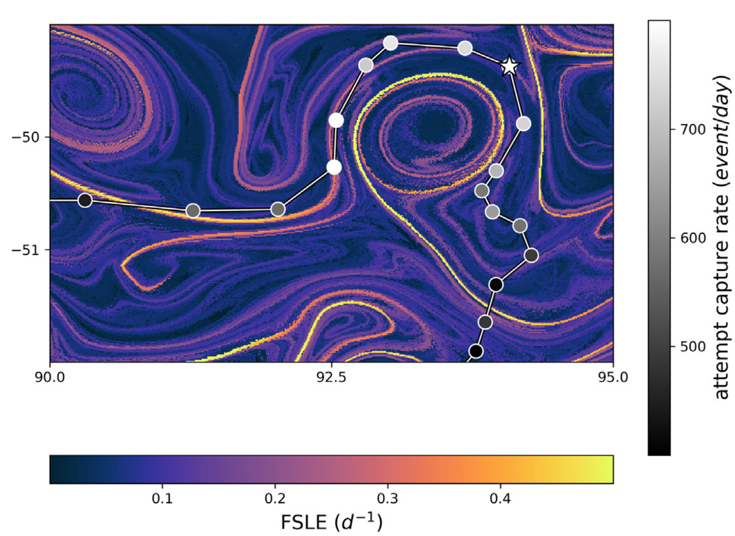

Fig. 8. The recent years have seen an evolution in the use of altimetry from biogeochemical applications to ecological ones, encompassing the study of phytoplankton diversity and higher trophic levels. The figure shows an example with altimetry-derived Finite-Scale Lyapunov Exponents (FSLE), providing Lagrangian fronts, and prey capture rate of a Kerguelen elephant seal (adapted from Della Penna et al., 2017). Note the augmentation of capture rate (black circles) on the frontal region around a mesoscale eddy. The use of altimetry for interpreting biologging data and for microbes, morphological or DNA and RNA sequencing observations, is possible today only when the biological observations occurs over large mesoscale features detected by conventional altimetry. In the future many more cases will be accessible thanks to the advent of higher resolution altimetry, contributing to an holistic view of the ocean biosphere.

key role for the structuring of marine biota. Higher spatial resolution is needed as well to go beyond the "large mesoscale" and observe SSH features smaller than 70–100 km resolution achieved today;

– Higher temporal resolution. An enhancement in spatial resolution should be also accompanied by an enhancement in temporal resolution, because smaller features in general evolve faster than larger ones. This means that the development of one higher resolving altimeter such as SWOT is not enough, but ideally should be accompanied by a larger altimetry constellation, including swath and conventional altimetry, and/or the use of an integrated altimeter and a Doppler Wave and Current Scatterometer such as SKIM. Higher spatial resolution without higher temporal resolution would result in important difficulties for co-localizing in situ biological data to remotely-sensed features, as well as the assimilation of high resolution features into circulation models; and
– New theoretical developments. At scales smaller than the "large mesoscale" detected today, important deviations from the approximation of quasi-geostrophic equilibrium may arise. The interpretation of SSH anomalies in terms of ocean current anomalies therefore is no longer straightforward. As already mentioned, ocean dynamics at these smaller scales may involve complex interactions between balanced dynamics and unbalanced ones (e.g., internal waves) and requires a full three dimensional view. At the same time, a better resolution of frontal systems on the horizontal is considered key to the reconstruction of the internal ocean dynamics. Transition from balanced to unbalanced motion, reconstruction of the internal ocean dynamics, and coupling between meso- and submesoscale processes are all active areas of research of great biological interest, where help from novel approaches like deep learning are welcome. These directions of research should be strongly encouraged in terms of theoretical studies, consistent use of satellite sensor synergy, design of in situ experiments (Pascual et al., 2017; d'Ovidio et al., 2019), if we want to be able to correctly interpret the higher resolution SSH observations of future missions and link them to the biogeochemical cycles and the comprehension of ocean biodiversity.

3. Applications

The four main altimetry applications fields are operational oceanography, weather and hurricane forecasting, wave and wind forecasting, as well as climate projection. It would also be desirable to expand the portfolio of present services to tackle future challenges especially in the directions of inland water hydrology (lake volume variation, river discharge, and floods), ice sheet and sea-ice thickness monitoring and this is starting to happen. More generally, it would be envisioned to expand the portfolio of services and associated Earth observation capacities to tackle future challenges such as climate/CO_2 monitoring, agriculture and forestry, changes in the Arctic and some security aspects.

3.1. Operational oceanography

The development of operational oceanography has been largely enabled by spatial altimetry and the near-real-time provision of repetitive products on a global scale and over significantly long periods of time. Several operational oceanography systems have been put in place through national initiatives. Then international coordinations were set up with successful initiatives such as GODAE (Smith, 2000) and today OceanPredict (http://oceanpredict19.net/). Since, many organizations throughout the globe have implemented operational ocean systems covering the globe and including higher resolution local predictions (Schiller et al., 2020; Lellouche et al., 2018; Lemieux et al., 2016; Metzger et al., 2014; Rowley and Mask, 2014).

Altimeter observations enable ocean forecasts. Forecast currents and water properties have become available to the public directly and there are extensive networks of data dissemination through commercial outlets for application to a wide range of commercial activities including fisheries management, minerals exploration, and aquaculture. Public use of the data has become widespread as the data is operationally incorporated into the ocean forecasts published by centers around the globe for recreation, health, and safety. There are enormous success stories in establishing the clear linkage from the satellite data to applications throughout the globe. All these applications would come to an end without the altimeter data. Operational oceanography requires foremost the continuity of service. Users applications depend every day on the data that are generated by the operational services (Le Traon et al., 2018). Sustainability of observations is critical. In addition, as users build systems using the resulting data, the data distribution system must be reliable for the foreseeable future. This means a need for reference missions, continuity in the programmes and sustainable programmes. In Europe, the Copernicus Programme (CMEMS) (Lellouche et al., 2018; Le Traon et al., 2019) is a major response to this necessity and ensures the continuity of operational Earth observation for the current situation and also for the future. Note that satellite observations, and in particular altimetry, are a main progenitor of CMEMS.

The observations critically required by all these systems are the satellite altimeter data and sustainable constellations are necessary. Operational oceanography also needs multi-sensor and multi-mission data like SST, SSS, ocean color, currents and other platforms (Escudier and Fellous, 2009; Bonekamp et al., 2010). It is also necessary to ensure consistency between and among all these data sets and that the design and use of these observations be optimized. In the same vein, one challenge continues to be relating the altimeter observation to the ocean subsurface structure across parameters such as temperature and salinity. This connection has been at the underpinnings of the ability to use altimeter data for operational oceanography at present, and there are significant deficiencies in ocean forecasts because we have not had sufficient temperature and salinity profile data to relate to the sea surface height. This builds the connection for support of programs such as Argo (Roemmich et al., 2009). Operational oceanography meets specific challenges when moving from large scale to mesoscale and sub-mesoscale, and these challenges impact global and regional ocean forecasting (Jacobs et al., 2019). Monitoring and forecasting of mesoscale ocean signals (with typical scales of 30–300 km and 20–90 days) have applications in fisheries, marine safety, search and rescue, monitoring of pollutants (e.g. oil spills), tracking plastic pollution, marine faunal surveys, supporting off-shore industries (oil and gas, cable, marine renewable energy), commercial navigation and military defense. Mesoscale, as well as coastal activities, have a rapid time-space evolution (less than 5 days) which requires dense and homogeneous temporal and spatial sampling making necessary the integration of multiple altimeter data streams with derived products being available with only short time delays.

Recommendations are as follows (and most of them apply also to the other applications fields):

- There is a need for high resolution altimetry. This will be best achieved through a combination of high-resolution (HR) (unfocused SAR and fully-focused SAR processing) nadir altimetry and swath altimetry (see Section 4). Developing new operational capabilities for a wide-swath altimetry constellation is, in particular, essential to constrain future HR open ocean and coastal models.
- The synergy between altimetry and other types of satellite-derived observations can also enhance the space-time resolutions of the present-day (and future) altimeter-derived products. Moreover, the fusion between altimetry and other data must occur in an operational context;
- Improving Mean Dynamic Topographies (based on the GRACE and GOCE satellite missions and in situ observations) is of utmost importance, given the impact in data assimilation systems. Multi-mission altimetry is key (Fig. 9): secured availability of constellation data in NRT, optimal sampling between missions;
- Multi-sensor, satellite/in situ combination: consistency and combination require dedicated pre-processing before or during data assimilation;
- In situ component has to be sustained and improved in the long term. Maintenance of complementary observing systems such as Argo (Roemmich et al., 2009) and higher density in situ observations (Rudnick, 2016) is critical. Essential complementary information with respect to space data; and
- Higher resolution wind and wave data (altimeters, SAR, CFOSAT) for coupled ocean/wave models are needed.

3.2. Weather and hurricane forecasting

Weather forecast agencies make use of significant wave height (SWH) data especially by assimilating SWH data into their weather forecast models to improve predictions of sea-state and in several cases the predictions of extreme events (Ponce de León and Bettencourt, 2019).

Hurricane forecasting is a specific application (Fig. 10). Hurricanes are among the most frequently occurring catastrophic events in the warm waters of the global oceans. Heat content within the ocean drives hurricane development and intensification. Many studies in recent years have noted the intensification of tropical cyclones as they pass over areas of ocean containing more heat (e.g. Shay et al., 2000). The heat is reflected in increased sea surface

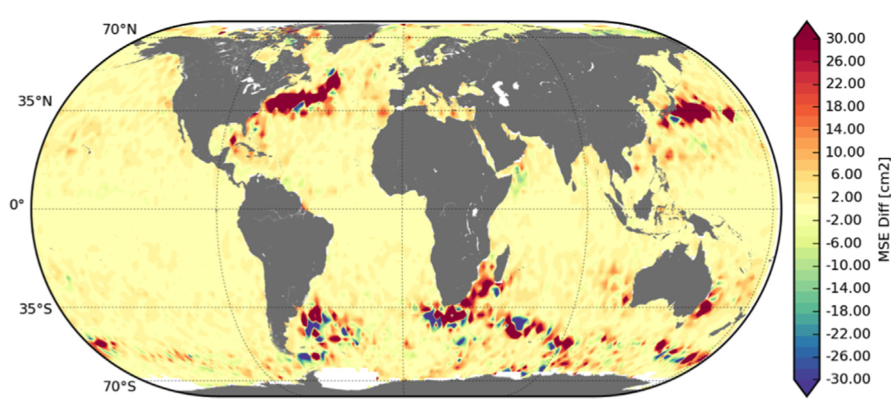

Fig. 9. Impact of the assimilation of Sentinel-3A data in the global Mercator Ocean 1/12° data assimilation system (M. Hamon, Mercator Ocean International). Two runs were carried out with and without assimilation of S3A. The forecast errors (observations - predictions) were then compared. The figure shows the forecast error reduction between the two runs. Adding S3-A data to Jason-3, SARAL/AltiKa and CryoSat-2 in May 2017 allowed reducing the variance of 7-day forecast errors by about 10%. Reduction of forecast errors reached up to 7 cm rms in Western Boundary Currents.

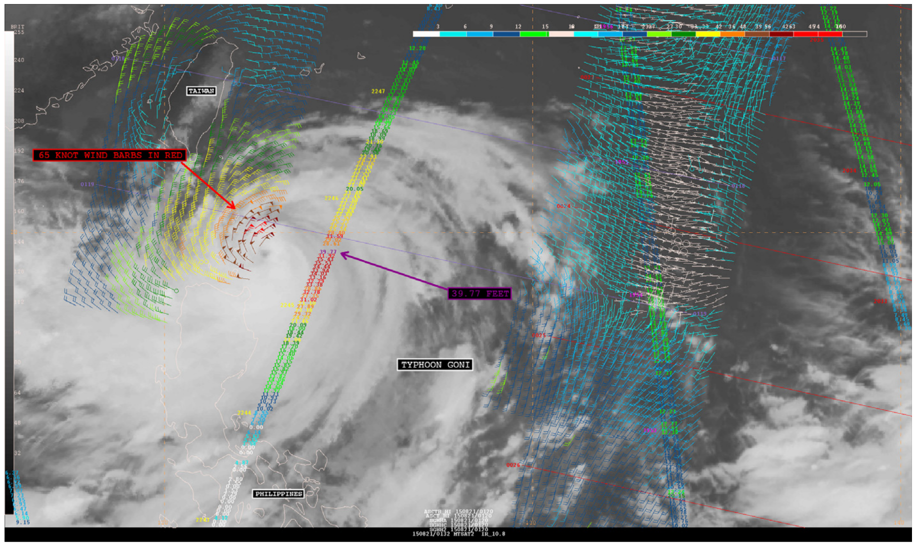

Fig. 10. Forecaster screen image of Typhoon Goni near the Philippines in August 2015 showing extreme wave conditions > 13 m observed by Jason-2. The image superimposes infrared weather satellite images, scatterometer winds, and significant wave heights from (left to right) Jason-2, CryoSat-2, and SARAL/AltiKa (Ocean Prediction Center).

height observed by the altimeter. This has led to generation of products of Tropical Cyclone Heat Potential (TCHP) at the Atlantic Oceanographic and Meteorological Laboratory of NOAA (https://www.aoml.noaa.gov/phod/cyclone/data/). This heat potential serves as an input to numerical weather models for hurricane forecasts. The accurate place of ocean mesoscale eddies is necessary to correctly construct a map of TCHP. For this problem, again the satellite resolution in space and time is critical to identify and track the ocean features related to the TCHP. Because of the strong connection between the ocean and atmosphere in driving hurricanes, recent development of coupled numerical prediction systems has led to advancement in hurricane prediction. The cost of mispredicting hurricane tracks and intensity can be enormous. Large errors and uncertainty in projected track lead to unnecessary evacuations of coastal areas that cost millions of dollars and disrupt local economies.

Regarding longer term prediction such as seasonal forecasting, prediction of El Niño-type events is a particularly important issue because of their impact on climate and the associated economic and social activities of affected countries. The skill of those forecasts, that previously utilized only in situ observations has further improved with the advent of altimeter and Argo data. Therefore, sustainability of the current observing system is paramount to continued progress in seasonal forecasting.

3.3. Wave and wind forecasting

SWH and wind speed are the primary sea state parameters that have established marine meteorological applications. Wind speed is not retrieved directly from altimetry measurements but is calculated from empirical parameterizations. The errors of model estimations based on the normalized radar cross-section can reach 1.5 m/s, or up to 20% of the measured value (e.g. Bonnefond et al., 2011; Lavrova et al., 2011). Still, applying them to detect interannual global wind speed changes is proven to be possible (Young et al., 2011). Wave periods can either be estimated by applying empirical dependencies to altimetry data (e.g. Gommenginger et al., 2003; Quilfen et al., 2004) or by physical models that consider features of wind-wave dynamics (Hwang et al., 1998; Badulin, 2014; Badulin et al., 2018). The typical error of wave period parameterizations is less than 1 s (Mackay et al., 2008). Global fields of wind speed and wave periods retrieved from altimetry show good qualitative and quantitative agreement for the approaches mentioned above. All wind and wave parameter distributions also demonstrate a good correspondence with Voluntary Observing Ships data on climatological scales (Gulev et al., 2003; Grigorieva and Badulin, 2016). Sea-state forecasts are crucial for many activities related to maritime industries (e.g. fishing, oil drilling, and navigation), and SWH, wind speed, and wave periods measured by altimetry are being used by operational forecast centres for assimilation into wave forecast models (Bhowmick et al., 2015), for validation of those models (Oztunali Ozbahceci et al., 2020), for developing wave climatologies on seasonal to decadal time scales (Fig. 11) (Stopa, 2019), and for assessing the role of waves in ocean-atmosphere coupling. Altimeter wave observations remain a key component of a global wave-observing program. Satellite radar altimeters provide information on significant wave height with global coverage and high accuracy (<10%), although spatial and temporal coverage is still marginal. Multiple altimeters are therefore required to provide denser coverage (Abdalla, 2019). Note that additional observations such as dominant wave direction, wave period, one-dimensional energy density spectra, and directional spectra are also required by operational

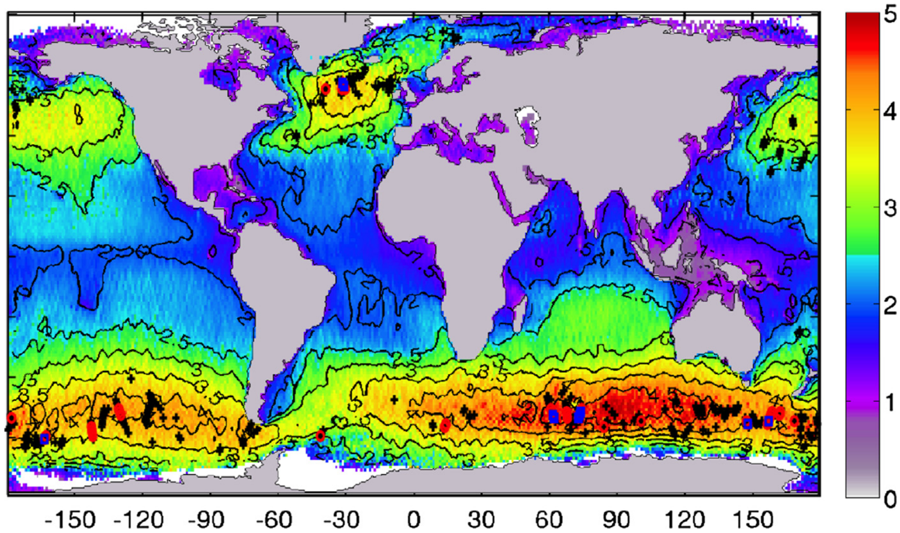

Fig. 11. Mean (color shades) and extreme significant wave heights (Hs), in meters. Although the Southern Ocean has the largest average Hs values, around 5 m, the largest storm waves are generally found in the North Atlantic, with Hs values exceeding 15 m (blue symbols) for individual 1 Hz altimeter data, 14 m (red symbols) are very rare in the North Pacific, but values over 12 m (black symbols) are often reached by typhoons. Trends in these extremes and their coastal impact are highly uncertain and the topic of active research.

centers to realize the full benefit from the potential capability of wave forecasting. To this aim, the recently launched CFOSAT mission will help to provide such important observations (Hauser et al., 2017, 2021). Even though SWH is the most straightforward and easy-to-use wave product from altimetry, and has been available for more than a decade and a half, it is not being used routinely today in most operational forecast centers in developing countries. The developed countries need to be aware of these deficiencies and help their developing country counterparts by providing easy access to, and an ability to work with these products.

3.4. Climate projection

Climate projections are simulations of Earth's climate in future decades (typically until 2100) based on assumed "scenarios" for the concentrations of greenhouse gases, aerosols, and other atmospheric constituents that affect the planet's radiative balance. Climate projections are obtained by running numerical models of Earth's climate, which may cover either the entire globe or a specific region (e.g. Europe). These models are referred to as Global Climate Models (GCMs) – also known as General Circulation Models – or Regional Climate Models (RCMs), respectively. In setting priorities for making projection results available, the Copernicus Climate Change Service (C3S) has put a strong focus on providing quantitative information about the uncertainties in projected outcomes, taking into account various sources. Such uncertainties arise from differences in emission scenarios, differences among the formulations of numerical models, and the natural variability of the climate system on decadal scales.

The role of altimetry in climate projection can be: (i) to be used as validation data for climate models run in nowcast or hindcast mode (e.g. Slangen et al., 2017; Meyssignac et al., 2017), (ii) to initialize models of future climate, particularly relevant to studies of changing water mass distributions and steric anomalies in future climates (e.g. Gasson et al., 2018), and (iii) to validate smaller-scale process studies concerning the energetics or interactions of multiple climate components through their expression in sea surface height over the altimeter era (e.g. Fox-Kemper et al., 2008; Fox-Kemper and Ferrari, 2008; Fox-Kemper et al., 2011).

4. Instrument developments

Spaceborne oceanic radar altimeters have evolved significantly since their first demonstrations aboard SkyLab more than 45 years ago (McGoogan et al., 1974). Progress and accomplishments over years has been comprehensively reviewed in (Fu and Cazenave, 2001 and Wilson et al., 2006) in particular. Challenges and successes in extending oceanic altimetry into the near-shore and coastal zones as of 2009 are introduced in Vignudelli et al. (2011). The altimeter aboard Seasat (MacArthur, 1976) in 1978 inaugurated technical features that set the standard for oceanic radar altimeters for two decades.

The evolutions over the past 25 years have allowed to improve measurement quality and to meet new scientific requirements. For instance, the delay-Doppler capability (also known as SAR-mode or SARM (Raney, 1998; Raney, 2013)) and the interferometric capabilities (also known as SARIn mode) of the SIRAL altimeter of CryoSat-2 (Drinkwater et al., 2004; Wingham et al., 2006; Phalippou et al., 2001; Rey et al., 2001) were a response to new glaciology requirements derived from the steep slopes of continental ice and better lead detection on sea-ice (Laforge et al., 2020). Because SAR-mode proved to be of interest for oceanographers and hydrologists (e.g. Dibarboure et al., 2014; Jiang et al., 2017; Vergara et al., 2019), this capability was also implemented in Sentinel-3's SRAL altimeters, and this mode is now operated globally. In the last years lots of studies improving the SAR processing have shown their added value notably for coastal measurements (Dinardo et al., 2020; Egido et al., 2020; Scagliola et al., 2019). In contrast, the SARIn mode of SIRAL was not adapted for small-slope surfaces over the oceans and land surface waters, although it may be flown on the proposed polar altimetry mission CRISTAL to meet specific glaciology requirements. Off-nadir SARIn technology was demonstrated on the Space Shuttle SRTM, and was proposed as the Wide-Swath Ocean Altimeter (WSOA) onboard Jason-2, and will soon be launched as the SWOT mission (Morrow et al., 2018; Morrow et al., 2019; Rodriguez et al., 2018).

New technologies, however, sometimes introduce a discontinuity with previous generations of instruments. For some research topics such as climate science, discrepancies between old and new technology (e.g. bias and drifts), may be a major limiting factor. For this reason, new technology is sometimes further improved to provide the best of both worlds. In the case of delay-Doppler altimetry, the space agencies and industry developed a new capability for Sentinel-6: the so-called interleaved mode (Gommenginger et al., 2013; Scharroo et al., 2016). This instrumental feature provides data in both the historical low-resolution mode (LRM) and a major evolution of the SAR-mode of Sentinel-3. This development was a response to new climate science requirements. The Sentinel-6 mission (Sentinel-6A/Michael Freilich and Sentinel-6B) will be able to ensure a seamless continuity with previous generations of climate reference altimeters (TOPEX/Poseidon and Jason-1 to 3) while providing, at the same time, high-resolution noise-reduced datasets in the open ocean and other SARM features (e.g. Fully-Focused SAR) such as in coastal margins and for inland water hydrology, for more than a decade.

In addition to science-driven technology changes, various instrumental changes were actually technology-driven demonstrators (i.e. related to science research topics, but not necessarily driven by scientific requirements). To illustrate, the "Open Loop" tracking mode is a radar altimeter tracking mode introduced with Jason-2 and SARAL/AltiKa (Desjonquères et al., 2010; Steunou et al., 2015). In contrast with autonomous tracking loops which showed significant limitations over inland waters and in coastal margins, the Open Loop mode was a technology demonstration to extend the altimetry capability to challenging hydrology targets. In this mode, the acquisition window of the radar altimeter is driven by external information (e.g. local Digital Elevation Model or DEM) to better track water topography even around rapid changes in terrain altitude. This new instrumental capability proved to be very beneficial for coastal and hydrology communities (e.g. Biancamaria et al., 2018), thus paving the way for new major science requirements. The Open-Loop tracking mode was ultimately implemented in all modern altimeters (including Sentinel-6 and the upcoming SWOT mission). With the last updates of on-board DEM of Jason 3, Sentinel-3A and Sentinel-3B, now more than 200 000 hydrological targets are monitored all over the world (Le Gac et al., 2019). The unique drawback is that out-of-scope targets not registered in the compressed DEM (to fit in the onboard memory) and yet-to-be-explored targets will never be acquired by the altimeter, which is acceptable for an operational mission aiming at monitoring known targets (there is a web site for users to upload their favorite target: https://www.altimetry-hydro.eu). Thanks to a larger onboard memory, the Sentinel-6 DEM is not compressed and probably Sentinel-3C&D DEM as well.

Similarly, AltiKa, the altimeter onboard the SARAL/AltiKa mission, is the first Ka-band altimeter (Bonnefond et al., 2018; Verron et al., 2018). Although not strictly necessary to meet SARAL/AltiKa's scientific requirement, the Ka-band technological demonstration proved to be a major asset for performance (e.g. noise reduction, physical footprint size, …). Most of the scientific benefits of this new technology are listed in Verron et al. (2020). Furthermore, before AltiKa, clouds and rain were considered to be a major concern for Ka-band altimetry. Yet SARAL/AltiKa demonstrated that it was possible to meet state-of-the-art science requirements with this technology. Ka-band is the operating frequency for the upcoming SWOT mission (Morrow et al., 2019). It will complement the Ku-band for the CRISTAL mission, and it has been proposed for the SKIM Earth Explorer 9 mission (Ardhuin et al., 2018; Ardhuin et al., 2019). In all cases, a science-driven mission was designed leveraging the lessons learned from AltiKa which was a technology-driven demonstrator but also aimed at being a gapfiller between Envisat and Sentinel-3A (Verron et al., 2020).

Radar altimetry technology advances are often focused on continuous performance improvements: e.g. capability of the onboard DORIS system to yield a 3 cm orbit determination precision onboard and autonomously (Jayles et al., 2015). It is also sometimes proven in breakthrough missions that altimeters can cover vastly different needs. For instance, the French/Chinese mission CFOSAT (Hauser et al., 2017, 2021) features a wave scatterometer that yielded the first global coverage of 2D ocean wave spectra. Moreover, the SWIM instrument of CFOSAT (Hauser et al., 2017) has inherited a lot of radar altimeter technology. Additionally, since it has a nadir beam to synchronize the off-nadir beams, the SWIM instrument of CFOSAT can contribute to measuring ocean mesoscale in a multi-missions merging system (DUACS). This demonstration from CFOSAT is important, because in turn, radar altimeters should now be expected to yield more than just ocean surface topography, wave height and wind speed. The concept was extended in the SKIM Earth Explorer 9 proposal (Ardhuin et al., 2018) where a single instrument was optimized to yield ocean surface topography measurements with the same performance as a traditional Jason-class altimeter, in addition to 2D wave spectra, and even total surface current vectors.

In contrast, other instrument concepts such as GNSS-Reflectometry were successfully developed and tested (e.g. Cartwright et al., 2018; Li et al., 2018), but the performance reported was 1 to 2 orders of magnitude better than current requirements of the Sentinel-3 or SWOT altimetry missions. Other technological concepts such as small compact radar altimeters flying in coordinated constellations of more than 10 satellites were proposed but not implemented to date, either because of technology limitations (e.g. a radar altimeter antenna is challenging to accommodate in a nano-satellite), or because of costs involved in large constellations. The concept of a radar altimetry constellation is still relevant, as proved with several recent Phase 0/A studies (e.g. Guerra et al., 2016; Blumstein et al., 2019), and new technologies might make it a reality in the near future.

A major technological breakthrough is expected from the SWOT mission (Morrow et al., 2018; Morrow et al., 2019) and the first 2D image of the ocean and inland water surface topography, but also probably sea ice thickness (Armitage and Kwok, 2019). Over the ocean, this unprecedented bidimensional view of ocean mesoscale, and the extremely low noise floor of the KaRIn interferometer instrument will help oceanographers observe and better understand ocean dynamics at scales that simply cannot be resolved with traditional 1D nadir altimetry profiles. To that extent, the SWOT mission is sometimes considered as the blueprint for all future altimeters: the ability to do swath altimetry is such a major advancement with respect to the 1D profiles used for 25 years, that it might be the most important technological breakthrough in satellite altimetry since TOPEX/Poseidon's capability to reach centimeter-level accuracy.

For future missions, one might expect technology to keep evolving as scientific requirements become ever more stringent: oceanographers try to observe smaller and faster mesoscale features (better sampling is needed), as well as SSH derivatives (smaller instrument noise is needed), and most importantly extremely small trends in the Earth Climate system (smaller biases and drifts are needed). This might become even more challenging because environmental conditions (e.g. potential corruption of actual microwave radiometry data with 5G networks) or space laws (e.g. deorbiting is substantially more difficult from the Sentinel-6 altitude than from lower altitudes). To that extent, it is essential that space agencies ensure not just continuity of existing datasets and performance, but also more precise instruments, higher space and time resolution and sampling, as well as more stable instruments and reprocessed calibrated products for climate science.

5. Key observations

First of all, the definition of "altimetric data", and generally of "spatial observations" must be put into perspective and in a realistic context. Between raw data coming directly from the satellite and a level 4 product or, in the hydrological context, of a "virtual station" there are gaps which can be enormous. The share of corrections of different nature, the role of complementary data (for example the geoid), the difference between NRT data and data from reanalysis, etc. All these elements make the concept of "data" and "observation" quite subtle. It is not the subject of this paper to discuss these points but we must obviously keep it in mind here.

5.1. SSH data

SSH is the first obvious product from altimetry. Again, the key recommendation concerns the requirements of the continuity of observations over time and that data be provided in real-time. Continuity is an important first criterion that is mentioned by scientists of all disciplines. Also, the time scales of the phenomena involved are important, and those with a long-time scale are key. The measurement of sea level is a good example of this. There are several recommendations regarding the resolution, in time and space. But not surprisingly, they are not necessarily consistent depending on the applications and scientific fields. Regarding swath altimetry, so far there is only the SWOT mission programmed. This is a limited edition wide-swath mission, and there is no continuity assured for the HR coverage after 2024, yet many research and operational users will make use of these data and systems will be put in place to exploit the high-resolution SWOT observations. Researchers can revisit and re-analyze these measurements for years. What happens, however, to these operational users and applications after SWOT? A clear recommendation is, therefore, to consider a mission extension for SWOT of some sort.

5.2. SWH and wind speed data

Wave height is another important piece of information provided by altimetry. High-resolution observations of wind and waves for coupling the ocean and wave models are crucial for operational oceanography. Measuring wind and waves and the "weather" of the ocean is one way to increase collaboration between different science teams and the meteorology community. Additional effort is required to secure an accurate wave height measurement as close to the coast as possible, and also to develop instruments permitting access to other important variables like wave direction, spectra, etc. (e.g. CFOSAT). This relates to coastal oceanography and also to sea level monitoring requirements as the evolution of the near shore wave field may contribute to sea level changes near the coast.

5.3. Backscattering coefficient

Radar altimetry backscattering coefficients (σ_0) provide useful information on the Earth surface roughness and nature. If this information is widely used over the ocean to retrieve the surface wind speed (Witter and Chelton, 1991), it is still underexploited over other types of Earth surfaces in spite of its demonstrated interest. Spatial patterns of radar altimetry backscattering coefficients were found to be similar to the distribution of land types (Prigent et al., 2015; Frappart et al., 2020). The temporal variations of the backscattering coefficients were also related to major components of the land water cycle (e.g., floods occurence, presence of snow, changes in soil moisture, ...) (Frappart et al., 2020). Surface soil moisture was found to be linearly related to this parameter over semi-arid areas (Fatras et al., 2012). Backscattering is also used, in combination with the brightness temperatures acquired by the radiometer onboard the same satellite platform, to identify the presence of snow and ice over inland water bodies (Kouraev et al., 2008), sea ice types (Tilling et al., 2018), and provides insights on the nature of snow and ice properties of the ice sheets (Adodo et al., 2018).

Backscattering coefficients and surface roughness are also important for detecting icebergs (Tournadre et al., 2016), over ice sheets and sea-ice, as well as over hydrological and coastal and estuarine targets to help differentiate the different water surfaces and radar reflections outside open water, water under vegetation, wet sand banks, etc. At fine-scales over the open ocean (Ardhuin et al., 2017), there are advanced studies on the colocation of σ_0 changes across sharp ocean temperature and SSH fronts, with small-scale air-sea interactions acting that can be observed by the simultaneous observations of SSH, SWH and σ_0. This is already being performed in 1-D from nadir altimetry (Quilfen and Chapron, 2019), and the 2D wind-front interactions will be observed by SWOT with its 2D SAR images and conjoint SSH fields (Morrow et al., 2019).

5.4. River and lake level

Monitoring water levels of lakes and rivers worldwide has been made possible using satellite altimetry. Hydrologists, some of them being not expert in altimetry, and, consequently, that are unable to calculate these variables for their region of study, can now find them in different databases such as "River&Lake", "Hydroweb", "USDA Lake database", "SAC-VEDAS database" and "DAHITI" already mentioned. All the data produced for these systems is provided at no additional cost to the user, and is easily accessible. Part of the data in these databases is updated in near real time using the IGDRs altimetry products. In Hydroweb and DAHITI moreover, water extent and water volume changes are produced for dozens of lakes, using synergy between altimetry and imagery. If combined with other available water extent time series data (e.g. Pekel et al., 2016; Zhao and Gao, 2018; Yao et al., 2019), the existing altimetry level databases can potentially be used to estimate multi-decadal volume changes for at least hundreds of lakes and reservoirs worldwide. The next step is to satisfy the requirement for automated space-borne estimation of river discharge, using in synergy altimetry and optical sensors to increase the space-time sampling, and also consider river discharge as a candidate for being the next Essential Climate Variable from space (Woolway et al., 2020; Williamson et al., 2009).

5.5. Tides

For barotropic tides, there is a good global network of tide gauges for Calibration/Validation (CAL/VAL). It is recommended to benchmark these tide gauges with GNSS for comparisons and retrieval of vertical crustal deformations. For the high-resolution along-track, and in the prospect of SWOT, a global network of moorings with upper ocean sampling for high-frequency internal wave signals would be beneficial.

There are challenging areas in this regard such as shelf seas, coastal seas and polar seas. A starting point could be to investigate barotropic tides non-stationarity or long-term change (linked with ice-cover change, sea level rise, etc.). Continuous efforts is required to make tidal correction errors and HF corrections more homogeneous with dedicated efforts in shallow water/high latitudes regions – the interleaved orbit would improve tidal estimates. It would be useful to study and quantify the duration of the interleaved phase that would significantly reduce errors on tidal estimates.

Nearly 40 years ago, (Munk and Wunsch, 1982) envisioned the beginnings of an operational ocean-observing system consisting of three major programs: ocean acoustic tomography, satellite observations of sea surface topography and wind stress, and modelling to integrate observations and ocean dynamics. It has played a primary role in the discovery of the internal tide signals and their nature. As the present article attests, considerable progress has been made in the latter two components - but implementation of the acoustical observations has lagged behind. In coming decades, active and passive acoustical methods should be providing data to complement the altimeter programs (Dushaw et al., 2011; Howe et al., 2019). Wide-swath altimetry has significantly unveiled the important internal tide signal. A recommendation is to develop an internal tide model for use by the community (e.g., in CMEMS processing, in Radar Altimetry Database System (RADS), etc.). It is necessary to better understand, estimate and model internal tide variability, its non-stationary element, and learn how to handle the high-frequency motions of internal tides and waves.

5.6. Other data

It is important to note that SSH and SWH data should not be considered alone. Using SSH with other satellite data is a priority, and in many cases also with in situ data. The same remark can be made for lake water level in order to retrieve extent and volume change, and the river water level to retrieve discharge. In other words, the building of multi-sensor, multi-mission, consistent data sets, as mentioned earlier, should be advocated. This implies that in several cases efforts must be made to support and participate in the development of consistent in situ components, as well as in supporting efforts to recover and reprocess historical in situ data for easy-of-use. In situ components should, in particular, be sustained and improved upon in coastal zones (more in situ data in the zone 0–3 km from the coast is needed for validation) and inland waters as well. Bathymetry improvements are needed in coastal and shallow water regions, notably for tides and internal tide modeling. Bathymetry along rivers would also allow improvements in the assimilation of levels, widths and slope products (as will be done with SWOT) in models for discharge calculations.

The development of multi-sensor, multi-mission, consistent data sets is therefore a key point as well as the ability to integrate across them.

6. Data and methods

6.1. Wet tropospheric correction

The wet tropospheric correction is considered as the largest source of uncertainty in the sea level estimate (Ablain et al., 2019), especially in the coastal zone (Cipollini et al., 2018; Vieira et al., 2019) and for inland waters. It has to be improved at all spatial and temporal scales (Vieira et al., 2019) so that as to comply with the main requirements of altimetry missions related to mesoscale observability, global mean sea level monitoring, and long-term sea level rise. The new generation of altimeters, either in SAR mode (CryoSat-2 over ocean, Sentinel-3, Sentinel-6) or in Ka-band (SARAL/AltiKa), have significantly improved the quality of altimetry range in terms of accuracy and spatial resolution. To take full benefit of these new instruments and associated processing, there is a need to have a better estimation of the wet tropospheric correction. The spatial resolution with the current radiometers (10 to 30 km) is coarse compared to the altimeter one. The resolution should be improved in the coming years with a new generation of radiometers providing observations at higher frequencies (>37 GHz), the first one to be launched onboard the Sentinel-6/Michael Freilich satellite (Maiwald et al., 2020). The resolution should be also improved by the integration of high frequency GNSS measurements (Fernandes et al., 2015; Lázaro et al., 2019). GNSS tropospheric values have been shown to have millimeter level bias and standard deviation compared to ECMWF tropospheric models (Pearson et al., 2020; Dousa et al., 2017; Pacione et al., 2017).

This will be supported by dedicated processing (Brown, 2010) to better characterize the variability of water vapor over open ocean, in coastal areas or even over continental waters where currently the models estimation of the wet tropospheric delay is preferred to the radiometric measurements (Fernandes et al., 2014; Crétaux et al., 2018). Sea level rise is one of the main parameters to monitor climate change. As any artificial temporal drift in the wet tropospheric correction will translate immediately into a similar drift in the mean sea level, there is a need for an extremely well calibrated system to retrieve this wet tropospheric correction (Maiwald et al., 2020).

6.2. Orbit and geodesy

Precise Orbit determination (POD) for altimetric satellites has made enormous progress owing to the continuous improvement in the quality of the tracking systems (SLR, DORIS and GNSS), the density of the data they provide and the continued improvements in the dynamical force models and in the definition of the underlying reference system in which the orbits are computed (e.g. Cerri et al., 2010; Lemoine et al., 2010; Rudenko et al., 2012; Couhert et al., 2015; Peter et al., 2017). For example, for the TOPEX/Poseidon mission, the requirement for the radial orbit accuracy requirement was 10 cm but only two years after the launch a 5 cm accuracy was achieved and the goal of 2 cm considered as reachable (Nouël et al., 1994). Both the expectation of users and the science requirements have evolved. Given the current state-of-the-art, intercomparisons between OSTM/Jason-2 and Jason-3 orbit solutions from different techniques and different analysis centers have demonstrated radial orbit accuracy is currently at the level of 6–8 mm radial RMS. The improvement in the quality of the Earth geopotential model has contributed both directly and indirectly to the improvements in altimetric satellite POD (Rudenko et al., 2014). Due to the GRACE (Tapley et al., 2004) and GOCE (Pail et al., 2011) missions, these models have a level of resolution and accuracy that was not available at the beginning of the precise altimetric missions era in 1992. Information about temporal variations of the Earth geopotential is now a required input for POD to reach the current and future accuracy requirement. The advent of space-borne GNSS receivers provided the second major leap in orbit precision. Continuous and precise 3D tracking allows to either correct or mitigate for errors in the surface force modelling, which leads to orbit precision that is very close to the GNSS phase noise (e.g. Bertiger et al., 2010). The DORIS tracking system has improved considerably in the past 25 years. Today DORIS delivers orbits on altimetric satellites at close to 10-mm radial RMS accuracy for SARAL/AltiKa (Zelensky et al., 2016) and between 8 and 9 mm for Sentinel-3A and Sentinel-3B (Fernández et al., 2020). The SLR network over the last 25 years has improved both in the precision of its data, and in the rigor with which it characterizes the errors in the satellite laser ranging systems (Pearlman et al., 2019; Wilkinson et al., 2019). In addition, SLR is the only tracking system that can provide absolute estimation of radial orbit accuracy. A stable reference frame is a fundamental requirement for altimetric satellite POD. New SLR systems providing better, and more frequent data have been deployed and are under development. The present realization, ITRF2014, used space geodetic data obtained over the last 30–40 years of the space age for its definition (Altamimi et al., 2016). Accurate and timely estimates of the Earth Rotation Parameters (e.g., polar motion and UT1, see Bizouard et al. (2019)) are also important both for low-latency products (including near-real-time) and longer latency products (for Geophysical Data Records). The challenge in the future will be to continue to deliver sub-cm radially accurate orbits for altimetric satellites. For POD, it is required that the precision and quality of the tracking systems, reference frame, Earth Rotation Parameters, and static and time-variable geopotential models be at a minimum maintained at current performance, and that information from a variety of sources be made available in a timely manner. While one can be pleased at the progress that has been made in the past 25 years, there is a societal obligation to deliver a stable and accurate orbit product, since the measurement of altimetric sea surface height, as well as the change in global mean sea level has such profound societal significance. The data and background geophysical models needed to achieve and improve the orbit accuracy (such as the terrestrial reference frame, and up-to-date models of time-varying gravity) can only be obtained from other sources. Thus it is recommended that the communities involved in generating these external data and models be sustained by the space agencies and national geodetic organizations involved in these endeavors.

6.3. Mean sea surface, geoid and mean dynamic topography

Radar altimetry, aimed at measuring oceanic surface features, also measures the topographic features of the ocean's floor for which dense orbital coverage is required. The general objectives and methodology were first described in Greenwood et al. (1969). When the data from Geosat were declassified in the mid-1980s, rapid progress ensued (Cheney et al., 1986), eventually followed by bathymetric charts of the world's oceans created largely from radar altimetric data (Smith and Sandwell, 1994). The radar altimetric community collectively is looking forward to the next generation of instruments, including the first demonstration from orbit of a wide swath altimeter (Rodriguez et al., 2018).

The development of accurate Mean Sea Surface (MSS), Mean Dynamic Topography (MDT) and Geoid models is an ongoing process incorporating both Exact Repeat Missions for the temporal mean and geodetic missions for fine scale spatial features (Sandwell et al., 2019). MSS products have improved over recent decades, even in the coastal regions (Ophaug et al., 2019; Karimi et al., 2020), particularly with the availability of the second generation altimeters (CryoSat-2 and SARAL/AltiKa) as well as longer time series and improved modeling techniques. Continuous improvement of data pre-processing and also of mapping methods for finer scale structures is essential for the improved value of satellite altimetry on new ground tracks (e.g. Sentinel-3, Dibarboure and Pujol, 2019) and for oceanographic use of geodetic mission altimetry in the future. Geoids have much improved with the availability of GRACE and GOCE data and shipborne gravimetry. Parallel development to resolve increasing finer scale of the MDT using GRACE, GOCE, Argo, altimetry and drifter data enables mutual constraint and benefit to the development of all three quantities as MSS $=$ MDT $+$ Geoid.

Currently CryoSat-2 and SARAL/AltiKa operate in geodetic mission. SARAL/AltiKa operates in an uncontrolled geodetic mission and CryoSat-2 operates with a 369-days repeat limiting the cross track spacing to 8 km. Likely CryoSat-2 will be moved to new groundtrack and Jason-2 has completed a Long-Repeat Orbit (LRO) as part of an Extension Of Life mission. The LRO orbit has been optimized to serve oceanographic and geodetic purposes. Jason-2 played a fundamental role to improve the spatial resolution of particular MSS and geoid models as the chosen 370 day LRO (8 km ground track spacing) has been interleaved in a controlled way creating a uniform 4 km across track pattern after two interleaved LRO cycles before the satellite ceased operating in October 2019.

The value of geodetic missions is paramount for deriving accurate sea level retrieval along non-repeated tracks (uncontrolled orbits like SARAL/AltiKa) and for future missions like SWOT. It is also important to consider the orbit choice for future polar mission satellites. Sea level anomaly is insufficiently sampled poleward of 66° latitude, i.e. outside the orbit range of the TOPEX/Poseidon and Jason series because existing satellites are sun-synchronous. This impacts the recovery of major tide constituents, which further impacts the accuracy of sea level recovery and MSS determination. These limitations directly impact the precision of sea ice thickness and sea ice drift retrievals. We must note that having polar orbits do not solve completely the sampling issue as these regions are seasonally covered by ice and as a consequence the sea level cannot be measured by altimetry. The geodetic orbit would help improve the mean sea surface, which is important to compute accurate SLA close to the coast.

6.4. Calibration and Validation (CAL/VAL)

Current estimates of regional and global change in mean sea level need continuity of altimeter data in term of missions but also in term of standards' homogeneity. This is only possible through careful and continuous CAL/VAL of the altimetry missions. Cross calibration of past, present and future altimetry missions will remain essential for the realization of a continuous and homogeneous series of sea level (Ablain et al., 2015; Fu and Haines, 2013). There is no doubt, however, that calibration of an altimeter requires a multiple approach, including using both in situ calibration sites and global studies based on the global tide gauge network (Bonnefond et al., 2011). The relative calibration between different missions flying on the same period through crossover analysis or by along-track comparisons during tandem phase (Ablain et al., 2010) of the missions is also a key contribution for the CAL/VAL activities. All these techniques are considered complementary and fundamental in oceanography.

The recognition of the importance of CAL/VAL is unanimous. This must include as much as possible comprehensive CAL/VAL as well as coordinated ocean science campaigns. It is also suggested that CAL/VAL infrastructure should have a durable vision (Haines et al., 2020) – as for space infrastructure – and not be only single agency/mission oriented (Bonnefond et al., 2019). Agencies seek involvement from the international community with experience in conducting scientific verification and validation of satellite data, and in using independent Fiducial Reference Measurements (FRM) (Mertikas and Pail, 2020; Mertikas et al., 2019), field experiments and campaigns to validate these data. As a consequence, the development of spatial observation must be accompanied by an evolution of in situ observation, whether for CAL/VAL or enhancement. It is essential that space agencies strengthen their cooperation with the organizations in charge of in situ observation and develop an inter-agency policy on CAL/VAL aspects. The challenge is to set up a long-term programmatic support for the in situ observation necessary for CAL/VAL activities (not limited to a specific mission but rather linked to a "sector", such as ocean color radiometry or altimetry). It also includes long-term and sustainable archiving of CAL/VAL data. These mechanisms should be organized jointly with national agencies, and also at the global, or at least regional levels, e.g. European level (Sterckx et al., 2020). The CEOS Working Group on Calibration/Validation (http://calvalportal.ceos.org) has been set-up for this aim and should be strengthened.

6.5. Data uncertainty

In addition to data, it is also essential to have information on the errors associated with these data. Characterization of the errors in the observations and complete knowledge for the users of the corrections that have been made to the data are crucial. A dedicated plan to properly characterize the uncertainty features of the observational data is recommended especially for data assimilation purposes. An uncertainty characterization of the observations must be provided. This is at the interface between the observations and the assimilation and for progress to be made in the assimilation schemes, but progress must also be made in the characterization of the uncertainties of the observations, not only for altimetry but for the other sources of data as well. There is a clear need for systematic (and rigorous) uncertainty estimations. An error formalism needs to be adopted to estimate drift impact and corrections, and to provide error budgets of altimeter missions with adequate and coordinated information. Note that error budget tables could be improved by independent studies based on uncertainty calculation dedicated to each source of error.

6.6. Data access and handling

As mentioned already, a strong message is the capability for users to have open and free access to data. Additionally, a concern of many scientists is the problem associated with the handling of massive data. Scientists often lack the work force and the tools necessary to handle, analyze, and exploit large amounts of data that are increasingly growing. Such issue is recognized by the agencies and efforts have being made to move forward but must be reinforced in the future. A pilot demonstration, dubbed ESA GPOD SARvatore (https://gpod.eo.esa.int), designed for custom processing SAR mode data over specific targets like coastal zone and inland water, which implies much higher volumes of data than classical low resolution mode, has been offered in the past 6 years using high computing power near the input product storage; users would have difficulties otherwise to perform research on SAR and SARIn mode algorithms relying solely on local computing and lengthy data transfers.

The SWOT mission is very much concerned by this difficulty (Hausman et al., 2019). Large volumes of data coupled with higher resolutions will likely require the use of data classification methods using big data and Artificial Intelligence (AI) techniques. With the increasing amount and diversity of data, data processing and access must be seen in its entirety. Data poles should evolve and be coupled with computing means to take into account new algorithmic strategies such as AI. In the long term, an overhaul of the spatial data acquisition, production and management strategy could be envisaged. This would include thoughts on the fine management of acquisitions, the flexibility of on-board processing, and the storage and processing of data. It is also important to mention that, as far as possible, data reprocessing from historical missions must be made in order to homogenize their standards to current ones. For example, in light of the need to maintain continuity and integrity of the 28-year record of sea level, the OSTST recommends that agencies continue to support ongoing reprocessing of the TOPEX/Poseidon and Jason records as new improvements become possible, and so that regular reprocessing of new follow-on missions does not impact the continuity and homogeneity of the climate record. For climate records of continental areas (lakes and rivers) it is also needed some reprocessing of historical missions, particularly thanks to efforts done by the altimetry community in the development of new retracking algorithms not available when the ERS-1 and ERS-2, Geosat Follow-On or TOPEX/Poseidon were operated, not mentioning also Geosat in the 80's.

The ultimate goal is to close gaps between data, information, and users (products fit for purpose). Data access in a consistent and easy to use format is key. There is a strong and continued advocacy for broad, open data policies and practices. Open data and open processing policies are required in the sense that while there are many communities of users that want to have the data already fully processed, there are also other users who need well detailed documentation on all data processing steps to be able to adapt them to their own needs.

It is generally recommended to develop product-availability at different processing levels. Most often, near real time products greatly improve uptake. Regarding the new observations, short-latency products should be prioritized in the coming years.

6.7. DUACS

In 1997 the first homogeneous and user friendly Sea Level data set based on TOPEX/Poseidon and ERS-1 & 2 missions was released to the scientific community: from this date, it was no longer necessary to be an altimetry expert to use sea level time series. This was the beginning of DUACS (Data Unification and Altimeter Combination System). For 25 years (Taburet et al., 2019), the system has integrated and merged all the altimeter missions into a multi-mission dataset Level 3 (along-track cross-calibrated SLA) and Level 4 products (multiple sensors merged as maps or time series). It was disseminated first on Aviso and now CMEMS (Europe) and used worldwide. Regional multi-mission datasets were also produced in NASA (US) and IMOS (Australia) showing some limits in the operational maps, notably in terms of spatial resolution. The improvement of sea level merged products at small scales through the development of new algorithms (non-linear scheme, AI techniques, multi-sensor fusion…) and the use of new satellite technology will be the challenge in the coming decade.

7. Transversal views

An important message is to keep an open mind with regards to the specific objectives of a mission. Even if a given mission is designed for a particular objective, it is important to maximize the science return from it. Therefore, beyond the many recommendations that have been made for specific missions or scientific objectives, including for an operational mission, it is important to try optimizing the science returns in all dimensions of science and applications. For example, CryoSat-2 was designed primarily for the cryosphere but it appeared to be very useful for oceanography and inland water even though the mission, per se, was not optimized for these objectives. Sentinel-6 is primarily an oceanographic mission but one can maximize the science return for coastal zones and for hydrology. SARAL/AltiKa was originally designed for oceanic mesoscales and also appeared to be very profitable for inland waters and cryospheric sciences and even for geodesy in the drifting phase (Verron et al., 2018; Verron et al., 2020).

7.1. Scales

The question of scale is underlined as such because it crosses many scientific issues in the field of Earth observation. As a summary of the challenge, a somewhat naive formulation would be to wish to establish a path to future altimetry missions addressing both the climate record and high-resolution observations of small-scale and fast signals, or, more simply, be able to work across spatial and temporal scales. More practically, it is likely that the space agencies will, in the future, have to confront wish-lists encompassing items such as higher spatial resolution, higher temporal resolution, guaranteed continuity, more multi-sensor satellites with more in situ data, etc. The example of SWOT is interesting as the excellent fine spatial coverage is accompanied by a less dense (and not dynamically consistent) time coverage. So, for the future, it would be useful to anticipate plans for better space-time coverage of SSH and surface currents in the open, coastal and polar oceans. The coastal ocean and marginal ice zones are especially challenging in terms of time scales and spatial scales. To try to sample spatial and temporal variability in such a highly dynamic environment is a great challenge from space. This concerns sea state and winds due to variability on very short time and spatial scales, complicated by the impact of local topography/bathymetry. Covering all relevant time scales and spatial scales for sea state is especially challenging and cannot be resolved with the currently available altimeter sampling, making integration with models and other measurements essential. One solution is to integrate satellite data with modeling and other measurement technologies, but if one can improve the sampling with either constellation or swath instruments, this becomes moot. Altimeters in a sun-synchronous orbit could introduce a diurnal bias for measuring coastal winds and waves, by only sampling at set local times of day (land breeze, sea breeze effects). For coastal investigations in general, more investigations on the real spatial and temporal resolution that satellites can achieve are recommended. For inland water bodies, the temporal and spatial scales are also a fundamental key issue. Higher temporal resolution (like with the Jason series) missed a high number of targets (lakes and reservoirs not overflown). High spatial resolution missions (e.g. CryoSat-2) lead to missed hydrological signals and do not allow an efficient survey of many of the flooding events occuring in rapid response time. For rivers, hydrologists can be reluctant to use altimetry due to the low temporal resolution, although it allows acquiring information in remote areas where no in situ measurements exist. Regarding scales there is an interesting contrast between hydrology and oceanography in the way scientists approach scales. In oceanography, the approach has been starting from the larger scale and moving to the mesoscales and now even smaller scales. In contrast, hydrologists have been focusing at the river basin scale mainly or lake or regional areas and are now focusing on global hydrology trying to solve questions in global water cycle, impact of climate change, etc. For these latter objectives, satellite data are really a good tool.

7.2. Integration

Models and data assimilation have appeared in all scientific domains whatever their developments, as key elements to extract all the benefits of observations and of altimetry in particular (for a recent review, see Chassignet et al., 2018). Data assimilation covers an ensemble of various mathematical techniques that provide a rational way to synthetize information provided by models and by observations (assuming estimations of their accuracy), in order to provide a realistic state estimation (and possibly forecast) with error estimates. These are key tools to use, analyze and understand current data, but also to anticipate the use of new observations. Modeling and OSSEs may be used to simulate these new observations, such as SWOT altimetry for example. There are key tools to give an integrated perspective of a system involving many observations of different types and some understanding translated in terms of dynamic equations. Models and data assimilation provide adequate tools to make consistent use of multi-sensors, and multi-missions datasets.

The status of model development is not similar in all disciplines. Efforts must be made to develop modeling for hydrology and the cryosphere. Such efforts must be made in the same consistent manner to improve the Earth observing system. For example, in order to understand upcoming observations from SWOT, what is needed is not only to do comprehensive CAL/VAL and to coordinate the ocean science campaigns, but also interpretation from high-resolution modeling and data simulation. With SWOT the resolution is high, but the temporal resolution is poor, so observations might be uncorrelated, implying an immediate need for modeling. It is even true prior to the launches as model outputs can provide some good indications ("simulators") of the data that will be observed, in order to prepare the right approach for exploitation. The quality of ocean models has increased in the past years especially because of the growing computing capabilities. Hydrological models of water cycle at continental to global scales have also emerged over the last ten years, and assimilation of altimetry in synergy with other mission products into land surface and global climate models, is a current big challenge. Even more, model outputs must be more and more used to simulate observing approaches and scenarios and then provide rationale to justify missions and also to optimize the data acquisition for current missions (see Section 6.6).

Another important point is the fact that space ocean observations relate to only the surface. Modeling can help provide a consistent vertical perspective: a 4D reconstruction. Regarding SWOT again and the need to help with interpreting higher resolution altimetry data, it is expected that models will help further disentangle the questions of the internal wave motions and the balanced dynamics. From a data assimilation perspective, it is important to have high quality data to ingest into models but even with imperfect data it is essential that they are supplied with a good estimate of errors' levels. In both cases, a clear recommendation is that the corresponding efforts must be recognized, as models and data assimilation are keys for the future of space observations and a better understanding and forecasting of the Earth System. One keyword that emerged from the discussions among scientists worldwide is "synergy". Synergy relies on altimetry seen as connected to other remote sensing techniques, as a part of a larger observational system and of modeling development. What are the future innovations in the synergy of satellite data and in situ observations including data assimilation methodologies and statistical and dynamical interpolations?

7.3. Artificial Intelligence (AI)

The concept of artificial intelligence (AI) is quite broad, sometimes confusing, and it is not yet completely clear what benefits can be derived from it in the field of altimetry. However, it is quite obvious that the abundance of spatial data and integrated data (notably from numerical models integrating altimetry data and other available data) can benefit from the tools developed in the field of AI sciences for manipulating, processing, interpreting, and understanding these large masses of data, and therefore increasing their value. It is, therefore, recommended to explore these tools as articulated above.

There are multiple other potential AI contributions worth developing. AI may enable a simplified representation of a model too complex to be able to be used in full time/space analysis. It thus may allow to better take into account the physics of a measure in these analyses or to provide essential auxiliary information (e.g. Fablet et al., 2018).

7.4. Education and training

Last but not least, it is necessary to develop the capacity of people to better understand satellite altimetry and remote sensing and how they can be used. For that, help must be sought from the agencies for training courses in summer schools, and also funding for the employment of young researchers, grants for students and young engineers, etc. There have already been a number of international schools on altimetry, and operational oceanography (with a strong component on space observations) (e.g. Chassignet et al., 2018). We should also assess the development of more specific schools on topics such as coastal altimetry, space hydrology and the cryosphere, and more generally of tutorials on tools/data products to increase use. Some important ressources already exist. For example, by accessing the Copernicus Research and User Support Service (RUS, https://rus-training.eu/) readers can find information on face-to-face lessons, online webinars and e-learning courses on both oceanography and radar altimetry. ESA annually offers training sessions during the Coastal Altimetry Workshop (http://www.coastalt.eu/, training material available for download) and has also funded many toolboxes and tutorials such as the Broadview Radar Altimetry Toolbox (BRAT, http://www.altimetry.info/), designed to facilitate the visualisation and processing of radar altimetry data and the Delay-Doppler Altimetry Studio (DeDop, https://dedop.org/), which is an open-source customizable and modifiable toolbox to process Sentinel-3 SRAL data. However, several regions of the world are under-represented in the international oceanographic, hydrologic, and cryospheric communities. Efforts are therefore needed throughout the world to diversify and widen the altimetry community. Education and training at the university as well as for PhD or post-doc students are also critical to the future success altimeter science missions. Another critical component of the successful development of this pipeline is the science-interested students in the younger community of learners–grade school through high school (Rosmorduc et al., 2020). Successful recruitment of students into Earth and ocean technical studies begins with science-literate children. Finally, we should consider another requirement in order to advance sea level science objectives: advocacy of the value and relevance of sea level science research and modeling outcomes in order to better communicate on the added-value to public and private sector user communities and to decision makers.

8. Programmatic issues

After the first technology concept demonstrations mostly conducted in the USA (Wilson et al., 2006), the development of modern altimetry has been based on multifold cooperation and partnership (e.g. Escudier et al., 2018):

- Partnership between space agencies developing and operating the missions (NASA, CNES, ESA, ISRO, CNSA, …), extended to operational organizations (NOAA, EUMETSAT, EU/Copernicus Services);
- Partnership between space agencies and oceanographic institutions to develop the synergies between the space component, the in situ component and the analysis and forecast capacities;
- Partnership between agencies and oceanographic community (science, applications) to optimize the definition of the system, develop the data processing tools, conduct the calibration and validation activities.

In particular the OSTST, gathering worldwide selected scientists together with engineers developing and operating the missions, has proved to be essential. This was a key element for the altimetry development success considering the complexity and diversity of expertise to be combined for such a system of systems that shall include:

- Multiple satellites flying on different orbits to provide the adequate time and space sampling and coverage up to the polar areas;
- Multiple instruments, each contributing to the global data set but providing specific characteristics (wide swath versus along track scanning, instrument optimization for ocean, land, ice, river and lake, …);
- In situ instrumentation to complement the satellites observation and provide adequate calibration activities;
- Multiple expertise to properly manage and handle the data (instrument processing and corrections, geophysical corrections, multi-satellite merging, assimilation into models, …)

The OSTST work and recommendations are of great benefit to the OST Virtual Constellation (VC) of the Committee on Earth Observation Satellites. The OST VC (NASA, ESA, CNES, CNSA, JAXA, ISRO, EUMETSAT, NOAA, US Navy) coordinates ocean inter-agencies actions.

Considering the challenges to be met in the future (increased time and space coverage and resolution, coastal, hydrology, cryosphere, …) it is essential to pursue these multifold partnerships. Priorities that shall be conducted in parallel are:

- Continuity of current missions allowing us to monitor on an operational basis large and medium scale oceanic variability. This requires specific care to guarantee the high level measurement performance necessary for altimetry considering applications such as mean sea level monitoring, and to maintain minimum time and space coverage performance. The latter implies close coordination between the various agencies flying altimetry missions;
- Minimizing likelihood of a gap in polar ocean and ice monitoring, Agencies should strive to launch CRISTAL in the early 2020s and maintain operation of CryoSat-2, ICESat-2, and SARAL/AltiKa as long as possible.
- Research, development and in orbit demonstration of the new mission concepts that are necessary to meet the identified challenges for the future in the various application fields. In this context, as was initiated 20 years ago for the ESA Earth Explorer CryoSat-2 for the Synthetic Aperture Radar Altimetry concept, in orbit demonstration of wide swath altimetry, such as the SWOT concept developed in cooperation between NASA, CNES, Canada and the UK, is a unique opportunity to meet the resolution challenges. In parallel, exploration of new mission concepts derived from altimetry, such as the SKIM concept aiming at monitoring directly the total surface current, is also essential to move in this direction;
- Research and development of new processing techniques, in particular algorithms to enhance our ability to merge different instrument measurements, will allow to maximize benefit from each technique's intrinsic advantage while bypassing their limitations. Support for AI applications should be encouraged as it may prove highly efficient;

– Continuous close cooperation between agencies and users to optimize the use of in orbit operational missions and the definition of future mission concepts. To support these discussions aiming at maximizing the science and operational return while optimizing resources it may be worthwhile to use OSSEs or equivalent techniques to define the most valuable evolutions that will allow to meet the challenges identified.

On the European side, the Copernicus programme is a key element for the future of altimetry and operational oceanography. The Copernicus programme is in routine mode with 7 satellites launched up to now, combined with services in charge of processing and delivering world-class data products used extensively by a large community of users from science, public bodies, private corporations, start-ups, to citizens. This is a success to be shared with space agencies and also with the community of scientists and operators that are building information products on top of remote sensing data, and users. The future of the programme is on the table. The Arctic, coastal zones and marine biology are the next big priorities for the Copernicus marine service. The European Commission, ESA and EUMETSAT are working together on a long-term scenario. In the 2030's timeframe, Sentinel-3 and Sentinel-6 series will need to be continued benefiting from latest technologies that will be available in coming years (e.g. wide swath altimetry). This will also be very important to keep the reference mission with Sentinel-6. Before that, the current priority is to define if and which gap-filler missions between 2025 and 2028 could be developed to tackle new challenges expressed by the space strategy. ESA has started many parallel phase-A studies, of which one is related to topography and many related to oceanography in general.

9. Conclusions

We, the altimetry community, are proud to celebrate the astounding successes of 25 years of precision radar altimetry from space. This saga started in the early 1980's, thanks to the efforts of a small group of visionary scientists and the leadership of a few space agency program managers. Radar altimetry from space started in the context of the World Ocean Circulation Experiment. Since its inception, the altimetry community has expanded in size and scope from a handful of ocean scientists and a couple of countries to a worldwide concerted effort involving both R&D and operational space agencies from China, Europe, India, and the USA, benefiting from the expertise of several hundreds of scientists and engineers, serving the needs of thousands of data users, and covering a variety of disciplines, from large-scale to mesoscale oceanography, through to coastal studies, ice sheets and ice cap surveys, marine geodesy, hydrology, biodiversity and limnology.

One crucial achievement of radar altimetry has been the 25-year record of sea level rise and its geographic pattern and variability, a key climate indicator of global warming, made possible by the incredible accuracy of the combined technique of sea surface height measurement and precise orbit determination. The iconic image of global mean sea level variations since 1992 (Fig. 4), showing not only an uninterrupted increase of 3.2 mm/yr, twice as much as the average rate over the 20th century, but also an acceleration in the past five years and regional variations of the global trends with 25 km resolution, are the symbol of the success of radar altimetry, supplying a global climate indicator for GCOS used also in the United Nations Framework Convention on Climate Change Conferences of Parties (CoPs).

More recently synthetic aperture radar altimetry has provided the first ever image of the rapidly declining Arctic sea ice cover (extent and thickness) and of the fast melting Greenland ice sheets. Radar altimetry is a key component of the Global Earth Observation System of Systems (GEOSS), and over the last 25 years has provided the principal global data source enabling the development of operational oceanography. Radar altimetry contributes to a large number of societal needs, from climate monitoring to weather forecasting, with subsequent applications in a range of activities of socioeconomic importance, including agriculture, energy, health, maritime safety, water, and many others.

In a very synthetic way, we could say that the main and unique virtues of altimetry are:

– Its intrinsic nature: composite measurement providing integrated information on multiple parameters, in 3D for the ocean part;
– Its metrological construction making it possible to aim for absolute precision (even though this includes the limits mentioned above);
– Its comprehensive, all-weather, repetitive coverage.

And that the limits of altimetry are:

– The complexity of its interpretation arising in particular from this composite nature, requiring the use of complex techniques and auxiliary modeling to be able to be analyzed (i.e., for the ocean model of tide, geoid, atmosphere and HF variations of the ocean, electro-magnetic bias, ...);
– Space-time coverage, very limited for nadir altimetry and relatively limited for "wide swath" altimetry (100 km field on SWOT while fields of more than 1000 km are used in passive imagery).

These 25 years of success cannot mask the fact that this complex system is fragile and at risk: today we are just one satellite-failure away from a gap in the 28+ year record. Such a situation should be taken seriously, in view of the dramatic and costly impact that sea level rise and associated extreme events will have on many coastal areas of the planet, coastal megacities and their inhabitants.

We, the global altimetry community, wish to express our collective will to work at ensuring the continuity of the historical climate data record and preparing the next generation of missions, which will continue the success and expansion of radar altimetry. The purpose of this summary is to express the following recommendations that are respectively addressed to the relevant scientific community, to space agencies, to intergovernmental entities, national governments and the European Union.

To conclude we provide a synthesis of the most important recommendations, most of which have a character common to all scientific disciplines, technological developments and/or applications benefiting from altimetry:

– Continuity of measurements is essential, including not only the continuity of altimetry, but also of the other observing systems that accompany altimetry. Such continuity needs also that the complete data set are regularly reprocessed, using most recent models and corrections;
– Continuation of a broad collaboration between engineering and science, research and operations, and international partners facilitating the transition of demonstrated capabilities from research agencies into corresponding capabilities within the operational agencies is needed;
– Sustainability of open data policies including near-real time data for operational purposes promoting timely access to data to all for the public good, typically within three hours of collection for operational use and with a reasonable delay to consolidate the data for research should be secured;
– A strong investment in the modeling developments and more generally to integration through AI and data assimilation methodology development is necessary; and
– A strong increase of investment of national and regional governments in research in terms on human resources is a necessary prerequisite.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This collective synthesis of the worldwide interdisciplinary altimetry community would not have been possible without the support that has been given to each of the contributors by numerous institutions at local, national and intergovernmental levels. At the forefront of this support, we must obviously mention the space agencies CNES, ESA and NASA which have played and still play a decisive role in the development and launch of several prominent altimetry missions from the outset. Other agencies such as DLR, EUMETSAT, ISRO, NOAA, NSOAS and organizations such as CMEMS, also contribute significantly to developments in all forms of altimetry.

We are very grateful to all the players in the previous organizations and many others that we cannot list extensively here, and that were all behind this remarkable success of radar altimetric technology and made the many scientific, technical and application developments possible.

Sincere thanks should be specifically addressed to all contributors either individually or as responsible in various capacities (thematic leaders, session chairmen, contributors to round tables, actors from different space agencies or national organizations or international, etc.), who provided their inputs in different forms to this document. We also warmly thank the reviewers for their helpful comments to improve the article.

The views, opinions, and findings contained in this article are those of the authors and should not be construed as an official National Oceanic and Atmospheric Administration (NOAA) or U.S. Government position, policy, or decision. This also applied to other Organizations or Institutes.

Appendix A. GCOS Essential Climate Variables (ECV)

Oceanic	Surface	Sea-surface temperature	**Terrestrial**	River discharge
		Sea-surface salinity		Water use
		Sea level, Sea state		Groundwater
		Sea ice, Surface current		Lakes
		Ocean colour		Snow cover
		Carbon dioxide partial pressure		Glaciers and ice caps
		Ocean acidity		Ice sheets
		Phytoplankton		Permafrost
	SubSurface	Temperature		Albedo
		Salinity		Land cover (including vegetation type)
		Current		Fraction of absorbed photosynthetically

continued on next page

	Nutrients	active radiation (FAPAR)
	Carbon dioxide partial pressure	Leaf area index (LAI)
	Ocean acidity	Above-ground biomass
	Oxygen	Soil carbon
	Tracers	Fire disturbance
		Soil moisture

Appendix B. Acronyms

- Argo: A program of free-drifting profiling floats that measures temperature and salinity
- AVISO: CNES data center for Altimetry and DORIS products
- CAL/VAL: Calibration/Validation
- CCI: Climate Change Initiative (https://tinyurl.com/ESA-CCI)
- CFOSAT: China France Oceanography SATellite
- Copernicus: Previously known as GMES (Global Monitoring for Environment and Security), is the European Union's Earth observation programme
- CMEMS: Copernicus Marine Environment Monitoring Service
- CNES: Centre National d'Etudes Spatiales, French space agency
- CRISTAL: Copernicus polaR Ice and Snow Topography ALtimeter
- CryoSat-2: ESA's Earth Explorer for Cryospheric studies (April 2010 -)
- DLR: Deutsches Zentrum für Luft- und Raumfahrt, German Aerospace Center
- 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 Variables
- Envisat: ESA Environmental Satellite (March 2002 - May 2012)
- ERS-1: ESA European Remote-Sensing Satellite-1 (July 1991 - March 2000; Altimetry mission ended in June 1996)
- ERS-2: ESA European Remote-Sensing Satellite-2 (April 1995 - Sept. 2011)
- ESA: European Space Agency
- EUMETSAT: European Organisation for the Exploitation of Meteorological Satellites
- GCOS: Global Climate Observing System
- GEO: Group on Earth Observations
- Geosat, Geosat Follow-On: GEOdetic SATellite
- GEOSS: Global Earth Observation System of Systems
- GNSS: Global Navigation Satellite Systems
- GOCE: Gravity field and steady-state Ocean Circulation Explorer
- GRACE: Gravity Recovery And Climate Experiment, NASA/DLR missions, (March 2002 - Oct. 2017) and GRACE-FO (May 2018 -)
- HR: High Resolution
- HY-2 (Haiyang-2): Second generation ocean observation/monitoring satellite series by CNSA (China National Space Administration). A (August 2011 - September 2020), B (October 2018 -) and C (September 2020 -)
- ICESat-2: NASA's Ice, Cloud and land Elevation Satellite-2
- IGDR: Interim Geophysical Data Record
- IMOS: Integrated Marine Observing System
- InSAR: Interferrometric Synthetic Aperature Radar
- 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
- Jason-CS: Jason-CS (Continuity of Service) was first used for the Sentinel-6 mission
- KaRIn: Ka-band Radar Interferometer onboard the future SWOT mission
- LRM: Low Resolution Mode
- MDT: Mean Dynamic Topography
- MSS: Mean Sea Surface
- NASA: National Aeronautical and Space Administration, US space agency
- NOAA: National Oceanic and Atmospheric Administration

– NSOAS: National Satellite Ocean Application Service
– NRT: Near Real Time
– OSSE: Observing System Simulation Experiment
– OSTST: Ocean Surface Topography Science Team
– RADS: Radar Altimetry Database System
– SAR: Synthetic Aperature Radar (SARM for SAR mode)
– SARIn: SAR Interferometry
– SARAL/AltiKa: Satellite with Argos and AltiKa, ISRO/CNES ka-band altimetry satellite (Feb. 2013 -)
– SCO: Space Climate Observatory (https://www.spaceclimateobservatory.org/)
– Sentinel: European Copernicus Programme operational satellites built and launched by ESA
– Sentinel-3: Four Copernicus operational altimetry missions (includes color and temperature sensors). The 2 first ones Sentinel-3A and Sentinel-3B were launched on 16 February 2016 and 25 April 2018 respectively
– Sentinel-6A/Michael Freilich: First of two Copernicus operational successors to the Jason series (initially called Jason-CS), launched on 21 November 2020
– SKIM: Sea surface KInematics Multiscale monitoring, pre-selected for Earth Explorer 9
– SLA: Sea Level Anomaly
– SLR: Satellite Laser Ranging or Sea Level Rise (depending on the context)
– SSB: Sea State Bias
– SSH: Sea Surface Height
– SST: Sea Surface Temperature
– STC: Short Time Critical
– SWH: Significant Wave Height
– SWOT: Surface Water Ocean Topography, NASA/CNES satellite mission (planned launch in 2022)
– TC, TCHP: Tropical Cyclone, Tropical Cyclone Heat Potential
– TOPEX/Poseidon, TP: NASA/CNES first satellite altimetry reference mission (1992) (Aug. 1992 - Jan. 2005)
– WiSA: WIde Swath Altimetry, a concept for Copernicus Next Generation satellite (including hydrology) (> 2030)

References

Abdalla, S., 2019. Are Jason-2 significant wave height measurements still useful. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.08.032 (in this issue).

Abileah, R., Scozzari, A., Vignudelli, S., 2017. Envisat RA-2 individual echoes: A unique dataset for a better understanding of inland water altimetry potentialities. Remote Sens. 9, 605. https://doi.org/10.3390/rs9060605.

Ablain, M., Cazenave, A., Larnicol, G., Balmaseda, M., Cipollini, P., Faugère, Y., Fernandes, M.J., Henry, O., Johannessen, J.A., Knudsen, P., Andersen, O., Legeais, J., Meyssignac, B., Picot, N., Roca, M., Rudenko, S., Scharffenberg, M.G., Stammer, D., Timms, G., Benveniste, J., 2015. Improved sea level record over the satellite altimetry era (1993–2010) from the climate change initiative project. Ocean Sci. 11, 67–82. https://doi.org/10.5194/os-11-67-2015.

Ablain, M., Legeais, J.F., Prandi, P., Marcos, M., Fenoglio-Marc, L., Dieng, H.B., Benveniste, J., Cazenave, A., 2017. Satellite altimetry-based sea level at global and regional scales. Surv. Geophys. 38, 7–31. https://doi.org/10.1007/s10712-016-9389-8.

Ablain, M., Meyssignac, B., Zawadzki, L., Jugier, R., Ribes, A., Spada, G., Benveniste, J., Cazenave, A., Picot, N., 2019. Uncertainty in satellite estimates of global mean sea-level changes, trend and acceleration. Earth Syst. Sci. Data 11, 1189–1202. https://doi.org/10.5194/essd-11-1189-2019.

Ablain, M., Philipps, S., Picot, N., Bronner, E., 2010. Jason-2 global statistical assessment and cross-calibration with jason-1. Mar. Geodesy 33, 162–185. https://doi.org/10.1080/01490419.2010.487805.

Adodo, F.I., Remy, F., Picard, G., 2018. Seasonal variations of the backscattering coefficient measured by radar altimeters over the antarctic ice sheet. Cryosphere 12, 1767–1778. https://doi.org/10.5194/tc-12-1767-2018.

Altamimi, Z., Rebischung, P., Métivier, L., Collilieux, X., 2016. ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions. J. Geophys. Res. Solid Earth 121, 6109–6131. https://doi.org/10.1002/2016JB013098.

Ardhuin, F., Aksenov, Y., Benetazzo, A., Bertino, L., Brandt, P., Caubet, E., Chapron, B., Collard, F., Cravatte, S., Delouis, J.M., Dias, F., Dibarboure, G., Gaultier, L., Johannessen, J., Korosov, A., Manucharyan, G., Menemenlis, D., Menendez, M., Monnier, G., Mouche, A., Nouguier, F., Nurser, G., Rampal, P., Reniers, A., Rodriguez, E., Stopa, J., Tison, C., Ubelmann, C., van Sebille, E., Xie, J., 2018. Measuring currents, ice drift, and waves from space: the sea surface kinematics multiscale monitoring (SKIM) concept. Ocean Sci. 14, 337–354. https://doi.org/10.5194/os-14-337-2018.

Ardhuin, F., Brandt, P., Gaultier, L., Donlon, C., Battaglia, A., Boy, F., Casal, T., Chapron, B., Collard, F., Cravatte, S., Delouis, J.M., De Witte, E., Dibarboure, G., Engen, G., Johnsen, H., Lique, C., Lopez-Dekker, P., Maes, C., Martin, A., Marié, L., Menemenlis, D., Nouguier, F., Peureux, C., Rampal, P., Ressler, G., Rio, M.H., Rommen, B., Shutler, J.D., Suess, M., Tsamados, M., Ubelmann, C., van Sebille, E., van den Oever, M., Stammer, D., 2019. SKIM, a candidate satellite mission exploring global ocean currents and waves. Front. Mar. Sci. 6, 209. https://doi.org/10.3389/fmars.2019.00209.

Ardhuin, F., Gille, S.T., Menemenlis, D., Rocha, C.B., Rascle, N., Chapron, B., Gula, J., Molemaker, J., 2017. Small-scale open ocean currents have large effects on wind wave heights. J. Geophys. Res. Oceans 122, 4500–4517. https://doi.org/10.1002/2016JC012413.

Armitage, T.W., Kwok, R., 2019. SWOT and the ice-covered polar oceans: An exploratory analysis. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.07.006 (in this issue).

Armitage, T.W.K., Bacon, S., Kwok, R., 2018. Arctic sea level and surface circulation response to the Arctic oscillation. Geophys. Res. Lett. 45, 6576–6584. https://doi.org/10.1029/2018GL078386.

Armitage, T.W.K., Bacon, S., Ridout, A.L., Thomas, S.F., Aksenov, Y., Wingham, D.J., 2016. Arctic sea surface height variability and change from satellite radar altimetry and GRACE, 2003–2014. J. Geophys. Res. Oceans 121, 4303–4322. https://doi.org/10.1002/2015JC011579.

Artana, C., Ferrari, R., Bricaud, C., Lellouche, J.M., Garric, G., Sennéchael, N., Lee, J.H., Park, Y.H., Provost, C., 2019b. Twenty-five years of Mercator ocean reanalysis GLORYS12 at drake passage: Velocity assessment and total volume transport. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.11.033 (in this issue).

Artana, C., Provost, C., Lellouche, J.M., Rio, M.H., Ferrari, R., Sennéchael, N., 2019a. The malvinas current at the confluence with the Brazil current: Inferences from 25 years of Mercator ocean reanalysis current at the confluence with the brazil current: Inferences from 25 years of mercator ocean reanalysis. J. Geophys. Res. Oceans 124, 7178–7200. https://doi.org/10.1029/2019JC015289.

Badulin, S., Grigorieva, V., Gavrikov, A., Geogjaev, V., Krinitskiy, M., Markina, M., 2018. Wave steepness from satellite altimetry for wave dynamics and climate studies. Russ. J. Earth Sci 18. https://doi.org/10.2205/2018ES000638.

Badulin, S.I., 2014. A physical model of sea wave period from altimeter data. J. Geophys. Res. Oceans 119, 856–869. https://doi.org/10.1002/2013JC009336.

Badulin, S.I., Grigorieva, V.G., Shabanov, P.A., Sharmar, V.D., Karpov, I.O., 2019. Sea state bias in altimetry measurements within the theory of similarity for wind-driven seas. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.11.040 (in this issue).

Benveniste, J., Cazenave, A., Vignudelli, S., Fenoglio-Marc, L., Shah, R., Almar, R., Andersen, O., Birol, F., Bonnefond, P., Bouffard, J., Calafat, F., Cardellach, E., Cipollini, P., Le Cozannet, G., Dufau, C., Fernandes, M.J., Frappart, F., Garrison, J., Gommenginger, C., Han, G., Høyer, J.L., Kourafalou, V., Leuliette, E., Li, Z., Loisel, H., Madsen, K.S., Marcos, M., Melet, A., Meyssignac, B., Pascual, A., Passaro, M., Ribó, S., Scharroo, R., Song, Y.T., Speich, S., Wilkin, J., Woodworth, P., Wöppelmann, G., 2019. Requirements for a coastal hazards observing system. Front. Mar. Sci. 6, 348. https://doi.org/10.3389/fmars.2019.00348.

Berry, P., Wheeler, J., 2009. River and Lake Product Handbook, v3.5, Issue 3, Revision 5. dmu-rivl-spe-03-110 ed.

Bertiger, W., Desai, S.D., Haines, B., Harvey, N., Moore, A.W., Owen, S., Weiss, J.P., 2010. Single receiver phase ambiguity resolution with GPS data. J. Geodesy 84, 327–337. https://doi.org/10.1007/s00190-010-0371-9.

Bhowmick, S.A., Modi, R., Sandhya, K.G., Seemanth, M., Nair, T.M.B., Kumar, R., Sharma, R., 2015. Analysis of SARAL/AltiKa wind and wave over Indian ocean and its real-time application in wave forecasting system at ISRO. Mar. Geodesy 38, 396–408. https://doi.org/10.1080/01490419.2015.1006380.

Biancamaria, S., Lettenmaier, D.P., Pavelsky, T.M., 2016. The SWOT mission and its capabilities for land hydrology. Surv. Geophys. 37, 307–337. https://doi.org/10.1007/s10712-015-9346-y.

Biancamaria, S., Schaedele, T., Blumstein, D., Frappart, F., Boy, F., Desjonquères, J.D., Pottier, C., Blarel, F., Niño, F., 2018. Validation of Jason-3 tracking modes over french rivers. Remote Sens. Environ. 209, 77–89. https://doi.org/10.1016/j.rse.2018.02.037.

Birkett, C.M., 1994. Radar altimetry: A new concept in monitoring lake level changes. Eos Trans. Am. Geophys. Union 75, 273–275. https://doi.org/10.1029/94EO00944.

Birkett, C.M., 1995. The contribution of TOPEX/Poseidon to the global monitoring of climatically sensitive lakes. J. Geophys. Res. Oceans 100, 25179–25204. https://doi.org/10.1029/95JC02125.

Birkett, C.M., 1998. Contribution of the TOPEX NASA radar altimeter to the global monitoring of large rivers and wetlands. Water Resour. Res. 34, 1223–1239. https://doi.org/10.1029/98WR00124.

Bizouard, C., Lambert, S., Gattano, C., Becker, O., Richard, J.Y., 2019. The IERS EOP 14C04 solution for Earth orientation parameters consistent with ITRF 2014. J. Geodesy 93, 621–633. https://doi.org/10.1007/s00190-018-1186-3.

Blumstein, D., Biancamaria, S., Guérin, A., Maisongrande, P., 2019. A potential constellation of small altimetry satellites dedicated to continental surface waters (SMASH mission). AGU Fall Meeting Abstracts, pp. H43N–2257. https://agu.confex.com/agu/fm19/meetingapp.cgi/Paper/492178.

Birkett, C.M., Reynolds, C., Beckley, B., Doorn, B., 2011. Coastal Altimetry. Springer, Berlin Heidelberg, Berlin, Heidelberg. chapter From Research to Operations: The USDA Global Reservoir and Lake Monitor. pp. 19–50. http://dx.doi.org/10.1007/978-3-642-12796-0_2.

Bonekamp, H., Parisot, F., Wilson, S., Miller, L., Donlon, C., Drinkwater, M., Lindstrom, E., Fu, L.L., Thouvenot, E., Lambin, J., Nakagawa, K., Gohil, B., Lin, M., Yoder, J., Le Traon, P.Y., Jacobs, G., 2010. In: Harrison, D., Stammer, D. (Eds.), Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society. ESA Publication WPP-306, p. 06. https://doi.org/10.5270/OceanObs09.

Bonnefond, P., Exertier, P., Laurain, O., Guinle, T., Féménias, P., 2019. Corsica: A 20-yr multi-mission absolute altimeter calibration site. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.09.049 (in this issue).

Bonnefond, P., Haines, B.J., Watson, C., 2011. In situ Absolute Calibration and Validation: A Link from Coastal to Open-Ocean Altimetry. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 259–296. doi: 10.1007/978-3-642-12796-0_11 (Chapter 11).

Bonnefond, P., Verron, J., Aublanc, J., Babu, K., Bergé-Nguyen, M., Cancet, M., Chaudhary, A., Crétaux, J.F., Frappart, F., Haines, B., et al., 2018. The benefits of the Ka-Band as evidenced from the SARAL/AltiKa altimetric mission: Quality assessment and unique characteristics of AltiKa data. Remote Sens. 10, 83. https://doi.org/10.3390/rs10010083.

Brooks, R., 1982. Lake elevations from satellite radar altimetry from a validation area in Canada. Technical Report. Geosci. Res. Corp., Salisbury, Md.

Brown, S., 2010. A novel near-land radiometer wet path-delay retrieval algorithm: Application to the Jason-2/OSTM Advanced Microwave Radiometer. IEEE Trans. Geosci. Remote Sens. 48, 1986–1992. https://doi.org/10.1109/TGRS.2009.2037220.

Carabajal, C.C., Boy, J.P., 2020. Lake and reservoir volume variations in south america from radar altimetry, ICESat laser altimetry, and GRACE time-variable gravity. Adv. Space Res. https://doi.org/10.1016/j.asr.2020.04.022 (in this issue).

Cartwright, J., Clarizia, M.P., Cipollini, P., Banks, C.J., Srokosz, M., 2018. Independent DEM of Antarctica using GNSS-R data from TechDemoSat-1. Geophys. Res. Lett. 45, 6117–6123. https://doi.org/10.1029/2018GL077429.

Cazenave, A., Palanisamy, H., Ablain, M., 2018. Contemporary sea level changes from satellite altimetry: What have we learned? what are the new challenges? Adv. Space Res. 62, 1639–1653. https://doi.org/10.1016/j.asr.2018.07.017.

Cerri, L., Berthias, J.P., Bertiger, W.I., Haines, B.J., Lemoine, F.G., Mercier, F., Ries, J.C., Willis, P., Zelensky, N.P., Ziebart, M., 2010. Precision orbit determination standards for the Jason series of altimeter missions. Mar. Geodesy 33, 379–418. https://doi.org/10.1080/01490419.2010.488966.

Chassignet, E.P., Pascual, A., Tintoré, J., Verron, J. (Eds.), 2018. New Frontiers in Operational Oceanography. GODAE OceanView. doi: 10.17125/gov2018.

Cheney, R.E., Douglas, B.C., McAdoo, D.C., Sandwell, D.T., 1986. Geodetic and oceanographic applications of satellite altimetry. Space Geodesy Geodyn., 377–405, https://topexucsd.edu/sandwell/publications/20.pdf.

Cipollini, P., Benveniste, J., Birol, F., Fernandes, M.J., Obligis, E., Passaro, M., Strub, P.T., Valladeau, G., Vignudelli, S., Wilkin, J., 2018. chapter Satellite Altimetry in Coastal Regions. In: Satellite Altimetry Over Oceans and Land Surfaces. CRC Press, Taylor & Francis Group, pp. 343–380. https://doi.org/10.1201/9781315151779-11.

Coe, M.T., Costa, M.H., Botta, A., Birkett, C., 2002. Long-term simulations of discharge and floods in the Amazon basin. J. Geophys.

Res. Atmosp. 107, LBA 11-1–LBA 11-17. https://doi.org/10.1029/2001JD000740.

Couhert, A., Cerri, L., Legeais, J.F., Ablain, M., Zelensky, N.P., Haines, B.J., Lemoine, F.G., Bertiger, W.I., Desai, S.D., Otten, M., 2015. Towards the 1mm/y stability of the radial orbit error at regional scales. Adv. Space Res. 55, 2–23. https://doi.org/10.1016/j.asr.2014.06.041.

Crétaux, J.F., Bergé-Nguyen, M., Calmant, S., Jamangulova, N., Satylkanov, R., Lyard, F., Perosanz, F., Verron, J., Samine Montazem, A., Le Guilcher, G., et al., 2018. Absolute calibration or validation of the altimeters on the Sentinel-3A and the Jason-3 over Lake Issykkul (Kyrgyzstan). Remote Sens. 10, 1679. https://doi.org/10.3390/rs10111679.

Crétaux, J.F., Biancamaria, S., Arsen, A., Bergé-Nguyen, M., Becker, M., 2015. Global surveys of reservoirs and lakes from satellites and regional application to the Syrdarya river basin. Environ. Res. Lett. 10, 015002. https://doi.org/10.1088/1748-9326/10/1/015002.

Crétaux, J.F., Jelinski, W., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M., Gennero, M.C., Nino, F., Abarca Del Rio, R., Cazenave, A., Maisongrande, P., 2011. SOLS: A lake database to monitor in the near real time water level and storage variations from remote sensing data. Adv. Space Res. 47, 1497–1507. https://doi.org/10.1016/j.asr.2011.01.004.

Della Penna, A., Koubbi, P., Cotté, C., Bon, C., Bost, C.A., d'Ovidio, F., 2017. Lagrangian analysis of multi-satellite data in support of open ocean marine protected area design. Deep Sea Res. Part II 140, 212–221. https://doi.org/10.1016/j.dsr2.2016.12.014.

Desjonquères, J.D., Carayon, G., Steunou, N., Lambin, J., 2010. Poseidon-3 radar altimeter: New modes and in-flight performances. Mar. Geodesy 33, 53–79. https://doi.org/10.1080/01490419.2010.488970.

Dhote, P.R., Thakur, P.K., Domeneghetti, A., Chouksey, A., Garg, V., Aggarwal, S., Chauhan, P., 2020. The use of SARAL/AltiKa altimeter measurements for multi-site hydrodynamic model validation and rating curves estimation: An application to Brahmaputra river. Adv. Space Res. https://doi.org/10.1016/j.asr.2020.05.012 (in this issue).

Dibarboure, G., Boy, F., Desjonqueres, J.D., Labroue, S., Lasne, Y., Picot, N., Poisson, J.C., Thibaut, P., 2014. Investigating Short-Wavelength Correlated Errors on Low-Resolution Mode Altimetry. J. Atmos. Oceanic Technol. 31, 1337–1362. https://doi.org/10.1175/JTECH-D-13-00081.1.

Dibarboure, G., Pujol, M.I., 2019. Improving the quality of Sentinel-3A data with a hybrid mean sea surface model, and implications for Sentinel-3B and SWOT. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.06.018 (in this issue).

Dieng, H.B., Dadou, I., Léger, F., Morel, Y., Jouanno, J., Lyard, F., Allain, D., 2019. Sea level anomalies using altimetry, model and tide gauges along the african coasts in the eastern tropical atlantic ocean: Inter-comparison and temporal variability. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.10.019 (in this issue).

Dinardo, S., Fenoglio-Marc, L., Becker, M., Scharroo, R., Fernandes, M.J., Staneva, J., Grayek, S., Benveniste, J., 2020. A RIP-based SAR retracker and its application in North East Atlantic with Sentinel-3. Adv. Space Res. https://doi.org/10.1016/j.asr.2020.06.004 (in this issue).

Dousa, J., Vaclavovic, P., Elias, M., 2017. Tropospheric products of the second GOP European GNSS reprocessing (1996–2014). Atmos. Meas. Techn. 10, 3589–3607. https://doi.org/10.5194/amt-10-3589-2017.

d'Ovidio, F., Pascual, A., Wang, J., Doglioli, A.M., Jing, Z., Moreau, S., Grégori, G., Swart, S., Speich, S., Cyr, F., Legresy, B., Chao, Y., Fu, L., Morrow, R.A., 2019. Frontiers in fine-scale in situ studies: Opportunities during the SWOT fast sampling phase. Front. Mar. Sci. 6, 168. https://doi.org/10.3389/fmars.2019.00168.

Drinkwater, M.R., Francis, R., Ratier, A., Wingham, D.J., 2004. The European Space Agency's Earth Explorer mission CryoSat: measuring variability in the cryosphere. Ann. Glaciol. 39, 313–320. https://doi.org/10.3189/172756404781814663.

Dubey, A.K., Gupta, P., Dutta, S., Singh, R.P., 2015. Water level retrieval using SARAL/AltiKa observations in the braided Brahmaputra river, eastern India. Mar. Geodesy 38, 549–567. https://doi.org/10.1080/01490419.2015.1008156.

Dushaw, B.D., Worcester, P.F., Dzieciuch, M.A., 2011. On the predictability of mode-1 internal tides. Deep Sea Res. Part I 58, 677–698. https://doi.org/10.1016/j.dsr.2011.04.002.

Egido, A., Dinardo, S., Ray, C., 2020. The case for increasing the posting rate in delay/Doppler altimeters. Adv. Space Res. https://doi.org/10.1016/j.asr.2020.03.014 (in this issue).

Egido, A., Smith, W.H.F., 2017. Fully focused SAR altimetry: Theory and applications. IEEE Trans. Geosci. Remote Sens. 55, 392–406. https://doi.org/10.1109/TGRS.2016.2607122.

Escudier, P., Couhert, A., Mercier, F., Mallet, A., Thibaut, P., Tran, N., Amarouche, L., Picard, B., Carrere, L., Dibarboure, G., Ablain, M., Richard, J., Steunou, N., Dubois, P., Rio, M., Dorandeu, J., 2018. chapter Satellite Radar Altimetry Principle Accuracy and Precision. In: Satellite Altimetry Over Oceans and Land Surfaces. CRC Press, Taylor & Francis Group, pp. 1–70. https://doi.org/10.1201/9781315151779-1.

Escudier, P., Fellous, J.L., 2009. The Next 15 Years of Satellite Altimetry. volume Ocean Surface Topography Constellation User Requirements Document, CLS. DOS/NT/09.092 CEOS, 47 pp.

Fablet, R., Verron, J., Mourre, B., Chapron, B., Pascual, A., 2018. Improving mesoscale altimetric data from a multitracer convolutional processing of standard satellite-derived products. IEEE Trans. Geosci. Remote Sens. 56, 2518–2525. https://doi.org/10.1109/TGRS.2017.2750491.

Fatras, C., Frappart, F., Mougin, E., Grippa, M., Hiernaux, P., 2012. Estimating surface soil moisture over Sahel using Envisat radar altimetry. Remote Sens. Environ. 123, 496–507. https://doi.org/10.1016/j.rse.2012.04.013.

Fellous, J.L., Wilson, S., Lindstrom, E., Bonekamp, H., Ménard, Y., Benveniste, J., 2006. Summary of the future of altimetry session. In: Benveniste, J., Ménard, Y. (Eds.), 15 Years of Progress in Radar Altimetry Symposium. ESA Special Publication SP-614, Venice, Italy. https://www.esa.int/esapub/conference/toc/tocSP614.pdf.

Fernandes, M., Lázaro, C., Nunes, A., Scharroo, R., 2014. Atmospheric corrections for altimetry studies over inland water. Remote Sens. 6, 4952–4997. https://doi.org/10.3390/rs6064952.

Fernandes, M.J., Lázaro, C., Ablain, M., Pires, N., 2015. Improved wet path delays for all ESA and reference altimetric missions. Remote Sens. Environ. 169, 50–74. https://doi.org/10.1016/j.rse.2015.07.023.

Fernández, J., Peter, H., Calero, E.J., Berzosa, J., Gallardo, L.J., Féménias, P., 2020. Sentinel-3a: Validation of orbit products at the Copernicus POD service. In: Mertikas, S.P., Pail, R. (Eds.), Fiducial Reference Measurements for Altimetry. Springer International Publishing, Cham, pp. 75–82. https://doi.org/10.1007/1345_2019_64.

Fox-Kemper, B., Danabasoglu, G., Ferrari, R., Griffies, S., Hallberg, R., Holland, M., Maltrud, M., Peacock, S., Samuels, B., 2011. Parameterization of mixed layer eddies. III: Implementation and impact in global ocean climate simulations. Ocean Model. 39, 61–78. https://doi.org/10.1016/j.ocemod.2010.09.002, Modelling and Understanding the Ocean Mesoscale and Submesoscale.

Fox-Kemper, B., Ferrari, R., 2008. Parameterization of Mixed Layer Eddies. Part II: Prognosis and Impact. J. Phys. Oceanogr. 38, 1166–1179. https://doi.org/10.1175/2007JPO3788.1.

Fox-Kemper, B., Ferrari, R., Hallberg, R., 2008. Parameterization of Mixed Layer Eddies. Part I: Theory and Diagnosis. J. Phys. Oceanogr. 38, 1145–1165. https://doi.org/10.1175/2007JPO3792.1.

Frappart, F., Blarel, F., Papa, F., Prigent, C., Mougin, E., Paillou, P., Baup, F., Zeiger, P., Salameh, E., Darrozes, J., Bourrel, L., Rémy, F., 2020. Backscattering signatures at Ka, Ku, C and S bands from low resolution radar altimetry over land. Adv. Space Res. https://doi.org/10.1016/j.asr.2020.06.043 (in this issue).

Frappart, F., Papa, F., da Silva, J.S., Ramillien, G., Prigent, C., Seyler, F., Calmant, S., 2012. Surface freshwater storage and dynamics in the Amazon basin during the 2005 exceptional drought. Environ. Res. Lett. 7, 044010. https://doi.org/10.1088/1748-9326/7/4/044010.

Fu, L.L., 2009. Pattern and velocity of propagation of the global ocean eddy variability. J. Geophys. Res. Oceans 114. https://doi.org/10.1029/2009JC005349.

Fu, L.L., Cazenave, A., 2001. Satellite altimetry and earth sciences: A handbook of techniques and applications. Academic Press, San Diego, https://www.elsevier.com/books/satellite-altimetry-and-earth-sciences/fu/978-0-12-269545-2.

Fu, L.L., Haines, B.J., 2013. The challenges in long-term altimetry calibration for addressing the problem of global sea level change. Adv. Space Res. 51, 1284–1300. https://doi.org/10.1016/j.asr.2012.06.005.

Fu, L.L., Le Traon, P.Y., 2006. Satellite altimetry and ocean dynamics. C. R. Geosci. 338, 1063–1076. https://doi.org/10.1016/j.crte.2006.05.015.

Gao, H., Birkett, C., Lettenmaier, D.P., 2012. Global monitoring of large reservoir storage from satellite remote sensing. Water Resour. Res. 48. https://doi.org/10.1029/2012WR012063.

Gardner, A.S., Moholdt, G., Cogley, J.G., Wouters, B., Arendt, A.A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W.T., Kaser, G., Ligtenberg, S.R.M., Bolch, T., Sharp, M.J., Hagen, J.O., van den Broeke, M.R., Paul, F., 2013. A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. Science 340, 852–857. https://doi.org/10.1126/science.1234532.

Gasson, E.G.W., DeConto, R.M., Pollard, D., Clark, C.D., 2018. Numerical simulations of a kilometre-thick arctic ice shelf consistent with ice grounding observations. Nat. Commun. 9, 1510. https://doi.org/10.1038/s41467-018-03707-w.

Gaube, P., Chelton, D.B., Strutton, P.G., Behrenfeld, M.J., 2013. Satellite observations of chlorophyll, phytoplankton biomass, and Ekman pumping in nonlinear mesoscale eddies. J. Geophys. Res. Oceans 118, 6349–6370. https://doi.org/10.1002/2013JC009027.

Getirana, A., Jung, H.C., Tseng, K.H., 2018. Deriving three dimensional reservoir bathymetry from multi-satellite datasets. Remote Sens. Environ. 217, 366–374. https://doi.org/10.1016/j.rse.2018.08.030.

Getirana, A., Jung, H.C., Van Den Hoek, J., Ndehedehe, C.E., 2020. Hydropower dam operation strongly controls Lake Victoria's freshwater storage variability. Sci. Total Environ. 726, 138343. https://doi.org/10.1016/j.scitotenv.2020.138343.

Getirana, A.C., Bonnet, M.P., Calmant, S., Roux, E., Rotunno Filho, O. C., Mansur, W.J., 2009. Hydrological monitoring of poorly gauged basins based on rainfall–runoff modeling and spatial altimetry. J. Hydrol. 379, 205–219. https://doi.org/10.1016/j.jhydrol.2009.09.049.

Getirana, A.C.V., Boone, A., Yamazaki, D., Mognard, N., 2013. Automatic parameterization of a flow routing scheme driven by radar altimetry data: Evaluation in the Amazon basin. Water Resour. Res. 49, 614–629. https://doi.org/10.1002/wrcr.20077.

Gleason, C.J., Durand, M.T., 2020. Remote sensing of river discharge: A review and a framing for the discipline. Remote Sens. 12, 1107. https://doi.org/10.3390/rs12071107.

Gómez-Enri, J., González, C., Passaro, M., Vignudelli, S., Álvarez, O., Cipollini, P., Mañanes, R., Bruno, M., López-Carmona, M., Izquierdo, A., 2019. Wind-induced cross-strait sea level variability in the Strait of Gibraltar from coastal altimetry and in-situ measurements. Remote Sens. Environ. 221, 596–608. https://doi.org/10.1016/j.rse.2018.11.042.

Gommenginger, C.P., Martin-Puig, C., Amarouche, L., Raney, R.K., 2013. Review of state of knowledge for SAR altimetry over ocean. Report of the EUMETSAT JASON-CS SAR mode error budget study (EUM/RSP/REP/14/749304, Version 2.2). National Oceanography Centre, Southampton, GB, pp. 1–57 https://eprints.soton.ac.uk/366765/, .

Gommenginger, C.P., Srokosz, M.A., Challenor, P.G., Cotton, P.D., 2003. Measuring ocean wave period with satellite altimeters: A simple empirical model. Geophys. Res. Lett. 30. https://doi.org/10.1029/2003GL017743.

Göttl, F., Dettmering, D., Müller, F., Schwatke, C., 2016. Lake level estimation based on CryoSat-2 SAR altimetry and multi-looked waveform classification. Remote Sens. 8, 885. https://doi.org/10.3390/rs8110885.

Gourmelen, N., Escorihuela, M., Shepherd, A., Foresta, L., Muir, A., Garcia-Mondéjar, A., Roca, M., Baker, S., Drinkwater, M., 2018. CryoSat-2 swath interferometric altimetry for mapping ice elevation and elevation change. Adv. Space Res. 62, 1226–1242. https://doi.org/10.1016/j.asr.2017.11.014, the CryoSat Satellite Altimetry Mission: Eight Years of Scientific Exploitation.

Greenwood, J.A., Nathan, A., Newman, G., Pierson, W.J., Jackson, F.C., Pease, T.E., 1969. Radar altimetry from a spacecraft and its potential applications to geodesy. Remote Sens. Environ. 1, 59–80.

Grigorieva, V.G., Badulin, S.I., 2016. Wind wave characteristics based on visual observations and satellite altimetry. Oceanology 56, 19–24. https://doi.org/10.1134/S0001437016010045.

Guerra, A.G., Francisco, F., Villate, J., Aguado Agelet, F., Bertolami, O., Rajan, K., 2016. On small satellites for oceanography: A survey. Acta Astronaut. 127, 404–423. https://doi.org/10.1016/j.actaastro.2016.06.007.

Guerreiro, K., Fleury, S., Zakharova, E., Kouraev, A., Rémy, F., Maisongrande, P., 2017. Comparison of CryoSat-2 and Envisat radar freeboard over Arctic sea ice: toward an improved Envisat freeboard retrieval. Cryosphere 11, 2059–2073. https://doi.org/10.5194/tc-11-2059-2017.

Guerreiro, K., Fleury, S., Zakharova, E., Rémy, F., Kouraev, A., 2016. Potential for estimation of snow depth on arctic sea ice from CryoSat-2 and SARAL/AltiKa missions. Remote Sens. Environ. 186, 339–349. https://doi.org/10.1016/j.rse.2016.07.013.

Gulev, S.K., Grigorieva, V., Sterl, A., Woolf, D., 2003. Assessment of the reliability of wave observations from voluntary observing ships: Insights from the validation of a global wind wave climatology based on voluntary observing ship data. J. Geophys. Res. Oceans 108. https://doi.org/10.1029/2002JC001437.

Guo, M., Xiu, P., Chai, F., Xue, H., 2019. Mesoscale and submesoscale contributions to high sea surface chlorophyll in subtropical gyres. Geophys. Res. Lett. 46, 13217–13226. https://doi.org/10.1029/2019GL085278.

Haines, B., Desai, S.D., Kubitschek, D., Leben, R.R., 2020. A brief history of the Harvest experiment: 1989–2019. Adv. Space Res. https://doi.org/10.1016/j.asr.2020.08.013 (in this issue).

Hauser, D., Tison, C., Amiot, T., Delaye, L., Corcoral, N., Castillan, P., 2017. SWIM: The first spaceborne wave scatterometer. IEEE Trans. Geosci. Remote Sens. 55, 3000–3014. https://doi.org/10.1109/TGRS.2017.2658672.

Hauser, D., Tourain, C., Hermozo, L., Alraddawi, D., Aouf, L., Chapron, B., Dalphinet, A., Delaye, L., Dalila, M., Dormy, E., Gouillon, F., Gressani, V., Grouazel, A., Guitton, G., Husson, R., Mironov, A., Mouche, A., Ollivier, A., Oruba, L., Piras, F., Suquet, R.R., Schippers, P., Tison, C., Tran, N., 2021. New observations from the swim radar on-board CFOSAT: Instrument validation and ocean wave measurement assessment. IEEE Trans. Geosci. Remote Sens. 59, 5–26. https://doi.org/10.1109/TGRS.2020.2994372.

Hausman, J., Moroni, D., Gangl, M., Zlotnicki, V., Vazquez-Cuervo, J., Armstrong, E.M., Oaida, C., Gierach, M., Finch, C., Schroeder, C., 2019. The evolution of the PO.DAAC: Seasat to SWOT. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.11.030 (in this issue).

Hogg, A.E., Gilbert, L., Shepherd, A., Muir, A.S., McMillan, M., 2020. Extending the record of Antarctic ice shelf thickness change, from 1992 to 2017. Adv. Space Res. https://doi.org/10.1016/j.asr.2020.05.030 (in this issue).

Hossain, F., Maswood, M., Siddique-E-Akbor, A.H., Yigzaw, W., Mazumdar, L.C., Ahmed, T., Hossain, M., Shah-Newaz, S.M., Limaye, A., Lee, H., Pradhan, S., Shrestha, B., Bajracahrya, B., Biancamaria, S., Shum, C.K., Turk, F.J., 2014. A promising radar altimetry satellite system for operational flood forecasting in flood-prone Bangladesh. IEEE Geosci. Remote Sens. Mag. 2, 27–36. https://doi.org/10.1109/MGRS.2014.2345414.

Howe, B.M., Miksis-Olds, J., Rehm, E., Sagen, H., Worcester, P.F., Haralabus, G., 2019. Observing the oceans acoustically. Front. Mar. Sci. 6, 426. https://doi.org/10.3389/fmars.2019.00426.

Hwang, P.A., Teague, W.J., Jacobs, G.A., Wang, D.W., 1998. A statistical comparison of wind speed, wave height, and wave period derived from satellite altimeters and ocean buoys in the Gulf of Mexico region. J. Geophys. Res. Oceans 103, 10451–10468. https://doi.org/10.1029/98JC00197.

Jacobs, G.A., D'Addezio, J.M., Bartels, B., Spence, P.L., 2019. Constrained scales in ocean forecasting. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.09.018 (in this issue).

Jayles, C., Chauveau, J.P., Auriol, A., 2015. DORIS/DIODE: Real-time orbit determination performance on board SARAL/AltiKa. Mar. Geodesy 38, 233–248. https://doi.org/10.1080/01490419.2015.1015695.

Jiang, L., Nielsen, K., Andersen, O.B., Bauer-Gottwein, P., 2017. Monitoring recent lake level variations on the Tibetan plateau using CryoSat-2 SARIn mode data. J. Hydrol. 544, 109–124. https://doi.org/10.1016/j.jhydrol.2016.11.024.

Johannessen, J., Andersen, O.B., 2018. Satellite Altimetry Over Oceans and Land Surfaces. CRC Press, Taylor & Francis Group, pp. 271–296. https://doi.org/10.1201/9781315151779-8. (chapter The High Latitude Seas and Arctic Ocean)

Karimi, A.A., Andersen, O.B., Deng, X., 2020. Mean sea surface and mean dynamic topography determination from CryoSat-2 data around Australia. Adv. Space Res. https://doi.org/10.1016/j.asr.2020.01.009 (in this issue).

Kern, M., Cullen, R., Berruti, B., Bouffard, J., Casal, T., Drinkwater, M. R., Gabriele, A., Lecuyot, A., Ludwig, M., Midthassel, R., Navas Traver, I., Parrinello, T., Ressler, G., Andersson, E., Martin-Puig, C., Andersen, O., Bartsch, A., Farrell, S., Fleury, S., Gascoin, S., Guillot, A., Humbert, A., Rinne, E., Shepherd, A., van den Broeke, M.R., Yackel, J., 2020. The Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) high-priority candidate mission. Cryosphere 14, 2235–2251. https://doi.org/10.5194/tc-14-2235-2020.

Klein, P., Lapeyre, G., Siegelman, L., Qiu, B., Fu, L.L., Torres, H., Su, Z., Menemenlis, D., Le Gentil, S., 2019. Ocean-scale interactions from space. Earth Space Sci. 6, 795–817. https://doi.org/10.1029/2018EA000492.

Knudsen, P., Andersen, O., Maximenko, N., 2019. A new ocean mean dynamic topography model, derived from a combination of gravity, altimetry and drifter velocity data. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.12.001 (in this issue).

Koblinsky, C., Gaspar, P., Lagerloef, G., 1992. Oceans and climate change: The future of spaceborne altimetry. Eos Trans. Am. Geophys. Union 73, 403. https://doi.org/10.1029/91EO00304.

Kouraev, A.V., Shimaraev, M.N., Buharizin, P.I., Naumenko, M.A., Crétaux, J.F., Mognard, N., Legrésy, B., Rémy, F., 2008. Ice and snow cover of continental water bodies from simultaneous radar altimetry and radiometry observations. Surv. Geophys. 29, 271–295. https://doi.org/10.1007/s10712-008-9042-2.

Kouraev, A.V., Zakharova, E.A., Samain, O., Mognard, N.M., Cazenave, A., 2004. Ob' river discharge from TOPEX/Poseidon satellite altimetry (1992–2002). Remote Sens. Environ. 93, 238–245. https://doi.org/10.1016/j.rse.2004.07.007.

Kumar, R., Stammer, D., Melville, W.K., Janssen, P., 2003. Electromagnetic bias estimates based on TOPEX, buoy, and wave model data. J. Geophys. Res. Oceans 108. https://doi.org/10.1029/2002JC001525.

Laforge, A., Fleury, S., Dinardo, S., Garnier, F., Remy, F., Benveniste, J., Bouffard, J., Verley, J., 2020. Toward improved sea ice freeboard observation with sar altimetry using the physical retracker SAMOSA +. Adv. Space Res. https://doi.org/10.1016/j.asr.2020.02.001 (in this issue).

Larson, K.M., Ray, R.D., Williams, S.D.P., 2017. A 10-Year Comparison of Water Levels Measured with a Geodetic GPS Receiver versus a Conventional Tide Gauge. J. Atmos. Oceanic Technol. 34, 295–307. https://doi.org/10.1175/JTECH-D-16-0101.1.

Lavrova, O.Y., Kostianoy, A.G., Lebedev, S.A., Mityagina, V.I., Ginzburg, A.I., Sheremet, N.A., 2011. Complex satellite monitoring of the Russian seas. Moscow: Space Res. Inst. RAS, 470 (in Russian).

Lawrence, I.R., Armitage, T.W., Tsamados, M.C., Stroeve, J.C., Dinardo, S., Ridout, A.L., Muir, A., Tilling, R.L., Shepherd, A., 2019. Extending the Arctic sea ice freeboard and sea level record with the Sentinel-3 radar altimeters. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.10.011 (in this issue).

Laxon, S.W., Giles, K.A., Ridout, A.L., Wingham, D.J., Willatt, R., Cullen, R., Kwok, R., Schweiger, A., Zhang, J., Haas, C., Hendricks, S., Krishfield, R., Kurtz, N., Farrell, S., Davidson, M., 2013. CryoSat-2 estimates of Arctic sea ice thickness and volume. Geophys. Res. Lett. 40, 732–737. https://doi.org/10.1002/grl.50193.

Lázaro, C., Fernandes, M.J., Vieira, T., Vieira, E., 2019. A coastally improved global dataset of wet tropospheric corrections for satellite altimetry. Earth Syst. Sci. Data Discuss. 2019, 1–31. https://doi.org/10.5194/essd-2019-171.

Le Gac, S., Boy, F., Blumstein, D., Lasson, L., Picot, N., 2019. Benefits of the Open-Loop Tracking Command (OLTC): Extending conventional nadir altimetry to inland waters monitoring. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.10.031 (in this issue).

Le Traon, P., Dibarboure, G., Jacobs, G., Martin, M., Remy, E., Schiller, A., 2018. & Francis Gro up. chapter Use of satellite altimetry for operational oceanography. In: Satellite Altimetry Over Oceans and Land Surfaces. CRC Press, Taylor, pp. 581–608. https://doi.org/10.1201/9781315151779-18.

Le Traon, P.Y., Reppucci, A., Alvarez Fanjul, E., Aouf, L., Behrens, A., Belmonte, M., Bentamy, A., Bertino, L., Brando, V.E., Kreiner, M.B., Benkiran, M., Carval, T., Ciliberti, S.A., Claustre, H., Clementi, E., Coppini, G., Cossarini, G., De Alfonso Alonso-Muñoyerro, M., Delamarche, A., Dibarboure, G., Dinessen, F., Drevillon, M., Drillet, Y., Faugere, Y., Fernández, V., Fleming, A., Garcia-Hermosa, M.I., Sotillo, M.G., Garric, G., Gasparin, F., Giordan, C., Gehlen, M., Gregoire, M.L., Guinehut, S., Hamon, M., Harris, C., Hernandez, F., Hinkler, J.B., Hoyer, J., Karvonen, J., Kay, S., King, R., Lavergne, T., Lemieux-Dudon, B., Lima, L., Mao, C., Martin, M.J., Masina, S., Melet, A., Buongiorno Nardelli, B., Nolan, G., Pascual, A., Pistoia, J., Palazov, A., Piolle, J.F., Pujol, M.I., Pequignet, A.C., Peneva, E., Pérez Gómez, B., Petit de la Villeon, L., Pinardi, N., Pisano, A., Pouliquen, S., Reid, R., Remy, E., Santoleri, R., Siddorn, J., She, J., Staneva, J., Stoffelen, A., Tonani, M., Vandenbulcke, L., von Schuckmann, K., Volpe, G., Wettre, C., Zacharioudaki, A., 2019. From observation to information and users: The Copernicus Marine Service perspective. Front. Mar. Sci. 6, 234. https://doi.org/10.3389/fmars.2019.00234.

L'Ecuyer, T.S., Beaudoing, H.K., Rodell, M., Olson, W., Lin, B., Kato, S., Clayson, C.A., Wood, E., Sheffield, J., Adler, R., Huffman, G., Bosilovich, M., Gu, G., Robertson, F., Houser, P.R., Chambers, D., Famiglietti, J.S., Fetzer, E., Liu, W.T., Gao, X., Schlosser, C.A., Clark, E., Lettenmaier, D.P., Hilburn, K., 2015. The Observed State of the Energy Budget in the Early Twenty-First Century. J. Clim. 28, 8319–8346. https://doi.org/10.1175/JCLI-D-14-00556.1.

Legeais, J.F., Ablain, M., Zawadzki, L., Zuo, H., Johannessen, J.A., Scharffenberg, M.G., Fenoglio-Marc, L., Fernandes, M.J., Andersen, O.B., Rudenko, S., Cipollini, P., Quartly, G.D., Passaro, M., Cazenave, A., Benveniste, J., 2018. An improved and homogeneous altimeter sea level record from the ESA Climate Change Initiative. Earth Syst. Sci. Data 10, 281–301. https://doi.org/10.5194/essd-10-281-2018.

Lehahn, Y., d'Ovidio, F., Koren, I., 2018. A satellite-based lagrangian view on phytoplankton dynamics. Ann. Rev. Mar. Sci. 10, 99–119. https://doi.org/10.1146/annurev-marine-121916-063204, pMID: 28961072.

Lellouche, J.M., Greiner, E., Le Galloudec, O., Garric, G., Regnier, C., Drevillon, M., Benkiran, M., Testut, C.E., Bourdalle-Badie, R., Gasparin, F., Hernandez, O., Levier, B., Drillet, Y., Remy, E., Le Traon, P.Y., 2018. Recent updates to the copernicus marine service global ocean monitoring and forecasting real-time 1/12 high-resolution system. Ocean Sci. 14, 1093–1126. https://doi.org/10.5194/os-14-1093-2018.

Lemieux, J.F., Beaudoin, C., Dupont, F., Roy, F., Smith, G.C., Shlyaeva, A., Buehner, M., Caya, A., Chen, J., Carrieres, T., Pogson, L., DeRepentigny, P., Plante, A., Pestieau, P., Pellerin, P., Ritchie, H., Garric, G., Ferry, N., 2016. The regional ice prediction system (rips): verification of forecast sea ice concentration. Quart. J. Roy. Meteorol. Soc. 142, 632–643. https://doi.org/10.1002/qj.2526.

Lemoine, F., Zelensky, N., Chinn, D., Pavlis, D., Rowlands, D., Beckley, B., Luthcke, S., Willis, P., Ziebart, M., Sibthorpe, A., Boy, J., Luceri, V., 2010. Towards development of a consistent orbit series for TOPEX, Jason-1, and Jason-2. Adv. Space Res. 46, 1513–1540. https://doi.org/10.1016/j.asr.2010.05.007.

Leon, J., Calmant, S., Seyler, F., Bonnet, M.P., Cauhopé, M., Frappart, F., Filizola, N., Fraizy, P., 2006. Rating curves and estimation of average water depth at the upper Negro River based on satellite altimeter data and modeled discharges. J. Hydrol. 328, 481–496. https://doi.org/10.1016/j.jhydrol.2005.12.006, the ICWRER - Symposium in Dresden, Germany.

Levin, J., Arango, H.G., Laughlin, B., Wilkin, J., Moore, A.M., 2019. The impact of remote sensing observations on cross-shelf transport estimates from 4D-Var analyses of the Mid-Atlantic Bight. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.09.012 (in this issue).

Lévy, M., Franks, P.J.S., Smith, K.S., 2018. The role of submesoscale currents in structuring marine ecosystems. Nat. Commun. 9, 4758. https://doi.org/10.1038/s41467-018-07059-3.

Li, W., Rius, A., Fabra, F., Cardellach, E., Ribó, S., Martín-Neira, M., 2018. Revisiting the GNSS-R waveform statistics and its impact on altimetric retrievals. IEEE Trans. Geosci. Remote Sens. 56, 2854–2871. https://doi.org/10.1109/TGRS.2017.2785343.

Li, Y., Gao, H., Zhao, G., Tseng, K.H., 2020. A high-resolution bathymetry dataset for global reservoirs using multi-source satellite imagery and altimetry. Remote Sens. Environ. 244, 111831. https://doi.org/10.1016/j.rse.2020.111831.

Ludwigsen, C.A., Andersen, O.B., 2020. Contributions to Arctic sea level from 2003 to 2015. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.12.027 (in this issue).

MacArthur, J.L., 1976. Design of the Seasat-A radar altimeter. Oceans 8, 222–229.

Mackay, E.B.L., Retzler, C.H., Challenor, P.G., Gommenginger, C.P., 2008. A parametric model for ocean wave period from Ku band altimeter data. J. Geophys. Res. Oceans 113. https://doi.org/10.1029/2007JC004438.

Mahadevan, A., Pascual, A., Rudnick, D.L., Ruiz, S., Tintoré, J., D'Asaro, E., 2020. Coherent pathways for vertical transport from the surface ocean to interior. Bull. Am. Meteorol. Soc. 1–21. https://doi.org/10.1175/BAMS-D-19-0305.1.

Maiwald, F., Brown, S.T., Koch, T., Milligan, L., Kangaslahti, P., Schlecht, E., Skalare, A., Bloom, M., Torossian, V., Kanis, J., Statham, S., Kang, S., Vaze, P., 2020. Completion of the AMR-C instrument for Sentinel-6. IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens. 13, 1811–1818. https://doi.org/10.1109/JSTARS.2020.2991175.

Marrec, P., Grégori, G., Doglioli, A.M., Dugenne, M., Della Penna, A., Bhairy, N., Cariou, T., Hélias Nunige, S., Lahbib, S., Rougier, G., Wagener, T., Thyssen, M., 2018. Coupling physics and biogeochemistry thanks to high-resolution observations of the phytoplankton community structure in the northwestern Mediterranean Sea. Biogeosciences 15, 1579–1606. https://doi.org/10.5194/bg-15-1579-2018.

Marti, F., Cazenave, A., Birol, F., Passaro, M., Léger, F., Niño, F., Almar, R., Benveniste, J., Legeais, J.F., 2019. Altimetry-based sea level trends along the coasts of Western Africa. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.05.033 (in this issue).

McGillicuddy, D.J., 2016. Mechanisms of physical-biological-biogeochemical interaction at the oceanic mesoscale. Ann. Rev. Mar. Sci. 8, 125–159. https://doi.org/10.1146/annurev-marine-010814-015606, pMID: 26359818.

McGoogan, J.T., Miller, L.S., Brown, G.S., Hayne, G.S., 1974. The S-193 radar altimeter experiment. Proc. IEEE 62, 793–803. https://doi.org/10.1109/PROC.1974.9519.

McMillan, M., Leeson, A., Shepherd, A., Briggs, K., Armitage, T.W.K., Hogg, A., Kuipers Munneke, P., van den Broeke, M., Noël, B., van de Berg, W.J., Ligtenberg, S., Horwath, M., Groh, A., Muir, A., Gilbert, L., 2016. A high-resolution record of Greenland mass balance. Geophys. Res. Lett. 43, 7002–7010. https://doi.org/10.1002/2016GL069666.

McMillan, M., Shepherd, A., Sundal, A., Briggs, K., Muir, A., Ridout, A., Hogg, A., Wingham, D., 2014. Increased ice losses from Antarctica detected by CryoSat-2. Geophys. Res. Lett. 41, 3899–3905. https://doi.org/10.1002/2014GL060111.

Melo, Getirana, 2019. Radar altimetry as a proxy for determining terrestrial water storage variability in tropical basins. Remote Sens. 11, 2487. https://doi.org/10.3390/rs11212487.

Mertikas, S.P., Donlon, C., Vuilleumier, P., Féménias, P., Tripolitsiotis, A., 2019. An action plan towards fiducial reference measurements for satellite altimetry. Remote Sens. 11, 1993. https://doi.org/10.3390/rs11171993.

Mertikas, S.P., Pail, R. (Eds.), 2020. Fiducial Reference Measurements for Altimetry, vol. 150. Springer International Publishing, International Association of Geodesy Symposia. doi: 10.1007/978-3-030-39438-7.

Metzger, E., Smedstad, O., Thoppil, P., Hurlburt, H., Cummings, J., Wallcraft, A., Zamudio, L., Franklin, D., Posey, P., Phelps, M., 2014. US Navy operational global ocean and Arctic ice prediction systems. Oceanography 27, 32–43. https://doi.org/10.5670/oceanog.2014.66.

Meyssignac, B., Boyer, T., Zhao, Z., Hakuba, M.Z., Landerer, F., Stammer, D., Kato, S., Köhl, A., Ablain, M., Abraham, J.P., Blazquez, A., Cazenave, A., Church, J.A., Rebecca, C., Cheng, L., Domingues, C., Giglio, D., 2019. Measuring global oceanheat content to estimate the earth energy imbalance. Front. Mar. Sci. 6, 8319–8346. https://doi.org/10.3389/fmars.2019.00432.

Meyssignac, B., Slangen, A.B.A., Melet, A., Church, J.A., Fettweis, X., Marzeion, B., Agosta, C., Ligtenberg, S.R.M., Spada, G., Richter, K., Palmer, M.D., Roberts, C.D., Champollion, N., 2017. Evaluating Model Simulations of Twentieth-Century Sea-Level Rise. Part II: Regional Sea-Level Changes. J. Clim. 30, 8565–8593. https://doi.org/10.1175/JCLI-D-17-0112.1.

Michailovsky, C.I., Milzow, C., Bauer-Gottwein, P., 2013. Assimilation of radar altimetry to a routing model of the Brahmaputra River. Water Resour. Res. 49, 4807–4816. https://doi.org/10.1002/wrcr.20345.

Morrow, R., Blumstein, D., Dibarboure, G., 2018. New Frontiers in Operational Oceanography. GODAE OceanView, pp. 191–226. doi: 10.17125/gov2018 (chapter Fine-scale altimetry and the future SWOT mission).

Morrow, R., Fu, L.L., Ardhuin, F., Benkiran, M., Chapron, B., Cosme, E., d'Ovidio, F., Farrar, J.T., Gille, S.T., Lapeyre, G., Le Traon, P.Y., Pascual, A., Ponte, A., Qiu, B., Rascle, N., Ubelmann, C., Wang, J., Zaron, E.D., 2019. Global observations of fine-scale ocean surface topography with the Surface Water and Ocean Topography (SWOT) mission. Front. Mar. Sci. 6, 232. https://doi.org/10.3389/fmars.2019.00232.

Morrow, R., Le Traon, P.Y., 2012. Recent advances in observing mesoscale ocean dynamics with satellite altimetry. Adv. Space Res. 50, 1062–1076. https://doi.org/10.1016/j.asr.2011.09.033, Oceanography, Cryosphere and Freshwater Flux to the Ocean.

Mulet, S., Etienne, H., Ballarotta, M., Faugere, Y., Rio, M., Dibarboure, G., Picot, N., 2020. Synergy between surface drifters and altimetry to increase the accuracy of sea level anomaly and geostrophic current maps in the Gulf of Mexico. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.12.024 (in this issue).

Munk, W.H., Wunsch, C.I., 1982. Observing the ocean in the 1990s. Philos. Trans. R. Soc. Lond. Ser. A Math. Phys. Sci. 307, 439–464. https://doi.org/10.1098/rsta.1982.0120.

Naylor, S., Siegert, M., Dean, K., Turchetti, S., 2008. Science, geopolitics and the governance of Antarctica. Nat. Geosci. 1, 143–145. https://doi.org/10.1038/ngeo138.

Nerem, R.S., 1995. Measuring global mean sea level variations using TOPEX/Poseidon altimeter data. J. Geophys. Res. Oceans 100, 25135–25151. https://doi.org/10.1029/95JC02303.

Nerem, R.S., Beckley, B.D., Fasullo, J.T., Hamlington, B.D., Masters, D., Mitchum, G.T., 2018. Climate-change–driven accelerated sea-level rise detected in the altimeter era. Proc. Nat. Acad. Sci. 115, 2022–2025. https://doi.org/10.1073/pnas.1717312115.

Nouël, F., Berthias, J.P., Deleuze, M., Guitart, A., Laudet, P., Piuzzi, A., Pradines, D., Valorge, C., Dejoie, C., Susini, M.F., Taburiau, D., 1994. Precise Centre National d'Etudes Spatiales orbits for TOPEX/

Poseidon: Is reaching 2 cm still a challenge? J. Geophys. Res. Oceans 99, 24405–24419. https://doi.org/10.1029/94JC01039.

Okeowo, M.A., Lee, H., Hossain, F., Getirana, A., 2017. Automated generation of lakes and reservoirs water elevation changes from satellite radar altimetry. IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens. 10, 3465–3481. https://doi.org/10.1109/JSTARS.2017.2684081.

Olascoaga, M.J., 2010. Isolation on the West Florida Shelf with implications for red tides and pollutant dispersal in the Gulf of Mexico. Nonlinear Process. Geophys. 17, 685–696. https://doi.org/10.5194/npg-17-685-2010.

Ophaug, V., Breili, K., Andersen, O.B., 2019. A coastal mean sea surface with associated errors in Norway based on new-generation altimetry. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.08.010 (in this issue).

Oppenheimer, M., Glavovic, B., Hinkel, J., van de Wal, R., Magnan, A., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B., Sebesvari, Z., 2019. IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (in press. chapter Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities).

Oztunali Ozbahceci, B., Turgut, A., Bozoklu, A., Abdalla, S., 2020. Calibration and verification of century based wave climate data record along the Turkish coasts using satellite altimeter data. Adv. Space Res. https://doi.org/10.1016/j.asr.2020.02.021.

Pacione, R., Araszkiewicz, A., Brockmann, E., Dousa, J., 2017. EPN-Repro2: A reference GNSS tropospheric data set over Europe. Atmos. Meas. Tech. 10, 1689–1705. https://doi.org/10.5194/amt-10-1689-2017.

Pail, R., Bruinsma, S., Migliaccio, F., Förste, C., Goiginger, H., Schuh, W.D., Höck, E., Reguzzoni, M., Brockmann, J.M., Abrikosov, O., Veicherts, M., Fecher, T., Mayrhofer, R., Krasbutter, I., Sansò, F., Tscherning, C.C., 2011. First GOCE gravity field models derived by three different approaches. J. Geodesy 85, 819. https://doi.org/10.1007/s00190-011-0467-x.

Paiva, R.C.D., Collischonn, W., Bonnet, M.P., de Gonçalves, L.G.G., Calmant, S., Getirana, A., Santos da Silva, J., 2013. Assimilating in situ and radar altimetry data into a large-scale hydrologic-hydrodynamic model for streamflow forecast in the Amazon. Hydrol. Earth Syst. Sci. 17, 2929–2946. https://doi.org/10.5194/hess-17-2929-2013.

Papa, F., Bala, S.K., Pandey, R.K., Durand, F., Gopalakrishna, V.V., Rahman, A., Rossow, W.B., 2012. Ganga-Brahmaputra river discharge from Jason-2 radar altimetry: An update to the long-term satellite-derived estimates of continental freshwater forcing flux into the Bay of Bengal. J. Geophys. Res. Oceans 117. https://doi.org/10.1029/2012JC008158.

Papa, F., Biancamaria, S., Lion, C., Rossow, W.B., 2012. Uncertainties in mean river discharge estimates associated with satellite altimeter temporal sampling intervals: A case study for the annual peak flow in the context of the future SWOT hydrology mission. IEEE Geosci. Remote Sens. Lett. 9, 569–573. https://doi.org/10.1109/LGRS.2011.2174958.

Paris, A., Dias de Paiva, R., Santos da Silva, J., Medeiros Moreira, D., Calmant, S., Garambois, P.A., Collischonn, W., Bonnet, M.P., Seyler, F., 2016. Stage-discharge rating curves based on satellite altimetry and modeled discharge in the Amazon basin. Water Resour. Res. 52, 3787–3814. https://doi.org/10.1002/2014WR016618.

Pascual, A., Ruiz, S., Olita, A., Troupin, C., Claret, M., Casas, B., Mourre, B., Poulain, P.M., Tovar-Sanchez, A., Capet, A., Mason, E., Allen, J.T., Mahadevan, A., Tintoré, J., 2017. A multiplatform experiment to unravel meso- and submesoscale processes in an intense front (AlborEx). Front. Mar. Sci. 4, 39. https://doi.org/10.3389/fmars.2017.00039.

Passaro, M., Nadzir, Z.A., Quartly, G.D., 2018. Improving the precision of sea level data from satellite altimetry with high-frequency and regional sea state bias corrections. Remote Sens. Environ. 218, 245–254. https://doi.org/10.1016/j.rse.2018.09.007.

Pearlman, M.R., Noll, C.E., Pavlis, E.C., Lemoine, F.G., Combrink, L., Degnan, J.J., Kirchner, G., Schreiber, U., 2019. The ILRS: approaching 20 years and planning for the future. J. Geodesy 93, 2161–2180. https://doi.org/10.1007/s00190-019-01241-1.

Pearson, C., Moore, P., Edwards, S., 2020. GNSS Assessment of Sentinel-3 ECMWF Tropospheric Delays over Inland Waters. Adv. Space Res. 66, 2827–2843. https://doi.org/10.1016/j.asr.2020.07.033.

Pedinotti, V., Boone, A., Ricci, S., Biancamaria, S., Mognard, N., 2014. Assimilation of satellite data to optimize large-scale hydrological model parameters: a case study for the SWOT mission. Hydrol. Earth Syst. Sci. 18, 4485–4507. https://doi.org/10.5194/hess-18-4485-2014.

Pekel, J.F., Cottam, A., Gorelick, N., Belward, A.S., 2016. High-resolution mapping of global surface water and its long-term changes. Nature 540, 418–422. https://doi.org/10.1038/nature20584.

Penduff, T., Llovel, W., Close, S., Garcia-Gomez, I., Leroux, S., 2019. Trends of coastal sea level between 1993 and 2015: Imprints of atmospheric forcing and oceanic chaos. Surv. Geophys. 40, 1543–1562. https://doi.org/10.1007/s10712-019-09571-7.

Peter, H., Jäggi, A., Fernández, J., Escobar, D., Ayuga, F., Arnold, D., Wermuth, M., Hackel, S., Otten, M., Simons, W., Visser, P., Hugentobler, U., Féménias, P., 2017. Sentinel-1a – first precise orbit determination results. Adv. Space Res. 60, 879–892. https://doi.org/10.1016/j.asr.2017.05.034.

Phalippou, L., Rey, L., de Chateau-Thierry, P., 2001. Overview of the performances and tracking design of the SIRAL altimeter for the CryoSat mission. In: IGARSS 2001. Scanning the Present and Resolving the Future. Proceedings. IEEE 2001 International Geoscience and Remote Sensing Symposium (Cat. No. 01CH37217), vol. 5, pp. 2025–2027. doi: 10.1109/IGARSS.2001.977891.

Ponce de León, S., Bettencourt, J., 2019. Composite analysis of North Atlantic extra-tropical cyclone waves from satellite altimetry observations. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.07.021 (in this issue).

Ponte, R.M., Carson, M., Cirano, M., Domingues, C.M., Jevrejeva, S., Marcos, M., Mitchum, G., van de Wal, R.S.W., Woodworth, P.L., Ablain, M., Ardhuin, F., Ballu, V., Becker, M., Benveniste, J., Birol, F., Bradshaw, E., Cazenave, A., De Mey-Frémaux, P., Durand, F., Ezer, T., Fu, L.L., Fukumori, I., Gordon, K., Gravelle, M., Griffies, S. M., Han, W., Hibbert, A., Hughes, C.W., Idier, D., Kourafalou, V.H., Little, C.M., Matthews, A., Melet, A., Merrifield, M., Meyssignac, B., Minobe, S., Penduff, T., Picot, N., Piecuch, C., Ray, R.D., Rickards, L., Santamaría-Gómez, A., Stammer, D., Staneva, J., Testut, L., Thompson, K., Thompson, P., Vignudelli, S., Williams, J., Williams, S.D.P., Wöppelmann, G., Zanna, L., Zhang, X., 2019. Towards comprehensive observing and modeling systems for monitoring and predicting regional to coastal sea level. Front. Mar. Sci. 6, 437. https://doi.org/10.3389/fmars.2019.00437.

Pörtner, H.O., Roberts, D., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., Weyer, N. (Eds.), 2019. IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (in press).

Prigent, C., Aires, F., Jimenez, C., Papa, F., Roger, J., 2015. Multiangle backscattering observations of continental surfaces in Ku-Band (13 GHz) from satellites: Understanding the signals, particularly in arid regions. IEEE Trans. Geosci. Remote Sens. 53, 1364–1373. https://doi.org/10.1109/TGRS.2014.2338913.

Quartly, G.D., Smith, W.H.F., Passaro, M., 2019. Removing intra-1-Hz covariant error to improve altimetric profiles of σ_0 and Sea Surface Height. IEEE Trans. Geosci. Remote Sens. 57, 3741–3752. https://doi.org/10.1109/TGRS.2018.2886998.

Quilfen, Y., Chapron, B., 2019. Ocean surface wave-current signatures from satellite altimeter measurements. Geophys. Res. Lett. 46, 253–261. https://doi.org/10.1029/2018GL081029.

Quilfen, Y., Chapron, B., Collard, F., Serre, M., 2004. Calibration/validation of an altimeter wave period model and application to TOPEX/Poseidon and Jason-1 altimeters. Mar. Geodesy 27, 535–549. https://doi.org/10.1080/01490410490902025.

Raney, R.K., 1998. The delay/Doppler radar altimeter. IEEE Trans. Geosci. Remote Sens. 36, 1578–1588. https://doi.org/10.1109/36.718861.

Raney, R.K., 2013. Maximizing the intrinsic precision of radar altimetric measurements. IEEE Trans. Geosci. Remote Sens. 5, 1171–1174. https://doi.org/10.1109/LGRS.2012.2235138.

Rey, L., de Chateau-Thierry, P., Phalippou, L., Mavrocordatos, C., Francis, R., 2001. SIRAL, a high spatial resolution radar altimeter for the CryoSat mission. In: IGARSS 2001. Scanning the Present and Resolving the Future. Proceedings. IEEE 2001 International Geoscience and Remote Sensing Symposium (Cat. No. 01CH37217), vol. 7, pp. 3080–3082. http://dx.doi.org/10.1109/IGARSS.2001.978261.

Richman, J.G., Arbic, B.K., Shriver, J.F., Metzger, E.J., Wallcraft, A.J., 2012. Inferring dynamics from the wavenumber spectra of an eddying global ocean model with embedded tides. J. Geophys. Res. Oceans 117. https://doi.org/10.1029/2012JC008364.

Rio, M.H., Mulet, S., Picot, N., 2014. Beyond GOCE for the ocean circulation estimate: Synergetic use of altimetry, gravimetry, and in situ data provides new insight into geostrophic and Ekman currents. Geophys. Res. Lett. 41, 8918–8925. https://doi.org/10.1002/2014GL061773.

Rocha, C.B., Chereskin, T.K., Gille, S.T., Menemenlis, D., 2016. Mesoscale to submesoscale wavenumber spectra in Drake Passage. J. Phys. Oceanogr. 46, 601–620. https://doi.org/10.1175/JPO-D-15-0087.1.

Rodriguez, E., Fernandez, D., Peral, E., Chen, C., Bleser, J.W., Williams, B., 2018. Satellite Altimetry Over Oceans and Land Surfaces. CRC Press, Taylor & Francis Group, pp. 71–112. doi: 10.1201/9781315151779-2 (chapter Wide-Swath Altimetry: A Review).

Roemmich, D., Johnson, G., Riser, S., Davis, R., Gilson, J., Owens, W., Garzoli, S., Schmid, C., Ignaszewski, M., 2009. The ARGO program: Observing the global ocean with profiling floats. Oceanography 22, 34–43. https://doi.org/10.5670/oceanog.2009.36.

Rosmorduc, V., Srinivasan, M., Richardson, A., Cipollini, P., 2020. The first 25 years of altimetry outreach. Adv. Space Res. https://doi.org/10.1016/j.asr.2020.08.026 (in this issue).

Rowley, C., Mask, A., 2014. Regional and coastal prediction with the relocatable ocean nowcast/forecast system. Oceanography 27, 44–55. https://doi.org/10.5670/oceanog.2014.67.

Rudenko, S., Dettmering, D., Esselborn, S., Schöne, T., Förste, C., Lemoine, J.M., Ablain, M., Alexandre, D., Neumayer, K.H., 2014. Influence of time variable geopotential models on precise orbits of altimetry satellites, global and regional mean sea level trends. Adv. Space Res. 54, 92–118. https://doi.org/10.1016/j.asr.2014.03.010.

Rudenko, S., Otten, M., Visser, P., Scharroo, R., Schöne, T., Esselborn, S., 2012. New improved orbit solutions for the ERS-1 and ERS-2 satellites. Adv. Space Res. 49, 1229–1244. https://doi.org/10.1016/j.asr.2012.01.021.

Rudnick, D.L., 2016. Ocean research enabled by underwater gliders. Ann. Rev. Mar. Sci. 8, 519–541. https://doi.org/10.1146/annurev-marine-122414-033913, pMID: 26291384.

Ruiz, S., Claret, M., Pascual, A., Olita, A., Troupin, C., Capet, A., Tovar-Sánchez, A., Allen, J., Poulain, P.M., Tintoré, J., Mahadevan, A., 2019. Effects of oceanic mesoscale and submesoscale frontal processes on the vertical transport of phytoplankton. J. Geophys. Res. Oceans 124, 5999–6014. https://doi.org/10.1029/2019JC015034.

Sandwell, D.T., Harper, H., Tozer, B., Smith, W.H., 2019. Gravity field recovery from geodetic altimeter missions. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.09.011 (in this issue).

Scagliola, M., Recchia, L., Maestri, L., Giudici, D., 2019. Evaluating the impact of range walk compensation in delay/Doppler processing over open ocean. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.11.032 (in this issue).

Scales, K.L., Hazen, E.L., Jacox, M.G., Castruccio, F., Maxwell, S.M., Lewison, R.L., Bograd, S.J., 2018. Fisheries bycatch risk to marine megafauna is intensified in lagrangian coherent structures. Proc. Nat. Acad. Sci. 115, 7362–7367. https://doi.org/10.1073/pnas.1801270115.

Scharffenberg, M.G., Stammer, D., 2019. Time-space sampling-related uncertainties of altimetric global mean sea level estimates. J. Geophys. Res. Oceans 124, 7743–7755. https://doi.org/10.1029/2018JC014785.

Scharroo, R., Bonekamp, H., Ponsard, C., Parisot, F., von Engeln, A., Tahtadjiev, M., de Vriendt, K., Montagner, F., 2016. Jason continuity of services: continuing the Jason altimeter data records as Copernicus Sentinel-6. Ocean Sci. 12, 471–479. https://doi.org/10.5194/os-12-471-2016.

Schiller, A., Brassington, G.B., Oke, P., Cahill, M., Divakaran, P., Entel, M., Freeman, J., Griffin, D., Herzfeld, M., Hoeke, R., Huang, X., Jones, E., King, E., Parker, B., Pitman, T., Rosebrock, U., Sweeney, J., Taylor, A., Thatcher, M., Woodham, R., Zhong, A., 2020. Bluelink ocean forecasting Australia: 15 years of operational ocean service delivery with societal, economic and environmental benefits. J. Oper. Oceanogr. 13, 1–18. https://doi.org/10.1080/1755876X.2019.1685834.

Schlembach, F., Passaro, M., Quartly, G.D., Kurekin, A., Nencioli, F., Dodet, G., Piollé, J.F., Ardhuin, F., Bidlot, J., Schwatke, C., et al., 2020. Round Robin Assessment of Radar Altimeter Low Resolution Mode and Delay-Doppler Retracking Algorithms for Significant Wave Height. Remote Sens. 12, 1254. https://doi.org/10.3390/rs12081254.

von Schuckmann, K., Cheng, L., Palmer, M.D., Hansen, J., Tassone, C., Aich, V., Adusumilli, S., Beltrami, H., Boyer, T., Cuesta-Valero, F.J., Desbruyères, D., Domingues, C., García-García, A., Gentine, P., Gilson, J., Gorfer, M., Haimberger, L., Ishii, M., Johnson, G.C., Killick, R., King, B.A., Kirchengast, G., Kolodziejczyk, N., Lyman, J., Marzeion, B., Mayer, M., Monier, M., Monselesan, D.P., Purkey, S., Roemmich, D., Schweiger, A., Seneviratne, S.I., Shepherd, A., Slater, D.A., Steiner, A.K., Straneo, F., Timmermans, M.L., Wijffels, S.E., 2020. Heat stored in the Earth system: where does the energy go? Earth Syst. Sci. Data 12, 2013–2041. https://doi.org/10.5194/essd-12-2013-2020.

Schwatke, C., Dettmering, D., Bosch, W., Seitz, F., 2015. DAHITI – an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry. Hydrol. Earth Syst. Sci. 19, 4345–4364. https://doi.org/10.5194/hess-19-4345-2015.

Shay, L.K., Goni, G.J., Black, P.G., 2000. Effects of a warm oceanic feature on hurricane Opal. Mon. Weather Rev. 128, 1366–1383. https://doi.org/10.1175/1520-0493(2000)128<1366:EOAWOF>2.0.CO;2.

Shepherd, A., Fricker, H.A., Farrell, S.L., 2018. Trends and connections across the Antarctic cryosphere. Nature 558, 223–232. https://doi.org/10.1038/s41586-018-0171-6.

Shepherd, A., Gilbert, L., Muir, A.S., Konrad, H., McMillan, M., Slater, T., Briggs, K.H., Sundal, A.V., Hogg, A.E., Engdahl, M.E., 2019. Trends in Antarctic Ice Sheet Elevation and Mass. Geophys. Res. Lett. 46, 8174–8183. https://doi.org/10.1029/2019GL082182.

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., Whitehouse, P., Briggs, K., Joughin, I., Krinner, G., Nowicki, S., Payne, T., Scambos, T., Schlegel, N., A, G., Agosta, C., Ahlstrøm, A., Babonis, G., Barletta, V., Blazquez, A., Bonin, J., Csatho, B., Cullather, R., Felikson, D., Fettweis, X., Forsberg, R., Gallee, H., Gardner, A., Gilbert, L., Groh, A., Gunter, B., Hanna, E., Harig, C., Helm, V., Horvath, A., Horwath, M., Khan, S., Kjeldsen, K.K., Konrad, H., Langen, P., Lecavalier, B., Loomis, B., Luthcke, S., McMillan, M., Melini, D., Mernild, S., Mohajerani, Y., Moore, P., Mouginot, J., Moyano, G., Muir, A., Nagler, T., Nield, G., Nilsson, J., Noel, B., Otosaka, I., Pattle, M.E., Peltier, W.R., Pie, N., Rietbroek, R., Rott, H., Sandberg-Sørensen, L., Sasgen, I., Save, H., Scheuchl, B., Schrama, E., Schröder, L., Seo, K.W., Simonsen, S., Slater, T., Spada, G., Sutterley, T., Talpe, M., Tarasov, L., van de Berg, W.J., van der Wal, W., van Wessem, M., Vishwakarma, B.D., Wiese, D., Wouters, B., team, T.I., 2018b. Mass balance of the Antarctic Ice Sheet from 1992 to 2017. Nature 558, 219–222. doi: 10.1038/s41586-018-0179-y.

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., Whitehouse, P., Briggs, K., Joughin, I., Krinner, G., Nowicki, S., Payne, T., Scambos, T., Schlegel, N., A, G., Agosta, C., Ahlstrøm, A., Babonis, G., Barletta, V.R., Bjørk, A.A., Blazquez, A., Bonin, J., Colgan, W., Csatho, B., Cullather, R., Engdahl, M.E., Felikson, D., Fettweis, X., Forsberg, R., Hogg, A.E., Gallee, H., Gardner, A., Gilbert, L., Gourmelen, N., Groh, A., Gunter, B., Hanna, E., Harig, C., Helm, V., Horvath, A., Horwath, M., Khan, S., Kjeldsen, K.K., Konrad, H., Langen, P.L., Lecavalier, B., Loomis, B., Luthcke, S., McMillan, M., Melini, D., Mernild, S., Mohajerani, Y., Moore, P., Mottram, R., Mouginot, J., Moyano, G., Muir, A., Nagler, T., Nield, G., Nilsson, J., Noël, B., Otosaka, I., Pattle, M.E., Peltier, W.R., Pie, N., Rietbroek, R., Rott, H., Sandberg Sørensen, L., Sasgen, I., Save, H., Scheuchl, B., Schrama, E., Schröder, L., Seo, K.W., Simonsen, S.B., Slater, T., Spada, G., Sutterley, T., Talpe, M., Tarasov, L., van de Berg, W.J., van der Wal, W., van Wessem, M., Vishwakarma, B.D., Wiese, D., Wilton, D., Wagner, T., Wouters, B., Wuite, J., Team, T.I., 2020. Mass balance of the Greenland Ice Sheet from 1992 to 2018. Nature 579, 233–239. doi: 10.1038/s41586-019-1855-2.

Siegel, D.A., McGillicuddy Jr., D.J., Fields, E.A., 1999. Mesoscale eddies, satellite altimetry, and new production in the Sargasso Sea. J. Geophys. Res. Oceans 104, 13359–13379. https://doi.org/10.1029/1999JC900051.

Simmons, A., Fellous, J.L., Ramaswamy, V., Trenberth, K., Asrar, G., Balmaseda, M., Burrows, J.P., Ciais, P., Drinkwater, M., Friedlingstein, P., Gobron, N., Guilyardi, E., Halpern, D., Heimann, M., Johannessen, J., Levelt, P.F., Lopez-Baeza, E., Penner, J., Scholes, R., Shepherd, T., 2016. Observation and integrated Earth-system science: A roadmap for 2016–2025. Adv. Space Res. 57, 2037–2103. https://doi.org/10.1016/j.asr.2016.03.008.

Slangen, A.B.A., Meyssignac, B., Agosta, C., Champollion, N., Church, J.A., Fettweis, X., Ligtenberg, S.R.M., Marzeion, B., Melet, A., Palmer, M.D., Richter, K., Roberts, C.D., Spada, G., 2017. Evaluating Model Simulations of Twentieth-Century Sea Level Rise. Part I: Global Mean Sea Level Change. J. Clim. 30, 8539–8563. https://doi.org/10.1175/JCLI-D-17-0110.1.

Smith, N., 2000. The global ocean data assimilation experiment. Adv. Space Res. 25, 1089–1098. https://doi.org/10.1016/S0273-1177(99)00868-6, remote Sensing and Applications: Earth, Atmosphere and Oceans.

Smith, W.H.F., Sandwell, D.T., 1994. Bathymetric prediction from dense satellite altimetry and sparse shipboard bathymetry. J. Geophys. Res. Solid Earth 99, 21803–21824. https://doi.org/10.1029/94JB00988.

Stammer, D., Cazenave, A., 2018. Satellite Altimetry Over Oceans and Land Surfaces. CRC Press, Taylor & Francis Group. https://doi.org/10.1017/aer.2019.81.

Stammer, D., Wunsch, C., 1994. Preliminary assessment of the accuracy and precision of TOPEX/Poseidon altimeter data with respect to the large-scale ocean circulation. J. Geophys. Res. Oceans 99, 24584–24604. https://doi.org/10.1029/94JC00919.

Sterckx, S., Brown, I., Kääb, A., Krol, M., Morrow, R., Veefkind, P., Boersma, K.F., Mazière, M.D., Fox, N., Thorne, P., 2020. Towards a European Cal/Val service for earth observation. Int. J. Remote Sens. 41, 4496–4511. https://doi.org/10.1080/01431161.2020.1718240.

Steunou, N., Desjonquères, J.D., Picot, N., Sengenes, P., Noubel, J., Poisson, J.C., 2015. AltiKa altimeter: Instrument description and in flight performance. Mar. Geodesy 38, 22–42. https://doi.org/10.1080/01490419.2014.988835.

Stopa, J.E., 2019. Seasonality of wind speeds and wave heights from 30 years of satellite altimetry. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.09.057 (in this issue).

Stroeve, J.C., Kattsov, V., Barrett, A., Serreze, M., Pavlova, T., Holland, M., Meier, W.N., 2012. Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. Geophys. Res. Lett. 39. https://doi.org/10.1029/2012GL052676.

Taburet, G., Sanchez-Roman, A., Ballarotta, M., Pujol, M.I., Legeais, J.F., Fournier, F., Faugere, Y., Dibarboure, G., 2019. DUACS DT2018: 25 years of reprocessed sea level altimetry products. Ocean Sci. 15, 1207–1224. https://doi.org/10.5194/os-15-1207-2019.

Tapley, B.D., Bettadpur, S., Watkins, M., Reigber, C., 2004. The Gravity Recovery and Climate Experiment: Mission overview and early results. Geophys. Res. Lett. 31. https://doi.org/10.1029/2004GL019920.

Tarpanelli, A., Barbetta, S., Brocca, L., Moramarco, T., 2013. River discharge estimation by using altimetry data and simplified flood routing modeling. Remote Sens. 5, 4145–4162. https://doi.org/10.3390/rs5094145.

Tarpanelli, A., Camici, S., Nielsen, K., Brocca, L., Moramarco, T., Benveniste, J., 2019. Potentials and limitations of Sentinel-3 for river discharge assessment. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.08.005 (in this issue).

Tchilibou, M., Gourdeau, L., Morrow, R., Serazin, G., Djath, B., Lyard, F., 2018. Spectral signatures of the tropical Pacific dynamics from model and altimetry: a focus on the meso-/submesoscale range. Ocean Sci. 14, 1283–1301. https://doi.org/10.5194/os-14-1283-2018.

Thakur, P.K., Garg, V., Kalura, P., Agrawal, B., Sharma, V., Mohapatra, M., Kalia, M., Aggarwal, S.P., Calmant, S., Ghosh, S., Dhote, P.R., Sharma, R., Chauhan, P., 2020. Water level status of Indian reservoirs: A synoptic view from altimeter observations. Adv. Space Res. https://doi.org/10.1016/j.asr.2020.06.015 (in this issue).

Tilling, R.L., Ridout, A., Shepherd, A., 2018. Estimating Arctic sea ice thickness and volume using CryoSat-2 radar altimeter data. Adv. Space Res. 62, 1203–1225. https://doi.org/10.1016/j.asr.2017.10.051, the CryoSat Satellite Altimetry Mission: Eight Years of Scientific Exploitation.

Tilling, R.L., Ridout, A., Shepherd, A., Wingham, D.J., 2015. Increased Arctic sea ice volume after anomalously low melting in 2013. Nat. Geosci. 8, 643–646. https://doi.org/10.1038/ngeo2489.

Tonani, M., Sykes, P., King, R.R., McConnell, N., Péquignet, A.C., O'Dea, E., Graham, J.A., Polton, J., Siddorn, J., 2019. The impact of a new high-resolution ocean model on the Met Office North-West European Shelf forecasting system. Ocean Sci. 15, 1133–1158. https://doi.org/10.5194/os-15-1133-2019.

Tournadre, J., Bouhier, N., Girard-Ardhuin, F., Rémy, F., 2016. Antarctic icebergs distributions 1992–2014. J. Geophys. Res. Oceans 121, 327–349. https://doi.org/10.1002/2015JC011178.

Tran, N., Vandemark, D., Zaron, E., Thibaut, P., Dibarboure, G., Picot, N., 2019. Assessing the effects of sea-state related errors on the precision of high-rate Jason-3 altimeter sea level data. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.11.034 (in this issue).

Van Den Hoek, J., Getirana, A., Jung, H., Okeowo, M., Lee, H., 2019. Monitoring reservoir drought dynamics with Landsat and Radar/Lidar altimetry time series in persistently cloudy eastern Brazil. Remote Sens. 11, 827. https://doi.org/10.3390/rs11070827.

Veng, T., Andersen, O.B., 2020. Consolidating sea level acceleration estimates from satellite altimetry. Adv. Space Res. https://doi.org/10.1016/j.asr.2020.01.016 (in this issue).

Vergara, O., Morrow, R., Pujol, I., Dibarboure, G., Ubelmann, C., 2019. Revised global wave number spectra from recent altimeter observations. J. Geophys. Res. Oceans 124, 3523–3537. https://doi.org/10.1029/2018JC014844.

Verron, J., Bonnefond, P., Andersen, O., Ardhuin, F., Bergé-Nguyen, M., Bhowmick, S., Blumstein, D., Boy, F., Brodeau, L., Crétaux, J.F., Dabat, M.L., Dibarboure, G., Fleury, S., Garnier, F., Gourdeau, L., Marks, K., Queruel, N., Sandwell, D., Smith, W.H., Zaron, E., 2020. The SARAL/AltiKa mission: A step forward to the future of altimetry. Adv. Space Res. https://doi.org/10.1016/j.asr.2020.01.030 (in this issue).

Verron, J., Bonnefond, P., Aouf, L., Birol, F., Bhowmick, S., Calmant, S., Conchy, T., Crétaux, J.F., Dibarboure, G., Dubey, A., et al., 2018. The benefits of the Ka-Band as evidenced from the SARAL/AltiKa altimetric mission: Scientific applications. Remote Sens. 10, 163. https://doi.org/10.3390/rs10020163.

Vieira, E., Lázaro, C., Fernandes, M.J., 2019. Spatio-temporal variability of the wet component of the troposphere – application to satellite altimetry. Adv. Space Res. 63, 1737–1753. https://doi.org/10.1016/j.asr.2018.11.015.

Vieira, T., Fernandes, M.J., Lázaro, C., 2019. Independent assessment of on-board microwave radiometer measurements in coastal zones using tropospheric delays from GNSS. IEEE Trans. Geosci. Remote Sens. 57, 1804–1816. https://doi.org/10.1109/TGRS.2018.2869258.

Vignudelli, S., Kostianoy, A.G., Cipollini, P., Benveniste, J. (Eds.), 2011. Coastal Altimetry. Springer Berlin Heidelberg, Berlin, Heidelberg. doi: 10.1007/978-3-642-12796-0.

Villar, E., Farrant, G.K., Follows, M., Garczarek, L., Speich, S., Audic, S., Bittner, L., Blanke, B., Brum, J.R., Brunet, C., Casotti, R., Chase, A., Dolan, J.R., d'Ortenzio, F., Gattuso, J.P., Grima, N., Guidi, L., Hill, C.N., Jahn, O., Jamet, J.L., Le Goff, H., Lepoivre, C., Malviya, S., Pelletier, E., Romagnan, J.B., Roux, S., Santini, S., Scalco, E., Schwenck, S.M., Tanaka, A., Testor, P., Vannier, T., Vincent, F., Zingone, A., Dimier, C., Picheral, M., Searson, S., Kandels-Lewis, S., Coordinators, Tara Oceans, Acinas, S.G., Bork, P., Boss, E., de Vargas, C., Gorsky, G., Ogata, H., Pesant, S., Sullivan, M.B., Sunagawa, S., Wincker, P., Karsenti, E., Bowler, C., Not, F., Hingamp, P., Iudicone, D., 2015. Environmental characteristics of Agulhas rings affect interocean plankton transport. Science 348. https://doi.org/10.1126/science.1261447.

Watson, C.S., Legresy, B., King, M.A., 2019. On the uncertainty associated with validating the global mean sea level climate record. Adv. Space Res. https://doi.org/10.1016/j.asr.2019.09.053 (in this issue).

Watson, J.R., Fuller, E.C., Castruccio, F.S., Samhouri, J.F., 2018. Fishermen follow fine-scale physical ocean features for finance. Front. Mar. Sci. 5, 46. https://doi.org/10.3389/fmars.2018.00046.

Wilkinson, M., Schreiber, U., Procházka, I., Moore, C., Degnan, J., Kirchner, G., Zhongping, Z., Dunn, P., Shargorodskiy, V., Sadovnikov, M., Courde, C., Kunimori, H., 2019. The next generation of satellite laser ranging systems. J. Geodesy 93, 2227–2247. https://doi.org/10.1007/s00190-018-1196-1.

Williamson, C.E., Saros, J.E., Vincent, W.F., Smol, J.P., 2009. Lakes and reservoirs as sentinels, integrators, and regulators of climate change. Limnol. Oceanogr. 54, 2273–2282. https://doi.org/10.4319/lo.2009.54.6_part_2.2273.

Wilson, W.S., Fellous, J.L., Kawamura, H., Mitnik, L., 2006. A History of Oceanography from Space. American Society of Photogrammetry and Remote Sensing, vol. 6, 3rd ed., pp. 1–31 (Chapter 1).

Wingham, D., Francis, C., Baker, S., Bouzinac, C., Brockley, D., Cullen, R., de Chateau-Thierry, P., Laxon, S., Mallow, U., Mavrocordatos, C., Phalippou, L., Ratier, G., Rey, L., Rostan, F., Viau, P., Wallis, D., 2006. CryoSat: A mission to determine the fluctuations in Earth's land and marine ice fields. Adv. Space Res. 37, 841–871. https://doi.org/10.1016/j.asr.2005.07.027.

Witter, D.L., Chelton, D.B., 1991. A Geosat altimeter wind speed algorithm and a method for altimeter wind speed algorithm development. J. Geophys. Res. Oceans 96, 8853–8860. https://doi.org/10.1029/91JC00414.

Woodworth, P.L., Melet, A., Marcos, M., Ray, R.D., Wöppelmann, G., Sasaki, Y.N., Cirano, M., Hibbert, A., Huthnance, J.M., Monserrat, S., Merrifield, M.A., 2019. Forcing factors affecting sea level changes at the coast. Surv. Geophys. 40, 1351–1397. https://doi.org/10.1007/s10712-019-09531-1.

Woolway, R., Kraemer, B., Lenters, J., Merchant, C., O'Reilly, C., Sharma, S., 2020. Global lake responses to climate change. Nat. Rev. Earth Environ. 1, 388–403. https://doi.org/10.1038/s43017-020-0067-5.

Yao, F., Wang, J., Wang, C., Crétaux, J.F., 2019. Constructing long-term high-frequency time series of global lake and reservoir areas using Landsat imagery. Remote Sens. Environ. 232, 111210. https://doi.org/10.1016/j.rse.2019.111210.

Yoder, J.A., McClain, C.R., Blanton, J.O., Oeymay, L.Y., 1987. Spatial scales in CZCS-chlorophyll imagery of the southeastern U.S. continental shelf. Limnol. Oceanogr. 32, 929–941. https://doi.org/10.4319/lo.1987.32.4.0929.

Young, I.R., Zieger, S., Babanin, A.V., 2011. Global trends in wind speed and wave height. Science 332, 451–455. https://doi.org/10.1126/science.1197219.

Zelensky, N.P., Lemoine, F.G., Chinn, D.S., Beckley, B.D., Bordyugov, O., Yang, X., Wimert, J., Pavlis, D., 2016. Towards the 1-cm SARAL orbit. Adv. Space Res. 58, 2651–2676. https://doi.org/10.1016/j.asr.2015.12.011.

Zhang, Z., Qiu, B., Klein, P., Travis, S., 2019. The influence of geostrophic strain on oceanic ageostrophic motion and surface chlorophyll. Nat. Commun. 10, 2838. https://doi.org/10.1038/s41467-019-10883-w.

Zhao, G., Gao, H., 2018. Automatic correction of contaminated images for assessment of reservoir surface area dynamics. Geophys. Res. Lett. 45, 6092–6099. https://doi.org/10.1029/2018GL078343.

Zhou, T., Nijssen, B., Gao, H., Lettenmaier, D.P., 2015. The Contribution of Reservoirs to Global Land Surface Water Storage Variations. J. Hydrometeorol. 17, 309–325. https://doi.org/10.1175/JHM-D-15-0002.1.

Zwally, H.J., Bindschadler, R.A., Brenner, A.C., Major, J.A., Marsh, J. G., 1989. Growth of Greenland Ice Sheet: Measurement. Science 246, 1587–1589. https://doi.org/10.1126/science.246.4937.1587.

Saleh Abdalla [a], Abdolnabi Abdeh Kolahchi [b], Michaël Ablain [bl], Susheel Adusumilli [c], Suchandra Aich Bhowmick [d], Eva Alou-Font [e], Laiba Amarouche [f], Ole Baltazar Andersen [g], Helena Antich [h], Lotfi Aouf [i], Brian Arbic [j], Thomas Armitage [k], Sabine Arnault [l], Camila Artana [m], Giuseppe Aulicino [n], Nadia Ayoub [o], Sergei Badulin [p], Steven Baker [q], Chris Banks [r], Lifeng Bao [s], Silvia Barbetta [t], Bàrbara Barceló-Llull [h], François Barlier [u], Sujit Basu [v], Peter Bauer-Gottwein [w], Matthias Becker [x], Brian Beckley [y], Nicole Bellefond [z], Tatyana Belonenko [aa], Mounir Benkiran [m], Touati Benkouider [ab], Ralf Bennartz [ac], Jérôme Benveniste [ad,*,1], Nicolas Bercher [ae], Muriel Berge-Nguyen [o,z], Joao Bettencourt [af], Fabien Blarel [o], Alejandro Blazquez [o,z], Denis Blumstein [o,z], Pascal Bonnefond [ag,*,1], Franck Borde [ah], Jérôme Bouffard [ad], François Boy [z], Jean-Paul Boy [ai], Cédric Brachet [aj], Pierre Brasseur [ak], Alexander Braun [al], Luca Brocca [t], David Brockley [q], Laurent Brodeau [am], Shannon Brown [an], Sean Bruinsma [ao,z], Anna Bulczak [ap], Sammie Buzzard [aq], Madeleine Cahill [ar], Stéphane Calmant [o], Michel Calzas [aj], Stefania Camici [t], Mathilde Cancet [as], Hugues Capdeville [f], Claudia Cristina Carabajal [at], Loren Carrere [f], Anny Cazenave [o,au], Eric P. Chassignet [av], Prakash Chauhan [aw], Selma Cherchali [z], Teresa Chereskin [c], Cecile Cheymol [z], Daniele Ciani [fp], Paolo Cipollini [ax], Francesca Cirillo [ay], Emmanuel Cosme [ak], Steve Coss [az], Yuri Cotroneo [n], David Cotton [ba], Alexandre Couhert [z], Sophie Coutin-Faye [z], Jean-François Crétaux [o,z], Frederic Cyr [bb], Francesco d'Ovidio [l], José Darrozes [ao], Cedric David [an], Nadim Dayoub [bc], Danielle De Staerke [z], Xiaoli Deng [bd], Shailen Desai [an], Jean-Damien Desjonqueres [an], Denise Dettmering [be], Alessandro Di Bella [g], Lara Díaz-Barroso [e], Gerald Dibarboure [z], Habib Boubacar Dieng [o,am], Salvatore Dinardo [f], Henryk Dobslaw [bf], Guillaume Dodet [bg], Andrea Doglioli [bh], Alessio Domeneghetti [bi], David Donahue [bj], Shenfu Dong [bk], Craig Donlon [ah], Joël Dorandeu [bl], Christine Drezen [aj], Mark Drinkwater [ah], Yves Du Penhoat [o], Brian Dushaw [bm], Alejandro Egido [bn], Svetlana Erofeeva [bo], Philippe Escudier [bp], Saskia Esselborn [bf], Pierre Exertier [ao], Ronan Fablet [bq], Cédric Falco [br], Sinead Louise Farrell [bs], Yannice Faugere [f], Pierre Femenias [ad], Luciana Fenoglio [bt], Joana Fernandes [bu], Juan Gabriel Fernández [e], Pascale Ferrage [z], Ramiro Ferrari [bv], Lionel Fichen [aj], Paolo Filippucci [t], Stylianos Flampouris [bw], Sara Fleury [o], Marco Fornari [bx], Rene Forsberg [g], Frédéric Frappart [o], Marie-laure Frery [f], Pablo Garcia [by], Albert Garcia-Mondejar [by], Julia Gaudelli [q], Lucile Gaultier [bz], Augusto Getirana [ca], Ferran Gibert [by], Artur Gil [cb], Lin Gilbert [q], Sarah Gille [c], Luisella Giulicchi [ah], Jesús Gómez-Enri [cc], Laura Gómez-Navarro [ak], Christine Gommenginger [bc], Lionel Gourdeau [o], David Griffin [cd], Andreas Groh [ce], Alexandre Guerin [z], Raul Guerrero [cf], Thierry Guinle [z], Praveen Gupta [d], Benjamin D. Gutknecht [ce], Mathieu Hamon [m], Guoqi Han [cg], Danièle Hauser [ch], Veit Helm [ci], Stefan Hendricks [ci], Fabrice Hernandez [cj], Anna Hogg [ck], Martin Horwath [ce], Martina Idžanović [cl], Peter Janssen [cm], Eric Jeansou [as], Yongjun Jia [cn], Yuanyuan Jia [az], Liguang Jiang [w], Johnny A. Johannessen [co], Masafumi Kamachi [cp], Svetlana Karimova [cq], Kathryn Kelly [cr], Sung Yong Kim [cs], Robert King [ct], Cecile M.M. Kittel [w], Patrice Klein [cu], Anna Klos [cv], Per Knudsen [g], Rolf Koenig [bf], Andrey Kostianoy [p], Alexei Kouraev [o], Raj Kumar [d], Sylvie Labroue [f], Loreley Selene Lago [cw], Juliette Lambin [z], Léa Lasson [o,am], Olivier Laurain [cx], Rémi Laxenaire [av], Clara Lázaro [bu], Sophie Le Gac [z], Julien Le Sommer [ak], Pierre-Yves Le Traon [m], Sergey Lebedev [cy], Fabien Léger [o], Benoît Legresy [cd], Frank Lemoine [cz], Luc Lenain [c], Eric Leuliette [da], Marina Levy [l], John Lillibridge [db], Jianqiang Liu [cn], William Llovel [bg], Florent Lyard [o], Claire Macintosh [dc], Eduard Makhoul Varona [by], Cécile Manfredi [z], Frédéric Marin [o], Evan Mason [h], Christian Massari [t], Constantin Mavrocordatos [ah], Nikolai Maximenko [dd], Malcolm McMillan [de], Thierry Medina [z], Angelique Melet [m], Marco Meloni [df], Stelios Mertikas [dg], Sammy Metref [ak], Benoit Meyssignac [o,z], Jean-François Minster [dh], Thomas Moreau [f], Daniel Moreira [di], Yves Morel [o], Rosemary Morrow [o], John Moyard [z], Sandrine Mulet [f], Marc Naeije [dj], Robert Steven Nerem [dk], Hans Ngodock [dl], Karina Nielsen [g], Jan Even Øie Nilsen [dm], Fernando Niño [o], Carolina Nogueira Loddo [dn], Camille Noûs [do], Estelle Obligis [dn], Inès Otosaka [dp], Michiel Otten [dq], Berguzar Oztunali Ozbahceci [dr], Roshin P. Raj [co], Rodrigo Paiva [ds], Guillermina Paniagua [dt], Fernando Paolo [an], Adrien Paris [am], Ananda Pascual [h], Marcello Passaro [be], Stephan Paul [du], Tamlin Pavelsky [dv], Christopher Pearson [dw], Thierry Penduff [ak], Fukai Peng [bd], Felix Perosanz [ao,z], Nicolas Picot [z], Fanny Piras [f], Valerio Poggiali [dx], Étienne Poirier [dy], Sonia Ponce de León [af], Sergey Prants [dz], Catherine Prigent [ea], Christine Provost [l], M-Isabelle Pujol [f], Bo Qiu [eb], Yves Quilfen [bg], Ali Rami [ab], R. Keith Raney [ec], Matthias Raynal [f], Elisabeth Remy [m], Frédérique Rémy [o], Marco Restano [df], Annie Richardson [an], Donald Richardson [ed], Robert Ricker [ci], Martina Ricko [ee], Eero Rinne [ef], Stine Kildegaard Rose [g], Vinca Rosmorduc [f], Sergei Rudenko [be], Simón Ruiz [h], Barbara J. Ryan [eg,*,1], Corinne Salaün [eh], Antonio Sanchez-Roman [h], Louise Sandberg Sørensen [g], David Sandwell [c], Martin Saraceno [ei], Michele Scagliola [ej], Philippe Schaeffer [f], Martin G. Scharffenberg [ek], Remko Scharroo [dn], Andreas Schiller [cd], Raphael Schneider [el], Christian Schwatke [be], Andrea Scozzari [em], Enrico Ser-giacomi [en], Frederique Seyler [eo], Rashmi Shah [an], Rashmi Sharma [d], Andrew Shaw [ep], Andrew Shepherd [dp], Jay Shriver [dl], C.K. Shum [az], Wim Simons [dj], Sebatian B. Simonsen [g], Thomas Slater [dp], Walter Smith [da], Saulo Soares [c], Mikhail Sokolovskiy [eq], Laurent Soudarin [f], Ciprian Spatar [dw], Sabrina Speich [er], Margaret Srinivasan [an], Meric Srokosz [bc], Emil Stanev [es], Joanna Staneva [es], Nathalie Steunou [z], Julienne Stroeve [aq], Bob Su [et], Yohanes Budi Sulistioadi [eu], Debadatta Swain [ev], Annick Sylvestre-baron [z], Nicolas Taburet [f], Rémi Tailleux [dc], Katsumi Takayama [ew], Byron Tapley [ex], Angelica Tarpanelli [t], Gilles Tavernier [z], Laurent Testut [o,dy], Praveen K. Thakur [d], Pierre Thibaut [f], LuAnne Thompson [ey], Joaquín Tintoré [e,h], Céline Tison [z], Cédric Tourain [z], Jean Tournadre [bg], Bill Townsend [ez], Ngan Tran [f], Sébastien Trilles [fa], Michel Tsamados [aq], Kuo-Hsin Tseng [fb], Clément Ubelmann [am], Bernd Uebbing [bt], Oscar Vergara [f,o], Jacques Verron [ak,am,*,1], Telmo Vieira [bu], Stefano Vignudelli [fc], Nadya Vinogradova Shiffer [fd], Pieter Visser [dj], Frederic Vivier [l], Denis Volkov [fe], Karina von Schuckmann [m], Valerii Vuglinskii [ff], Pierrik Vuilleumier [ah], Blake Walter [fg], Jida Wang [fg], Chao Wang [dv], Christopher Watson [fh], John Wilkin [fi], Josh Willis [an], Hilary Wilson [dn], Philip Woodworth [r], Kehan Yang [fj], Fangfang Yao [fg], Raymond Zaharia [bp], Elena Zakharova [fk], Edward D. Zaron [fl], Yongsheng Zhang [fm], Zhongxiang Zhao [fn], Vadim Zinchenko [fo], Victor Zlotnicki [an]

[a] ECMWF, Shinfield Park, Reading, Berkshire RG2 9AX, United Kingdom
[b] SCWMRI, AREEO, Jalal St. Shahrak Esteglal, Tehran 1389817635, Iran
[c] Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093, United States
[d] Space Applications Centre, ISRO, Ahmedabad, Gujarat 380058, India
[e] SOCIB, Parc Bit, Palma de Mallorca 07121, Spain
[f] CLS, 11 rue Hermès, Parc Technologique du Canal, 31520 Ramonville St Agne, France
[g] DTU Space, Technical University of Denmark, Kgs. Lyngby DK-2800, Denmark
[h] IMEDEA (CSIC-UIB), C/Miquel Marquès, 21, Esporles, Baleares 07190, Spain

[i] Meteo-France, 42 Avenue G. Coriolis, 31057 Toulouse, France
[j] University of Michigan, Dept Earth Env. Sci., 1100 North University Avenue, 2534 North Univ. Bldg, Ann Arbor, MI 48109, United States
[k] Formerly at NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, United States
[l] Sorbonne Université, LOCEAN-IPSL, CNRS, IRD, MNHN, 75005 Paris, France
[m] Mercator Ocean International, 8-10 rue Hermès, 31520 Ramonville Saint Agne, France
[n] Università Degli Studi Di Napoli Parthenope, Centro Direzionale Is C4, Napoli 80143, Italy
[o] LEGOS, Université de Toulouse, CNES, CNRS, UPS, IRD, 14, Avenue Edouard Belin, 31400 Toulouse, France
[p] Shirshov Institute of Oceanology, 36, Nakhimovskii Pr., Moscow, 117997, Russian Federation
[q] UCL-MSSL, Department of Space and Climate Physics, Mullard Space Science Laboratory, Holmbury St Mary, Surrey RH5 6NT, United Kingdom
[r] National Oceanography Centre, Joseph Proudman Building, 6 Brownlow Street, Liverpool, L3 5DA, United Kingdom
[s] Institute of Geodesy and Geophysics, Chinese Academy of Sciences, 340 Xudong Dajie, Wuhan, Hubei 430077, China
[t] IRPI-CNR, Via Madonna Alta 126, Perugia 06128, Italy
[u] Retired from Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, IRD, Géoazur, 250 rue Albert Einstein, 06560 Valbonne, France
[v] Formerly professor at Space Applications Centre, Arohi Club Road; Ghuma, Ahmedabad, Gujarat 380058, India
[w] Department of Environmental Engineering, Technical University of Denmark, Kgs. Lyngby DK-2800, Denmark
[x] TU Darmstadt, Franziska-Braun-Strasse-7, Darmstadt, Hesse 64287, Germany
[y] SGT Inc./NASA GSFC, 11901 Van Brady Road, Upper Marlboro, MD 20772, United States
[z] CNES, Centre Spatial de Toulouse, 18 Avenue Edouard Belin, 31401 Toulouse Cedex 9, France
[aa] Saint Petersburg State University, 7-9, Universitetskaya Nab., Saint Petersburg 199034, Russian Federation
[ab] Centre of Space Techniques, PO Box 13, Arzew, Oran 31200, Algeria
[ac] Vanderbilt University, Stevenson Center, Nashville, TN 37216, United States
[ad] European Space Agency (ESA-ESRIN), Largo Galileo Galilei, 1, Frascati, RM 00044, Italy
[ae] Altihydrolab.fr, 25 Avenue Du 11 Novembre, 69110 Sainte-foy-lès-lyon, France
[af] CENTEC-IST-Instituto Superior Tecnico, Universidade de Lisboa, Pav. Central, Av. Rovisco Pais 1, Lisboa 1049-001, Portugal
[ag] SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, LNE, 77 Avenue Denfert Rochereau, 75014 Paris, France
[ah] European Space Agency, ESTEC, Keplerlaan 1, Noordwijk, 2201 AZ, The Netherlands
[ai] EOST/IPGS, 5 Rue Rene Descartes, 67084 Strasbourg, France
[aj] CNRS/INSU/DT, Bâtiment IPEV CS 50074, 29280 Plouzané, France
[ak] Univ. Grenoble Alpes, CNRS, IRD, Grenoble INP, IGE, 38000 Grenoble, France
[al] Queen's University, 36 Union St, Kingston, Ontario K7L3N6, Canada
[am] Ocean Next, 90 chemin du Moulin, 38660 La Terrasse, France
[an] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, United States
[ao] Géosciences Environnement Toulouse (GET), Université de Toulouse, CNRS, IRD, CNES, UT3 - Paul Sabatier (UPS), 31400 Toulouse, France
[ap] Institute of Oceanology PAS, Powstancow Warszawy55, Sopot, Pomorskie 81-712, Poland
[aq] University College London, Centre for Polar Observation and Modelling, Dept. of Earth Sciences, Gower Street, London, London WCE1 6BT, United Kingdom
[ar] Australian Institute of Marine Science, PMB 3, Townsville MC, Queensland 4810, Australia
[as] NOVELTIS, 153 Rue du Lac, 31670 Labège, France
[at] Science Systems and Applications, Inc., NASA Goddard Space Flight Center, Code 61A, Greenbelt, MD 20771, United States
[au] International Space Science Institute (ISSI), Hallerstrasse 6, 3012 Bern, Switzerland
[av] Center for Ocean-Atmospheric Prediction Studies, Florida State University, 2000 Levy Avenue, Building A, Room 259, Tallahassee, FL 32306, United States
[aw] Indian Institute of Remote Sensing, IIRS-ISRO, 4-kalidas Road, Dehradun, Uttarakhand 248001, India
[ax] European Space Agency, ESA/ECSAT, Harwell, Didcot, ESA-ECSAT, Fermi Avenue, Harwell Campus, Didcot OX11 0FD, United Kingdom
[ay] Airbus, Claude Dornier Strasse, Immenstaad, Baden-Württemberg 88090, Germany
[az] School of Earth Sciences, The Ohio State University, 275 Mendenhall Laboratory, 125 South Oval Mall, Columbus, OH 43210, United States
[ba] SATOC, Coach House Farm, Castle Edge Road, New Mills, Derbyshire SK22 4QF, United Kingdom
[bb] Northwest Atlantic Fisheries Centre, Fisheries and Oceans Canada, 80 East White Hills Rd., St. John's, Newfoundland and Labrador A1C 5X1, Canada
[bc] National Oceanography Centre, European Way, Southampton, SO14 3ZH, United Kingdom
[bd] School of Engineering, The University of Newcastle, University Drive, Callaghan, NSW 2308, Australia
[be] Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM), Arcisstrasse 21, Munich 80333, Germany
[bf] GFZ Helmholtz Centre Potsdam, Telegrafenberg, Potsdam 14473, Germany
[bg] Univ Brest, CNRS, Ifremer, IRD, Laboratoire d'Océanographie Physique et Spatiale (LOPS), IUEM, 29280 Plouzané, France
[bh] Aix Marseille Univ., Université de Toulon, CNRS, IRD, MIO, 13288 Marseille, France
[bi] DICAM, University of Bologna, Viale Risorgimento 2, Bologna 40136, Italy
[bj] NOAA Office of Satellite and Product Operations, 5830 University Research Court, College Park, MD 20740, United States
[bk] Atlantic Oceanographic and Meteorological Laboratory, NOAA, 4301 Rickenbacker Causeway, Miami, FL 33149, United States
[bl] Magellium, 1 Rue Ariane, 31520 Ramonville Saint Agne, France
[bm] Unaffiliated, Carrer De La Barca 10, 3-1, Girona, Girona 17004, Spain
[bn] NOAA-LSA/GST Inc., 5830 University Research Court, College Park, MD 20740, United States
[bo] Oregon State University, 104 Ocean Admin Bldg, Corvallis, OR 97331, United States
[bp] Retired from CNES, 18 Avenue Edouard Belin, 31401 Toulouse Cedex 9, France
[bq] LMT Atlantique, Technopôle Brest-iroise, 29238 Brest, France
[br] Université de Perpignan, 52 avenue Paul Alduy, 66000 Perpignan, France
[bs] University of Maryland, Department of Geographical Sciences, College Park, MD 20740, United States
[bt] Institute For Geodesy and Geoinformation, University of Bonn, Nußallee 17, Bonn, Nrw 53115, Germany

[bu] Faculdade de Ciências, Universidade do Porto; Centro Interdisciplinar de Investigacão Marinha e Ambiental (CIIMAR/CIMAR), Rua do Campo Alegre, Porto 4169-007, Portugal
[bv] Cima - Conicet, Dr. Pedro I. Rivera 5010, Buenos Aires, Buenos Aires 1431, Argentina
[bw] STC at NOAA/NWS/STI, 1325 East West Highway, Silver Spring, MD 20910, United States
[bx] Rhea for European Space Agency, ESTEC, Keplerlaan 1, Noordwijk, 2201 AZ, The Netherlands
[by] isardSAT S.L., Marie Curie 8-14, A-219, Barcelona 08042, Spain
[bz] OceanDataLab, 870 route de Deolen, 29280 Locmaria-Plouzané, France
[ca] Science Applications International Corporation, NASA Goddard Space Flight Center, Hydrological Sciences Laboratory, Greenbelt, MD 20771, United States
[cb] cE3c/Azorean Biodiversity Group & IVAR - University of the Azores, FCT, Complexo Científico, Campus Universitário de Ponta Delgada, Ponta Delgada, Azores Autonomous Region 9500-321, Portugal
[cc] University of Cadiz, Casem. Av. Republica Saharaui, s/n, Puerto Real, Cádiz 11510, Spain
[cd] CSIRO Oceans and Atmosphere, GPO Box 1538, Hobart, Tasmania 7001, Australia
[ce] Technische Universität Dresden, Institut für Planetare Geodäsie, Helmholtzstr. 10, Dresden, Saxony 01062, Germany
[cf] Universidad Nacional De Mar Del Plata, +542235900598, Mar Del Plata, Buenos Aires 7600, Argentina
[cg] Fisheries And Oceans Canada, 9860 W. Saanich Road, Sidney, British Columbia V8L 4B2, Canada
[ch] Latmos (CNRS-UVSQ- Sorbonne-université), 11 Boulevard D'alembert, 78280 Guyancourt, France
[ci] Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Am Handelshafen 12, Bremerhaven 27570, Germany
[cj] IRD/LEGOS/UFPE/DOCEAN, Departamento De Oceanografia Da Universidade Federal De Pernambuco Av Arquitetura S/n, Recife, Pernambuco 50740-550, Brazil
[ck] School of Earth and Environment, University of Leeds, Leeds, Yorkshire, LS2 9JT, United Kingdom
[cl] Faculty of Science and Technology, Norwegian University of Life Sciences, P.O. Box 5003, Ås, Viken 1432, Norway
[cm] Retired from ECMWF, Shinfield Park, Reading, Berkshire RG2 9AX, United Kingdom
[cn] National Satellite Ocean Application Service, 8 Da Hui Si Road, Haidian District, Beijing, Beijing 100081, China
[co] NERSC, Thormoehlensgate 47, Bergen 5006, Norway
[cp] Jamstec, 3173-25 Showa-machi, Kanazawa-ku, Yokohama, Kanagawa 236-0001, Japan
[cq] Tolka Analytics, 21 Komsomolskaya Str., #54, Ufa, Republic of Bashkortostan 450001, Russian Federation
[cr] Retired from University of Washington, 6533 44th Ave Ne, Seattle, WA 98115, United States
[cs] Environmental Fluid Mechanics Laboratory, Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon 32141, Republic of Korea
[ct] UK Met Office, Met Office, Exeter, Devon EX1 3PB, United Kingdom
[cu] CNRS, Ecole Normale Supérieure, 75005 Paris, France
[cv] Military University of Technology, Sylwestra Kaliskiego 2, Warsaw, Mazowieckie 00-908, Poland
[cw] University of Buenos Aires (fcen Uba, Buenos Aires, Argentina) and CIMA (fcen Uba, Buenos Aires, Argentina), Intendente Güiraldes 2160 - Ciudad Universitaria - Pabellón II - 2do. piso, Buenos Aires, Ciudad Autónoma de Buenos Aires C1428EGA, Argentina
[cx] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, IRD, Géoazur, 250 Rue Albert Einstein, 06560 Valbonne, France
[cy] Geophysical Center of the Russian Academy of Sciences, GC RAS, 3, Str. Molodezhnaya, Moscow 119296, Russian Federation
[cz] NASA/Goddard Space Flight Center, Code 61A, Geodesy & Geophysics Laboratory, Greenbelt, MD 20771, United States
[da] NOAA Laboratory For Satellite Altimetry, 5830 University Research Court, College Park, MD 20740, United States
[db] Retired from NOAA, 29 Shore Lane, Wells, ME 04090, United States
[dc] University of Reading, Department of Meteorology, Whiteknights Road, Earley Gate, Reading, RG6 6ET, United Kingdom
[dd] University of Hawaii, 1680 East West Road, POST #401, Honolulu, HI 96822, United States
[de] Lancaster University, Lancaster, Lancashire LA1 4YW, United Kingdom
[df] SERCO c/o European Space Agency (ESA-ESRIN), Largo Galileo Galilei, 1, Frascati, RM 00044, Italy
[dg] Technical University of Crete, Geodesy And Geomatics Engineering Laboratory, Chania, Crete GR-73100, Greece
[dh] Retired from Ifremer, 18 Rue Du Mont Vallier, 31130 Quint-Fonsegrives, France
[di] CPRM, Av. Pasteur 404, Rio De Janeiro, RJ 22290290, Brazil
[dj] Delft University of Technology, Faculty of Aerospace Engineering, Kluyverweg 1, Delft, 2629 HS, The Netherlands
[dk] University of Colorado, 3775 Discovery Drive, AERO 456, Boulder, CO 80309, United States
[dl] The U.S. Naval Research Laboratory, 1009 Balch Blvd, Stennis Space Center, MS 39529, United States
[dm] Institute For Marine Research, Strandgaten 196, Bergen 5004, Norway
[dn] EUMETSAT, Eumetsat Allee 1, Darmstadt, Hessen 64295, Germany
[do] Cogitamus Laboratory, Rue Descartes, 75005 Paris, France
[dp] Centre for Polar Observation and Modelling, University of Leeds, Leeds, LS2 9JT, United Kingdom
[dq] European Space Agency, Robert-bosch-strasse 5, Darmstadt, Hessen 64293, Germany
[dr] Izmir Institute of Technology, Civil Engineering Dept., Gulbahce Urla, Izmir 35430, Turkey
[ds] IPH UFRGS, Av. Bento Gonçalves, 9500, Porto Alegre, RS 91501-970, Brazil
[dt] Centro De Investigaciones Del Mar Y La Atmósfera (cima-conicet/uba), Av. Libertador 5740, 12-7, Ciudad Autónoma de Buenos Aire, Buenos Aires 1428, Argentina
[du] Universität München, Luisenstr. 37, München, Bavaria 80333, Germany
[dv] University of North Carolina, Chapel Hill, NC 27599, United States
[dw] Newcastle University, Cassie Building, School of Engineeing, Newcastle, NE17RU, United Kingdom
[dx] Cornell University, 410 Space Sciences Building, Ithaca, NY 14853, United States
[dy] LIttoral ENvironnement et Sociétés (LIENSs), UMR 7266, CNRS/La Rochelle Université, 2, Rue Olympe de Gouges, 17000 La Rochelle, France
[dz] Pacific Oceanological Institute of The Russian Academy of Sciences, 43 Baltiiskaya St., Vladivostok, Primorye 690041, Russian Federation
[ea] CNRS, LERMA, Observatoire de Paris, 61 avenue de l'Observatoire, 75014 Paris, France
[eb] University of Hawaii At Manoa, 1052 Kamahele Street, Kailua, HI 96734, United States

[ec] *2kr, Llc, 1588 Keswick Pl, Annapolis, MD 21401, United States*
[ed] *NOAA Center for Weather and Climate, 5830 University Research Court, College Park, MD 20740, United States*
[ee] *KBR, at NASA/GSFC, 7701 Greenbelt Rd., Suite 400, Greenbelt, MD 20770, United States*
[ef] *Finnish Meteorological Institute, Po Box 503, Helsinki 00101, Finland*
[eg] *Former Director Group on Earth Observations (GEO), 10090 Tropical Drive, Bonita Springs, Florida 34135, United States*
[eh] *Shom, 13 Rue De Chatellier, 29200 Brest, France*
[ei] *Universidad de Buenos Aires and Consejo Nacional de Investigaciones Científicas y Técnicas, Departamento de Ciencias de la Atmósfera y de los Océanos, CIMA, UMI IFAECI/CNRS-CONICET-UBA-IRD, Av Intendente Guiraldes 2160, Ciudad Universitaria, Pab 2, 2do Piso, Ciudad Autonoma De Buenos Aires, Capital Federal C1428EHA, Argentina*
[ej] *Aresys Srl, Via Privata Flumendosa, 16, Milano 20132, Italy*
[ek] *Universität Hamburg, Centrum für Erdsystemforschung und Nachhaltigkeit (CEN), Bundesstraße 53, Hamburg 20146, Germany*
[el] *Geological Survey of Denmark and Greenland (GEUS), Department of Hydrology, Oester Voldgade 10, Copenhagen K 1350, Denmark*
[em] *CNR - ISTI, Via Moruzzi 1, Pisa 56124, Italy*
[en] *Mit-eaps, Via Forli' 13, Perugia 06134, Italy*
[eo] *Univ. Montpellier, IRD, UMR Espace-Dev, 500 Rue Jean Francois Breton, 34093 Montpellier Cedex5, France*
[ep] *Skymat Ltd, 11 Cedar Crescent, North Baddesley, Southampton, Hampshire, United Kingdom*
[eq] *Water Problems Institute of Russian Academy of Science, 3 Gubkina Str., Moscow, Moscow 119333, Russian Federation*
[er] *LMD-IPSL, ENS-PSL, 24 Rue Lhomond, 75231 Paris Cedex 05, France*
[es] *Institute of Coastal Systems, Helmholz Zentrum Geesthacht (HZG), Max-Planck-str. 1, Geesthacht 21502, Germany*
[et] *University of Twente, Hengelosestraat 99, P.O. Box 217, Enschede 7500 AE, The Netherlands*
[eu] *Center for Geo-spatial Information Infrastructure Development (CGIID) and Faculty of Forestry, Mulawarman University, Jl. Krayan No 1, Samarinda, Kalimantan Timur 75117, Indonesia*
[ev] *Indian Institute of Technology Bhubaneswar, Room 10 (SEOCS), SBS Building, IIT Bhubaneswar, Argul, Jatni, Odisha 752050, India*
[ew] *Kyushu University, 6-1 Kasuga-kouen, Kasuga, Fukuoka 816-8580, Japan*
[ex] *University of Texas At Austin, 5603 Lands End St, Austin, TX 78734, United States*
[ey] *University of Washington, Box 355351, School of Oceanography, Seattle, WA 98195, United States*
[ez] *Townsend Aerospace Consulting, LLC, 270 King George St, Annapolis, MD 21401, United States*
[fa] *Thales Alenia Space, 26 Avenue Jean François Champollion, 31037 Toulouse Cedex h1, France*
[fb] *Center for Space and Remote Sensing Research, National Central University, 300 Jhongda Rd, Jhongli Dist, Taoyuan32001, Taiwan*
[fc] *CNR, C/o Area Ricerca Cnr - Via Moruzzi 1, Pisa 56127, Italy*
[fd] *NASA HQ, Science Mission Directorate, 300 E Street S.W., Washington, DC 02546, United States*
[fe] *Cooperative Institute for Marine and Atmospheric Studies, University of Miami, and Atlantic Oceanographic and Meteorological Laboratory, NOAA, 4301 Rickenbacker Causeway, Miami, Florida 33149, United States*
[ff] *State Hydrological Institute, 2nd Line 23, St. Petersburg 199053, Russian Federation*
[fg] *Kansas State University, 1002 Seaton Hall, Manhattan, KS 66506, United States*
[fh] *University of Tasmania, Private Bag 76, Discipline of Geography and Spatial Sciences, Hobart, TAS 7001, Australia*
[fi] *Rutgers University, 71 Dudley Rd, New Brunswick, NJ 08901, United States*
[fj] *University Of Colorado Boulder, Department of Geography, Institute of Arctic and Alpine Research, 4001 Discovery Drive, Boulder, CO 80303, United States*
[fk] *EOLA ME/ Water Problem Institute RAS, Goubkina, 3, Moscow 117971, Russian Federation*
[fl] *Portland State University, PO Box 751, Portland, OR 97207, United States*
[fm] *NOAA/NESDIS/National Centers for Environmental Information (NCEI) - UMD/ESSIC/CISESS, 1315 East-West Highway, Silver Spring, MD 20910, United States*
[fn] *Applied Physics Laboratory, University of Washington, 1013 NE 40th Street, Seattle, WA 98105, United States*
[fo] *St. Petersburg State University, University Embankment, 7/9, Saint-Petersburg, Saint-Petersburg 199034, Russian Federation*
[fp] *CNR-ISMAR, Via del Fosso del Cavaliere 100, Rome 00133, Italy*

* Corresponding authors: Jacques Verron, Barbara Ryan, Pascal Bonnefond and Jérôme Benveniste.

E-mail addresses: saleh.abdalla@ecmwf.int (S. Abdalla), kolahchi@yahoo.com (A. Abdeh Kolahchi), michael.ablain@magellium.fr (A. Michaël), suadusum@ucsd.edu (S. Adusumilli), suchandra81@yahoo.com (S. Aich Bhowmick), suchandra81@yahoo.com (E. Aich Bhowmick), ealou@socib.es (E. Alou-Font), lamarouche@groupcls.com (L. Amarouche), oa@space.dtu.dk (O.B. Andersen), helena.antich@gmail.com (H. Antich), lotfi.aouf@meteo.fr (L. Aouf), arbic@ umich.edu (B. Arbic), tom.w.armitage@gmail.com (T. Armitage), sa@ locean-ipsl.upmc.fr (S. Arnault), cartana@mercator-ocean.fr (C. Artana), giuseppe.aulicino@uniparthenope.it (G. Aulicino), giuseppe.aulicino@ uniparthenope.it (N. Aulicino), nadia.ayoub@legos.obs-mip.fr (N. Ayoub), badulin.si@ocean.ru (S. Badulin), Steven.Baker@ucl.ac.uk (S. Baker), chris.banks@noc.ac.uk (C. Banks), baolifeng@whigg.ac.cn (L. Bao), s.barbetta@irpi.cnr.it (S. Barbetta), b.barcelo.llull@gmail.com (B. Barceló-Llull), Francois.Barlier@oca.eu (F. Barlier), rumi_jhimli@rediffmail.com (S. Basu), pbau@env.dtu.dk (P. Bauer-Gottwein), becker@psg.tu-darmstadt.de (M.

Becker), brian.d.beckley@nasa.gov (B. Beckley), nicole.bellefond@cnes.fr (N. Bellefond), btvlisab@yandex.ru (T. Belonenko), mbenkiran@mercator-ocean.fr (M. Benkiran), touatibk@yahoo.fr (T. Benkouider), bennartz@me.com (R. Bennartz), Jerome.Benveniste@esa.int (J. Benveniste), nicolas.bercher@altihydrolab.fr (N. Bercher), mumubn@gmail.com (M. Berge-Nguyen), joao.bettencourt@centec.tecnico.ulisboa.pt (J. Bettencourt), blarel@legos.obs-mip.fr (F. Blarel), alejandro.blazquez@cnes.fr (A. Blazquez), denis.blumstein@legos.obs-mip.fr (D. Blumstein), Pascal.Bonnefond@obspm.fr (P. Bonnefond), franck.borde@esa.int (F. Borde), jerome.bouffard@esa.int (J. Bouffard), francois.boy@cnes.fr (F. Boy), jeanpaul.boy@unistra.fr (J.-P. Boy), cedric.brachet@cnrs.fr (C. Brachet), pierre.brasseur@univ-grenoble-alpes.fr (P. Brasseur), braun@queensu.ca (A. Braun), luca.brocca@irpi.cnr.it (L. Brocca), d.brockley@ucl.ac.uk (D. Brockley), laurent.brodeau@ocean-next.fr (L. Brodeau), shannon.t.brown@jpl.nasa.gov (S. Brown), sean.bruinsma@cnes.fr (S. Bruinsma), annabulczak@gmail.com (A. Bulczak), s.buzzard@ucl.ac.uk (S. Buzzard), madeleine.cahill@csiro.au (M. Cahill), stephane.calmant@ird.fr (S. Calmant), michel.calzas@cnrs.fr (M. Calzas), s.camici@irpi.cnr.it (S. Camici), mathilde.cancet@noveltis.fr (M. Cancet), hcapdeville@cls.fr (H. Capdeville), Claudia.C.Carabajal@nasa.gov (C.C. Carabajal), Claudia.C.Carabajal@nasa.gov (L. Carabajal), lcarrere@groupcls.com (L. Carrere), anny.cazenave@legos.obs-mip.fr (A. Cazenave), echassignet@fsu.edu (E.P. Chassignet), prakash@iirs.gov.in (P. Chauhan), selma.cherchali@cnes.fr (S. Cherchali), tchereskin@ucsd.edu (T. Chereskin), cecile.cheymol@cnes.fr (C. Cheymol), daniele.ciani@cnr.it (D. Ciani), paolo.cipollini@esa.int (P. Cipollini), francesca.cirillo@airbus.com (F. Cirillo), Emmanuel.Cosme@univ-grenoble-alpes.fr (E. Cosme), coss.31@osu.edu (S. Coss), yuri.cotroneo@uniparthenope.it (Y. Cotroneo), d.cotton@satoc.eu (D. Cotton), alexandre.couhert@cnes.fr (A. Couhert), sophie.coutin-faye@cnes.fr (S. Coutin-Faye), jean-francois.cretaux@legos.obs-mip.fr (J.-F. Crétaux), Frederic.Cyr@dfo-mpo.gc.ca (F. Cyr), francesco.dovidio@locean-ipsl.upmc.fr (F. d'Ovidio), jose.darrozes@get.omp.eu (J. Darrozes), cedric.david@jpl.nasa.gov (C. David), nayoub@noc.ac.uk (N. Dayoub), danielle.destaerke@cnes.fr (D. De Staerke), xiaoli.deng@newcastle.edu.au (X. Deng), shailen.desai@jpl.nasa.gov (S. Desai), jean-damien.m.desjonqueres@jpl.nasa.gov (J.-D. Desjonqueres), denise.dettmering@tum.de (D. Dettmering), adia@space.dtu.dk (A. Di Bella), ldiaz@socib.es (L. Díaz-Barroso), gerald.dibarboure@cnes.fr (G. Dibarboure), habib.dieng@legos.obs-mip.fr (H.B. Dieng), sdinardo@groupcls.com (S. Dinardo), dobslaw@gfz-potsdam.de (H. Dobslaw), guillaume.dodet@ifremer.fr (G. Dodet), andrea.doglioli@univ-amu.fr (A. Doglioli), alessio.domeneghetti@unibo.it (A. Domeneghetti), david.r.donahue@noaa.gov (D. Donahue), shenfu.dong@noaa.gov (S. Dong), craig.donlon@esa.int (C. Donlon), joel.dorandeu@magellium.fr (J. Dorandeu), christine.drezen@cnrs.fr (C. Drezen), mark.drinkwater@esa.int (M. Drinkwater), yves.du-penhoat@ird.fr (Y. Du Penhoat), brian.dushaw@gmail.com (B. Dushaw), alejandro.egido@noaa.gov (A. Egido), Svetlana.Erofeeva@oregonstate.edu (S. Erofeeva), philippe.escudier@gmail.com (P. Escudier), essel@gfz-potsdam.de (S. Esselborn), pierre.exertier@get.omp.eu (P. Exertier), ronan.fablet@imt-atlantique.fr (R. Fablet), cedric.falco@univ-perp.fr (C. Falco), sinead.farrell@noaa.gov (S.L. Farrell), yfaugere@cls.fr (Y. Faugere), Pierre.Femenias@esa.int (P. Femenias), fenoglio@geod.uni-bonn.de (L. Fenoglio), mjfernan@fc.up.pt (J. Fernandes), jfernandez@socib.es (J.G. Fernández), pascale.ferrage@cnes.fr (P. Ferrage), ramiro.ferrari@cima.fcen.uba.ar (R. Ferrari), lionel.fichen@cnrs.fr (L. Fichen), paolo.filippucci@irpi.cnr.it (P. Filippucci), stylianos.flampouris@noaa.gov (S. Flampouris), sara.fleury@legos.obs-mip.fr (S. Fleury), marco.fornari@esa.int (M. Fornari), rf@space.dtu.dk (R. Forsberg), frederic.frappart@legos.obs-mip.fr (F. Frappart), mdenneulin@groupcls.com (M.-l. Frery), pablo.garcia@isardsat.cat (P. Garcia), pablo.garcia@isardsat.cat (A. Garcia), albert.garcia@isardsat.cat (A. Garcia-Mondejar), j.gaudelli@ucl.ac.uk (J. Gaudelli), lucile.gaultier@oceandatalab.com (L. Gaultier), augusto.getirana@nasa.gov (A. Getirana), ferran.gibert@isardsat.cat (F. Gibert), artur.jf.gil@uac.pt (A. Gil), l.gilbert@ucl.ac.uk (L. Gilbert), sgille@ucsd.edu (S. Gille), luisella.giulicchi@esa.int (L. Giulicchi), jesus.gomez@uca.es (J. Gómez-Enri), lauragomnav@gmail.com (L. Gómez-Navarro), cg1@noc.ac.uk (C. Gommenginger), lionel.gourdeau@legos.obs-mip.fr (L. Gourdeau), David.Griffin@csiro.au (D. Griffin), andreas.groh@tu-dresden.de (A. Groh), alexandre.guerin@cnes.fr (A. Guerin), raul.guerrero@inidep.edu.ar (R. Guerrero), thierry.guinle@cnes.fr (T. Guinle), pkgupta@sac.isro.gov.in (P. Gupta), benjamin.gutknecht@tu-dresden.de (B.D. Gutknecht), mathieu.hamon@mercator-ocean.fr (M. Hamon), Guoqi.Han@dfo-mpo.gc.ca (G. Han), daniele.hauser@latmos.ipsl.fr (D. Hauser), veit.helm@awi.de (V. Helm), stefan.hendricks@awi.de (S. Hendricks), fabrice.hernandez@ird.fr (F. Hernandez), a.e.hogg@leeds.ac.uk (A. Hogg), martin.horwath@tu-dresden.de (M. Horwath), maid@nmbu.no (M. Idžanović), p.janssen@ecmwf.int (P. Janssen), eric.jeansou@noveltis.fr (E. Jeansou), jiayongjun@mail.nsoas.org.cn (Y. Jia), jia.102@osu.edu (Y. Jia), ljia@env.dtu.dk (L. Jiang), johnny.johannessen@nersc.no (J.A. Johannessen), kamachimasa@jamstec.go.jp (M. Kamachi), feba@list.ru (S. Karimova), kkelly.ocean@gmail.com (K. Kelly), syongkim@kaist.ac.kr (S.Y. Kim), robert.r.king@metoffice.gov.uk (R. King), ceki@env.dtu.dk (C.M.M. Kittel), patrice.klein@ifremer.fr (P. Klein), anna.klos@wat.edu.pl (A. Klos), pk@space.dtu.dk (P. Knudsen), koenigr@gfz-potsdam.de (R. Koenig), kostianoy@gmail.com (A. Kostianoy), kouraev@legos.obs-mip.fr (A. Kouraev), rksharma@sac.isro.gov.in (R. Kumar), slabroue@groupcls.com (S. Labroue), loreley.lago@cima.fcen.uba.ar (L.S. Lago), juliette.lambin@cnes.fr (J. Lambin), lea.lasson@legos.obs-mip.fr (L. Lasson), Olivier.Laurain@geoazur.unice.fr (O. Laurain), rlaxenaire@fsu.edu (R. Laxenaire), clazaro@fc.up.pt (C. Lázaro), sophie.legac@cnes.fr (S. Le Gac), julien.lesommer@univ-grenoble-alpes.fr (J. Le Sommer), pierre-yves.letraon@mercator-ocean.fr (P.-Y. Le Traon), sergey_a_lebedev@mail.ru (S. Lebedev), fabien.leger@legos.obs-mip.fr (F. Léger), benoit.legresy@csiro.au (B. Legresy), Frank.G.Lemoine@nasa.gov (F. Lemoine), llenain@ucsd.edu (L. Lenain), Eric.Leuliette@noaa.gov (E. Leuliette), marina.levy@upmc.fr (M. Levy), mrmole@twc.com (J. Lillibridge), jqliu@mail.nsoas.org.cn (J. Liu), wllovel@ifremer.fr (W. Llovel), florent.lyard@legos.obs-mip.fr (F. Lyard), c.r.macintosh@reading.ac.uk (C. Macintosh), edumak@gmail.com (E. Makhoul Varona), Cecile.manfredi@cnes.fr (C. Manfredi), frederic.marin@ird.fr (F. Marin), frederic.marin@ird.fr (E. Marin), evanmason@gmail.com (E. Mason), christian.massari@irpi.cnr.it (C. Massari), constantin.mavrocordatos@esa.int (C. Mavrocordatos), maximenk@hawaii.edu (N. Maximenko), m.mcmillan@lancaster.ac.uk (M. McMillan), thierry.medina@cnes.fr (T. Medina), amelet@mercator-ocean.fr (A. Melet), marco.meloni@esa.int (M. Meloni), mertikas@mred.tuc.gr (S. Mertikas), sammy.metref@univ-grenoble-alpes.fr (S. Metref), benoit.meyssignac@legos.obs-mip.fr (B. Meyssignac), djf.minster@numericable.fr (J.-F. Minster), tmoreau@groupcls.com (T. Moreau), daniel.moreira@cprm.gov.br (D. Moreira), yves.morel@legos.obs-mip.fr (Y. Morel), rosemary.morrow@legos.obs-mip.fr (R. Morrow), john.moyard@cnes.fr (J. Moyard), smulet@groupcls.com (S. Mulet), m.c.naeije@tudelft.nl (M. Naeije), nerem@colorado.edu (R.S. Nerem), Hans.Ngodock@nrlssc.navy.mil (H. Ngodock), karni@space.dtu.dk (K. Nielsen), jan.even.oeie.nilsen@hi.no (Jan Even Øie Nilsen), fernando.nino@ird.fr (F. Niño), carolina.nogueiraloddo@eumetsat.int (C. Nogueira Loddo), camille.nous@cogitamus.fr (C. Noûs), (E. Noûs), estelle.obligis@eumetsat.int (E. Obligis), eeino@leeds.ac.uk (I. Otosaka), michiel.otten@esa.int (M. Otten), berguzaro@yahoo.com (B. Oztunali Ozbahceci), roshin.raj@nersc.no (R. P. Raj), rodrigo.paiva@ufrgs.br (R. Paiva), guillermina.paniagua@cima.fcen.uba.ar (G. Paniagua), fspaolo@gmail.com (F. Paolo), adrien.paris@ocean-next.fr (A. Paris), ananda.pascual@imedea.uib-csic.es (A. Pascual), marcello.passaro@tum.de (M. Passaro), stephan.paul@lmu.de (S. Paul), pavelsky@unc.edu (T. Pavelsky), christopher.pearson@ncl.ac.uk (C. Pearson), Thierry.Penduff@cnrs.fr (T. Penduff), fukai.peng@uon.edu.au (F. Peng), felix.perosanz@cnes.fr (F. Perosanz), nicolas.picot@cnes.fr (N. Picot), fpiras@groupcls.com (F. Piras), vpoggiali@astro.cornell.edu (V. Poggiali), etienne.poirier@univ-lr.fr (É. Poirier), sonjapdla@protonmail.com (S. Ponce de León), prants@poi.dvo.ru (S. Prants), catherine.prigent@obspm.fr (C. Prigent), cp@locean-ipsl.upmc.fr (C. Provost), mpujol@groupcls.com (M-Isabelle Pujol), bo@soest.hawaii.edu (B. Qiu), yquilfen@ifremer.fr (Y. Quilfen), rami_alidz@yahoo.fr (A. Rami), rami_alidz@yahoo.fr (R.K. Rami), rkraney@gmail.com (R.K. Raney), mraynal@groupcls.com (M. Raynal), eremy@mercator-ocean.fr (E.

Remy), remy.omp@free.fr (F. Rémy), Marco.Restano@esa.int (M. Restano),Annie.Richardson@jpl.nasa.gov (A. Richardson), donald.richardson@noaa.gov (D. Richardson), robert.ricker@awi.de (R. Ricker), mricko@sgt-inc.com (M. Ricko), eero.rinne@fmi.fi (E. Rinne), stine@space.dtu.dk (S.K. Rose), vrosmorduc@cls.fr (V. Rosmorduc), sergei.rudenko@tum.de (S. Rudenko), simon.ruiz@imedea.uib-csic.es (S. Ruiz), bjrgeneva@gmail.com (B.J. Ryan), corinne.salaun@shom.fr (C. Salaün), asanchez@imedea.uib-csic.es (A. Sanchez-Roman), slss@space.dtu.dk (L. Sandberg Sørensen), dsandwell@ucsd.edu (D. Sandwell), saraceno@cima.fcen.uba.ar (M. Saraceno), michele.scagliola@aresys.it (M. Scagliola), pschaeffer@groupcls.com (P. Schaeffer), martinscharffenberg@web.de (M. G. Scharffenberg), remko.scharroo@eumetsat.int (R. Scharroo), Andreas.Schiller@csiro.au (A. Schiller), rs@geus.dk (R. Schneider), christian.schwatke@tum.de (C. Schwatke), a.scozzari@isti.cnr.it (A. Scozzari), enricosg@mit.edu (E. Ser-giacomi), frederique.seyler@ird.fr (F. Seyler), rashmi.shah@jpl.nasa.gov (R. Shah), rashmi@sac.isro.gov.in (R. Sharma), agps@skymat.co.uk (A. Shaw), A.shepherd@leeds.ac.uk (A. Shepherd), jay.shriver@nrlssc.navy.mil (J. Shriver), ckshum@osu.edu (C.K. Shum), W.J.F.Simons@tudelft.nl (W. Simons), ssim@space.dtu.dk (S.B. Simonsen), t.slater1@leeds.ac.uk (T. Slater), Walter.HF.Smith@noaa.gov (W. Smith), saulo@ucsd.edu (S. Soares), sokolovskiy@iwp.ru (M. Sokolovskiy), lsoudarin@groupcls.com (L. Soudarin), ciprian.spatar@ncl.ac.uk (C. Spatar), sabrina.speich@lmd.ens.fr (S. Speich), margaret.srinivasan@jpl.nasa.gov (M. Srinivasan), margaret.srinivasan@jpl.nasa.gov (M. Srinivasan), mas@noc.ac.uk (M. Srokosz), emil.stanev@hzg.de (E. Stanev), joanna.staneva@hzg.de (J. Staneva), nathalie.steunou@cnes.fr (N. Steunou), j.stroeve@ucl.ac.uk (J. Stroeve), z.su@utwente.nl (B. Su), bsulistioadi@gmail.com (Y.B. Sulistioadi), dswain@iitbbs.ac.in (D. Swain), annick.sylvestre-baron@cnes.fr (A. Sylvestre-baron), ntaburet@groupcls.com (N. Taburet), R.G.J.Tailleux@reading.ac.uk (R. Tailleux), katsumit@riam.kyushu-u.ac.jp (K. Takayama), tapley@csr.utexas.edu (B. Tapley), angelica.tarpanelli@irpi.cnr.it (A. Tarpanelli), gilles.tavernier@cnes.fr (G. Tavernier), laurent.testut@univ-lr.fr (L. Testut), praveen.thakur@alumni.iitd.ac.in (P.K. Thakur), pthibaut@groupcls.com (P. Thibaut), luanne@uw.edu (L. Thompson), jtintore@socib.es (J. Tintoré), celine.tison@cnes.fr (C. Tison), cedric.tourain@cnes.fr (C. Tourain), jean.tournadre@ifremer.fr (J. Tournadre), wtownsend@aol.com (B. Townsend), ntran@groupcls.com (N. Tran), sebastien.trilles@thalesaleniaspace.com (S. Trilles), m.tsamados@ucl.ac.uk (M. Tsamados), khtseng@csrsr.ncu.edu.tw (K.-H. Tseng), clement.ubelmann@ocean-next.fr (C. Ubelmann), uebbing@geod.uni-bonn.de (B. Uebbing), oscar.vergara@legos.obs-mip.fr (O. Vergara), jacques.verron@univ-grenoble-alpes.fr (J. Verron), telmo.vieira@fc.up.pt (T. Vieira), vignudelli@pi.ibf.cnr.it (S. Vignudelli), nadya@nasa.gov (N. Vinogradova Shiffer), P.N.A.M.Visser@tudelft.nl (P. Visser), frederic.vivier@locean-ipsl.upmc.fr (F. Vivier), denis.volkov@noaa.gov (D. Volkov), karina.von.schuckmann@mercator-ocean.fr (K. von Schuckmann), vvuglins@mail.ru (V. Vuglinskii), pierrik.vuilleumier@esa.int (P. Vuilleumier), bawalter@ksu.edu (B. Walter), bawalter@ksu.edu (J. Walter), jidawang@ksu.edu (J. Wang), waynechao128@gmail.com (C. Wang), cwatson@utas.edu.au (C. Watson), jwilkin@rutgers.edu (J. Wilkin), Joshua.k.willis@jpl.nasa.gov (J. Willis), hilary.wilson@eumetsat.int (H. Wilson), plw@noc.ac.uk (P. Woodworth), Kehan.Yang@Colorado.EDU (K. Yang), fyao@ksu.edu (F. Yao), arzi77@gmail.com (R. Zaharia), zavocado@gmail.com (E. Zakharova), ezaron@pdx.edu (E.D. Zaron), yongsheng.zhang@noaa.gov (Y. Zhang), zzhao@apl.uw.edu (Z. Zhao), vdmzinchenko@gmail.com (V. Zinchenko).