

Success Stories of Satellite Radar Altimeter Applications

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ABSTRACT: For nearly three decades, satellite nadir altimeters have provided essential information to understand primarily ocean but also inland water dynamics. A variety of parameters can be inferred via altimeter measurements, including sea surface height, sea surface wind speeds, significant wave heights, and topography of land, sea ice, and ice sheets. Taking advantage of these parameters with the long record of altimeter data spanning multiple decades has allowed a diverse range of societal applications. As the constellation of altimeter satellites grows, the proven value of the missions to a diverse user community can now be demonstrated by highlighting a selection of verifiable success stories. In this paper, we review selected altimeter success stories that incorporate altimetry data, alone or in conjunction with numerical models or other Earth observations, to solve a key societal problem. First, we define the problem or the key challenge of each use case, and then we articulate the uptake of the successful altimeter-based solution. Our review revealed steady progress by scientific and stakeholder communities in bridging the gap between data availability and their actual uptake to address a variety of applications. Highlighting these altimeter-based success stories can serve to further promote the widespread adoption of future satellite missions such as the Surface Water and Ocean Topography (SWOT) mission scheduled for launch in 2022. Knowledge of the breadth of current utility of altimeter observations can help the scientific community to demonstrate the value in continuing radar altimeter and similar missions, particularly those with expanded capabilities, such as SWOT.

KEYWORDS: Altimetry; Decision making; Education; Satellite observations

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Satellite radar altimetry is a key source of space geodetic data that has been widely used in many land and ocean applications (Fu and Cazenave 2000; Crétaux et al. 2011). Regardless of cloud cover, satellite altimeters measure the distance, called the radar range, between the satellite and the surface based on a beam with a footprint of a few kilometers (Birkett 1998; Calmant et al. 2008). Unlike data retrieved from remote sensing satellites with laser or in the visible and infrared wavelengths, satellite radar altimeter measurements are taken along a nadir track directly under the satellite using microwave energy. Altimeter radar pulses and their echoes, which are bounced back from the surface of its target (e.g., ocean, sea ice, desert, lake, or river), contain information such as the roughness of the surface, wave heights, water surface elevation, and surface wind speed over water (Vignudelli et al. 2011). Hence, satellite altimetry (hereafter the term will also mean satellite radar altimetry) can be portrayed as a spaceborne virtual gauge that provides temporally discrete water-related measurements at the repeat cycle of the satellite ground track orbit.

Initial development of satellite radar altimetry technology occurred in the 1970s through missions such as *GEOS-3* (1975–78) and *Seasat* (1978). *Geosat* was launched by the U.S. Navy in 1985, followed by the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the French space agency (Centre National d’Etudes Spatiales; CNES), which developed and launched a series of satellite altimeters that have provided an uninterrupted series of measurements of ocean-surface topography. *Geosat* preceded nearly continuous coverage of global observations from satellite radar altimeters including the European Remote Sensing Satellite Program (*ERS-1* in 1991, and later *ERS-2* in 1995), and TOPEX/Poseidon (joint mission between NASA and CNES launched in 1992). Later, *Jason-1* (launched in December 2001) and *Environmental Satellite (Envisat)*, launched in March 2002) were added to follow-on the TOPEX/Poseidon and ERS missions, respectively, in tandem. The Jason series continued to launch newer missions (*Jason-2*, and currently, *Jason-3*) to maintain continuity of data collection. Consequently, the Jason series has played a critical role in allowing numerous near-real-time applications, thus paving the way for operational uses. More recently, the ESA and its partners [such as NASA, National Oceanic Atmospheric and Administration (NOAA), EUMETSAT, and CNES] have launched the Sentinel series of satellites including three (*Sentinel-3A*, *Sentinel-3B*, and *Sentinel-6 Michael Freilich*) radar altimeters as part of the European Union’s Copernicus program. Since 1985, a total of 16 satellite nadir altimeter missions have been operated, with the four latest being *Jason-3* and *Sentinel-3A* in 2016, *Sentinel-3B* in 2018, and *Sentinel-6 Michael Freilich*. Both *Jason-3* and *Sentinel-6 Michael Freilich* are significant partnerships with NOAA and EUMETSAT (Fig. 1).

Today’s data on satellite altimetry time series span more than 35 years, starting with *Geosat* and presently supported by seven concurrent satellites (*SARAL*, *CryoSat-2*, *Jason-3*, *Sentinel-3A*, *Sentinel-3B*, *HY-2B*, and *Sentinel-6 Michael Freilich*). *SARAL* and *HY-2B* were contributed by Indian Space Research Organization (ISRO) and Chinese National Satellite Ocean Application Service (NSOAS), respectively, which represents the international dimension of current altimeter constellation. This growing satellite record has accelerated global analyses

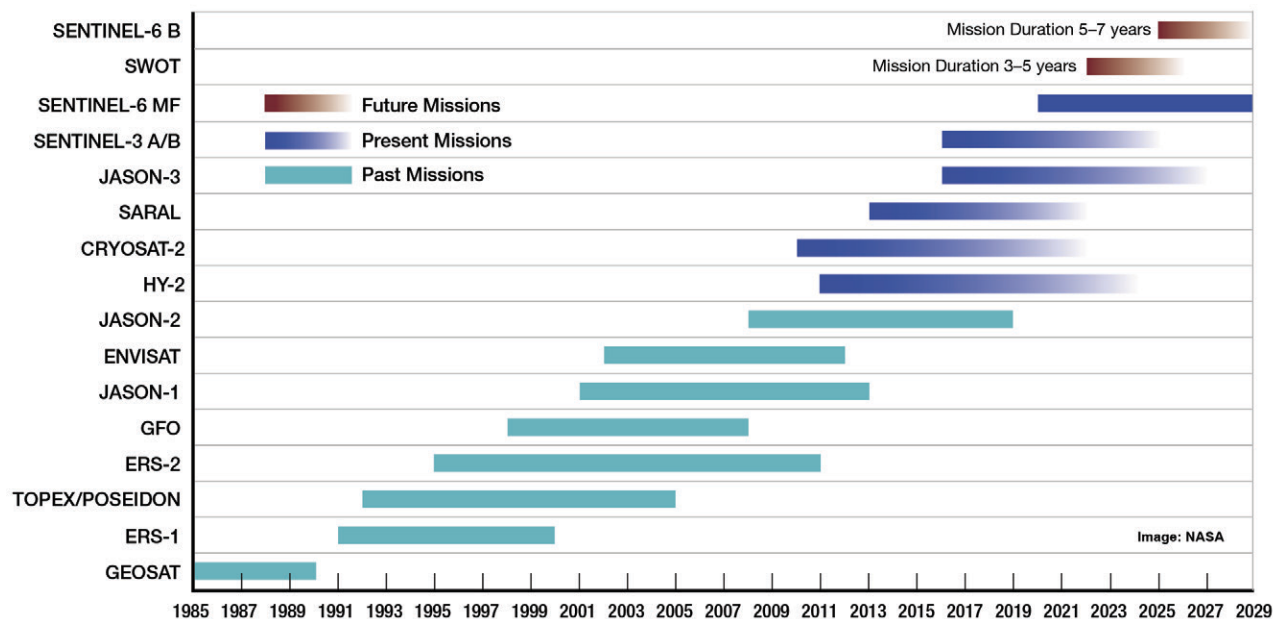


Fig. 1. Timeline of the satellite radar altimetry missions since 1985. Sentinel-6 MF stands for *Sentinel-6 Michael Freilich*. HY-2 is inclusive of the series A, B, and C, with A no longer fully functional according to https://space.oscar.wmo.int/satellites/view/hy_2a (last accessed 11 Jan 2021).

of decadal changes as altimeter products become more accessible [such as Timmermans et al. (2020) and Young and Ribal (2019) for ocean records and Coss et al. (2020) for inland waters]. Satellite altimetry has contributed extensively to the monitoring of water height variations over the Earth's oceans, lakes, rivers, reservoirs, wetlands, and floodplains (Calmant et al. 2008; Domeneghetti et al. 2014; Benveniste 2017). In addition, measurements from different altimeter missions have been used to estimate river discharge, which is a key variable of interest for hydrological applications (Michailovsky et al. 2013; Tarpanelli et al. 2013; Birkinshaw et al. 2014). The global coverage of wind speed and wave height from satellite altimeters have been used to inform offshore infrastructure design and operation and validate numerical models (Young et al. 2011; Meucci et al. 2020). The availability of a longer satellite altimeter observational record has provided a much more suitable basis for the assessment of extreme value analysis of wind speed and wave height (Alves and Young 2003; Vinoth and Young 2011; Takbash et al. 2019). It should be mentioned that the 35-yr-long time series of altimeter data are comprised of different orbits, space time samplings, and sensor signal-to-noise characteristics.

Major efforts have been recently undertaken to improve the uptake of satellite altimetry in decision support applications for societal benefit through projects operated by space agencies of CNES in France, NASA in the United States, and ESA in Europe. Public outreach has always been a key component in these efforts. Rosmorduc et al. (2020) reviewed the outreach efforts of CNES, NASA, ESA, and international partners and concluded that ongoing outreach activities can effectively communicate altimetry research to a broader audience including educators, decision-makers, media, and the general public. In another study, Kansakar and Hossain (2016) have argued for capacity-building that is crucial to establishing sustainable solutions when using satellite data for science-based decision-making. Therefore, articulating success stories of altimeter-based societal applications can inform and educate research and stakeholder communities representing diverse sectors of the economy regarding the value of satellite altimeter data and information products. In particular, such stories can demonstrate to those lacking topical expertise in altimetry the indispensable role satellite altimetry will continue to play in improving decisions in a range of applications for societal benefit.

In this review, we present selected success stories (SS) of altimetry-based applications for an audience who may want to understand the societal value of, or explore how best to

consume, altimeter data (Table 1). Our definition of a “success story” is broad. We define a success story as one that has resulted in an improvement from the baseline or the status quo due to introduction of satellite altimeter observations. This improvement may be in the form of routine operations, generation of an innovative data product, or creation of a map that may not be frequently updated, but has resulted in more robust decision-making, planning, or a societal impact. The impact of each success story is presented in the form of the “problem” and “solution” that the altimeter data enabled (“Examples of successful radar altimetry-based applications” section). Where information was available, we summarized application requirements on the key physical variable, spatial and temporal resolutions and data latency. The section “Discussion of opportunities and challenges” discusses existing challenges and future opportunities for altimetry applications. The paper concludes with key lessons learned based on overviewed applications. Our review is not intended to be exhaustive, nor is it our objective to cover all reported successful applications of altimeter data. The goal of our review is to communicate the application potential of altimeter data to readers representing a wide range of disciplines who may not have topical expertise in the subject matter of radar altimetry, but who represent potential or future consumers of the data. For a more comprehensive review of accomplishments of what the multidecadal history of radar altimetry has achieved in terms of scientific advancement and its societal impact, the reader should refer to International Altimetry Team (2021), which provides an in-depth review of 25 years of progress in radar altimetry.

Examples of successful radar altimetry-based applications

This section provides examples of inland, coastal, and marine operational or practical (as opposed to research-focused) applications that have incorporated altimeter-based measurements. For each application, we first introduce the existing challenge or a problem needing a solution (hereafter we shall use “problem” to refer interchangeably to a challenge or a problem). Next, the altimeter data-based solution is described and the scientific validity of the concept is explained based on peer-reviewed studies. The use cases presented in our review are summarized in Table 1 and described in detail in the next sections.

Fish tracking

PROBLEM. Fish distribution and abundance varies transiently in accordance with a dynamic marine environment. Thus, it is challenging for fishermen to determine potential fishing zones (PFZ). Understanding PFZ is critical for the fisheries community since it provides a reliable and timely advisory on where and when to fish, thereby reducing fuel and manpower requirements. It can also save boat time in search of fish, and can potentially reduce harmful bycatch. Accurate determination of PFZ is key to improving profitability of the commercial fishing industry, and can similarly benefit recreational fishing communities.

SOLUTION AND PROOF OF CONCEPT. Satellite altimetry can improve knowledge of PFZ by integrating sea surface height (SSH) data with sea surface temperature (SST) and sea surface chlorophyll-a (SSC-a) to study the relationship between physical and biological processes in the sea. Although the key physical predictors from satellites that dictate fish abundance are SST and chlorophyll-a (CHL-a), altimeter-based SSH with a latency of a few hours and spatial footprint of a few kilometers has been reported to improve the predictive skill of modeling PFZ. The utility of satellite altimetry and derived SSH measurements has been demonstrated more generally in fisheries oceanography (Santos 2000; Polovina and Howell 2005). For instance, Balaguru et al. (2014) found that altimetry data are suitable to identify hot spots of fish catch areas (or PFZ advisories) in India by considering different environmental variables (e.g., SST, CHL-a) combined with altimetry-based SSH anomalies and eddy kinetic energy (EKE).

Table 1. Summary of selected success stories that have implemented satellite altimetry in their application.

Success story	User	Goal	Spatial coverage	End product	Commercial application? Yes/no
FishTrack	Surflin/Wavetrak	Fish tracking	Global	www.fishtrack.com (after August 2021, this site will be wavailable only as a mobile app)	Yes
Hilton's Real-time Navigator	Hilton's Fishing Charts, LLC	Fish tracking	North and South America	https://realtime-navigator.com	Yes
TerraFin Satellite Imaging	TerraFin Software	Fish tracking	North and South America	www.terrafin.com	Yes
EcoCast	NOAA	Fish tracking	Pacific Ocean (West Coast)	https://coastwatch.pfeg.noaa.gov/ecocast/	No
NOAA Satellite-Derived Oceanic Heat Content product	NOAA	Severe storm forecasting	Global	www.ospo.noaa.gov/Products/ocean/assets/ATBD_OHC_NESDIS_V3.2.pdf	No
Integrated Forecasting System	ECMWF	Weather and climate forecast	Global	www.ecmwf.int/en/forecasts	No
NOAA Gulf of Mexico Monitoring (GOM)	NOAA	Oil spill response	Gulf of Mexico	www.aoml.noaa.gov/phod/dhos/index.php	No
BlueSIROS	ESA and National Space Institute at the Technical University of Denmark (DTU)	Ship routing	Global	https://business.esa.int/projects/blue-siros	No (feasibility demonstrated in 2018)
ALTIBERG	French Space Agency (CNES)	Iceberg detection	Global	ftp://ftp.ifremer.fr/ifremer/cersat/projects/altiberg/	No (last update is from 2020)
Bangladesh Water Bodies Mapper	University of Washington (SASWE Research Group)	Wetland dynamics	Bangladesh	http://depts.washington.edu/saswe/haors	No
Hydroweb	LEGOS Laboratory	Rivers, lakes and reservoir monitoring	Global	http://hydroweb.theia-land.fr/	No
GREALM	USDA-FAS/NASA/UMD	Reservoir monitoring	Global	https://ipad.fas.usda.gov/cropexplorer/global_reservoir/	No
Reservoir Assessment Tool	University of Washington (SASWE Research Group)	Reservoir monitoring	Developing nations	www.satellitedams.net	No (last update from 15 Jun 2021)
ISRO Applications	Indian Space Research Organization (ISRO)	Reservoir monitoring	India	www.isro.gov.in/	No
Advanced Weather, Climate and Satellite based Water Forecasting System	Bangladesh Water Development Board co-developed with University of Washington (SASWE Research Group)	Flood forecasting	Bangladesh	http://103.141.9.106/saswms/	No (subject to frequent change in URL)
Dynamic River Width based Altimeter Height Visualizer	University of Washington (SASWE Research Group)	River morphology	South and Southeast Asia	https://depts.washington.edu/saswe/jason3/	No (last update from Aug 8 2021)
Virtual Rain and Stream Gauge Data Service (VRSG)	Asian Disaster Preparedness Center (ADPC)/ NASA SERVIR Project	River morphology	Mekong River basin	https://vrsg-servir.adpc.net/	No

Table 1. (Continued)

Hybrid Coordinate Ocean Model (HYCOM)	National Ocean Partnership Program (NOPP)	Hypoxia prediction	Global	www.hycom.org	No
MetOcean	Danish Hydraulic Institute (DHI)	Offshore wind farms	Global	www.metocean-on-demand.com/	Yes
Behavior of elephant seals	French Centre for Biological Studies of Chizé (CEBC)	Wildlife habitat	Southern Ocean	www.cebc.cnrs.fr/?lang=en	No

SUCCESS STORIES FOR ALTIMETER-BASED FISH TRACKING

SS1) FishTrack is a commercial Surfline/Wavetrak product (www.fishtrack.com) that offers a valuable tool when planning offshore fishing excursions (Fig. 2a; Table 1). FishTrack integrates altimetry data with sea surface temperature and chlorophyll to provide the user with information on hot spots of more fish to catch.

SS2) Another commercial application is the “Hilton’s Real-Time Navigator” (<https://realtime-navigator.com>) that uses altimetry-based imagery to create a contour map of surface height of the ocean (Fig. 2b; Table 1). These maps can be used to detect the upwelling cold water (depressions or nutrient rich), and downwelling warm water (bulges or nutrient poor) regions.

SS3) TerraFin Satellite Imaging (www.terrafin.com) is a commercial service that produces computer-enhanced charts of SST, CHL-a, and altimetry-based SSH anomaly for anglers and divers (Table 1). The TerraFin service covers the entire continental U.S. coastline, Hawaii, Alaska, Mexico, the Caribbean, the Pacific coast of Central America, Venezuela, and Brazil.

SS4) Many of the key observations required for fisheries application are made publicly available by a NOAA CoastWatch online tool, called the EcoCast. This is a fishery sustainability tool that helps to better evaluate how to allocate fishing effort to optimize the catch of target species (e.g., swordfish) while minimizing accidental bycatch of endangered and protected species (blue sharks, leatherback sea turtles, California sea lions). EcoCast makes maps available at <https://coastwatch.pfeg.noaa.gov/ecocast/> for such fisheries application based on sea surface height and other variables estimated from altimeters.

Severe storm forecasting

PROBLEM. Prediction of frequent and severe coastal storms is crucial to mitigate damage to property and life in coastal communities. Traditionally, tidal gauge data have been used to understand storm surge features. However, tide gauges are usually sparse and can be damaged during the storm event (Han et al. 2017). Therefore, enhancing the forecasting skill of these ocean and coastal hazards requires alternate sources of data that are not vulnerable to outage.

SOLUTION AND PROOF OF CONCEPT. Key physical variables required for improving severe storm forecasting are wind speed and wave height. Historical records of altimeter-based wind speed and wave heights measurements can be integrated with ocean model outputs to better understand the spatial structure of storm surges and their timing, which can then be used for forecast model validation and improvement. The European Center for Medium Range

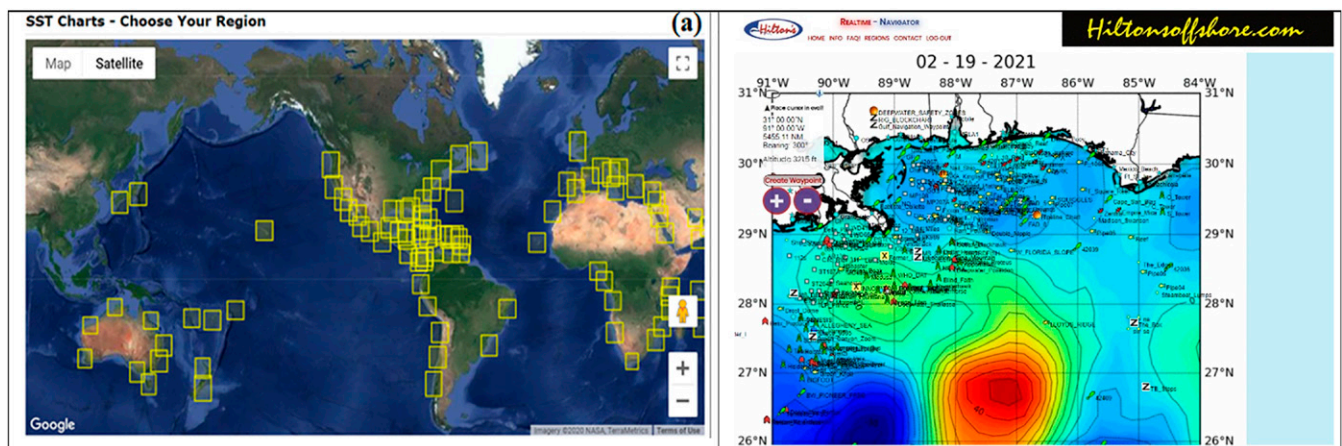


Fig. 2. Examples of commercial fish tracking applications: (a) FishTrack and (b) Hilton's Real-Time Navigator (image used with permission from the stakeholder/user agency in Table 1).

Forecasting (ECMWF) uses radar altimeter products to initialize forecasts and to monitor the performance of its Integrated Forecasting System (IFS). Experiments carried out by the ECMWF have shown that assimilating altimeter observations of wave height improve monthly and seasonal atmospheric forecasts as well as wave height forecasts that are needed during an evolving severe coastal storm event (Abdalla 2015; see also www.ecmwf.int/en/news-letter/149/meteorology/use-radar-altimeter-products-ecmwf). Using satellite altimetry, Scharroo et al. (2005) demonstrated the intensification of Hurricane Katrina (which made landfall off the coast of Louisiana in the United States on 29 August 2005) over areas of anomalously high dynamic topography rather than areas of unusually warm surface waters. Similarly, Lillibridge et al. (2013) showed that the largest storm surge signal during Hurricane Sandy (which made landfall on the East Coast of the United States on 30 October 2012) was captured by *HaiYang 2A* (HY-2A) satellite altimeter.

SUCCESS STORIES FOR SEVERE STORM FORECASTING

SS5) In the NOAA Satellite-Derived Oceanic Heat Content product, ocean altimetry data are routinely used to derive improved estimates of ocean heat content (OHC) by NOAA to improve the forecasting of hurricane intensity and propagation at the National Hurricane Center (Lin et al. 2013; Table 1).

SS6) ECMWF IFS provides global forecasts, climate reanalyses, and specific datasets based on assimilation of altimeter observations, among others. These forecasts are designed to meet different user requirements and are available via the web, point-to-point dissemination, data servers, and broadcasting. The data are made fully available to the national meteorological services of 34 member and cooperating states of ECMWF.

Oil spill response

PROBLEM. Detecting oil spills in the ocean is an important element of monitoring coastal zones in order to protect fragile marine habitats. Attention to the problem of oil pollution resulting from accidents or damage to tankers and offshore drilling platforms accelerated after dramatic global incidents, including the *Sea Empress* oil spill in 1996 (Wales), the *Erika* oil spill in 1999 (France), the *Prestige* oil spill in 2002 (Spain), and the *Deepwater Horizon* incident (Gulf of Mexico) in 2010, the largest offshore oil spill in U.S. history. Monitoring of these incidents is typically conducted by aircraft or ships, which are both expensive and constrained by limits to availability.

SOLUTION AND PROOF OF CONCEPT. Satellite altimetry can provide valuable information on surface currents, which is the key physical variable of interest used to predict the movement and trajectory of oil spills in the ocean. Consequently, near-real-time altimeter data on SSH available within a latency of a few hours can facilitate rapid response and efficient management of the spill response. Several studies have proven the utility of satellite altimetry to identify and track oil spill movement (Kostianoy et al. 2013; Liu et al. 2014; Cheng et al. 2017). Liu et al. (2014) used a series of altimetry-derived surface current products to hindcast the drifter trajectories in the eastern Gulf of Mexico from May to August 2010 following the *Deepwater Horizon* oil spill incident. They concluded that the performance of the altimetry-based trajectory models was comparable to observed drifter trajectories. When compared to numerical models, the altimetry-based trajectory models had higher skill scores, particularly within the transition zone from the deep ocean to the shelf. This validated the benefit of assimilating altimetry data in global ocean models to improve the monitoring of offshore oil and gas operations and in mitigating hazardous spills.

SUCCESS STORY FOR OIL SPILL RESPONSE

SS7) NOAA Gulf of Mexico (GOM) monitoring provides altimetry-based maps to monitor the ocean conditions in the Gulf of Mexico in response to extreme events, e.g., the *Deepwater Horizon* oil spill during the summer of 2010 (www.aoml.noaa.gov/phod/dhos/index.php).

Ship route tracking

PROBLEM. Marine ecosystems are highly impacted by anthropogenic pressures from marine and terrestrial activities (Halpern et al. 2007). Harmful anthropogenic activities in marine ecosystems are often related to disturbances caused by shipping and marine vessel activity (Schwemmer et al. 2011; Fan et al. 2016). Thus, precise maps of vessel density and ship traffic are needed to improve the modeling of pollutants and alleviate the potential threat to marine biota.

SOLUTION AND PROOF OF CONCEPT. Altimetry-based wave height and current velocities allow tracking of ship traffic and are complementary to automated identification system (AIS)-based methods used in vessel monitoring system (VMS) and vessel traffic system (VTS) applications. Tournadre (2014) used an archive of seven altimeter datasets to detect and monitor ship traffic through a method of analyzing echo waveforms. A two-decade-long database of ship locations was produced and the estimated annual density maps from altimetry compared well with those obtained from the PASTA MARE project (an AIS application based on spaceborne and terrestrial sensors to estimate vessel density).

SUCCESS STORIES FOR SHIP ROUTE TRACKING

SS8) The National Space Institute at the Technical University of Denmark (also known as DTU Space), with the support of the ESA, has completed a feasibility study of an operational system for marine route optimization, namely, BlueSIROS (Satellite Integrated Route Optimization Service). The BlueSIROS system benefits from technological developments in satellite altimetry to provide accurate estimates of currents, wind speed, and wave height that can be used to improve ship routing (<https://business.esa.int/projects/blue-siros>). The system is intended to integrate altimeter missions including *CryoSat-2*, *Jason-2*, *Jason-3*, *Sentinel-3A/3B*, and, in the future, *Sentinel-6*. The proof-of-concept of the BlueSIROS system showed potential to minimize fuel consumption and air pollution, and to reduce fuel costs (Pedersen 2015).

Iceberg detection

PROBLEM. Monitoring changes in iceberg position and size and thus their impacts on marine conservation is of growing interest since they can affect safe navigation or transport of nutrients such as labile (potentially bioavailable) iron that significantly controls ocean productivity.

SOLUTION AND PROOF OF CONCEPT. Icebergs in open water produce a detectable signature in the thermal noise section of spaceborne altimeter echo waveforms, which can then be detected and analyzed. Although icebergs last for 3–6 years or less if they float into warmer water, their dynamic spatial distribution requires regular updating. It is not clear how frequently satellite altimeter-based iceberg mapping efforts are updated. However, the spatial resolution of altimeters is well suited to mapping of icebergs smaller than 3 km in length. Tournadre et al. (2008, 2012) demonstrated the validity of detecting small icebergs in the noise part of high-resolution (HR) altimeter waveforms. Tournadre et al. (2008), for example, detected more than 8,000 icebergs between December 2004 and November 2005 in the open water around Antarctica. They also showed that the annual distribution of icebergs is in good agreement with the main trends of Antarctic iceberg motion.

SUCCESS STORIES FOR ICEBERG DETECTION

SS9) The ALTIBERG project (supported by CNES) was launched in 2015, with the goal to develop a small iceberg database using the high-resolution waveforms of all past and present altimetry missions. The ALTIBERG database currently contains icebergs detected from 1992 to present for both Southern Ocean and Northern Hemisphere regions. In addition, the database provides estimates of mean monthly probability of iceberg, presence the mean iceberg area and the volume of ice on regular geographical grids. The ALTIBERG database is distributed through the CERSAT website (Centre ERS d'Archivage et de Traitement—the French processing and archiving facility for the satellites *ERS-1* and *ERS-2*, launched by the ESA) (<http://cersat.ifremer.fr/user-community/news/item/473-altiberg-a-database-for-small-icebergs>).

Monitoring marine wildlife habitat

PROBLEM. The Antarctic Circumpolar Current (ACC) hosts a small number of standing meanders that trigger mesoscale eddies. Such eddies are favorable feeding grounds for top predators such as elephant seals. The dynamics of these mesoscale eddies are not well documented and poorly quantified in the ocean due to the lack of in situ observations (Siegelman et al. 2019).

SOLUTION AND PROOF OF CONCEPT. Altimeter data have shown their potential use to identify meander areas in the Southwest Indian Ridge (Kostianoy et al. 2003). In addition, altimeter-derived diagnostics can infer the relation between mesoscale turbulence and the response of marine top predator, particularly when combined with increasingly available animal telemetry data for the region (www.meop.net/). Altimetry currently provides the most feasible approach to overcome the lack of biophysical observations capable of resolving oceanic mesoscale features at 40–50-km scales (Cotté et al. 2015; Dufau et al. 2016).

SUCCESS STORIES FOR MONITORING MARINE WILDLIFE HABITAT

SS10) The French Center for Biological Studies of Chizé (CEBC) from CNRS (www.cebc.cnrs.fr/?lang=en) uses satellite data, in particular from altimeters, to monitor the feeding

behavior of marine animals such as elephant seals. Satellite altimeter data provide CEBC the essential information needed to understand how elephant seals move and where they travel and feed with respect to ocean currents and eddy structures. The long record of ocean altimeter data enables marine biologists to analyze interannual and intra-annual variations in elephant seal behavior, and hence understand the impact of climate change on their habitat, feeding patterns, and population size, and to estimate their capacity to adapt to environmental change (www.cebcsnrs.fr/predateurs-marins/?lang=en).

Monitoring wetland dynamics

PROBLEM. Wetlands are crucial elements in the hydrological water cycle that can significantly affect terrestrial water storage. Ecosystem services provided by wetlands include fisheries support, water quality improvement, carbon sequestration, coastal protection from storm waves, and many more (Mitsch et al. 2015), and rank among the highest value in ecosystem service assessments (Costanza 1997) for all landscapes. Knowledge of the extent, seasonality, and other temporal and spatial characteristics of wetlands are of vital importance to promote their wise use and to halt the alarming decline in global areal extent of this crucial ecosystem resource (Finlayson and Spiers 1999). This is particularly important for managing shared wetlands and river basins that cross international borders (Ramsar Convention Secretariat 2010).

SOLUTION AND PROOF OF CONCEPT. Because wetland's physical extent changes seasonally, satellite altimeters, where available, adequately meet the requirements for wetland monitoring given its short latency (of less than a day) and a revisit period that can range from about a month to 10 days. Numerous studies have been performed to monitor seasonal changes in the storage of wetlands (Birkett 1995; Calmant et al. 2008; Ahmad et al. 2020). These studies have proven the power of using satellite nadir altimeters in assessment of hydrological water balance and anthropogenic impact on wetland water storage.

SUCCESS STORIES FOR MONITORING OF WETLAND DYNAMICS

SS11) Ahmad et al. (2020) recently quantified variations in volumetric storage for the seasonal wetlands of northeastern Bangladesh, locally known as “haors.” (Fig. 3). Haors support waterfowl populations (Ahmad et al. 2020), as well as subsistence and commercial fisheries, rice-growing activities, and rich grazing lands for domestic livestock, among other benefits (Nishat 2002). The study team used three radar altimeters, *Jason-3*, *Sentinel-3A*, and *Sentinel-3B*, to monitor haors heights and developed an operational monitoring system for Bangladesh Water Development Board (see <http://depts.washington.edu/saswe/haors>; Table 1). The altimetry data complemented the water height data gathered by NASA-supported citizen science-based project, the Lake Observations by Citizen Scientists and Satellites, to understand water storage variations in ungauged water bodies (LOCSS; see www.locss.org).

Reservoir monitoring in ungauged regions

PROBLEM. Understanding reservoir operation has become increasingly important with growing population, increasing water demands, and climate variability. However, monitoring reservoir operation in ungauged regions is hindered by limited, outdated, or nonexistent hydrologic data. The issue is exacerbated for international river basins due to the lack of data-sharing mechanisms between nations (Plengsaeng et al. 2014).

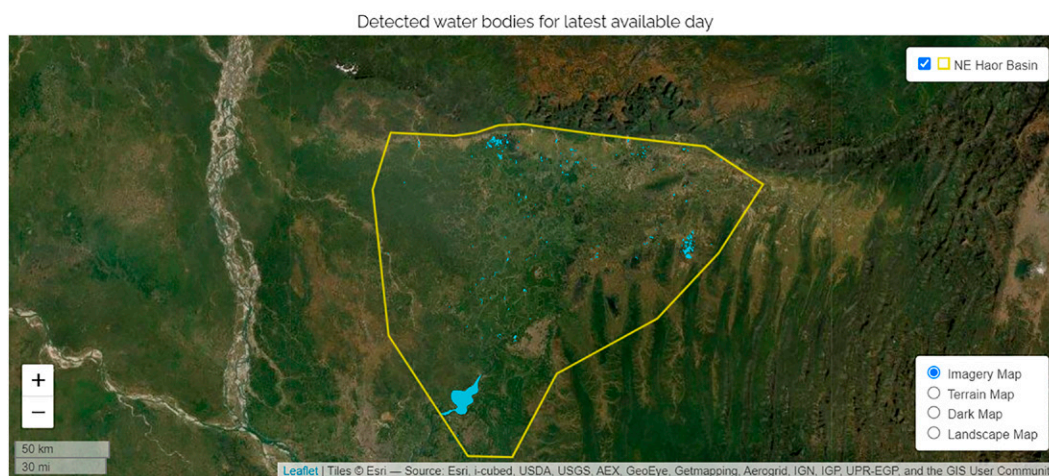
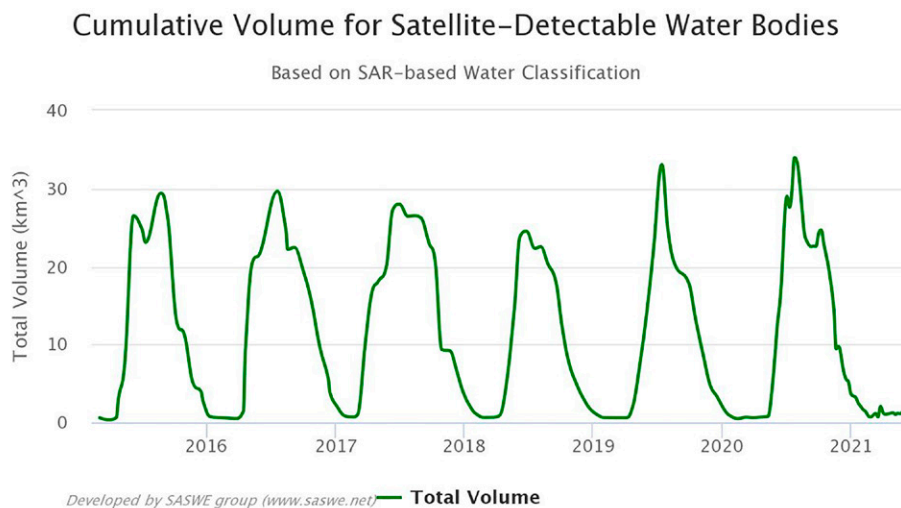


Fig. 3. Mapping total storage volume in a wetland located in northeastern Bangladesh (source: <http://depts.washington.edu/saswe/haors>).

SOLUTION AND PROOF OF CONCEPT. Various techniques have been developed and validated to provide accurate estimation of reservoir storage levels using altimeter measurements. Most reservoir operations are typically carried out at weekly or biweekly time scales. Therefore, most altimeters with overpasses are able to meet the latency and spatial resolution requirement for reservoirs with a surface area larger than 10 km². These altimeter-based water levels are currently made available globally through various operational satellite altimetry databases and archives, such as Hydroweb, and the Physical Oceanography Distributed Active Archive Center (PO.DAAC), maintained publicly by international space agencies. The use of such satellite-driven methods in modeling reservoir operations and river systems has been successfully implemented in operational environments for transboundary basins such as the Mekong basin (Bonnema and Hossain 2017), the Ganges–Brahmaputra–Meghna (GBM) basin in Southeast Asia (Biswas et al. 2021; Siddique-E-Akbor et al. 2014), the Indus River basin (Zhang et al. 2014; Iqbal et al. 2016, 2017), and the Nile River basin (Muala et al. 2014; Eldardiry and Hossain 2019). These studies concluded that, in most basins, satellite-based estimation of storage levels is in a high level of agreement with in situ data.

SUCCESS STORIES FOR RESERVOIR MONITORING IN UNGAUGED REGIONS

SS12) The Hydroweb database, developed at the LEGOS laboratory (Laboratoire d'Etudes en Géophysique et Océanographie Spatiales) in Toulouse, France, contains time series of water levels over large rivers, lakes, and wetlands at the global scale

(<http://hydroweb.theia-land.fr/>). The water levels are based on six radar altimetry missions including the U.S. Navy *Geosat Follow-On (GFO)*, the U.S. and French *TOPEX/Poseidon (T/P)*, *Jason-1*, *Jason-2*, and *Jason-3* and *Sentinel-3* missions, and the ESA *Envisat*. The reader is referred to Crétaux et al. (2011) for a detailed description of the procedures used for processing of water level data products in the link mentioned here or in Table 1. It should be mentioned that this service has now evolved to an operational time series with more than a decade of records that is constantly growing.

- SS13) The Global Reservoirs and Lakes Monitor (G-REALM) database, developed by the U.S. Department of Agriculture's Foreign Agricultural Service (USDA-FAS), in cooperation with NASA and the University of Maryland, routinely monitors lake and reservoir height variations every 10 days based on Jason series nadir altimeter data. Surface elevation time series data for large inland water bodies around the world are produced operationally using a semi-automated process. The products are provided to the USDA and for public viewing at https://ipad.fas.usda.gov/cropexplorer/global_reservoir/.
- SS14) The Sustainability, Satellites, Water and Environment (SASWE) research group at the University of Washington has developed a satellite-based operational system to monitor reservoir operation in ungauged regions. Recently, Biswas et al. (2021) built a comprehensive global reservoir monitoring framework to investigate the impact of existing and proposed dams on river systems using a satellite-based mass balance approach (www.satellitedams.net; Fig. 4). This satellite-based framework comprises two main components: 1) a hydrological model for the basin contributing to the flow upstream of the reservoir under consideration and 2) the integration of satellite imagery (from SRTM and Landsat) and altimetry-based water level to understand reservoir operation (i.e., deriving storage change and reservoir releases).
- SS15) The Indian Space Research Organization has successfully established many operational applications that now help in better assessment and management of water resources within India (www.isro.gov.in/). It provides data to monitor water levels in different Indian river basins (Ganga, Godavari, Brahmaputra, Gandak, Kosi, Yamuna, Son, Ghaghara) as well as 50 major reservoirs over India. Thakur et al. (2020) produced long-term time series of water level of 29 geometrically complex inland water bodies in India. The water level of these features was retrieved over two decades using

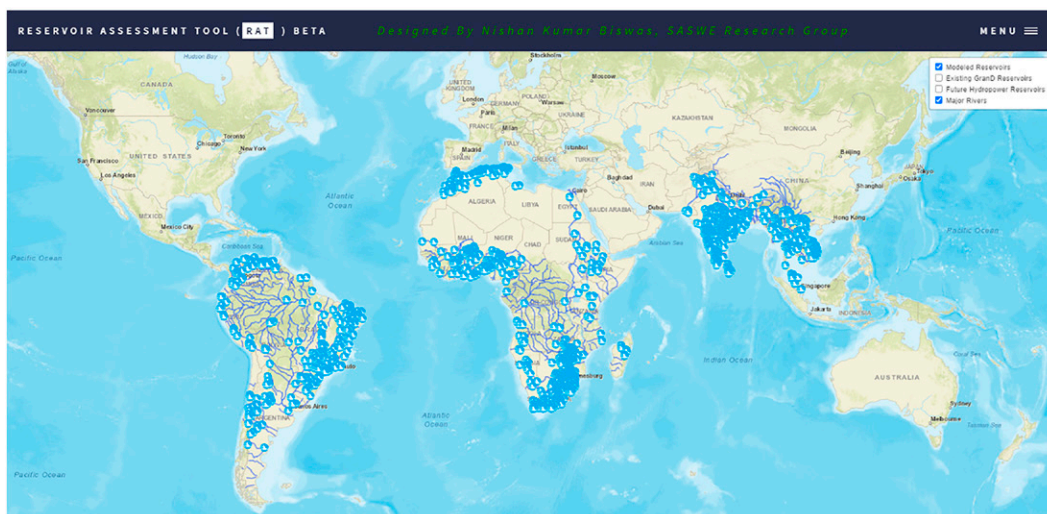


Fig. 4. Reservoir Assessment Tool (RAT) modeling reservoir operation in developing nations (source: www.satellitedams.net).

the *European Remote-Sensing Satellite-2 (ERS-2)*, *Environmental Satellite Radar Altimeter-2 (Envisat RA-2)*, and *SARAL altimeter data*.

Flood forecasting in international river basins

PROBLEM. Floods are among the most frequent natural disasters, and they are expected to become more destructive to life and property due to increasing populations living in floodplains (Yucel et al. 2015) coupled with increased occurrence of extreme events due to climate change (IPCC 2007). However, in international river basins, flood forecasting is challenging as sharing of near-real-time data on rivers across political boundaries among riparian countries is required, but not always forthcoming (Hossain and Siddique-E 2013). Therefore, it is critically important to develop flood forecasting systems in flood-prone international river basins that can assist in emergency preparedness and decision-making and can mitigate loss of life and property damage during flooding events.

SOLUTION AND PROOF OF CONCEPT. Previous studies have demonstrated the potential of satellite altimetry to forecast the flow in downstream stations by estimating the daily water levels in the upstream river reaches (Biancamaria et al. 2011; Paiva et al. 2013; Hossain et al. 2014a,b). For example, Hossain et al. (2014a) used *Jason-2* altimetry data at shortest latency (known as interim geophysical data records) to derive daily water levels and forecast the discharge downstream of the transboundary Ganges–Brahmaputra basin. Flow forecasts at 17 downstream stations (located in Bangladesh) was accomplished by propagating forecasts derived from upstream stations (located in India) through a hydrodynamic river model. The results showed that satellite altimetry, e.g., *Jason-2*, can be used to build a robust daily forecasting system for transboundary river flow that modulates according to the monsoon.

SUCCESS STORIES FOR FLOOD FORECASTING IN INTERNATIONAL RIVER BASINS

SS16) Work by Hossain et al. (2014a,b) was successfully implemented operationally by the Bangladesh Water Development Board (BWDB) to extend the range of flood forecasting and water management (see Table 1; www.ffwc.gov.bd and www.bwdb.gov.bd). The operational system is now being used by the BWDB to drive decisions during the flood season from July through October when daily warnings are issued nationwide for protection of life and property.

River level monitoring of changing rivers

PROBLEM. River stage and width are fundamental measurements required to understand the spatiotemporal hydrologic response of rivers to changing hydrological conditions. However, most global river basins are poorly gauged, or are ungauged completely (Brown 2002). Satellite altimetry can play a vital role in advancing understanding of river geometry. However, most altimeter processing techniques are developed for large rivers that maintain a relatively stationary width and course. In cases where rivers are relatively narrow or are subject to dynamic changes in width and course, such as in monsoonal climates and in alluvial floodplains, there is a higher chance of altimeter height data products representing non-water features of the radar return.

SOLUTION AND PROOF OF CONCEPT. Biswas et al. (2019) considered variable river geometry (time varying width and course) to improve altimeter height extraction techniques. They incorporated information on river extent composed of river width and course (i.e., path) from visible (Landsat) and Synthetic Aperture Radar (SAR) platforms (Sentinel-1). Applying the extent-based approach in South and Southeast Asia, they found that SAR was able to improve the

altimeter (*Jason-3*) based river height estimation at locations where rivers change width and course more frequently. Having such up-to-date information on river height for dynamically changing rivers is critical for water agencies to calibrate hydrodynamic models for flood forecasting and floodplain management.

SUCCESS STORIES FOR RIVER LEVEL MONITORING OF CHANGING RIVERS

SS17) The extent-based approach by Biswas et al. (2019) is currently publicly available and is operational as a dynamic river width-based altimeter height visualizer application (<https://depts.washington.edu/saswe/jason3/>). Through this application, the user can retrieve river heights in near-real time for more than 150 virtual river stations in South and Southeast Asia. The river height extraction in the visualizer application provides two different estimates: 1) based on using only *Jason-3* altimeter and assuming a static (fixed) river width and 2) based on the latest river condition inferred from the most recent Sentinel-1 SAR imagery (i.e., extent-based approach). The altimeter height visualizer has been in operation since 2019 serving many water managements stakeholders of South and Southeast Asian nations (Fig. 5).

SS18) The Asian Disaster Preparedness Center (ADPC) launched a Virtual Rain and Stream Gauge Data Service (VRSGS) for the Lower Mekong nations. This service provides improved near-real-time rainfall and stream height data products from publicly available satellite measurements by creation of a virtual network of rain gauges and stream gauges over the entire Lower Mekong region. The VRSGS service uses water elevation estimates from satellite altimetry, e.g., *Jason-2* and *Sentinel-3A/B* data products, and leverages a wider range of ground measurements to ensure better calibration of satellite-based estimates (<https://vrsg-servir.adpc.net/>). The goal of the VRSGS is to support effective decision-making by ADPC for Cambodia, Laos, Myanmar, Thailand, and Vietnam of the Mekong region. Examples for applications that can benefit from VRSGS service include nowcasting, flood forecasting and warnings, water resource management and landslide early warnings, and reservoir operation and transboundary river flow management (Basnayake et al. 2016, 2017).

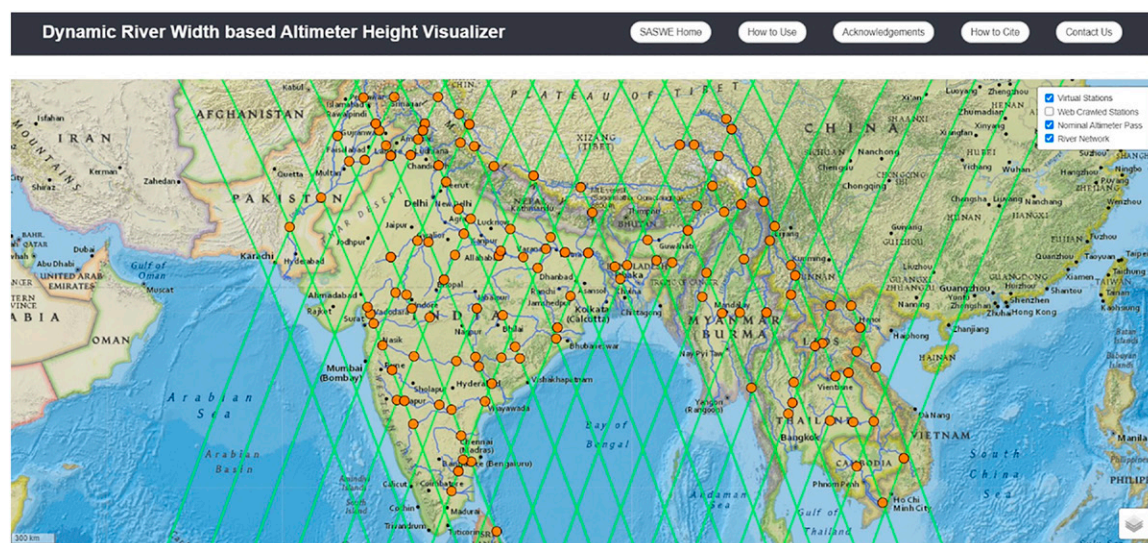


Fig. 5. Dynamic River Width based Altimeter Height Visualizer serving stakeholders in South and Southeast Asian nations (image from <https://depts.washington.edu/saswe/jason3/>).

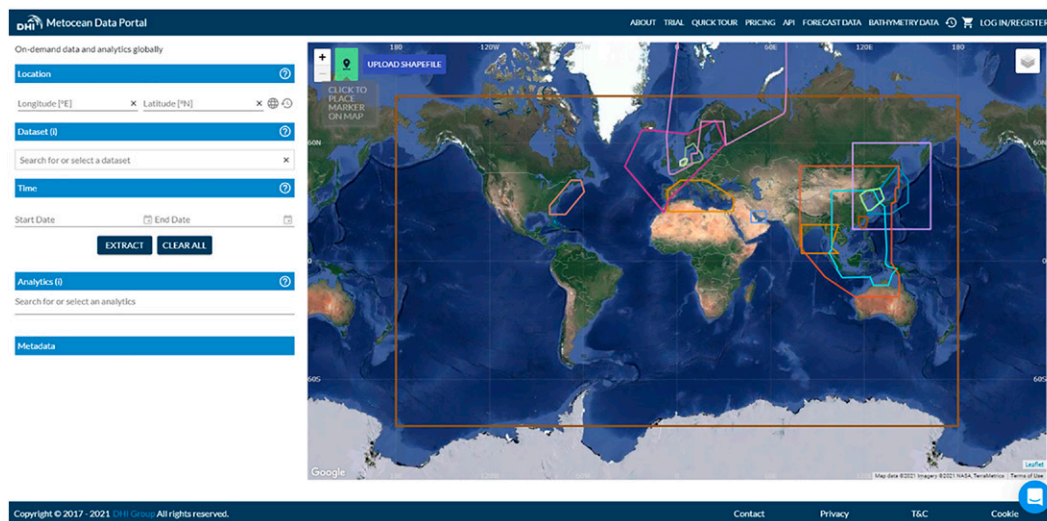


Fig. 6. MetOcean database portal developed by the DHI group to download and validate meteorological and oceanographic data (image taken with kind permission from www.metocean-on-demand.com/).

Development of offshore wind farms

PROBLEM. As global economies and governments strive to minimize reliance on fossil fuels, research and operational focus looks toward the sustainable development of renewable energy sources. Wind farms, including those offshore, are one of the most promising alternative methods to generate power based on renewable energy sources for coastal regions. Thus, identifying the potential location of wind energy production is essential for successful deployment of offshore wind farms. However, in situ measurements are usually limited to discrete locations, while model simulations are typically run at coarser resolutions.

SOLUTION AND PROOF OF CONCEPT. Unlike the limitations of models and in situ data, satellite altimeter data can provide horizontal wind speed variations offshore in great detail and over large areas (Badger et al. 2014; Hasager 2014; Zen et al. 2021). Zaman et al. (2019) evaluated offshore wind energy resources in Malaysia using multimission satellite altimeter data. They found that the satellite altimetry technique was able to provide accurate coverage for wind and wave data (validated with buoy measurements from two offshore sites).

SUCCESS STORIES FOR DEVELOPMENT OF OFFSHORE WIND FARMS

SS19) The Danish Hydraulic Institute (DHI) in collaboration with Ørsted (formerly DONG Energy) developed a 35-yr database, named the MetOcean database, which includes meteorological, hydrodynamics, and wave data covering northern European seas. The database was developed through a combination of meteorological data, in situ measurements, and satellite altimeter data (Fig. 6, www.metocean-on-demand.com/). Ørsted is now using MetOcean to decrease the amount of time needed to identify potential locations of offshore wind farms. DHI and Ørsted have successfully applied the MetOcean data in several local wind farm projects in Denmark.

Discussion of opportunities and challenges

In general, our review indicates that a few common factors have enabled the gradual multiplication of success stories of altimeter data application. For example, the global all-weather coverage, particularly over the oceans and vast ungauged water bodies such as large lakes, contributed to altimeter data becoming an indispensable source for water height data.

In addition, the availability of near-real-time data at the relatively short latency of a few hours has encouraged operational assimilation for many time-sensitive applications. Finally, the multidecadal record of altimeter data has allowed potential users to perform retrospective studies of altimeter data during key historical anomalies of societal importance (e.g., flood forecasting during a wet year, or reservoir monitoring during a drought).

By virtue of having a multidecadal heritage, the altimeter data time series has supported many applications spanning multiple sectors of the economy over time. In our review, the tracking of fishing zones in the early 1990s was one of the earliest, tangible success stories we identified. As awareness of altimeter data applications grew, the natural progression of use was for marine, coastal, and estuarine applications, such as marine shipping, storm surge modeling, and offshore engineering, among others. As altimeter data continued to become more accessible, thanks to the advancements in information technology and publicly accessible data portals developed by programs of CNES (Aviso), NASA (PO.DAAC), and the European Union's Copernicus program, terrestrial applications that traditionally use in situ (gauge) data on lakes and rivers started to expand by the early 2010s. Last, but not least, the sustained outreach efforts by space agencies that began in the early 2010s, and the increased collaboration between scientists and data experts (Hausman et al. 2021), appears to have played a role in recent acceleration of altimeter applications (Hossain et al. 2019).

However, significant limitations and challenges remain in order for new success stories of altimeter data to flourish. The International Altimetry Team (2021) provides an excellent summary of these challenges. For example, the team reported that even though there is global coverage, the footprint of each nadir altimeter track spans only a few kilometers and provides a spatially limited view of targets that are geographically vast (such as oceans and large lakes). The planned Surface Water and Ocean Topography (SWOT) mission, with its wide swath (spanning 120 km) altimetry measurement, is expected to mitigate this issue of limited footprint. However, SWOT is a research mission with a nominal life span of only 3–5 years. SWOT also will not improve the temporal sampling, particularly in the tropics. Thus, further investments in altimeter missions will be required to address current temporal sampling limitations. The constellation of altimeters today with its limited design span remains vulnerable to discontinuity in data record. The International Altimetry Team (2021) reports that “today we are just one satellite-failure away from a gap in the 28+-yr record that has, so far, been accumulated on sea level rise.”

Development of altimeter data and improvements to tracking algorithms have always hinged on the availability of quality-controlled in situ data on oceans and water bodies. Many of the success stories on altimeter application required in situ records on river, reservoir, or storm levels to validate and calibrate an operational system. With the gradual decline of in situ monitoring networks in many regions of the world, successful altimeter application may require a reinvestment in ground networks, including citizen science-driven monitoring programs (Little et al. 2021). Another challenge is that of data informatics. Cloud computing, which no longer requires local download and storage of data, is becoming the norm for accessing, analyzing, and using Earth observation data. Data from missions such as *Sentinel-6 Michael Freilich* (and SWOT, after launch) are now being hosted in repositories where users require basic literacy in cloud computing (Hausman et al. 2021) or where access to emerging cloud-based data archives is completely transparent to users. However, most among the scientific and end-user community lack such literacy. This essential need will require additional training and education (Hossain et al. 2019, 2020) in order to satisfy the requirements of satellite data users. The scientific community must keep up with advances in data informatics in order to continue its vital role in brokering science-based application of altimeter data into the future, particularly with newer and more innovative missions, such as SWOT.

Conclusions and future perspectives

Satellite altimeter data provide reliable, long-term observations of the dynamics of the global ocean, inland waters, sea ice, and ice sheets. These observations also make it possible to understand ocean, lake, wetland, and river dynamics, particularly in regions that lack in situ observations. The growing constellation of altimeter satellites, coupled with a longer time series and improved access to higher-level data products, results in greater quantity (increasing record) and quality (increasing accuracy) of data and information products available to researchers and decision-makers. To fully reap the benefit of satellite altimetry, however, an understanding of altimeter products is required, as well as an understanding of their scientific basis, and their utility for a range of diverse applications. With the availability of nearly three decades of altimeter data, agencies involved in environmental monitoring and natural resource management have become increasingly keen on leveraging altimeter data for operational decision support applications. Our review presented selected success stories that incorporated altimeter data into a wide range of inland and ocean applications. These stories provide further inspiration for creating more opportunities for the world to benefit from and more fully realize the potential of altimeter data.

Our review of altimeter success stories demonstrates the value of altimeter data for diverse oceanographic applications. Altimeter data are the only source of global sea surface height observations. Capturing ocean dynamics using satellite altimetry is of critical importance for the development of operational oceanography services such as safe marine operations, navigation at sea, and pollution monitoring. In coastal and inland areas, altimeter data were found to be particularly effective for use by developing countries and in ungauged regions where in situ data are not readily available or are made inaccessible between nations. Flood forecasting and global monitoring of reservoir operations are two examples of altimeter applications in developing nations. In addition, our review revealed that altimeter data have become a fundamental input to various models used routinely in decision-making. This was evident in several success stories reviewed in this study, such as commercial and recreational fisheries, ship navigation, and offshore wind farm design.

Development of altimeter-based datasets and the continued promotion of success stories at the global scale will support and highlight the potential societal applications of the forthcoming SWOT mission (<https://swot.jpl.nasa.gov/>). SWOT will provide global river elevations and slopes, and water extent of inland water bodies with an unprecedented global spatial resolution (Pavelsky et al. 2014; Biancamaria et al. 2016). SWOT, with its newly developed wide swath technology, is expected to overcome some of the challenges of using satellite altimetry, especially limited ground track spatial resolution and low revisit time. For example, global observations of small mesoscale oceanographic signals, within a scale of 10–200 km, are not well captured with the present constellation of altimeter coverage. SWOT will have the potential to improve our understanding of the ocean dynamics by resolving the full spectrum of mesoscale variability within this scale. Conventional altimeters are generally limited to features that are roughly 200 km or larger. SWOT will also host a Jason-class nadir altimeter that will function synergistically with the novel wide swath measurements of water surface. It must be noted, however, that SWOT is primarily a science mission with a duration planned for 3–5 years. The value of SWOT data for research topics and modeling beyond this time span is clear. To support sustainable operational applications from stakeholders, or for commercial uses, continued expansion and maintenance of the current suite of altimeters in conjunction with the SWOT mission (as reported by Bonnema and Hossain 2019) is critical. This limited life span can thus be mitigated while a possible continuity mission for SWOT is planned and launched.

The success stories presented in our review represent significant efforts by the scientific and stakeholder communities to bridge the gap between the availability of satellite products

and their real-world uptake for making practical decisions for societal benefit. Our review has revealed that relying on satellite altimeter data, and integrating it into decision-making processes, requires continuous public outreach and delivery of training programs to user communities. For instance, as a part of the COASTALT project (www.coastalt.eu), an international coastal altimetry community has been built with participation of scientists, engineers, and managers who contribute to the development of altimetry applications in the coastal zone. The opportunity exists for the community of experts to hold regular workshops to feature relevant studies in altimetry and to provide training for early career scientists and potential stakeholders. We believe similar efforts, scaled up to more users, and offered more frequently by the scientific community, would successfully support and promote the use of data and information products of future missions such as SWOT, and of current altimeter missions such as *Jason-3* and *Sentinel-6 Michael Freilich*, to synergistically address many unsolved global to regional environmental challenges posed to society today.

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