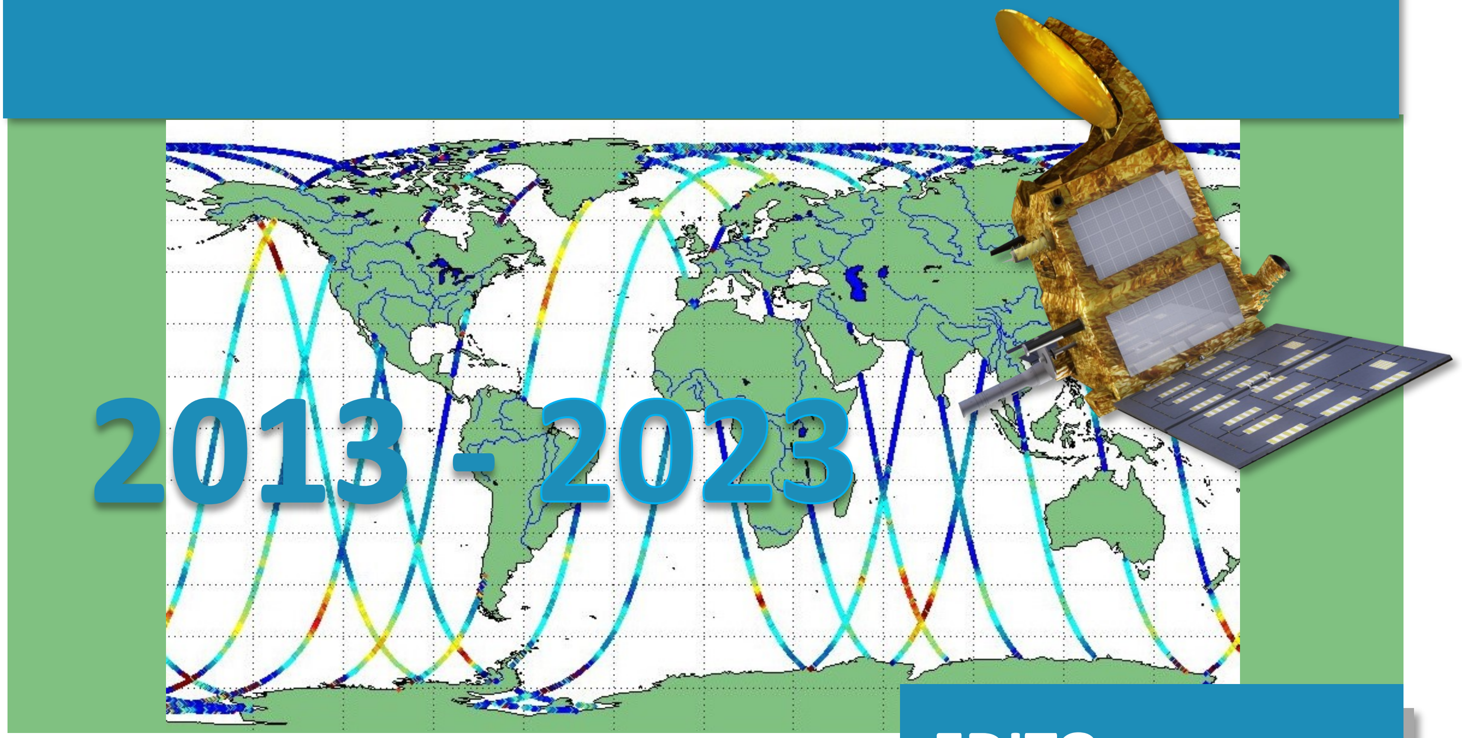
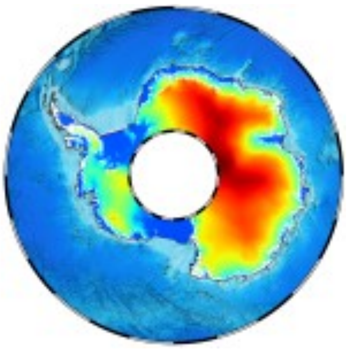
Special Issue

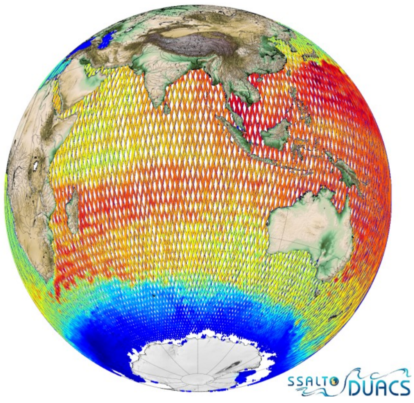
Newsletter SARAL



Special 10 years

The scope of this Special Issue, celebrating SARAL/AltiKa 10-yr anniversary, is to highlight several domains in which SARAL/AltiKa has highly contributed, being a real driver of innovation.





Topics

SARAL/AltiKa is an altimetric satellite mission that opens the doors of interdisciplinarity. The extended capabilities offered by the Ka-band allowed to further open some new frontiers of altimetry, such as coastal oceanography, cryosphere sciences, hydrology, beyond the traditional scope of open ocean studies.

EDITO

The SARAL/AltiKa mission was launched on February 25, 2013 as part of a collaboration between the Indian Space (ISRO) and the French Space Agency (CNES). The mission objectives are primarily the observation of oceanic mesoscale features, as well as coastal oceanography, global and regional sea level monitoring, data assimilation and operational oceanography. Secondary objectives include ice sheet, sea ice and inland water monitoring. The success of SARAL/AltiKa has been made possible by a very fruitful and efficient collaboration between ISRO and CNES and thanks to the highly valuable exchanges between scientists from both countries.

Summary

Page 3 **Introduction**
Pascal Bonnefond, Jacques Verron

Page 5 **Contribution from SARAL/AltiKa towards various applications for last 10 years in INDIA**
JV Thomas, Rashmi Sharma, Suchandra Aich Bhowmick, Pierre Sengenes, Jacques Verron and Pascal Bonnefond

Page 11 **Daily assimilation in operational wave forecasting models**
Lotfi Aouf

Page 12 **Space geodetic observations for estimating Ocean Heat Content change over the Atlantic Ocean**
Rousseau Victor, Meyssignac Benoît, Ablain Michaël, Fraudeau Robin, Blazquez Alejandro, Marti Florence

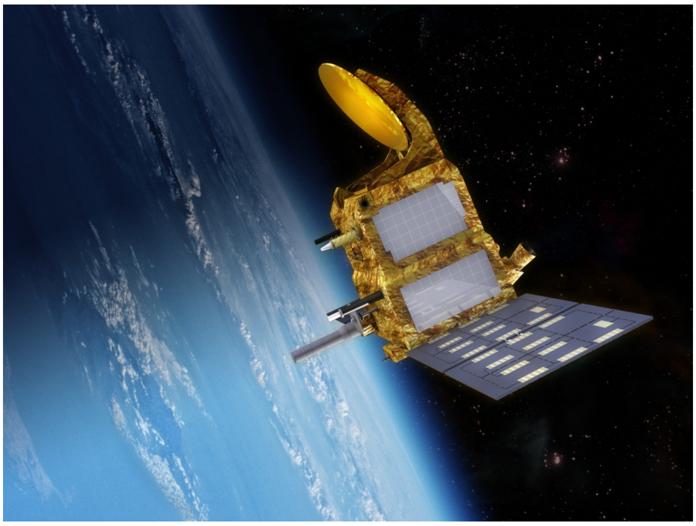
Page 14 **SARAL's contribution to advances in understanding the fine scales of the coastal ocean**
Alice Carret, Florence Birol

Page 16 **Added-value of SARAL for coastal sea level processes**
Diego Vega, Ananda Pascual

Introduction

JV Thomas, Rashmi Sharma, Suchandra Aich Bhowmick, Pierre Sengenes, Jacques Verron and Pascal Bonnefond

The SARAL/AltiKa (SARAL also means “Easy” in Sanskrit) mission conducted by the Indian Space Agency (ISRO) and the French Space Agency (CNES), is the first altimetric mission based on the Ka-band. Launched on February 2013, Calibration and validation investigations have rapidly shown that the quality of the data meets the expectations and initial mission requirements. Data delivery to users has also been very rapid and has been available on EUMETSAT, CMEMS and CNES servers. The quality of all products met or exceeded mission requirements. Many scientific investigations were conducted and much of the scientific community has been quick to take advantage of the data.



In 2015, SARAL/AltiKa had an increasing need to reduce the load on its reaction wheels in order to extend the mission beyond the nominal 4-year lifetime of the satellite. ISRO and CNES finally decided that the best strategy was to stop all orbit control maneuvers and let the altitude decay naturally. SARAL/AltiKa left its repetitive orbit to begin a new phase called "Drifting Phase" (DP) starting on July 4, 2016. Data processing and latency remained unchanged. From this date, the SARAL satellite is free of station maneuvers; the repetitive ground track is no longer maintained and slowly drifting. In short, this new orbital configuration has required some user adjustments, especially in hydrology, as the algorithms needed to be modified accordingly. On the contrary, some other applications benefited from this new orbital configuration.

The SARAL/AltiKa’s main scientific objectives were to provide data to oceanographers to improve knowledge and understanding of the ocean mesoscale variability. These scientific objectives regarding mesoscale ocean dynamics come under different aspects: observations, theoretical analyses, modeling and data assimilation. Climate studies are also concerned by SARAL/AltiKa not only through the improved access to the sea-level measurements but also by contributing to understand the role of mesoscale features on the climate variability at large space and time scales. Coastal oceanography was also directly interested by the SARAL/AltiKa data as well as many downstream applications including operational oceanography. SARAL/AltiKa's other objectives include inland waters (lakes, rivers, enclosed seas), monitoring of sea-level changes, polar oceans, wave and wind fields, continental and sea ice, etc.

Clearly, SARAL/AltiKa is an altimetric satellite mission that opens more than previously the doors of interdisciplinarity. Indeed, the extended capabilities that are offered by the Ka-band allow to open even more widely some new frontiers of altimetry such as coastal oceanography, cryospheric sciences, hydrology, beyond the traditional scope of the open ocean investigations. It is therefore very significant to note that an initially oceanography-dedicated satellite like SARAL/AltiKa opens the way – thanks to the Ka-band – to satellite projects not only in oceanography like SWOT but also in glaciology (CRISTAL), in hydrology (SWOT, SMASH) or even in geodetic directions.

Since the beginning of the mission, the SARAL/AltiKa Ka-band altimetric mission has taken a full position in the altimetric satellite constellation that has been built over years providing a major push to oceanographic sciences. The huge scientific results are exemplified by the special issue dedicated to SARAL/AltiKa and many other more recent papers, notably in the “25 Years of Progress in Radar Altimetry Special Issue”, in which readers can refer to go in further details. The scope of this NewsLetter, celebrating SARAL/AltiKa 10-year anniversary, is to highlight only some of the several domains in which SARAL/AltiKa has highly contributed, being a real driver of innovation.

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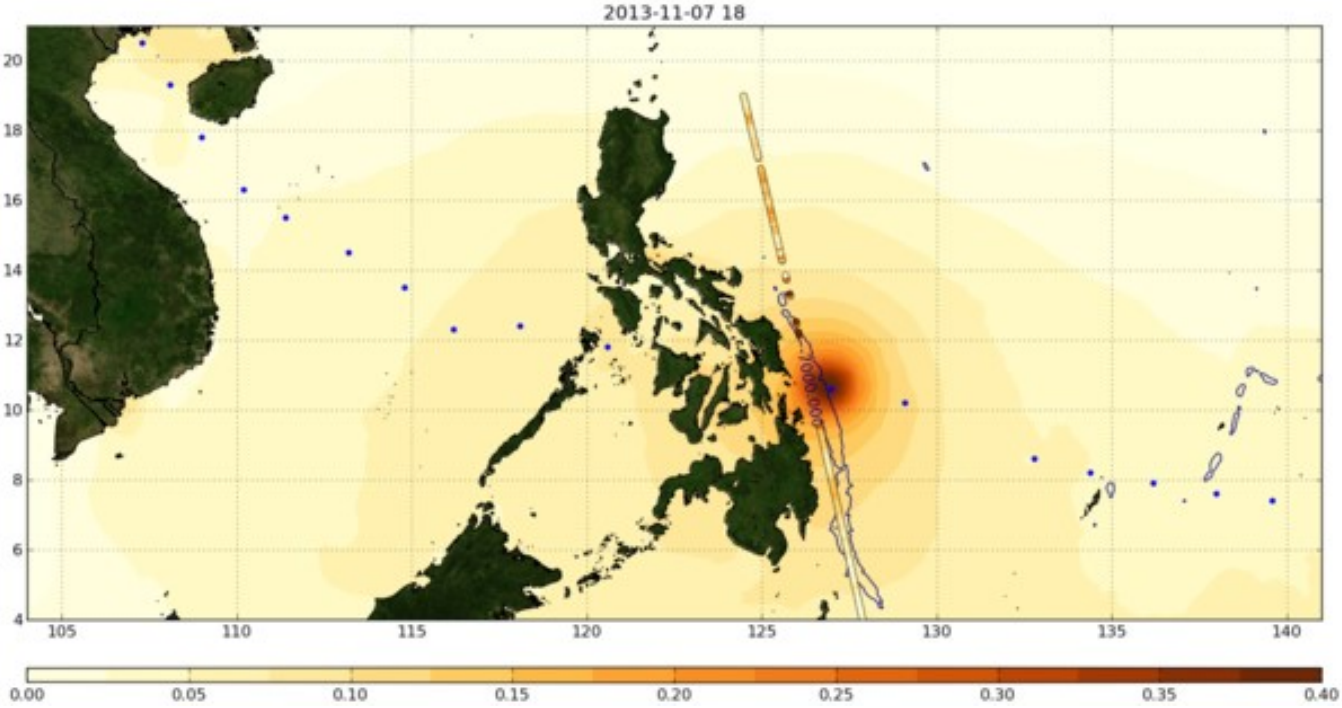

Pass 821 of SARAL/AltiKa altimeter flying over Haiyan superimposed on MOG-2D combined sea level on 2013-11-07 at 18:00 UTC (in meters). The trajectory of the Typhoon is superimposed with blue circles. Credits CNES/CLS, Further information on Image of the month, Nov. 2013 : Typhoon Haiyan seen by SARAL.

Contribution from SARAL/AltiKa towards various applications for last 10 years in INDIA

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The SARAL (Satellite with ARGOS and AltiKa) a joint mission, by CNES (Centre National d'Etudes Spatiales) and ISRO (Indian Space Research Organization) launched in 2013, was world's first high frequency altimeter, supposed to be technology demonstration, broke the boundaries of traditional altimetry (Verron et al 2020). AltiKa on-board SARAL, was first ever high frequency Ka-band altimeter unlike traditional Ku or C band altimeters. Major advantage of the higher frequency was significant reduction in ionospheric correction, improved vertical resolution and smaller footprint size (Verron et *al* 2018). It was originally designed to be the gap filler between ENVISAT and Sentinel-3, but it demonstrated its capabilities, beyond its primary objectives of oceanic mesoscales and is still going strong. Apart from climate change and operational oceanographic studies, due to its better sampling, it contributed immensely for the coastal areas, inland water studies, cryosphere domain and geodesy, even in the drifting phase. This also demonstrated that one is able to meet science requirement with Ka-band without much noise in signal due to clouds and rain. February, this year, SARAL/AltiKa has successfully completed a decade of earth observations with different phases of operations, viz. Exact Repeat Mission, (ERM, March 2013 - July 2016), Drifting phase, (DP, July 2016 - January 2018) and then to Mis-Pointing phase, (MP, February 2018 - till date). A comprehensive compilation of the initial results from this wonderful mission is available in [special issue of Marine Geodesy]() (2018). During these various phases of the mission, ISRO has also extensively utilised the data, not only to demonstrate its capabilities but also for various applications in the domain of retrievals, coastal and deep ocean, data assimilation and geodesy.

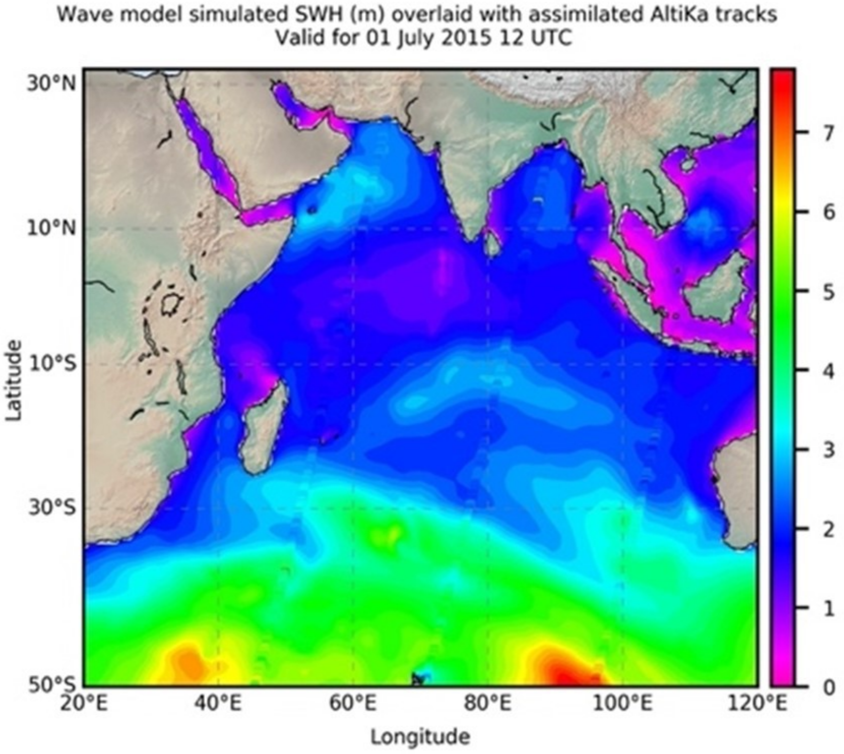

Figure 1: AltiKa assimilated wave model output, with AltiKa tracks overlaid

Data assimilation in Wave model

Significant Wave Height (SWH) observations from SARAL/AltiKa over Indian Ocean region were assimilated in spectral wave models (WAVEWATCH III and Simulating Wave Near shore, SWAN) with state-of-the-art techniques like particle filter, optimum interpolation, etc. (Bhowmick et *al.*, 2015, 2019). Near real time predictions are made available through ISRO's data centre MOSDAC (Meteorological and Oceanographic Satellite Data Archival Centre). Even with the degradation of attitude in MP phase, AltiKa is able to provide useful wave height observations, and are being assimilated in the wave models till date (Sharma et *al.,* 2022, Bhowmick et *al* 2023). Technology transfer of these wave prediction systems to Indian operational agency (Indian National Centre for Ocean Information Services, INCOIS) and Indian Navy (Seemanth et *al.*, 2021) were pivotal activities undertaken by ISRO under SARAL/AltiKa utilization project. A snapshot of data assimilative wave model output is shown in Figure 1 (see on previous page).

Data assimilation in ocean model

Ensemble Optimum Interpolation (EnOI) based assimilation technique was developed (Agarwal et *al.*, 2022, Ratheesh et *al.*, 2014) and AltiKa data was assimilated in the Modular Ocean Model (MOM3) and Princeton Ocean Model (POM, Ratheesh et *al.*,2015) for improved prediction of ocean currents and sea level. The incorporation of SARAL/AltiKa SLA successfully simulated the presence of a deep depression during cyclone Phailin in the vicinity of the eastern coast of India and is presented in Figure 2. Several sensitivity experiments were also conducted with ocean model to study the impact of orbital shifts of SARAL/ALtiKa from ERM to DP and MP mode. It was observed that domain averaged errors in simulated SLA for the ERM, DP and MP were 2.48 cm, 2.88 cm and 2.7 cm respectively. This signifies trivial differences in simulated SLA even for the mesoscale signals emphasizing suitability of SLA data from SARAL till date. Near real time predictions of ocean state is available at MOSDAC.

Coastal geostrophic current estimation

SARAL/AltiKa have been used for estimating the alongshore geostrophic current in the Indian coastal region with a more spatial coverage at a cost of reduced temporal coverage as compared to the reference altimeter missions like Jason-2 (Chaudhary et *al.* 2019). A quantitative analysis of the SARAL/AltiKa derived coastal currents with high frequency radar currents in Eastern coast of India for the period 2013-2016 demonstrated that altimeter derived currents match fairly well with HF radar data beyond 30 -40 km (Figure 3, below).

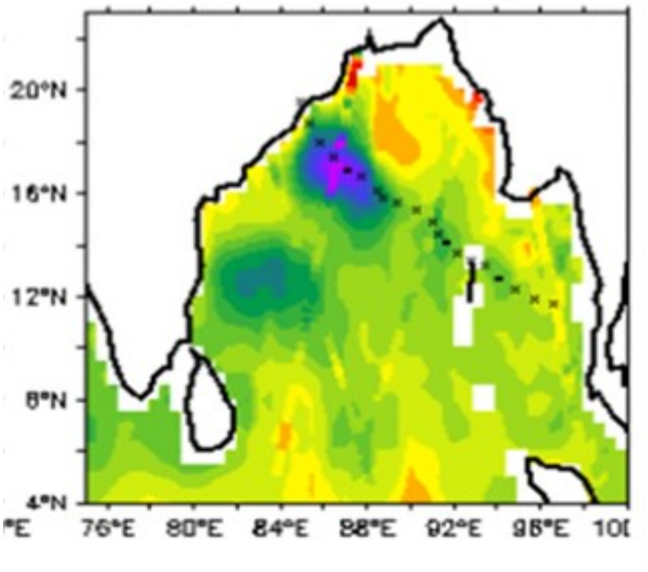

Figure 2: Snapshot of SLA for 12 October 2013 during Cyclone Phailin with assimilation of from SARAL/AltiKa, Jason-2 and Cryosat-2. The black dots show the cyclone track.

Inland water studies

One of the major concerns in the current century is depletion of freshwater in the rivers, lakes, and reservoirs. Radar altimeters over inland water bodies generally acquire complex waveforms due to land contamination within the foot-print. The accuracy of the retrieved water level can be enhanced, with the

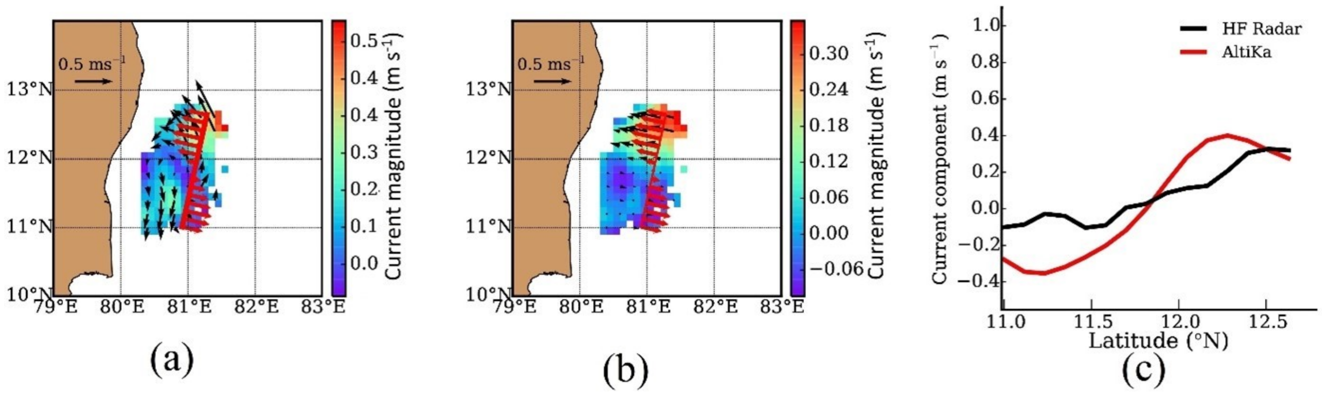

Figure 3: Across-track current component from SARAL/AltiKa (a) overlaid over actual geostrophic currents from HF radar. (b) overlaid over geostrophic current component of HF radar along the altimeter across-track direction. (c) Geostrophic current component (ms^{-1}) for (black) HF radar and (red) SARAL/AltiKa

knowledge of the waveform shape prior to retracking, the choice of the retracking algorithm and dedicated inland geophysical range correction algorithms (Chander et *al.* 2017). AltiKa waveforms along with traditional Ku band waveforms from Jason-2 were analyzed for observing the land to water and water to land transitions impact on the waveform-shape over Brahmaputra River, India (Desai et *al.* 2015). Further a study was carried out over Ukai reservoir to identify the dominant waveform shapes over the inland water and for these multipeak echoes a sub waveform based retracker was developed especially for inland waters (Ganguly et *al.* 2015). The retrieved range was found to be performing better than the retackers available in the Geophysical data Records products (Chander et *al.* 2017). SARAL/AltiKa due to its better vertical resolution and smaller footprint was an excellent instrument for hydrology. It was used extensively (Figure 4, can provide good image) for monitoring the water level of major Indian rivers (Dubey et *al.* (2014, 15a, 2015b), Gupta et *al.*, 2015a, 2015b), reservoirs (Chander et *al.* 2017, Ghosh et *al.* 2015, Thakur et *al.,* 2021), predictive model development between upstream and downstream track, and providing boundary conditions to hydrodynamic models (Dhote et *al.* 2021). One such work was carried out in a sparsely gauged Brahmaputra River, India where SARAL altimeter deceived water level was used for multi-site validation of the HD model (MIKE 11) and construction of rating curves (RCs) for estimation of river-discharges (Dhote et *al.* 2021).

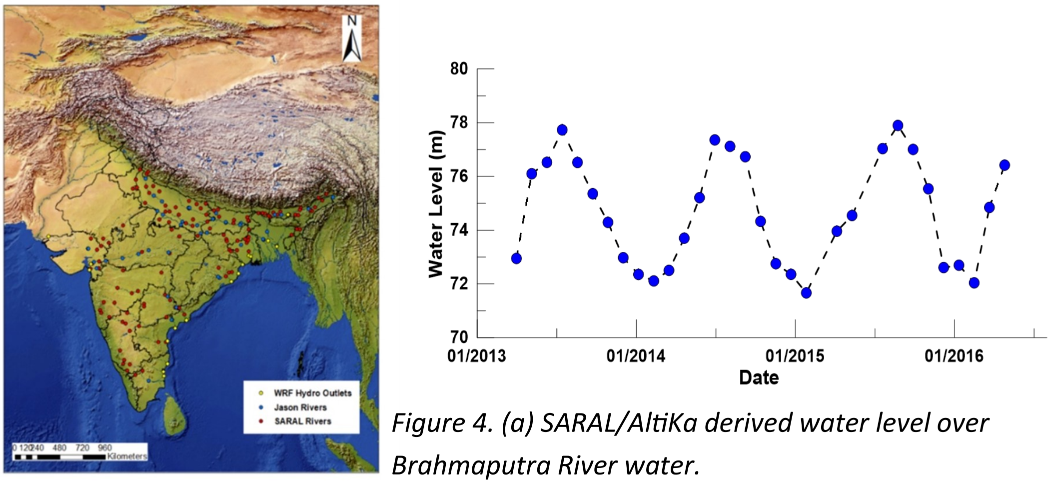

Figure 4. (a) SARAL/AltiKa derived water level over Brahmaputra River water.

Geodetic Applications

Global crossover analysis of Sea Surface Height (SSH) observations from SARAL/AltiKa suggests a stable performance throughout its life with similar range of standard deviations during ERM (5.8 cm), DP (5.9 cm) and MP (5.9 cm) periods (Krishna et *al.,* 2023). A Mean Sea Surface (MSS) model generated by adding DP and MP data from SARAL/AltiKa to the ERM stacks of SARAL/AltiKa and Jason satellite series is shown in Fig. 5a. Along-track sea surface slope estimates reveal that 99.9% of ERM and DP data and 93.8% of MP data are well within the bound of 1 micro radians (Fig. 5b). In addition, Higher along-track resolution achieved by SARAL/AltiKa (Krishna and Sreejith, 2021) would be beneficial in improving the marine gravity field which is essential for both scientific and exploration applications (Sreejith et *al.,* 2013; Sreejith et *al.,* 2016). Hence, continuity of the mission in the mispointing phase is highly recommended.

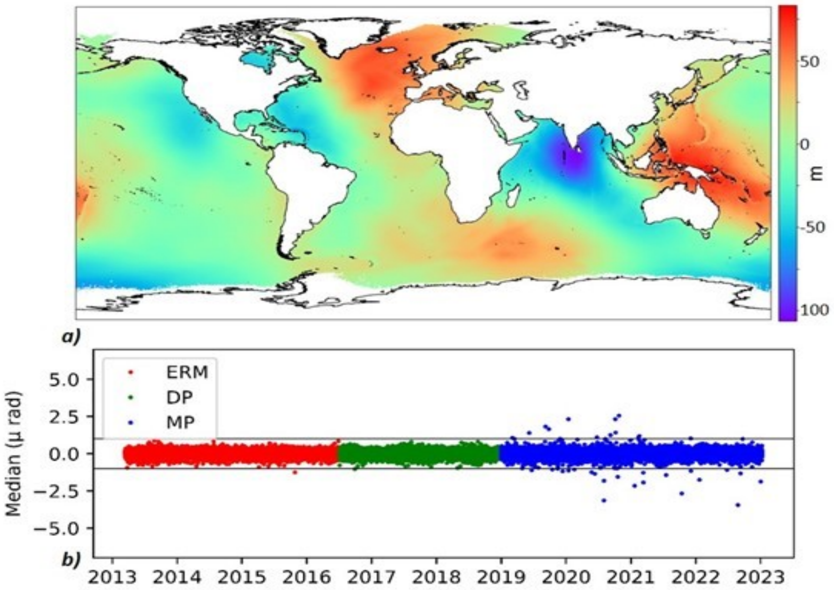

Figure 5: a) MSS model derived using SARAL/ALtiKa data b) Along-track sea surface slope estimates for ERM, DP and MP phases.

Cryosphere Studies

Altimetry provides a tool to monitor the changes observed over polar ice sheet and sea ice cover. Using AltiKa, an attempt was made to derive sea ice freeboard over Arctic region for the spring and autumn period of 2013 (Maheshwari et *al.* 2015) and Joshi et *al.* (2020) derived the sea ice thickness in the Antarctic region. AltiKa derived sea ice thickness was also utilised for the safer ship navigation (Gupta et *al.,* 2019). Spatial variation in the AltiKa derived elevations were investigated over Antarctic ice sheet (Suryawanshi et *al*., 2019a; Patel et *al.,* 2023) and ice volume loss over Greenland ice sheet (Chander et *al.,* 2015; Suryawanshi et *al.,* 2019b). Ku-band (Oceansat-2 scatterometer- OSCAT) and Ka-band (SARAL-AltiKa altimeter) data are concurrently utilised by (Singh et *al.,* 2015) to characterize polar surface features over the Antarctic region. An exercise was also carried out to understand surface properties in the polar regions using Principal Component analysis of normalised waveform for 5 x 5 km grid. The analysis shows that during mid-winter time, first 6 PCs contain approximately 95% target dependent spatial variations and first 3 PCs 83% variability. The visual appearance of surface features with first three PCs are shown in Figure 6. As 98 percent of Antarctica is covered with ice, the explained variation is assumed to be mainly ice surface variation.

Conclusion

SARAL/AltiKa has completed a productive decade of in-orbit operations. During this timeframe, despite several attitude related issues in between, it is continuing to provide us quality observations. AltiKa, a first time Ka band altimeter, demonstrated its ability to sample oceans with higher accuracy and smaller footprint. SARAL has been instrumental in providing high-quality observations and has made substantial contributions in serving key areas of operational oceanography, inland waters, cryosphere studies and geodetic applications. ISRO has taken a lead role in promoting the SARAL data in India through several technique developments, demonstrative applications and technology transfers for its utilisation by operational agencies for improvements in the ocean observations and predictions. SARAL still continuing its journey, expected to continue delivering valuable data to quench the scientific thrust and practical applications and contributing towards meeting the goals of UN Ocean decade (2021-2030).

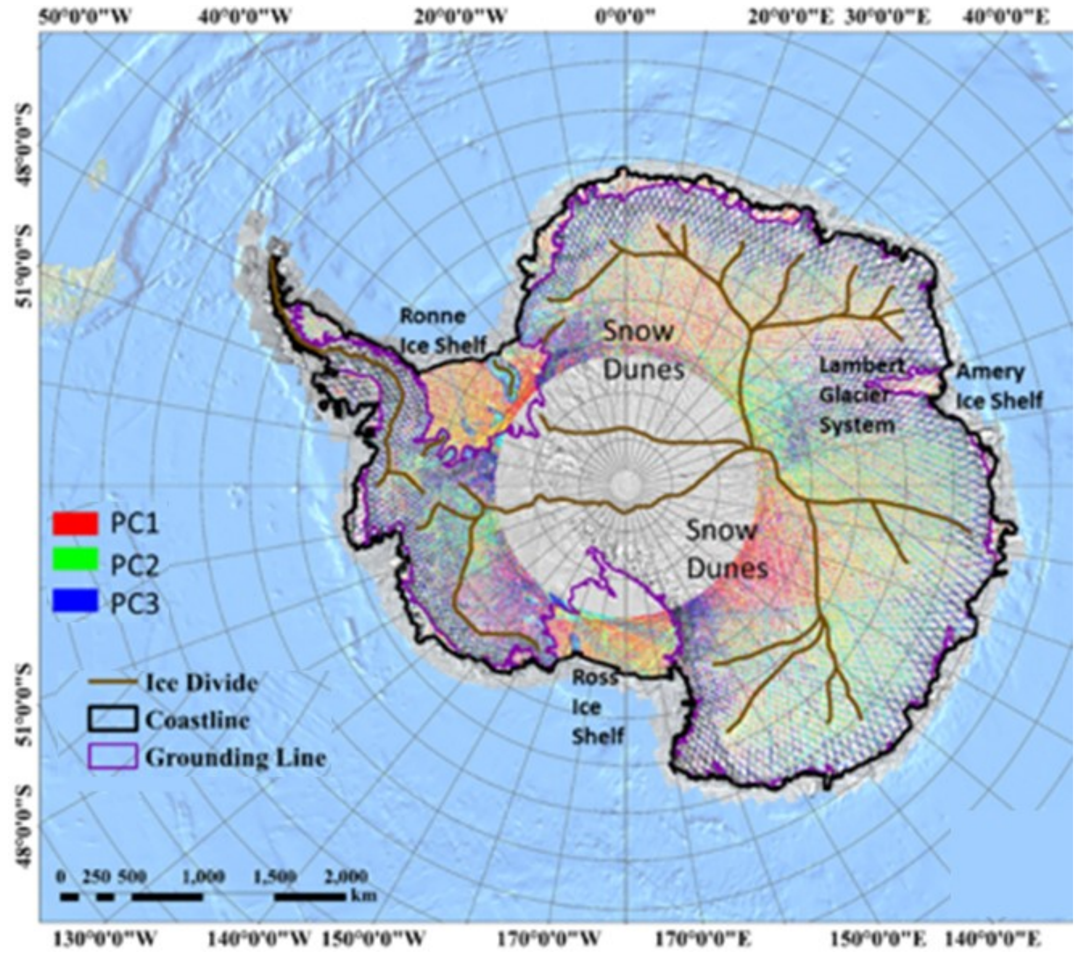

Figure 6:RGB composite of various ice features depicted by the first 3 PCA components over 5 x 5 km grid box.

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Daily assimilation in operational wave forecasting models

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Ten years of exploitation of SARAL mission shed light on improvement of wave forecast in typical coastal regions such Gulf of Biscay in the Atlantic Ocean and Gulf of Lion in the Mediterranean Sea. Significant Wave Height provided by SARAL/AltiKa are assimilated daily in operational wave forecasting models at Météo-France.

This plays an important role in the reliability of wave products distributed to the global and regional Copernicus Marine Service, and also for the improvement of wave submersion warnings during critical storm events in the metropolita coasts and overseas territories.

The AltiKa altimeter of SARAL has demonstrated its ability to observe with good quality all ranges of SWH, particularly for coastal forecasting models. The performance of the operatonal coastal wave model MFWAM with 2.5 km grid resolution driven by high resolution AROME winds has been significantly improved with the assimilation of SARAL small-scale SWH.

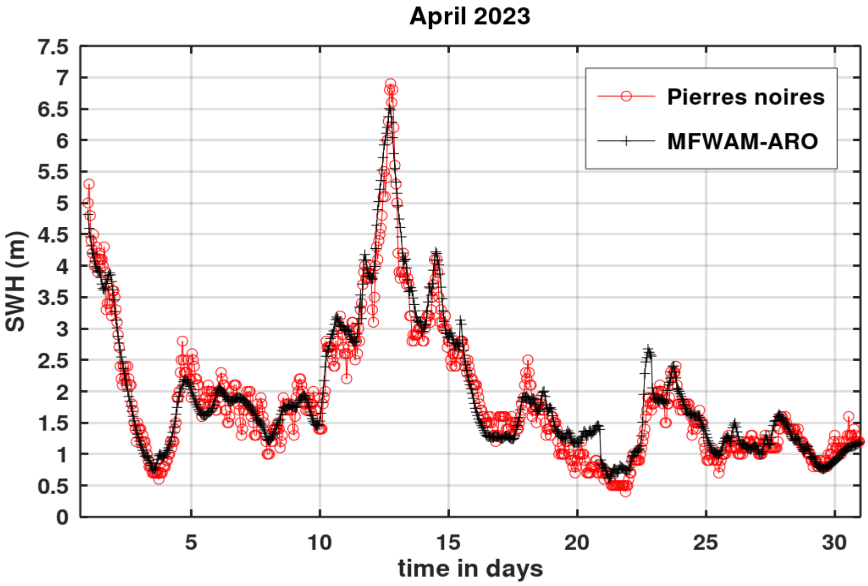

Figure 1 : Significant Wave height from the coastal model MFWAM-AROME (black line) and the buoy Pierres noires (red circle line) during April 2023.

Good agreement with models

Figure 2 shows SARAL track passing over the domain. We can notice the passage of SARAL near the French coast of Brittany, which is strongly affected by wave/current interactions, with one of the strongest tidal currents in Europe. Comparison of SWH from the MFWAM-Arome coastal system shows very good consistency with SWH from the Pierres Noires coastal buoy, thanks to the assimilation of SARAL wave data on a daily basis. The good agreement of the MFWAM-Arome model with the coastal buoy is clearly visible for both high and small SWH events.

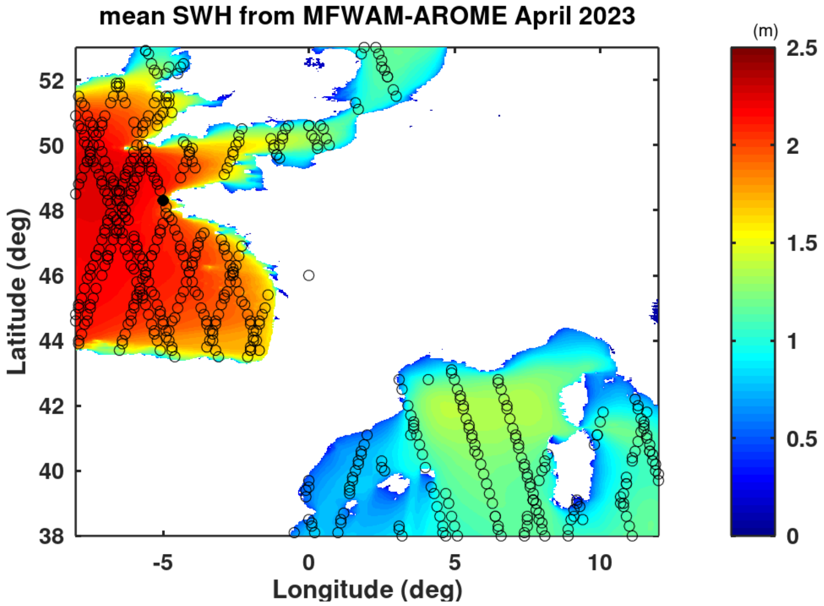

Figure 2 : Average of SWH from the coastal model MFWAM-AROME for April 2023. Black circles indicates the daily passage of SARAL at 06:00 and 18:00 UTC, and filled black triangle stand for the location of the coastal buoy

Space geodetic observations for estimating Ocean Heat Content change over the Atlantic Ocean

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The Ocean Heat Content (OHC) change can be estimated directly from net ocean surface heat fluxes derived from Clouds and the Earth's Radiant Energy System (CERES) space measurements, from in situ data observed by the ARGO floats or from ocean model re-analyses. For the first time, we estimate here the regional OHC change using an alternative method based on space altimetry and space gravimetry data.

From the expansion of the sea water measured by satellite altimetry and space gravimetry...

Altimetry missions now provide 30 years of accurate, continuous and near-global sea level measurements thanks to the TOPEX/Poseidon, Jasons (1,2,3) and more recently Sentinel-6 Michael Freilich reference missions. Complementary missions like SARAL/AltiKa are used to increase the spatial coverage and the spatial resolution in sea-level gridded products provided by the Copernicus Marine Environment Monitoring service (CMEMS), in particular at high latitudes. By combining these accurate and precise measurements with space gravimetry measurements (GRACE and GRACE-FO), which provides estimates of the ocean mass variations, we can derive the expansion of the sea water due to the change in density, otherwise known as the steric sea level change. The steric sea level change is estimated by calculating the difference between the total sea level height derived from altimetry measurements and the mass component derived from space gravimetry data. This approach provides consistent spatial and temporal sampling of the ocean, covering nearly all the global ocean, except for polar regions where the sea is completely covered by sea ice and it provides estimates of steric sea level change integrated over the ocean's entire depth.

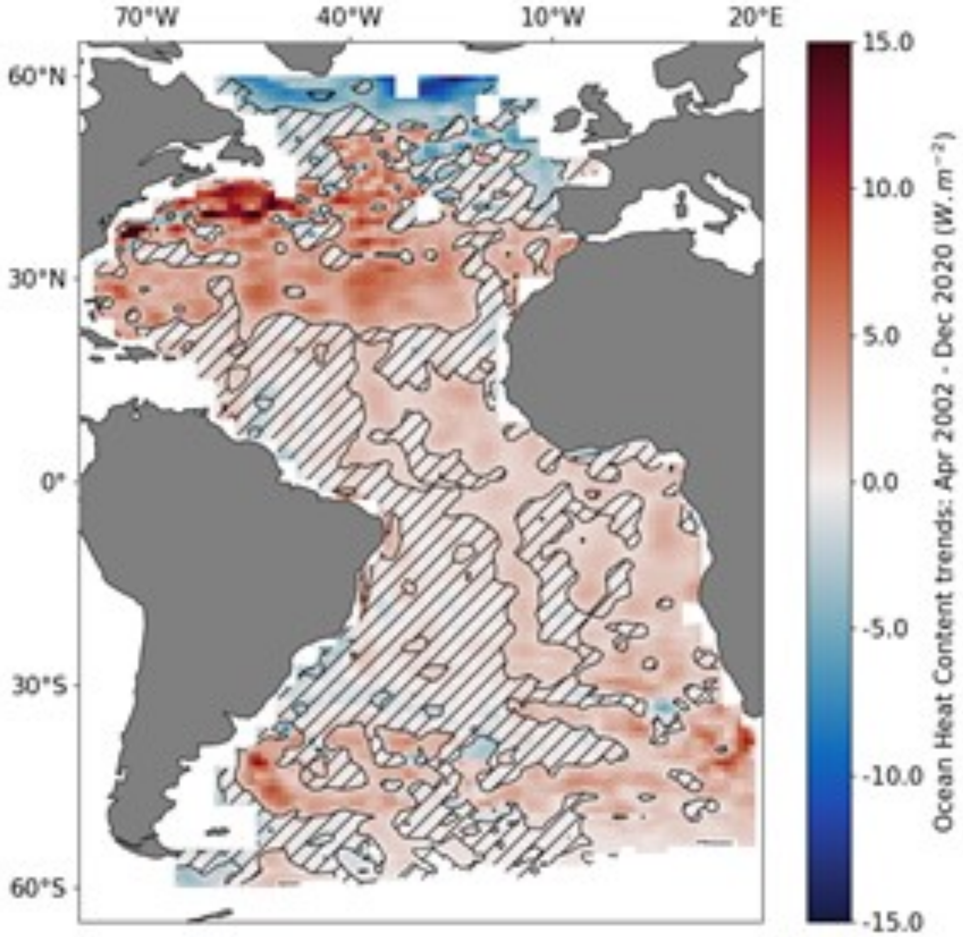


Figure 1 : Map of regional OHC change trends on the Atlantic Ocean computed over April 2002-December 2020 with the space geodetic approach. Hatched areas are regions where regional OHC trends are not significant at the 68% confidence level. Credits ESA / LEGOS / Magellium.

At regional scales, the influence of salinity change in the total sea level is not negligible. The thermosteric sea level change is obtained by correcting the regional steric sea level estimated by the geodetic approach with halosteric variations due to salinity change derived from *in situ* measurements.

… to an estimate of the regional Ocean Heat Content change

The thermosteric sea level change is then converted into Ocean Heat Content (OHC) change with the Integrated Expansion Efficiency of Heat (IEEH) coefficient. The IEEH coefficient directly relates the thermal expansion of an ocean water column to its change in ocean heat content. It depends on the water column temperature and salinity. It is estimated from in-situ measurement from the ARGO network

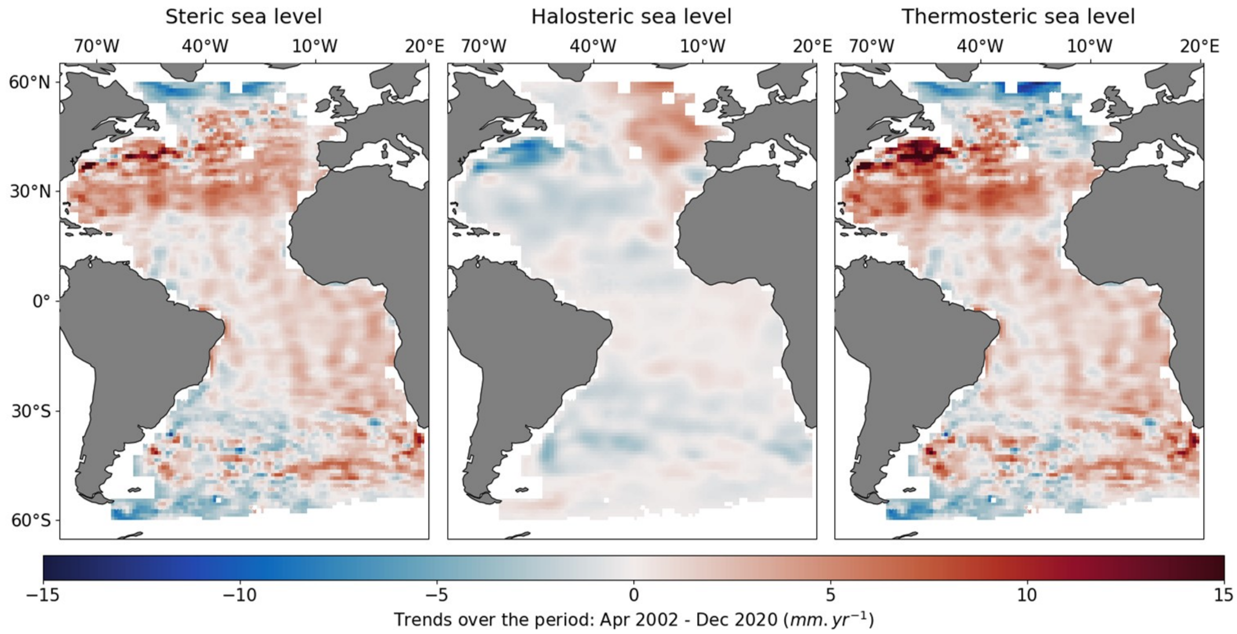
The OHC change trend estimated over the Atlantic basin is 0.17 W/m² (equivalent TOA) which represents 21% of the global OHC trend over April 2002-December 2020, with significant trends observed in 52% of the Atlantic basin. The space geodetic OHC trends reveal a warming pattern in the southern and western parts of the North Atlantic, particularly in the Gulf Stream region, while the northeastern part exhibits cooling trends.

The importance of the space geodetic OHC product lies in its potential to support operational decadal predictions by providing high resolution vertically integrated estimates of the OHC. It is also useful to monitor climate indicators such as the meridional heat transport (MHT). In particular, the space geodetic OHC in combination with CERES and atmospheric reanalyses enable to estimate the MHT in the North Atlantic and thus to characterize the Atlantic Meridional Overturning Circulation (AMOC). The AMOC is known to be a primary source of decadal variability in the global climate. Future projections with global warming suggest a weakening of the AMOC circulation with potential profound regional climate effects over Europe in particular. One advantage of using space geodetic OHC to estimate MHT is that it can be estimated over the whole North Atlantic, so that we can see directly how AMOC heat transport fluctuates in latitude as well as in time. Another interesting feature of this approach is that we can extend the AMOC record back in time until 2002 with the space geodetic approach.

Access to the product

OHC change at regional scales or "4DAtlantic-OHC" product from space altimetry and space gravimetry was produced by Magellium/LEGOS and distributed by AVISO+ with support from ESA.

The results of this study were obtained with the first version of the dataset (V1.0). It is available online, from the DOI. The complete associated documentation is available on the website (experimental dataset description and algorithm theoretical basis document). Further information and documentation are also available on the project website.



Map of regional trends of steric sea level change estimated with the geodetic approach (left), halosteric sea level change estimated with in situ measurements (center) and their difference which gives an estimate of the thermosteric sea level change (right) on the Atlantic Ocean computed over April 2002-December 2020. Credits ESA / LEGOS / Magellium

SARAL's contribution to advances in understanding the fine scales of the coastal ocean

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Coastal areas concentrate many challenges. They are the interface between the land and the open ocean. They are prime habitats for human populations and are being hard hit by climate change. They are characterised by small scale processes (10-100 km) which allows the transport of heat, nutrients, salt and energy.

New technologies such as the Ka-band of SARAL and the development of data processing enable to increase our knowledge of these fine scale structures (eddies, recirculation, meanders, etc).

Indeed the footprint of Ka-band altimeters is reduced to about 4 km – radius. The noise level is less important than for conventionnal altimetry which leads to a lower filtering and thus to a better observation of smaller-scale structures.

In the following we will focus on SARAL's contribution in the North-Western Mediterranean Sea which is a laboratory region because of its large panel of fine-scale physical processes and its huge number of in situ measurements and campaigns.

Focus on Mediterranean Sea

SARAL has brought huge gains in the knowledge of coastal currents and especially the Northern Current which flows cyclonically along the Italian, French and Spanish coasts. With reliable data closer to the coast the structures are almost entirely captured by this mission. The Northern Current is 30 km wide with some seasonal variations and is associated to a lot of fine scale processes which are also quite well captured by the satellite. The comparison to in situ data such as gliders, HF radars, ADCP and moorings also leds to good results. Pascual et al., 2015 showed that in the Ibiza channel the agreement with HF radars is fine concerning mesoscale processes. Still in comparison with HF radars, Morrow et al., 2017 showed good consistency in the current's capture (Figure 1) near Toulon. In the same region, Casella et al., 2020 highlights SARAL's ability to observe coastal intrusions in the Gulf of Lion using a Random Forest Algorithm. In the Ligurian Sea, where there are repetitive gliders and ADCP tracks SARAL is very close to in situ data in several cases (Carret et al., 2019). Figure 2 shows an example of a comparison between gliders, ADCP and 2 satellite missions (Jason-2 and SARAL). Negative values correspond to the Northern Current near the coast. Using SARAL HF data enables a very good match between the gliders and altimetry. Jebri, 2017 also confirms the detection of fine scale structures by comparing SARAL to tide gauges and SST images. However one of the main limit of SARAL is its temporal resolution as it passes again over the track every 35 days which make sometimes the comparison with *in situ* data difficult and don't

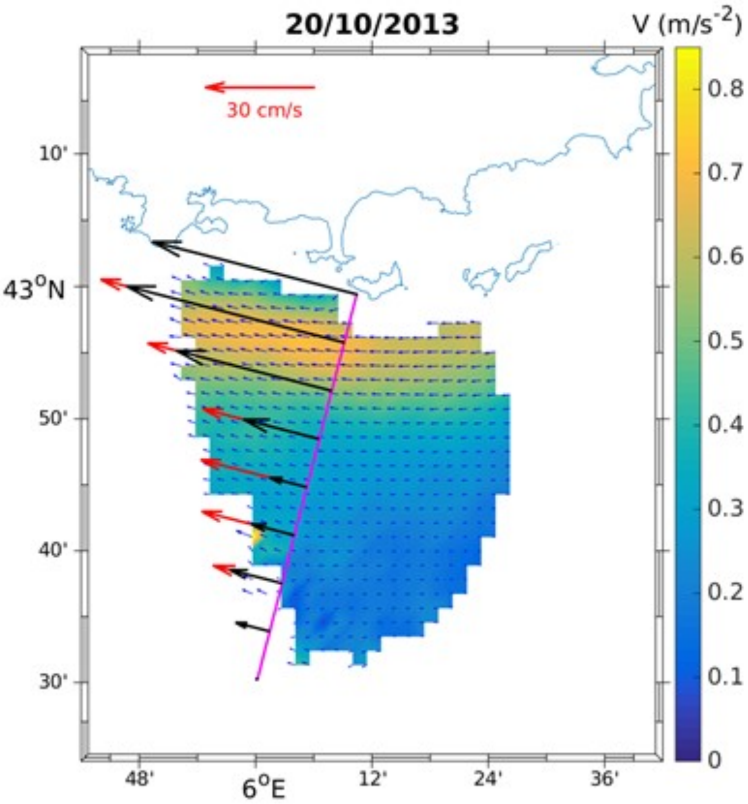

Figure 1 :HF radar surface currents near Toulon for one date (20 October 2013); direction with small arrows, current speed is in colour. SARAL track 302 is marked in pink; 1 Hz cross-track geostrophic currents from SARAL altimetry are in black; the HF radar total currents projected in the altimetric cross-track direction are in red. The current scale of 0.3 m s−1 is associated with the projected currents.

enable seasonal climatologies because there are not enough data. This could be one potential improvement using the Ka-Band in the future.

Some studies (Dufau et *al.*, 2016, Morrow et *al.*, 2017) have estimated SARAL's noise level and its mesoscale resolution using statistics approach.

Morrow et *al.,* 2017 concluded that thanks to its reduced noise level, SARAL is able to detect 35 km – structures which is better than Jason-2 and CryoSat-2. Jebry 2017 drew the same conclusions: SARAL is able to detect smaller scale processes than Jason-2, 21 km against 40 km respectively.

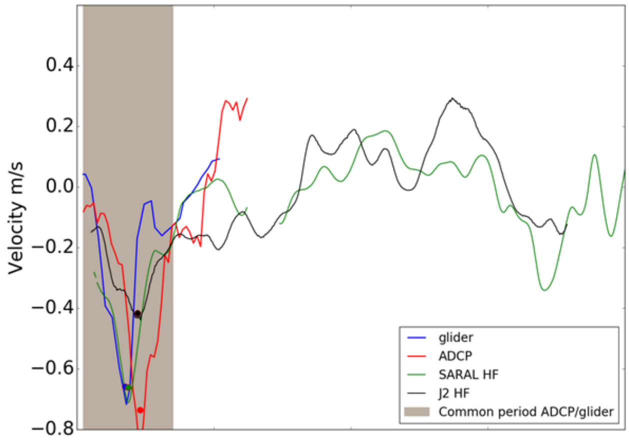

Figure 2 : Cross-shore sections of currents deduced from the glider (blue), ADCP (red), SARAL (green) and J2 (black) HF altimetry data for an individual case occuring over 11-14 April 2013. Overlapping periods between the different observations are also indicated.

Better pattern of the circulation

Concerning the contribution of SARAL compared to other satellite, Birol and Nino, 2015 showed that the quality and quantity of SARAL data near the coasts were greater than for Jason-2 and its Ku-band. Carret et *al.,* 2023 used a validated model as a reference to analyse the contribution of different missions (Jason-2, SARAL and Sentinel-3). SARAL has the better results with reference to the model. It allows to detect the sea level increase associated to the Northern Current with more accuracy. The weak repetitivity of SARAL is balanced by a good spatial coverage which gives a more complete pattern of the circulation than Jason-2.

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Added-value of SARAL for coastal sea level processes

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The Western Mediterranean Sea, which includes the Alboran Basin and extends into the Balearic and Algerian Basins, holds a central role in regional ocean circulation dynamics. Its importance lies in the complex interaction between incoming fresh Atlantic water and the existing saline Mediterranean water. This interaction results in highly dynamic circulation patterns, characterized by the presence of energetic mesoscale structures which leads to the formation of both cyclonic and anticyclonic eddies.

Despite the pivotal role of the Western Mediterranean in regional circulation, our comprehensive understanding of its meso- and submesoscale features remains incomplete. To bridge this knowledge gap, during the last decade the Western Mediterranean Sea has been the spot for several studies (e.g. Ruiz et *al.,* 2009; Bouffard et *al.,* 2012; Pascual et *al.,* 2013; Aulicino et *al.,* 2018) which have brought to light the key role of underwater gliders and High Frequency (HF) radars as instrumental platforms for validating and inter-calibrating altimetry data.

The launch of the AltiKa altimeter in 2013 was a step forward in this context, as it constituted the first oceanographic altimeter using a wideband Ka-band (Verron et *al.* 2015), characterized by improved resolution of the measurements, optimized along-track sampling, enhanced discrimination in transition zones as well as reduced footprint compared to other satellites based on Ku-bands (e.g. Jason-2, Envisat, CryoSat-2).

In addition, SARAL/AltiKa data are retrieved at a distance of only 7 km from shore, highlighting the emerging capabilities of the new altimeter. This unique instrumental design results in more precise measurements allowing a better characterization of ocean and coastal processes in addition to

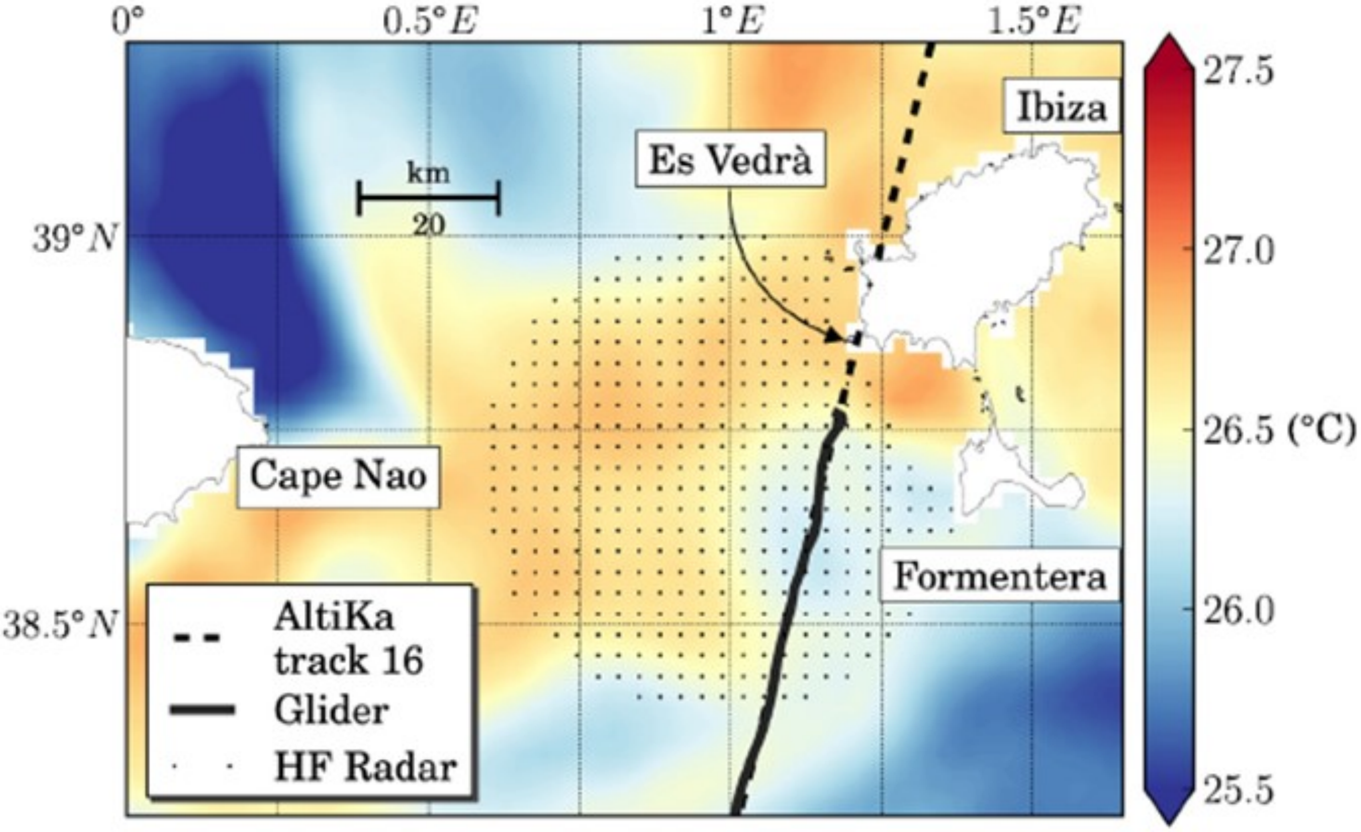

Figure 1 : Study area and data. HF radar, glider and altimetry data locations overlaid on the Sea Surface Temperature corresponding to August 1, 2013. From Troupin et al., 2015.

ice sheet and inland waters monitoring (Verron et al. 2018).

Comparisons across data platforms

As an example of comprehensive study in this framework, in August 2013, the collaborative G-AltiKa mission led by IMEDEA and SOCIB, embarked on a journey along a SARAL track (Troupin et al., 2015). This particular track was strategically selected in the Western Mediterranean, adjacent to Ibiza. During this mission, the SOCIB HF radar facility provided hourly surface current velocity data. Complementing this dataset, surface drifters were strategically deployed within the study region (Fig. 1). It's noteworthy that the glider mission (spanning from the 2nd to the 5th of August 2013) coincided almost perfectly with the satellite's trajectory along the designated SARAL track.

What emerged from these observations were insights of significant importance as the initial comparisons across all data platforms - including drifters, SARAL/AltiKa along-track data, and HF radar - unveiled a good agreement. The dynamic height gradients retrieved from glider observations are within the range of 2-3 cm, signifying the presence of a coherent meander with associated velocities peaking at approximately 20 cm/s. Also noteworthy were the findings from SARAL/AltiKa records, which leveraged 40 Hz along-track near real-time data to capture this meander. SARAL/AltiKa's rendition preserved the meander's size, amplitude, and spatial position, aligning seamlessly with glider observations. This achievement was even more remarkable when considering that SARAL/AltiKa effectively delineated the northern boundary of the meander - a feature positioned atop shallow bathymetry, located less than 10 km from the coastline.

With the aim of giving a step forward into validating the potential of the SARAL/AltiKa measurements in coastal areas, another different approach analysis was conducted in the Ibiza channel corresponding to the period of April 2013 – May 2014 (Pascual et al., 2015). The study focused on analyzing 12 cycles of the 16th SARAL/AltiKa along-track and 36 cycles of the 187th Jason-2 which crosses SARAL/AltiKa track in the vicinity of Ibiza Island. For the study was selected the Ssalto/Duacs delayed-time along-track Sea Level Anomaly (SLA) delivered by AVISO. The main interest was focused on the comparison between geostrophic velocities calculated from altimeter heights and total surface velocities estimated from SOCIB's coastal HF radar.

The results indicated that the obtained velocities from SARAL/AltiKa effectively capture the fundamental characteristics of seasonal mesoscale variability, demonstrating reasonable agreement with HF radar datasets, as evidenced by significant correlations of 0.54. The root mean square (RMS) of AltiKa velocities were 14.0 cm/s while the equivalent for HF radar were 10.3 cm/s. However, the intercomparison between velocities

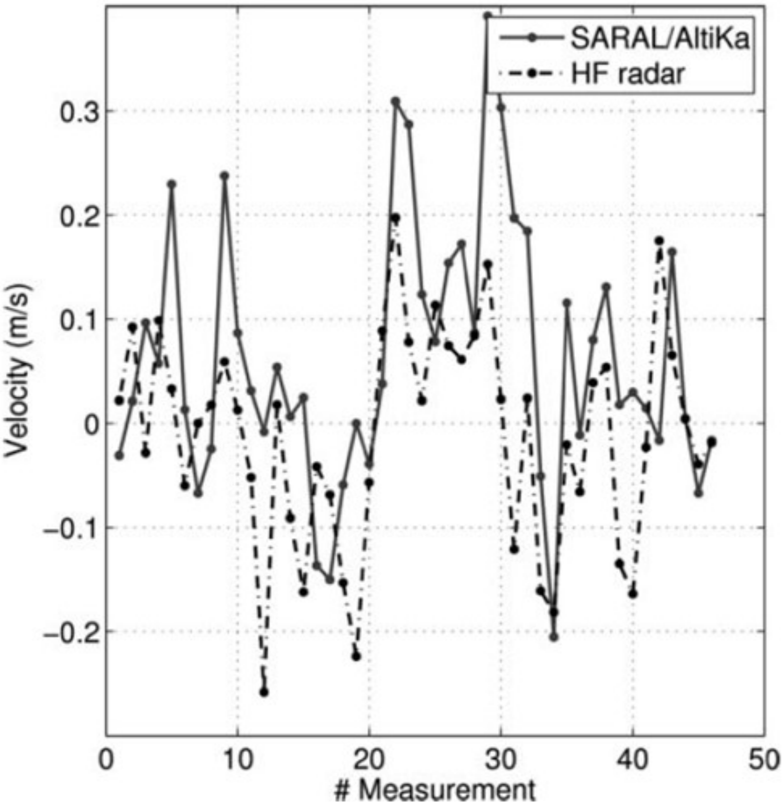

Figure 2: Cross-track velocity for SARAL/AltiKa (continuous line) and HF radar data at the satellite measurement point (dashed line). This corresponds to the concatenation of all velocity data available for the 12 selected cycles (i.e., 4 points are available for each cycle, which gives a total of 46 measurements). Positive (negative) values indicate north-westward (south-eastward) flow.
From Pascual et al. 2015.

derived from both sensors (Fig. 2) showed that although there were discrepancies between both sensors with peaks more pronounced for SARAL/AltiKa reflected in the RMS, a general agreement at low frequencies was observed. On the contrary, in the section sampled by Jason-2 (which is less than 10 km apart from SARAL/AltiKa), the time series are much noisier, translated in an insignificant correlation between Jason-2 and HF radar observations (Verron et al., 2018).

Nevertheless, some inconsistencies appeared potentially stemming from radar hardware errors, ageostrophic velocities, and inaccuracies in altimeter data corrections and processing giving as a result RMS discrepancies between estimated SARAL/AltiKa and HF radar velocities of ~13 cm/s, in agreement with other studies comparing HF radar and alternative sensors (e.g., Chapman et al. 1997; Kohut et al. 2012). Furthermore, it was also found that the combined effects of spatial sampling, editing criteria and spatial filtering techniques are critical issues, so high-frequency measurements seem to be necessary. This is especially relevant near the coast (Pascual et al., 2015; Aulicino et al., 2018) and in areas of moderate variability such as in the Ibiza channel.

Complementary to the studies carried out in the Ibiza channel, during fall 2014 and 2015 a study focused in the Algerian Basin was carried out by Aulicino et al. (2018). The study focused on the analysis of four high resolution glider missions collected along the Algerian Basin Circulation Unmanned Survey (ABACUS/ABACUS-2) crossing between Mallorca and Algerian coasts, in synergy with co-located SARAL/AltiKa altimetric products and CMEMS numerical simulations.

The outcomes derived from high resolution glider observations, as well as SST and ADT data acquired from SARAL/AltiKa revealed good correlations along the tracks and similar patterns, with RMS of the differences ranging between 1.11 and 2.90 cm. This results shows a marked basin-scale seasonal variability driven by the presence of several mesoscale structures that break away from their main trajectory, generating coastal eddies and filaments that extend throughout the basin. Most of these features have been observed in the CMEMS model products tested suggesting that numerical simulations can be useful contributors to information about the upper ocean when autonomous underwater vehicles (AUV) are not available (Aulicino et al., 2018).

A key tool for coastal zone management

In essence, these SARAL/AltiKa satellite mission results highlighted the commendable quality of the data, especially in the coastal domain. These data not only subtly capture gradients, but also accurately depict the intricate dynamics of meanders and mesoscale structures. These results reaffirm the importance of the mission and its important contributions to advancing our understanding of coastal and mesoscale ocean dynamics, confirming the role of SARAL/AltiKa as a key tool for scientific research and coastal zone management.

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