13th COASTAL ALTIMETRY WORKSHOP & COASTAL ALTIMETRY TRAINING

FINAL REPORT

6–10 February 2023 | Universidad de Cádiz, Spain

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&

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CAW-13 Final Report

by

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Published by:

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Cite as:

Marco Restano, Jérôme Benveniste, Anrijs Abele, Lotfi Aouf, Florence Birol, David Cotton, Nicole Delpeche-Ellmann, Luciana Fenoglio, Guoqi Han, Clara Lázaro, Claire Maraldi, Francesco Nencioli, Julius Oelsmann, Sonia Ponce de León, Marie-Isabelle Pujol, Laura Ruiz-Etcheverry, Matea Tomic, Stefano Vignudelli, and John Wilkin (2023) 13th Coastal Altimetry Workshop Final Report, ESA Publication, https://doi.org/10.5270/esa.caw13_2023.final_report

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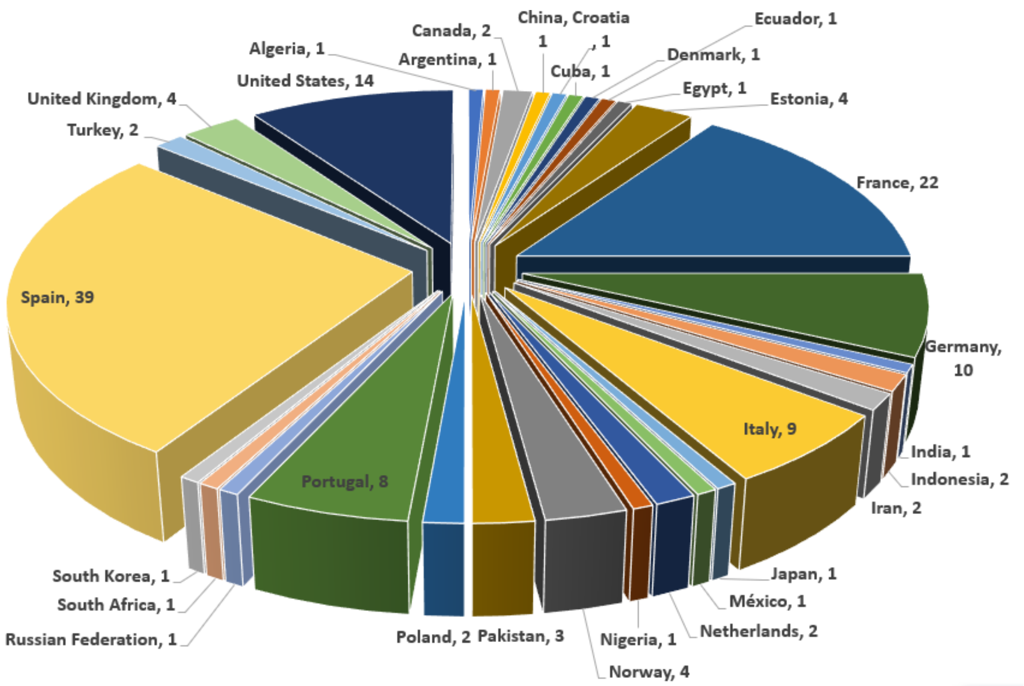
Image: ESA

Introduction

The 13th edition of the Coastal Altimetry Workshop was organised by the European Space Agency (ESA) with the support from 16 institutions. The workshop brought together 108 scientists from 31 countries and included a Coastal Altimetry Training course for students and young researchers.



Introduction

Key topics discussed at the workshop covered 5 themes:

1. Retracking
2. Corrections, Calibration & Products
3. Application of Coastal Altimetry Data
4. Sea Level, Currents & Data Assimilation
5. Synergistic and Climate Studies

and were discussed in 4 sessions:

1. Technical issues in coastal altimetry
2. Applications of coastal altimetry data
3. Synergistic, Climate Studies & Operationalisation
4. Wave & Wind

This final report includes the main recommendations, the summaries of all the presented oral contributions and a summary of the discussion slots.

All presentations (46 oral and 34 poster) given during the Workshop and the Coastal Altimetry Training course can be downloaded at www.coastalaltimetry.org.

Highlights

The 13th Coastal Altimetry Workshop was quite impressive by the high quality of the work reported and, in particular, the wealth of information and recommendations discussed. The output from this workshop can be highlighted as follows:

- The state-of-the-art, by modelers, in situ and remote sensing scientists and application developers:
  - Results from on-going research on technical issues and science and application activities.
  - Available and planned processing and prototype products.
  - Operational and planned oceanographic information services and applications.
  - Focus on waves and wind.
- Identification of gaps and priorities for future science and applications.
- Characterisation of the capacity to address these priorities.
- Elaboration of a "Roadmap" of priorities to address opportunities and gaps.

Following the talks, the interactive presentations (aka posters), large time slots were dedicated to discussions, which led to the recommendation and roadmap for the future that are reported in the next sections.

With this output, space agencies and any other funding agencies are encouraged to prioritise the actions to be designed, funded and executed with a special focus on the exploitations of the next generation of altimetric missions that are already planned for the decade ahead.

The synergistic potential offered by the Earth Explorers Next Generation Missions, the Copernicus Sentinel Next Generation Missions, the Copernicus Sentinel Expansion Missions, formerly known as Copernicus High Priority Candidate Missions (HPCM) was also discussed in combination with the other set of missions that will fly during the same period (2027 and beyond) and along with the needed R&D activities to prepare for this future wealth of data.

Historical Recall

At the 15 Years of Progress in Radar Altimetry Symposium, 2006, in Venice, Italy, a recommendation was put forth with a general consensus on finding solutions to bring altimetry closer to the coast. The recommended best way to achieve this was to organise a series dedicated workshops offering much more time to discuss issues, challenges, solutions, and results, and organise international cooperation, than what was affordable during the regular Ocean Surface Topography Science Team meetings. The Coastal Altimetry community has been over the past 15 years a vibrant group of scientists and engineers, well supported by space agencies. As a first step, a lacking textbook on Coastal Altimetry was written. The book, published by Springer, came out 2 years later (https://doi.org/10.1007/978-3-642-12796-0).

The first 2 workshops were organised in 2008 on both sides of the Atlantic. Then the CAWs followed the rhythm of the OSTST meetings, preceding them so as to report the progress and the findings at the OSTST, until 2015 when the CAW has grown so large that it needed its own rhythm and was organised every ~18 months in Europe. This 13th edition suffered from a 3 year wait after the previous one due to the difficulty for people to get together physically and the strong motivation to interact in person and not virtually. Meeting in person was expressed as a sine qua non requirement.

Coastal Altimetry Training is an essential component of every Coastal Altimetry Workshop and this has been commended by the early career scientists as very beneficial warm-up before the Workshop itself. In the future, Organising Committees should consider offering the training over several days prior to the workshop as numerous new tools, computing platforms and altimetry processing techniques are blooming, and much more coastal oceanographic knowledge needs to be assimilated.

To paraphrase the United Nation Ocean Decade motto, the Coastal Altimetry Workshop series contributes to establishing "The Science we Need for the Coastal Zone we Want!" the next step is to produce more and new science and to publish it, to convince Coastal Oceanographers on the maturity and capability of Coastal Altimetry. Therefore, the name of next workshop may well be: "Coastal Altimetry Oceanography and Hydrology".


Image: ESA

Session 1 – Discussion & Recommendations

Processing

- Whilst specialist retrackers are needed to get valid measurements close to the coast, it is important to maintain continuity with ocean data. Biases should be understood and managed.
    - Suggested that SAMOSA+ could be used as a baseline reference for coastal altimetry data.
    - Retrackers can be designed to change waveform fitting approach according to the waveform shape.
    - Development of new approaches should continue (e.g., the Univ. of Stuttgart retracking method that takes advantage of the spatio-temporal variation of power in a radargram stack).
    - The round-robin evaluation of retrackers for coastal and inland water domains performed in the frame of the ESA HYDROCOASTAL project (https://www.satoc.eu/projects/hydrocoastal/) should be considered along with other retrackers (SAMOSA+/++, RiwiSAR-SWH…) by the Sentinel-3 and CryoSat-2 validation teams to update ground segment retrackers for future thematic products.
    - A relative improvement of more than 20% in the measurement noise of both sea surface height and significant wave height can be achieved just by increasing the posting rate from 20 to 40 Hz and an even further improvement is obtained at 80 Hz (https://doi.org/10.1016/j.asr.2020.03.014). This should be evaluated for specific analyses as high posting rate products can be produced with specialised SAMOSA coastal retrackers by Earth Console Altimetry Virtual Lab Services (https://earthconsole.eu/virtual-labs/).
- Analyses aiming at understanding radar altimetry waveforms should make use of artificial intelligence (Machine learning and deep learning) for investigating how to clean and filter the altimetry signals in the coastal contaminating zone.
- Currently there is no common sea state bias correction available for SAR altimetry:
    - A consistent approach for Sea State Bias for SAR and conventional altimetry, and open and coastal data is needed.
    - FFSAR data could be used to better tie the correction to the underlying physics of the wavefield.

Session 1 – Discussion & Recommendations

- Filtering - Need to improve identification of bad waveform fits, so that valid observations are not excluded.
    - Suggestion to limit misfit calculation in analytical retrackers (e.g., SAMOSA) to range bins defining and surrounding the leading edge (sub-waveform approach) to limit the influence of contamination in the trailing edge which could alter the misfit and lead to discard usable estimates.
- Processing platforms and open-source software: Many presented contributions used Earth Console Altimetry Virtual Lab Services (e.g., SARvatore for Sentinel-3 and CryoSat-2 data including SAMOSA+/++ L2 estimates, https://earthconsole.eu/wp-content/uploads/2022/03/SARvatore_br_singlepages_220315.pdf) and the ESA CNES CLS SMAP Sentinel-3 processor for Fully Focused SAR (https://github.com/cls-obsnadir-dev/SMAP-FFSAR).
    - It is important to update the current portfolio of Altimetry Virtual Lab services to include more advanced retrackers along with the processing of Sentinel-6 data with both Unfocused and Fully-Focused SAR processors.
    - The ESA CNES CLS SMAP Sentinel-3 open-source processor for Fully Focused SAR has been appreciated by the Community, its extension to Sentinel-6 data processing is envisaged as well as its development in the faster omega-K implementation (the current back-projection implementation is slow). More retrackers could be added.

Corrections

- Higher resolution tidal models are needed at the coast:
    - In regions where tidal corrections are particularly challenging the TWLE is the preferred measurement for comparison with Tide Gauge data.
- Access to accurate bathymetry is still a major limitation (and is a constraint on improved tide models).
    - Computation of coastal currents requires accurate shelf slopes.
    - Note the possibility to use existing remote sensing technology to improve coastal bathymetries (e.g., ICESat-2 for shallow depths).
- Geoid needed at higher degree and resolution. As improved models become available, they should be included.
- Corrections (SSB, wet and dry troposphere, ionosphere) needed at 20 Hz for coastal zones and inland waters.
- Multi-mission investigations comparing Sentinel-3, Sentinel-6, CryoSat-2 and ICESat-2 should be performed to compare performances and evaluate the impact of corrections and geoid at different posting rates.

Session 1 – Discussion & Recommendations

Products

- Parallel requirement for a product that provides regional/global continuity and the best regional solution.
- Need to develop/implement improved gridding techniques for coastal products to match coastline better and be more useful to users.
  - BALTIC+ SEAL could provide a useful model.
  - Can data sets from multi-sensor sources be mapped together?
- Information on new coastal altimetry products should be shared with the coastal altimetry and wider coastal oceanography community:
  - Provide regulars update of available products and documentation through https://coastalt.eu/, the coastal thematic hub and the altimetry virtual laboratory on EarthConsole (https://earthconsole.eu/virtual-labs/).
- Request an extension/repeat of the EU OCRE call (access to cloud infrastructure), or similar initiative, to support more large-scale processing.
  - Data download speeds from portals now a major time constraint
  - Need more functionality on portals to allow data selection to sub-select from whole orbit product. At present pole-to-pole L1A products (~2 GB and ~16 GB each for Sentinel-3 and Sentinel-6, respectively) shall be downloaded to run Unfocused and Fully Focused SAR processors. This is not optimal when studies are focused on coastal areas and inland water bodies.

Validation

- The lack of in situ data for the validation of coastal altimetry was identified as a major limitation in several presentations. Need of "super sites" for coastal CAL/VAL analysis?
- We need to establish benchmark reference data sets (in situ and satellite altimetry) and standard methodology for use in evaluating new coastal altimetry products.
  - Should identify well suited areas with good in situ instrumentation, accurate tide models, and with a well-defined and accurate DEM.
  - Need several sites to represent different coastal dynamical conditions.

Session 2 – Discussion & Recommendations

The world's land-sea interface is variable over a wide range of space, sheltering/shielding typology, and time scales. It cannot be globally surveyed with only ground-based measurements. Satellites provide global coverage and regular repeated observations since decades. There is a growing demand for improved/new data for training machine learning (AI) models.

Satellite radar altimetry at land-sea interface – Technical improvement

- FF-SAR: Which are the advantages of FF-SAR processing of near-altimetry near coast in term of precision, accuracy, data quality, distance to coast reached? How relevant is the retracking step in FF-SAR?
  - FF-SAR needs to be further investigated; the extracted along-track information must be better quantified.
  - Joint FF/UF-SAR datasets available to experiment with would be valuable and efficient. Stick to one retracker for the initial FF-SAR evaluation.
- Vertical Velocity (VV): How does this affect in coastal region the SWH estimated by un-focused SAR processing?
  - Users ask for the VV impact to be included within the processing rather than to be corrected by an additional LUT.
- Surface reflectivity/specularity: How to understand water surface reflectivity in the typical environments (coastal zone, lagoons, estuaries, deltas)?
  - Natural surfaces to be used for calibration, in particular exploiting specularity in salt lakes or lagoons.
  - More cooperation with imaging SAR community to understand the problems and potential solutions for SAR altimetry.
- 2D resolution: Which are today the new and more urgent requirements in coastal zone for the new altimeter missions, i.e., to build 2D maps of SSH?
  - Requirements depend on application: for dynamical processes the along-track nadir altimetry is not the best solution, also in coastal zone.
  - Altimetry data to be seen as a component of a system, i.e., in synergy with other sensors (laser altimetry, optical and radar imagery, SST, *in situ*). SWOT and nadir-altimetry to be cross validated (both USAR and FFSAR).
- Cal/Val in situ: Which additional ground truth do we need for altimetry validation?

  - Today, in situ Cal/Val sites are mostly TGs along the coast. Gaps need to be filled for modelers who need more offshore data.

  - Add bottom pressure sensors to moorings (engaging with the coastal observation community), add sensors to offshore wind turbines (engaging with offshore wind energy sector).

Satellite radar altimetry at land-sea interface – Scientific impact

- How frequent and in which detail do coastal hydrology processes need to be observed?
  - Synergy with hydrologists to better exploit the possibilities of altimetry performance for studying inland waters. Recently developed products (e.g., Cryo-TEMPO products, Sentinel-3 Inland Water Thematic products and HYDROCOASTAL inland water products) shall be considered to investigate improvements.
- How can altimetry contribute to understand processes depending on mission, measured frequency, enhanced overcome coastal challenges and fill in the coastal gap. Any specific need in new derived products from altimetry LR/SAR data for coastal studies?
  - 2D altimetry, study impact of constellations (MAGAL) vs. mini-SWOT.
  - Diverge in interests between ocean dynamics and water level communities. Water level community might want more of along-track (1D) with ever higher resolution. Dynamics community might want an addition of across-track (2D) observations.
- Do dedicated coastal altimetry products give an improvement over conventional products in complex coastal zones?
  - Allow sub-setting in distribution platforms – Copernicus SciHub, EarthConsole ESA Altimetry Virtual Lab and EUMETSAT – to avoid waste of computation resources and storage space, speed up the processing.
- What are the main hindrances to reconcile open ocean and coastal/inland water altimetry?
  - Computing a consistent MSS based on the new reprocessed 5 Hz data, which means no extrapolation of the 1 Hz MSS to the coast, and consistent averaging of the 5 Hz corrections and retracking. Clearly, this is a point of consensus.
- Geophysical corrections: Are present high resolution SSHA products referenced to a consistent Mean Sea Surface (MSS) to allow multi-mission uses?
  - Consistent MSS for SSHA products for multi-mission use. Might not be useful for local applications (different definitions of MSL in different countries), MSS based on the new reprocessed 5 Hz data → no extrapolation.
- SSB in coastal regions needed. Many coupled circulation/wave modelling projects exist, trend in using spectral information in wave-current interaction coupling. Several intense field experiments, e.g., ONR Inner Shelf. https://journals.ametsoc.org/view/journals/bams/102/5/BAMS-D-19-

0281.1.xml#affiliation43. With wave models and observations - view into fetch & duration limited sea states, SWH directions unaligned with wind, etc.

- Which new/existing methodologies of altimetric post-processing need to be developed/improved to study fine scales observed by SWOT altimetry?
    - Put resources into SWOT: develop a reliable reference, consistent data constraints, pair with coastal monitoring systems.
- Product Format: How to better access L1A echo data and get more documentation on radar instrument functioning?
    - Better documenting L1A products and radar instrument (e.g., point target response), simplified products for non-experts, more resources for beginners through trainings, handbooks, and products (which include only basic parameters).
    - Simplifying access to resources, cooperation with coastal engineers and manager community to popular coastal altimetry (do not exclude co-located corrections, due to need to restore/replace these for specific applications, e.g., better regional tides, wet tropospheric corrections, etc.).
    - CAW trainings need to start with the basics. Lecturers & Organisers: interest in collaborating to improve/update toward a better course.
- Can laser altimetry, due to its higher spatial resolution, provide more valid observations in complex coastal zones than radar altimetry?
    - Laser altimeters should only be complimentary/auxiliary sources.
- Which are the processes that swath-altimetry is expected to significantly improve and under which assumptions? Swath-altimetry: Are the nominal requirements of the launched SWOT mission expected to fill all coastal requirements? if not, what do we still miss after SWOT?
- Can specularity of natural surfaces be used as a Cal/Val tool? Can specularity behaviour be used as a geophysical tool?

Understanding reflectance at land-sea interface calls for using L1A products and knowing more radar processing at low level. Scientific echoes can contribute to new R&D developments.

Session 3 – Discussion & Recommendations

- How to better promote and support the use of coastal altimetry toward the oceanographic community?
    - Keep https://coastalt.eu/ updated with latest publications and datasets (including mailing list, **COASTALT-SWT**).
    - Make https://coastalt.eu/ an interactive platform, where users can add links, descriptions, (and comments) to different coastal datasets.
    - Provide product information about their applications and limitations.
    - Improve interaction between the altimetry community, modellers, and oceanographers.
    - Design projects to integrate different disciplines and approaches (storm surges, tides, long term changes, observations, models).
- What are the existing product limitations and how to fill the gap with needs/applications?
    - Improve availability of in situ data and their documentation (TGs, GNSS, Meta data, processing).
    - Encourage publication of databases, i.e., for validation.
    - Provide uncertainty estimates in products.
    - Provide coastal products ideally at a global scale.
    - Synergy of altimetry data with other data sources (Sea Surface Temperature, Sea Level Pressure, winds, ocean colour, in situ data, …)
    - Use AI to synergise multiple data sources, to improve spatio-temporal resolution of altimeter data, and to enhance process understanding.
    - Improve presently available geoids at the regional scale.
- Transfer of R&D products to operational production:
        - Identify the (number of) users and their requirements.
        - Provide regular updates of products.
- Are the existing R&D products mature enough for transfer to operational production?

Session 3 – Discussion & Recommendations

- Specification of the processing to be applied/compatibility with operational constraints.
- Specification and availability of the upstream products required.
- Number of users & applications/feedback from users/how to check that a product is used?

- How can we improve the timeliness, completeness, and accuracy of coastal altimetry products for operational service delivery and societal applications?
- How to ensure the transfer to operational production?
  - Link with Copernicus services.
  - Specific funding from space agencies for operational production of coastal L3/L4 coastal products & necessary upstream (if not yet covered by existing L2 and auxiliary production).
- Methods of synergising different sources of sea level data:
  - Different sources of sea level data are using different datums and also different countries tide gauges refer to different datums.
  - Should there be some conformity of the vertical datum used and are the methods used robust enough for their application?
- Consistent validation strategies for coastal sea level trends at tide gauges (Vertical land motion; Local specificities).
- Should we attempt to improve the geoid so that there is some consistency?
- What about uncertainty?
  - Satellite altimetry is showing much more small-scale features especially at the coast and offshore than the hydrodynamic models.
- Are we effectively using the satellite sea level data? Or are we somewhat stuck on validation?
- How can we merge the different sources of data to assist our understanding of ocean dynamics and the role of machine learning in this?


Image: ESA

Opening Session Keynote

Waves in the Coastal Zone

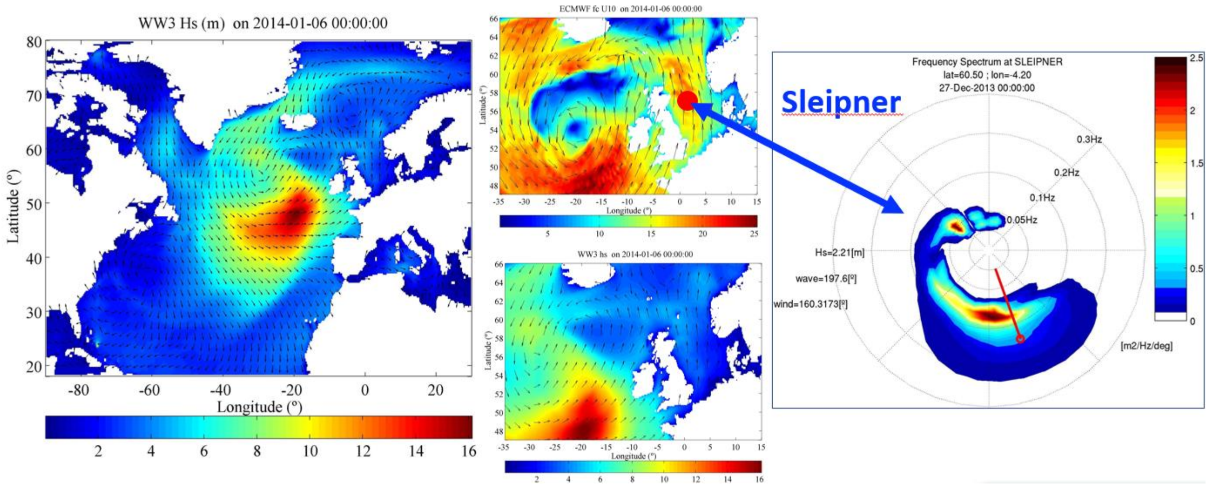
Sonia Ponce de León

The keynote started by presenting the state of the art of wave modelling and associated challenges. Focus was on how to best use wave information when interacting with other processes (air-fluxes, wave-current interactions, wave breaking, among others) and understand how wave interacts with extreme winds (> 35 m/s), as processes are not well represented in spectral wave models.

Spectral wave models evolution over three generations was discussed up to the introduction of SWAN (Van Vledder 2002; SWAN Team 2019), WAM (WAMDIG 1988, Komen et al. 1994) and WAVEWATCH III (Tolman et al. 2009), which are the commonly used models.

To describe the evolution of wave spectrum, the energy balance equation was introduced. This equation describes the evolution of the wave spectrum along the geographical domain as a function of the time, position, frequency, and direction. The source term is the summation of all physical processes (generation of waves by wind (S_{in}), wave dissipation (S_{dis}), and nonlinear interactions (S_{nl}) that allow the growth and the decay of waves along a geographical domain.

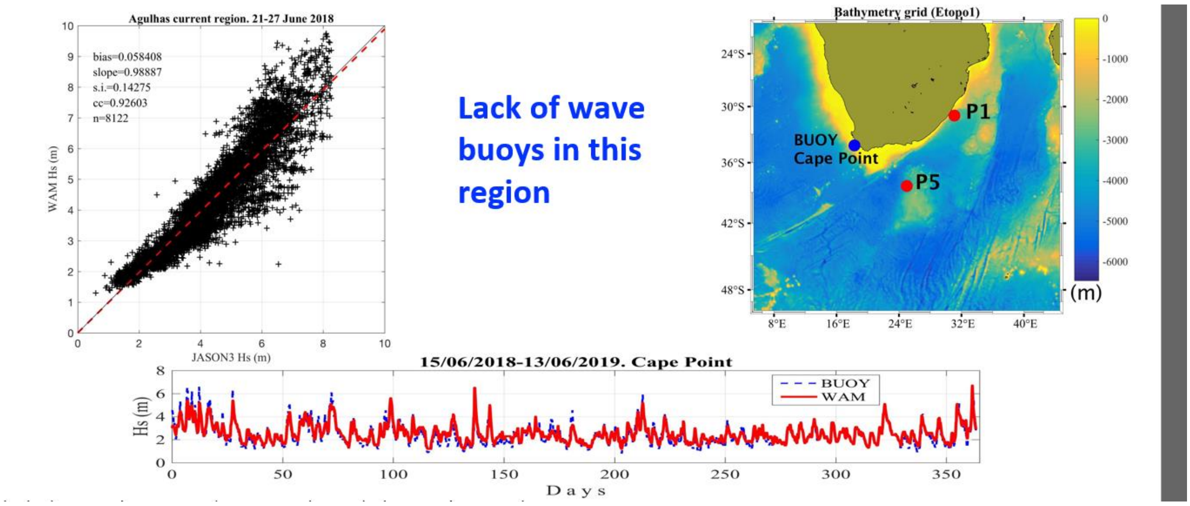
Traditionally, in most operational wave forecasts, the discrete interaction approximation (DIA) for computing the 4-wave nonlinear interactions is used. However, DIA leads to the underestimation of the spectral wave energy. To overcome this issue, a tuning is typically required by using wave buoys and satellite altimetry as references. The exact computation of S_{nl} is possible but it requires huge computational resources to solve a six-fold Boltzmann integral at every grid point for a certain domain over time.



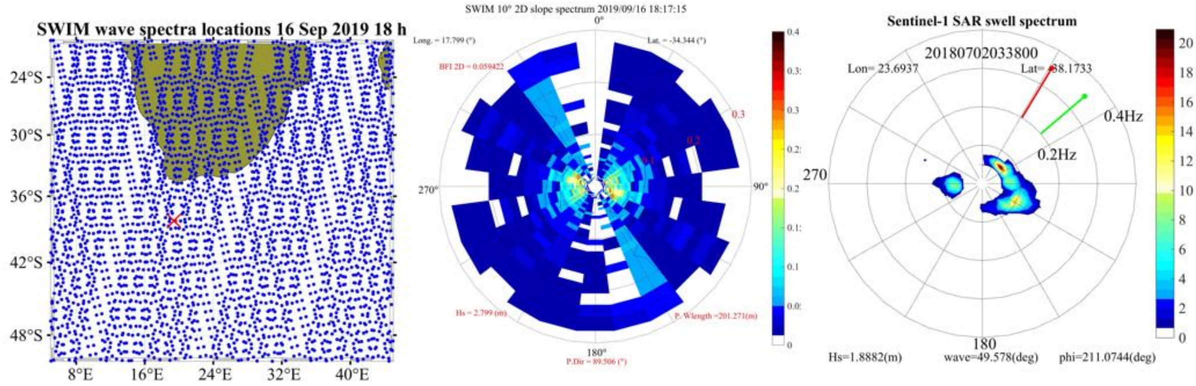
At scales of 100 km, wave modulation by currents accounts for about 75% of the spatial variability of wave heights (Ardhuin et al. 2017).

Opening Session Keynote

Validation of WAM-modelled results, using satellite altimetry data and wave buoys, was presented for the Agulhas region (Ponce de León, Guedes Soares 2022):



Data Assimilation in operational wave forecasts was then discussed. Weather and ocean models depend upon initial conditions and, secondly, upon data ingestion and assimilation. An example of Data Assimilation using SAR swell data and CFOSAT (Le Merle et al., 2021) wave spectra was presented.



ECMWF has been assimilating altimeter data since the early 90's (starting with ERS-1). It was noted that there are other sources of wave data, currently not assimilated: Sentinel-1 SAR, CFOSAT, SWOT, in situ (moored buoys, platforms, ships, and more recently drifting buoys). Envisat SAR wave mode data were assimilated in operational, but never in reanalysis.

Currently, only data from SARAL/AltiKa and Jason-3 are assimilated (only SARAL/AltiKa in the ECMWF Reanalysis v5 - ERA5). ESA CryoSat-2 data should soon be assimilated again in ERA5 and Sentinel-3A/B and Sentinel-6A added. The lack of resources limited the progress in this area.

Then, an assimilation of SWH data from 6 altimeters was presented. The verification against in-situ data reported a relative improvement in the standard deviation of error.

Processes affecting the evolution of waves in oceanic and coastal waters were then discussed in order of importance*:

Process	Oceanic waters	Coastal waters		
		Shelf seas	Nearshore	Harbour
Wind generation	●●●	●●●	●	○
Quadruplet wave–wave interactions	●●●	●●●	●	○
White-capping	●●●	●●●	●	○
Bottom friction	○	●●	●●	○
Current refraction / energy bunching	○/●	●	●●	○
Bottom refraction / shoaling	○	●●	●●●	●●
Breaking (depth-induced; surf)	○	●	●●●	○
Triad wave–wave interactions	○	○	●●	●
Reflection	○	○	●/●●	●●●
Diffraction	○	○	●	●●●

●●● = dominant, ●● = significant but not dominant, ● = of minor importance, ○ = negligible.

*Table is taken from Holthuijsen 2007.

The effect of refraction, turning waves toward the coast, has been evidenced in SWAN high-resolution simulations.

Shoaling, which is the variation of waves due to depth-induced changes in the group velocity, generally increases the wave amplitude as the waves propagate into shallower water. It has been discussed presenting WW3 simulations (Ponce de León et al., 2022).

Many additional processes take place in shallow waters:

- Bottom friction
- Shallow water wave breaking
- Triad interactions

Shallow water (depth-induced) breaking is a dominant dissipation mechanism in the surf zone. Nonlinear triad interactions occur in extremely shallow waters and shift the energy to higher frequencies. This has been implemented in the SWAN model.

For nearshore wave prediction, wave models need high-resolution current fields to properly resolve wave height gradients due to currents.

The benefits of the Sea State CCI dataset (https://climate.esa.int/en/projects/sea-state/) in estimating site wind and wave power energy on the European shelf were highlighted along with the need of valid retracker estimates (e.g., the SAMOSA+ retracker data).

The SARWAVE project (https://www.sarwave.org/es), which aims at developing a new sea state processor from SAR images for several regions of interest and exploring potential synergies with microwave and optical EO products, was presented. Swell estimates from Fully-Focused SAR (https://doi.org/10.24400/527896/a03-2022.3280) are also expected to be further developed.

Conclusions and recommendations:

- All wave physical processes in coastal zone need to be better monitored taking advantage of all available ESA data.

Opening Session Keynote

- **SARWAVE** project focuses in the coastal zone and could benefit from advanced coastal datasets.
- The EarthConsole® Altimetry Virtual Lab (https://vlab-test.earthconsole.eu/wp-content/uploads/2022/03/SARvatore_br_singlepages_220315.pdf), funded by ESA can be used to process data at high posting rates (up to 80 Hz) in unfocused SAR mode and to even higher posting rates and resolutions using the latest Fully-Focused SAR processing services.

- Satellite high-resolution altimetry products are needed for any kind of research or application in coastal zone, together with high-resolution spectral wave modelling. Both are complementary.

- Future ESA's research activities should focus on wave and tidal current interactions.

- Most of the time, ESA's resources are dedicated to the development of new algorithms, products, and tools. We recommend ESA to:

    - Launch more research calls on waves.

      Support the development of research activities in the domain of accurate renewable energy assessment near the coast (e.g., by developing new retrackers and processing schemes).

    - Support the creation of coastal altimetry products to fill the gap in the coastal zone with the highest possible spatial resolution.

- In addition, the quality of the existing coastal satellite altimetry products needs to be improved and validated with other independent observations.

To the in-situ data agencies such as Puertos del Estado, we recommend installing more wave buoys to monitor the African coasts in the Mediterranean Sea where the assessment of wave power is urgently needed and elsewhere, e.g., near the Atlantic coast. The number of coastal wave buoys needs to be increased to assess the quality of coastal altimetry products.

- As there is a significant gap between the wave modelers community and the coastal altimetry community regarding waves, we recommend improving the diffusion and the description of coastal products.

- Real-time coastal altimetry products are needed for operational wave forecasts.

- High-resolution spectral wave modelling and coastal altimetry need to be complementary to better understand and predict coastal hazards.

Possible benefits from our research activities to the SARWAVE project are the following:

- Spectral wave high-resolution simulations for all regions of interest: Mediterranean Sea, Agulhas current system, French façade, and Iberian Peninsula.

- 20 Hz SAR altimetry data covering the Atlantic coasts will soon be available. In the frame of the 2022 OCRE call, our team will process CryoSat-2 and Sentinel-3 altimetry data with the SAMOSA+ retracker along the whole Atlantic Ocean.

- Assessment of wave energy resource: We propose an assessment of the wave power for the coastal zones of interest of the SARWAVE project using the high-resolution altimetry products provided by the EarthConsole® Altimetry Virtual Lab. The wave power assessment is an added value for SARWAVE and this information would be vital for stakeholders (e.g., local renewable energy companies) considering the present energetic crisis.

- Trends of the SWH and the sea level rise: We propose the estimation of the SWH trends along the coasts using the SAMOSA+ high-resolution data, which is in line with a collaboration which is under development with LEGOS (Dr. Anny Cazenave) to understand whether wave setup contributes to the coastal sea level trend or not.

- **References**

Ardhuin, F., S. T. Gille, D. Menemenlis, C. B. Rocha, N. Rascle, B. Chapron, J. Gula, and J. Molemaker, 2017. Small-scale open ocean currents have large effects on wind wave heights, J. Geophys. Res. Oceans, 122.

Holthuijsen H. L., 2007, Waves in Oceanic and Coastal waters, 405 pp, Cambridge University Press.

Komen, G.J., Cavaleri, L., Donelan, M. A., Hasselmann, K., Hasselmann, S., Janssen, P.A.E.M., 1994. Dynamics and Modelling of Ocean Waves. Cambridge University Press.

Le Merle, E., Hauser, D., Peureux, C., Aouf, L., Schippers, P., Dufour, C., Dalphinet, A. 2021, Directional and frequency spread of surface ocean waves from SWIM measurements. Journal of Geophysical Research: Oceans, 126

Ponce de León, Guedes Soares C., 2022, Numerical study of the effect on waves in the Agulhas Current Retroflection. Ocean Engineering 264, 112333

Ponce de León Sonia,Yvan Gouzenes, Anny Cazenave, Jérôme Benveniste, 2022, Revisiting the coastal sea level rise using altimetry, wave buoys and a high-resolution spectral wave modeling in the French and Iberian peninsula Atlantic coast", American Geophysical Union Fall Meeting, 12-16 December 2022, Chicago, USA.

Ponce de León Sonia and Jérôme Benveniste, 2022, Predicting extreme waves in the French and Iberian Peninsula façade", OCEAN FROM SPACE, 24-28 October 2022, Venice, Italy POSTER.

Tolman, H. L., 2009, User manual and system documenta- tion of WAVEWATCH III TM version 3.14. Tech. Note 276, NOAA/NWS/NCEP/MMAB, 194 pp. + Appendices

Van Vledder, G. P., 2002, A subroutine version of the Webb/Resio/Tracy method for the computation of nonlinear quadruplet interactions in a wind-wave spectrum. Report 151b, Alkyon, The Netherlands.

WAMDI Group, 1988. The WAM Model - A Third Generation Ocean Wave Prediction Model. Journal of Physical Oceanography, 18(12), 1775–1810.

Image: ESA

Session 1: Technical issues in coastal altimetry

Co-chairs: Florence Birol and David Cotton

Round Robin Assessment of altimetry algorithms for coastal sea surface height data

Florence Birol; François Bignalet-Cazalet; Mathilde Cancet; Jean-Alexis Daguze; Yannice Faugère; Wassim Fkaier; Ergane Fouchet; Fabien Léger; Claire Maraldi; Fernando Niño; Marie-Isabelle Pujol; Ngan Tran; Pierre Thibaut

Objective of the study is to compare different sets of algorithms to compute the SSH in the coastal zone. Authors aim at:

1) Gaining insight on the sea level components (range, correction, MSSH) that limit the most the data quality near the coast;

2) Defining a baseline for the generation of a new global coastal SLA product. 20 Hz Jason-2 & Jason-3 data are studied over a period of 3 years (global coastal ocean; regional: Mediterranean Sea, NEA, Eastern Australia). In this round robin assessment several solutions are evaluated for each SLA component of interest (Range, Iono, WTC, Ocean Tide, SSB & MSSH). A total of 24 algorithms are tested.

Performances are assessed considering 3 frameworks:

1) Intercomparison between the different algorithms for each SLA component. 2) External data comparison using in situ measurements.
3) Intercomparison between 2 altimetry missions.

Results indicate that for the:

- WTC: STD Differences between the 3 solutions (RADS, GPD, ECMWF) < 0.3 cm. Differences between RAD & GPD solutions are very small up to 7-8 km to the coast. Impact on STD(SLA) < 0.1 cm near the coast at global scale but can be slightly larger locally.
- Ocean Tide: 6 model families (DTU16, EOT20, FES2014 & 2022, GOT4.10, TPX09, RegATm) compared with tide gauge and altimetry, assessing DAC compatibility. Best performance for FES2022 (gridded, unstructured mesh).
- Range + SSB (111 cycles): Compared to other retrackers, MLE4 stalls at 10km to the coast. Adaptive and ALES retrackers both recover significantly more data within 10 km from the coast. In terms of number of valid coastal SLA data, ALES is the most efficient algorithm. For each solution, the SSB used changes depending on the retracker (2D solutions used for MLE4 & Adaptive). In particular:

Summary of Session 1: Technical issues in coastal altimetry

- **15 km < dist < 200 km:** the adaptive retracker gives the lowest values in terms of STD(SLA).
- **2 km < dist < 15 km** (if we discard MLE4, not significant because of data loss): The ALES retracker gives the lowest values in terms of STD(SLA).

The following baseline is defined for the generation of a new global coastal SLA product:

Baseline selected considering algorithms available on J2&3 and results on the entire [0-200 km] coastal band

SLA component	List of algorithms	
Range	MLE4, **Adaptive**, ALES	→ NEW
Ionospheric correction	Dual frequency filtered, **GIM**	→ NEW
Wet tropo correction	Radiometer, ECMWF, **GPD+**	→ NEW
Ocean tide	GOT4.10, FES2014 regular grid, FES2014 unstructured mesh, CNES regional models (NEA, Med, Australia, Arctic), TPXO9v4, EOT20, FES2022 regular grid, **FES2022 unstructured mesh**	→ NEW
SSB	MLE4 2D 1Hz, MLE4 20Hz, MLE4 3D 20Hz, Adaptive 2D 20Hz, **Adaptive 3D 20Hz**, solution ALES 20Hz	→ NEW
MSSH	CNES15, SIO, **CNES22**	→ NEW

A new global product (L2P) covering the [0-500 km] coastal band and the Jason-3 mission will be released in May 2023 (V1).

Main recommendations:

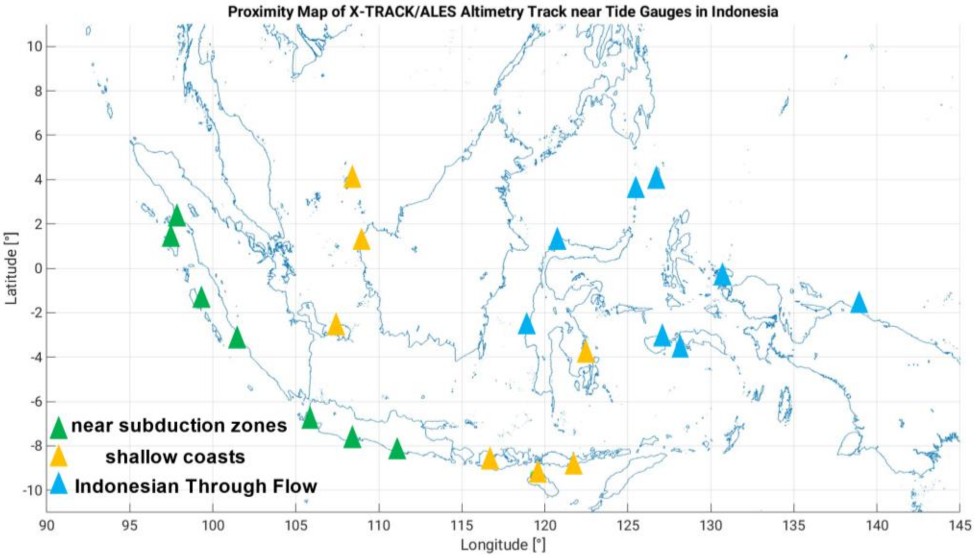
- Calculation of altimeter corrections at 20 Hz in L2 products (SSB, iono, tide, MSS, ...).
- Regular round robin exercises to test new algorithms and/or adopt common metrics.
- Transfer of coastal altimetry products in operational mode.
- Ensure long time series (combination of the LRM, SAR & SARin).
- Continue to improve the reprocessing of LRM data.
- Need of CAL/VAL sites adapted to the needs of coastal altimetry: cross-shore observations and not only at the coast.
- Development of derived products (including multi-satellite obs.) for coastal applications, in conjunction with the users.
- Fund training activities.

Summary of Session 1: Technical issues in coastal altimetry

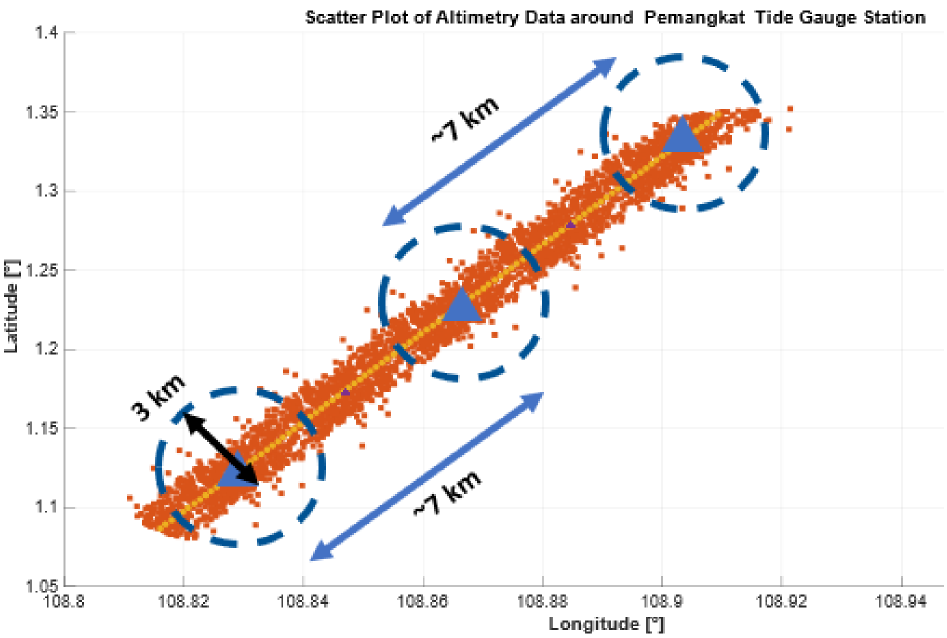
Coastal Altimetry Datasets Performance in Indonesian Seas

Zulfikar A. Nadzir, Luciana Fenoglio, Jürgen Kusche

This study aims to compare coastal datasets on Indonesian seas using high-frequency tide gauge stations: **24** hourly TG stations were divided into **3** group locations according to the geographical and oceanographical condition (Water height referenced to ellipsoid using levelling data and nearest GPS station/campaign):



Input datasets considered in the coastal band (3-20 km from the coast) were X-TRACK/ALES SLCCI+ (2002-2018) **[XA]**, ALES **[AL]** (2002-2020) & CMEMS **[NM]** (2002-2019). A 'nominal-point' method was developed to build time series:



It works by averaging data inside 3 km radius from the nominal-point that was harmonised among all datasets. The error assigned (called **internal noise level**) represents the **standard deviation** of averaged data. Evaluated parameters are the **precision** (internal noise level) & **accuracy** (num. of observation, Pearson correlation, STDD, MAD). Results indicate that:

- AL and XA 'improve' the noise level by ~69% [from 40 to 15 cm] compared to NM.
- X-TRACK/ALES provides the highest number of data, followed by ALES, then CMEMS.
- All three datasets perform almost similarly, with a correlation R ~=0.80 (XA outperforms other datasets).
- STDD: Two datasets [XA and NM] performs equally with ~18 cm STD.
- MAD: In average, all three datasets perform alike, by ~7.3 cm MAD.

All datasets best perform in Group 2 ['normal' coastal zone].

An additional analysis was made by using the AVL SARvatore services for Sentinel-3 and comparing SAMOSA+ & SAMOSA++ SAR Sentinel-3 outputs to LRM data in the 2-14 km coastal band. SAMOSA++ outperforms SAMOSA+, while having smaller magnitude of STD compared to the LRM-mode results [~13 cm vs. 20.5 cm].

Conclusions:

1. Coastal retrackers are more **precise** (by ~15 cm) and provide more observations (by 33%) compared to CMEMS data, from 4 to 20 km to the coast.
2. X-TRACK/ALES [XA] and CMEMS [NM] perform similarly in terms of **accuracy** (Correlation Coefficient/STDD/MADD →0.86/19/8.3 | 0.83/17/6.1).
3. In locations with steeper bathymetry slope, or of strong current, the performance is slightly **worse** in comparison to flat coastal zone locations (by 5% and 16% → MADD 6.2/7.2/6.9).
4. The comparison shows that in terms of STDD SAR data perform **better** than the LRM counterpart by 34% (~7 cm difference).

Recommendations:

1. Add more SAR datasets into computation.
2. Expand the study including 45 additional TG.
3. Dive deep into the combined effect of bathymetry + topography, waves and possibly tides on the coastal sea surface height retrieval.

Summary of Session 1: Technical issues in coastal altimetry

Improving SAR Altimeter Processing Over the Coastal Zone - The ESA HYDROCOASTAL Project

David Cotton and the HYDROCOASTAL Project Team

HYDROCOASTAL is funded under the ESA Science for Society Programme Element. The aim is to maximise exploitation of SAR and SARin altimeter measurements in the coastal zone and inland waters, by evaluating and implementing new approaches to process SAR and SARin data from CryoSat-2, and SAR altimeter data from Sentinel-3A and Sentinel-3B.

New SAR and SARin processing algorithms for the coastal zone and inland waters have been developed and tested, and a processing scheme implemented to generate global coastal zone and river discharge data sets.

The HYDROCOASTAL project in numbers:

- 18 regions of interest to cover a wide range of inland water and coastal zone characteristics.

- 2 years data (2018-2019), 3 years for regions with river discharge estimates

Inputs:

- CryoSat FBR baseline D SAR and SARin mode data. All mission to 21/08/21.

- Sentinel 3A and 3B SIRAL L1A data. All mission to 30/09/22.

- Enhanced Wet and Dry Troposphere Corrections (U Porto).

Documented descriptions of processing schemes and products at
www.satoc.eu/projects/hydrocoastal

Six candidate L2 processing algorithms have been implemented:

1. Two Step Analytical Processor – coastal and inland: isardSAT
2. Specialised SARin – coastal: Aresys
3. MWaPP – Multiple Waveform Persistent Peak – inland: DTU Space
4. ICC-ER (Isolate, Cleanse, Classify - Empirical Retracker – inland: ATK
5. Statistical Re-tracker STARS type – coastal: U Bonn
6. ALES+ for SAR - coastal: TU Munich

Their performance has been evaluated, and the best performing algorithms have been selected to generate global coastal zone and inland water products in the second year of the project.

From the evaluation of the first test data set, the U Bonn and DTU algorithms have been selected to generate a “global” coastal and river data set, respectively.

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L1a to L2 Processor implemented on G-BOX Virtual Machine (64 threads) provided by EarthConsole® (https://earthconsole.eu/)

The global data set comprises:

- Global L2 data sets for coastal zone and inland water.
- Global L3 data sets (time series) for selected "large to medium" rivers.
- Global L4 data sets (river discharge) for selected "large to medium" rivers.
- Experimental data set for "small rivers and tributaries".

This product will be made freely available. We expect this product to be available in Q2 2023. A series of impact assessment studies will be carried out, to test and demonstrate the potential impact and benefits of the global dataset.

If external users would like to propose other areas for their own study, then please contact the project manager: d.cotton@satoc.eu.

The outcomes of the HYDROCOASTAL will include:

- State of the art review of SAR Radar Altimetry and current challenges.
- Initial SAR/SARin satellite altimeter L2, L3 and L4 test data set over 18 regions of interest.
- Full descriptions of processing algorithms and output products.

Global output products:

- A global L2 coastal and inland water SAR altimeter data set.
- Time series (L3) and river discharge (L4) data sets for medium to large rivers

Scientific Road Map (September 2023) will provide recommendations for further improvements to processing, and to generate improved global SAR altimeter coastal and inland water data set:

- Along-track nature of altimeter data limits uptake by users. Investigations needed to find approaches to derived gridded data.
- What is the impact of freshwater river discharges on sea level variations in transition zones between estuary mouths and surrounding coastal waters?

Different re-trackers perform better in different locations/environments. How to build a processor to accommodate this and create a consistent data set?

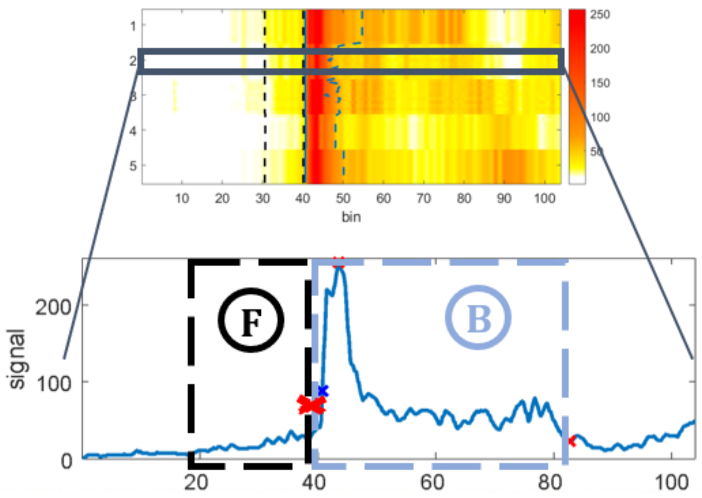
Session 1: Technical issues in coastal altimetry (cont'd)

Co-chairs: Florence Birol and David Cotton

Improving coastal water altimetry retracking by incorporating spatial dependency of waveforms

Omid Elmi, Mohammad J. Tourian

Authors reminded limitations of LRM and SAR altimetry in coastal domain. The objective is to develop a retracking method that takes advantage of the spatio-temporal variation of power in a radargram stack. In particular, the retracker offset obtained from the radargram stack benefits from the spatio-temporal correlation of recorded power and is independent from a prescribed waveform type. The method aims at determining the retracking offset by segmenting the radargram into two regions: front and back of the retracking line.



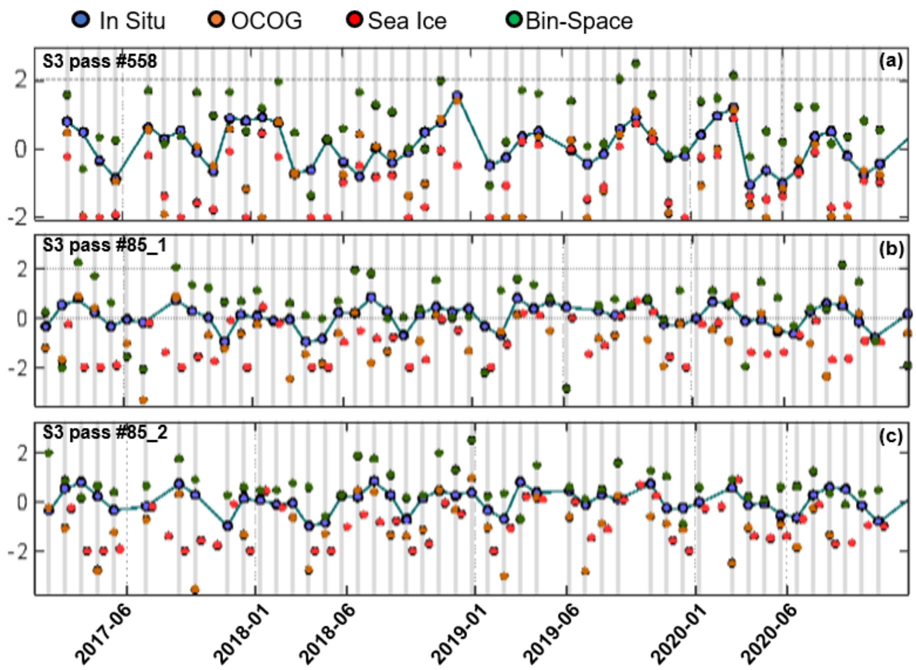
Front region represents the area spanned by the leading edge

Back region includes the peak and the portion of the trailing edge that still contains strong signal

A case study is presented for Sentinel-3 data along with a description of the method and the associated formulation.

Conclusion:

- All waveforms are re-aligned to a fixed height (absolute alignment), allowing stacking in time and space.
- The absolute alignment enables the assignment of probabilities to fixed bin values.
- Accounting for spatial dependencies allows us to deal with waveforms that originate from off-nadir targets in coastal region.
- Within 0-10 km from the coast, the bin-space retracker improves the height estimate by more than 25%:



- The bin-space retracker is insensitive to the waveform type.

Outlook

- Assessing the sensitivity of the results to the initial retracker.
- Employing the methodology for more case studies.

Analysis of Sea Level Variability in German Bight and Baltic Sea by Using Fully-Focused and Unfocused SAR Altimeter Products and GNSS Reflectometry

H. Uyanik J. Chen, Z. Nazdir, L. Fenoglio, K. Larson, B. Uebbing, J. Kusche

After an introduction on SAR & GNSS-IR, authors discussed the Study Area and Products:

- **S3A Altimeter Products (2018.06 to 2020.06):**
  - L1a from Eumdac (input to SMAP-FFSAR).
  - 20 Hz HYDROCOASTAL L2 dataset.
  - 20 Hz L2 SAMOSA+ estimates from EarthConsole.
- **Tide Gauge Data:**
  - Provided by BfG.

Summary of Session 1:
Technical issues in coastal altimetry

- **GNSS-IR Data:**

  - Rinex data from BfG and Sonel (input to GNSS-IR program in SNR form).

Adopted methodology included:

- Overpass Method.
- Overpass Method Common Number of Points.
- Binned Along Track Comparison (mean and median over 0-20 km dist. from coast).

SLA = Altitude – Range – Corrections

Corrections = iono + wet tropo + dry tropo + earthtide + loadtide + polartide*0.468 + oceantide

No DAC applied following Hydrocoastal Project agreed methodology.

Analyses were presented and **conclusions are the following**:

- Various retracker algorithms were used in the HYDROCOASTAL Project, the accuracy (stdd wrt nearest TG) is between 5-9 cm depending on the retracker.

- For UF-SAR, among all considered retrackers, SAMOSA+ has the best accuracy (median stdd 0.057 m).

- Both FF-SAR and UF-SAR have median and mean of STDD over 0-20 km between 9 and 17 cm, respectively.

- For FF-SAR, least noisy are results from SAMOSA+ retracker compared to OCOG and PTR (PTR has the highest noise, STDD 10/20/25 cm).

- GNSS-IR accuracy in coastal zone (STDD w.r.t nearest TG) is 4 cm/9 cm (daily/sub-daily).

Summary of Session 1: Technical issues in coastal altimetry

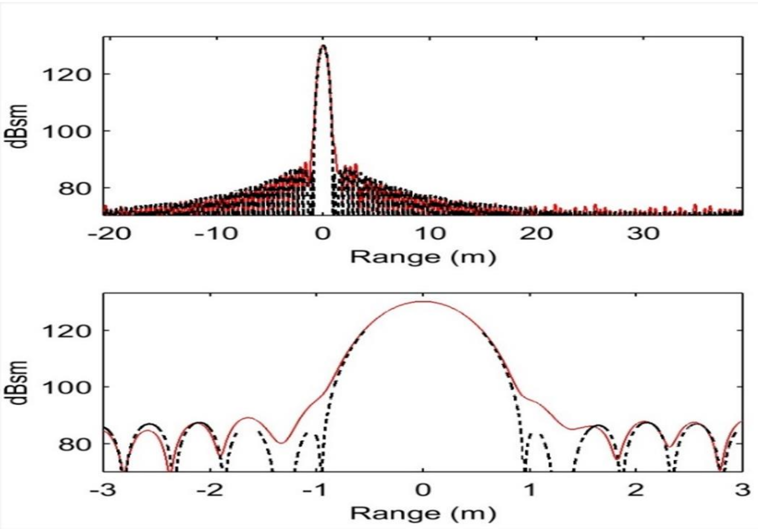
A phase error in Sentinel-3 Individual Echoes, and how to correct the error in post processing

R. Abileah and S. Vignudelli

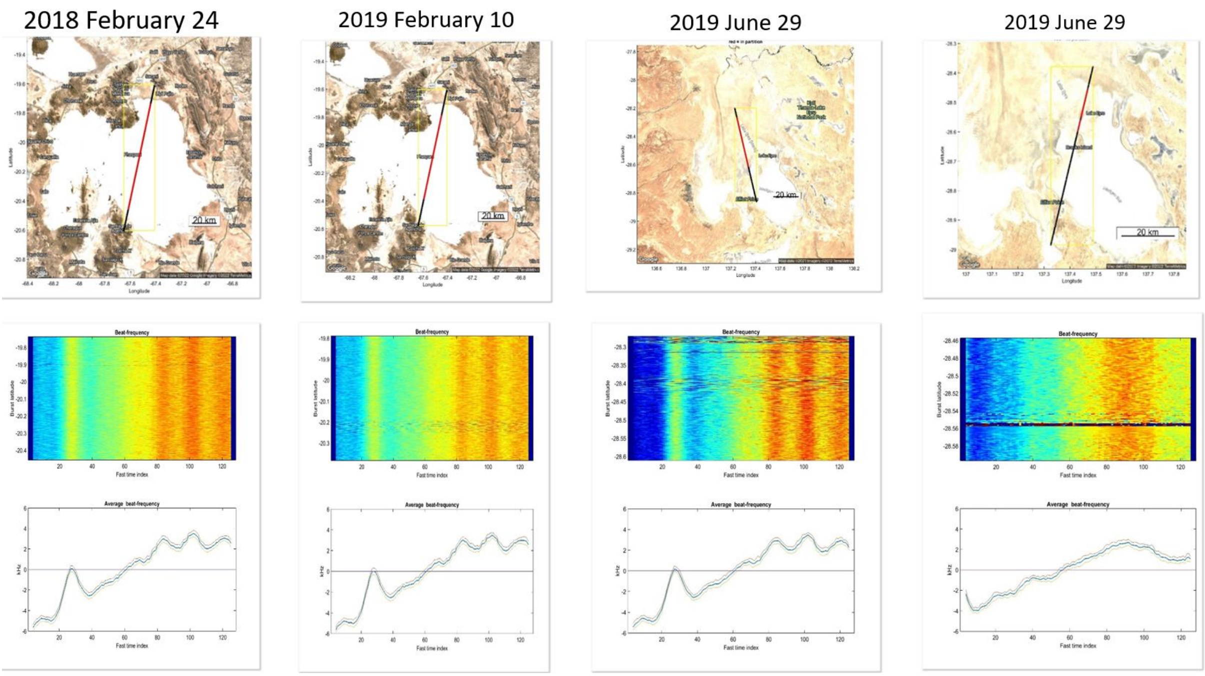
Authors found an anomaly in the waveforms associated specular echoes. They tracked it down to an 8 kHz drift in the beat-frequency. It is still unclear where it comes from but the empirical data points to the radar pulse compression stage.

Selected area of analysis is Salar de Uyuni. From January to March the Salar de Uyuni (Bolivia) is covered by a thin layer of water, which makes it an excellent specular target for testing radar altimeters.

Waveform anomaly: In the plots below, red is the waveform of Salar de Uyuni echoes (with Hamming window) and black is the expected waveform for a specular echo. The broadening in the near sidelobes [Abileah and Vignudelli, 2022] led to the discovery of a beat-frequency drift.



In the first two figures below from the left, the **Sentinel-3A** (S3A) beat-frequency of echoes over the 80 km altimetry track on the Salar de Uyuni is reported (middle panel) and averaged (bottom panel). In the average plot the beat-frequency (blue curve) varies 8 kHz over the pulse duration. The red and yellow curves are averages over the first and second halves of the track, offset +3 kHz for clarity. The next panel set is the same S3A track a year later. The last two panel sets are from Lake Eyre (another large salt lake), comparing S3A and S3B. The drift in S3B is also 8 kHz, but distinctive from S3A.



From the examples shown, authors conclude that a beat-frequency, which in theory should be constant, drifts 8 kHz during a pulse period. Their hypothesis is that the drift comes from filters in the pulse compression circuits.

References:

Abileah and Vignudelli, Precise inland surface altimetry (PISA) with nadir specular echoes from Sentinel-3: Algorithm and performance assessment, Remote Sensing of Environment, Volume 264, 2021, https://doi.org/10.1016/j.rse.2021.112580)

Evaluating the new HRMR wet tropospheric correction from Sentinel-6MF over coastal regions

M. Joana Fernandes, Telmo Vieira, Clara Lázaro, Bernard Vasconcellos, Pedro Aguiar

Authors presented the first results about New Sentinel-6 Michael Freilich (S6MF) wet tropospheric corrections (WTC) amr_wet_tropo_cor (AMR) & rad_wet_tropo_cor (AMR + HRMR) by performing:

- An Assessment of the availability of the new WTC
- An Analysis of the WTC differences
    - ✓ AMR vs Rad
- A Comparison with GNSS-derived WTC

Summary of Session 1:
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- ✓ GNSS vs AMR
- ✓ GNSS vs Rad

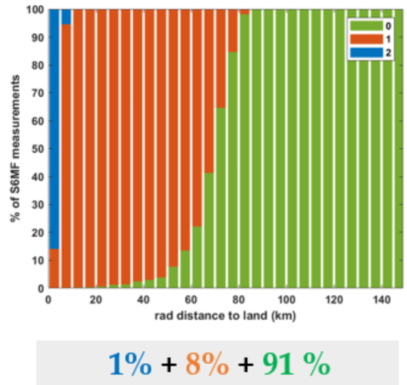
- For GPD+ WTC for S6MF
  - ✓ A first version
  - ✓ Independent assessment GNSS vs **GPD+**

Input data are the Sentinel-6 climate-quality Advanced Microwave Radiometer Level 2 NTC Products from EUMETSAT Data Centre (20 Hz). 12 cycles since the beginning of the F07 ground processor have been considered: Cycles 65-76, 15 Aug – 11 Dec 2022 (~4 months).

The availability of the WTC computed with a combination of AMR and HRMR was presented in relation to the distance to the coast:

- open ocean processing
  rad_surface_type_flag = 0
- nominal coastal processing
  rad_surface_type_flag = 1
- coastal processing with only AMR data
  rad_surface_type_flag = 2

- **rad_wet_tropo_cor derived only with AMR covers data for distances to land up to 10 km.**
- **Coastal processing covers measurements with distances to land up to ~80 km.**

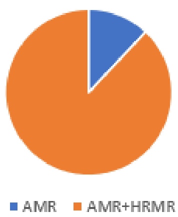


Over coastal zones, for WTC computed with a combination of AMR and HRMR [coastal processing - rad_surface_type_flag = 1,2]

- **88% of the measurements consider AMR + HRMR data**
  [nominal coastal processing - rad_surface_type_flag = 1]
  - ✓ rad_wet_tropo_cor ≠ amr_wet_tropo_cor

- **12% of the measurements are derived only with AMR data**
  [coastal processing with only AMR data - rad_surface_type_flag = 2]
  - ✓ rad_wet_tropo_cor = amr_wet_tropo_cor

  Distance to land in the range 0-10 km



The talk also included AMR versus Rad WTC analyses, an independent assessment with GNSS-derived WTC and a discussion of the GPD+ WTC for S6MF and its validation against GNSS data.

Summary of Session 1:
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Summarising the results:

- A very first version of GPD+ WTC has been computed for S6MF:
  - WTC_{Rad} with distances from coast ≤ 10 km have been rejected.
  - For all points with coastal processing flagged as invalid by GPD+: RMS of WTC cycle differences (WTC_{Rad} - WTC_{GPD+}) range from 2.3 to 2.8 cm.
  - For points estimated with AMR only (D<10 km): these RMS values range from 2.8 to 3.2 cm (24% of the points with coastal processing).
  - Independent comparison with GNSS:
    - Most significant impact of GPD+ for distances to land in the range 0-10 km.
      - ✓ More pronounced in the range 0-5 km.
  - Capability of GPD+ to remove the land contamination and provide a continuous solution.

Session 1: Technical issues in coastal altimetry (cont'd)

Co-chairs: Clara Lázaro and Francesco Nencioli

Fully Focused SAR Altimetry and Innovative River Level Gauges for Coastal Monitoring – the FFSAR-Coastal Project

David Cotton and the FFSAR-Coastal Project Team

The FFSAR-Coastal Project, Funded by ESA through the EO4Society Open Call: https://www.satoc.eu/projects/ffsar/, is applying the SMAP Fully Focused SAR (FFSAR) altimetry processor (https://github.com/cls-obsnadir-dev/SMAP-FFSAR) on Sentinel-3A and Sentinel-3B data in order to evaluate the potential of FFSAR altimeter data to contribute to coastal and estuarine monitoring and identify optimum processing choices.

Two different environments:

- The **Severn Estuary**: Highly dynamic mixed tidal estuary environment, confluence between a river and its estuary experiencing large tidal range and strong tidal currents.

- The lower **Rhone Delta and Camargue**: A low lying, flat river delta and wetland environment, susceptible to inundation and rising water levels.

Validation will be made:

- Against in situ data, evaluate ability to map key features.
- Using vortex.io (https://www.vortex-io.fr/) micro-gauges:
    - Install 4 micro gauges (2 per region) for in situ validation.
    - Drone campaigns to map water level from in situ sites to satellite track.

Benefits of the Vortex.io micro gauges are:

- LIDAR, 8 Mpx camera, real time data, remote management.
- Lightweight, small, and easy to install.

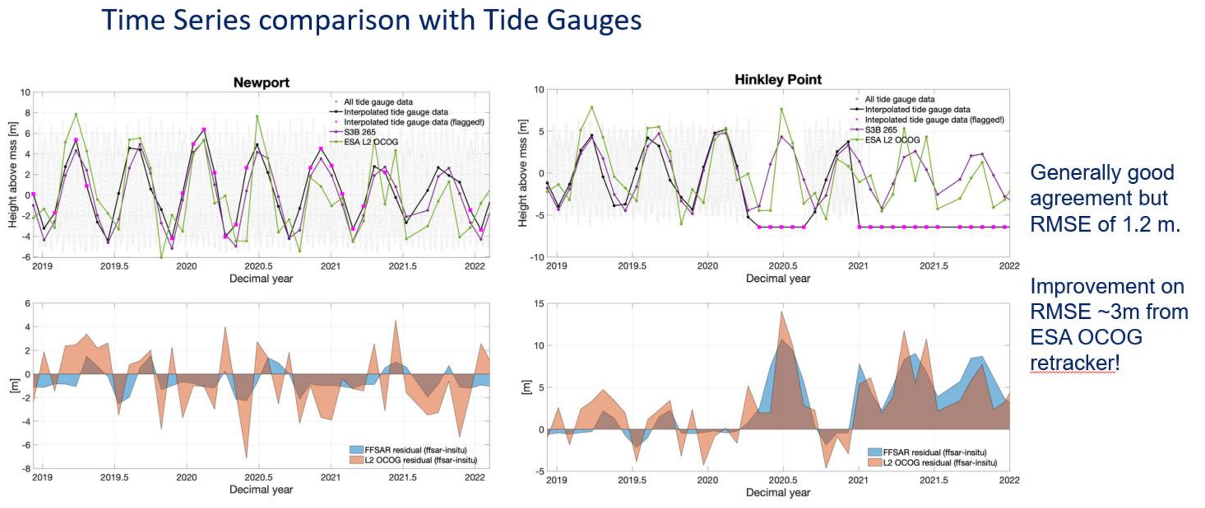
For Drone campaigns, the Team aims at connecting water level at gauge to satellite track at the time of overpass.

- LIDAR: cm level accuracy, 50 cm to 90 m range.
- 8 Mpx camera: water mask, orthophotos.
- 900g.

Initial results for FF-SAR processing have been presented. In some places, the water level is present in FFSAR where it is not available in standard processing. Improved results have been obtained by using the Multi-PTR (10 peak) re-tracker available in SMAP to extract true water level

Summary of Session 1: Technical issues in coastal altimetry

For the Severn Estuary, the following preliminary results were discussed:



The approach used in Severn does not work as well for the Rhône delta and more analyses are needed.

Final Outputs will include:

- FF-SAR, Drone & Vortex.io micro-station data (https://cco.geodata.soton.ac.uk/ccoresources/FFSAR-Coastal/').
- Product Validation and Evaluation (Small scale physical signals in highly tidal regions, Tidal asymmetry/gradients across estuaries, Understanding interaction of tides and river discharge).
- Application Road Map (Key requirements from User Groups, Recommendations for application of FFSAR in coastal monitoring systems, Recommendations for use of “micro” gauges as part of coastal monitoring systems).

Outlook and Recommendations:

- Next steps
  - Optimise FFSAR processing options for Severn and Rhône.
  - Generate along track time series.
  - Evaluate capability to map small scale signals as close as possible to the coast.
- Recommendations
  - User interests (UK):
    - Contribute to SWOT validation campaign in the Severn?
    - Possible contribution to UK Hydrographic Office plans to update Vertical Offshore Reference Frame (VORF).
    - Interest in ability to map difficult to access inter-tidal regions.

- User interests (FR):
  - Coastal flooding/erosion.
  - River discharge, salinisation, water quality

ALBATROSS: Improving the bathymetry and ocean tide knowledge in the Southern Ocean with satellite observations

Carole Belot, Mathilde Cancet, Ramiro Ferrari, Ole Andersen, Michel Tsamados, Geir Moholdt, Florent Lyard, Marco Restano, Jérôme Benveniste

The ALBATROSS project aims to improve knowledge on:

1. Bathymetry around Antarctica.
2. Ocean tides in the Southern Ocean (high resolution hydrodynamic model).
3. Use satellite observations to improve the bathymetry the grounding line and the coastline information.
4. Explore linkage between sea ice roughness bathymetry gradients and tides.
5. Retrieve tidal estimates from CryoSat-2 data.
6. Implement a new high resolution tidal model with data assimilation.
7. Share information and knowledge with other polar science initiatives and projects.

Among the presented results:

- Tidal estimates from CryoSat-2 altimetry data (DTU) have been presented resulting in an Extremely valuable new altimetry dataset to explore tides in the Southern Ocean, and for validation/assimilation into models.
- High resolution regional tidal modelling (Tidal modelling strategy based on TUGO-m hydrodynamic model (LEGOS)) including Regional/local tuning of the model parameters and altimetry and tide gauge data assimilation to constraint the solution and to validate tidal simulations.
- Bathymetry improvement: Local improvement observed but direct validation is quite limited due to lack of (independent) data.
- Tidal modelling based on the ALBATROSS bathymetry datasets reporting:
  - Clear improvement when considering the new ALBATROSS bathymetry products fine-tuned coastline & ice shelf).

- Without assimilation, ALBATROSS hydrodynamic simulation (no data constraint) at the level of FES2014 (assimilated)!

It has been reminded that bathymetry controls ocean currents, temperature and sea ice presence. The project searched for a surface signature of bathymetry in the sea ice roughness to explore linkage between sea ice roughness, bathymetry and ocean tides. Novel technique has been developed at UCL using 20 years of NASA MISR (Multi Multi-angle Imaging Spectro Spectro-Radiometer) with Operation Ice Bridge airborne data for training.

Conclusions:

- CryoSat-2 data are extremely valuable for tidal estimates and bathymetry retrievals.
- The new ALBATROSS products bring clear improvement.
- Results on tidal simulations are very encouraging.
- Main difficulty: independent validation (lack of in situ observations for bathymetry & tides.

Last steps:

- Finalization of the regional tidal atlas (early 2023): Assimilation
- WP3 Impact Assessment (early 2023):
    - In the ocean (UCL): Impact on the CryoSat-2 SSH and sea ice products (ESA CryoSat+ Antarctic Ocean project).
    - Ice shelves (NPI): Impact on monitoring of Antarctic ice shelf dynamics parameters.
- Redaction of a public scientific roadmap with recommendations for future projects, available soon.

Planned outcomes:

- Southern Ocean composite bathymetry.
- Antarctic grounding line and coastline.
- Sea ice surface roughness product.
- Southern Ocean high resolution tidal atlas.

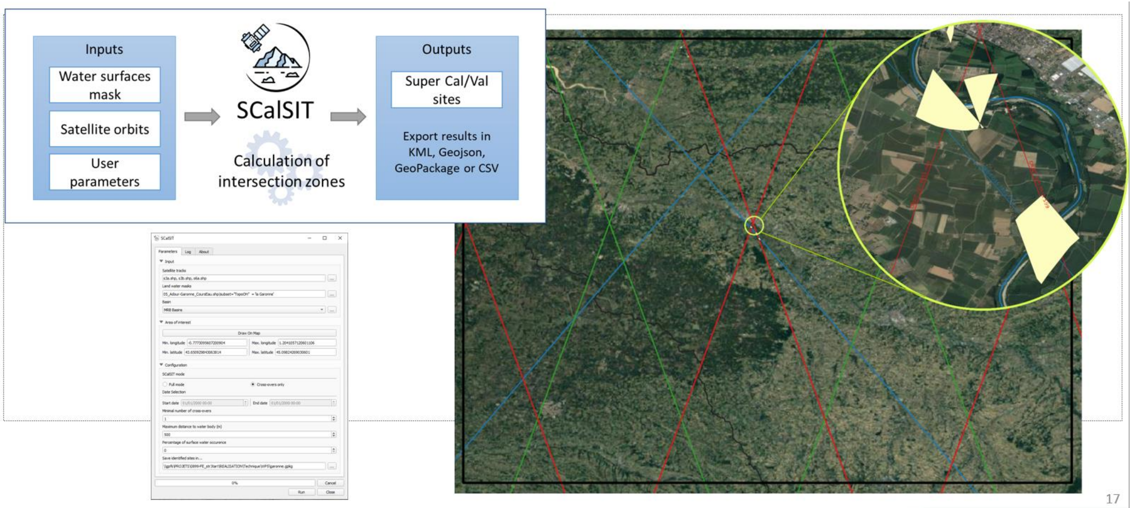
Sentinel-3 Topography mission Assessment through Reference Techniques – The ESA St3TART project

Elodie Da Silva, Nicolas Picot, Jean-Christophe Poisson, Henriette Skouras, Geir Moholdt and the ESA St3TART project Team

Main objective of the project (running from July 2021 to April 2023) is to prepare the ground to ensure an operational provision of FRM (Fiducial Reference Measurement) to support the S3 Land STM mission over Inland Water, Sea Ice and Land Ice. Detailed objectives are the followings:

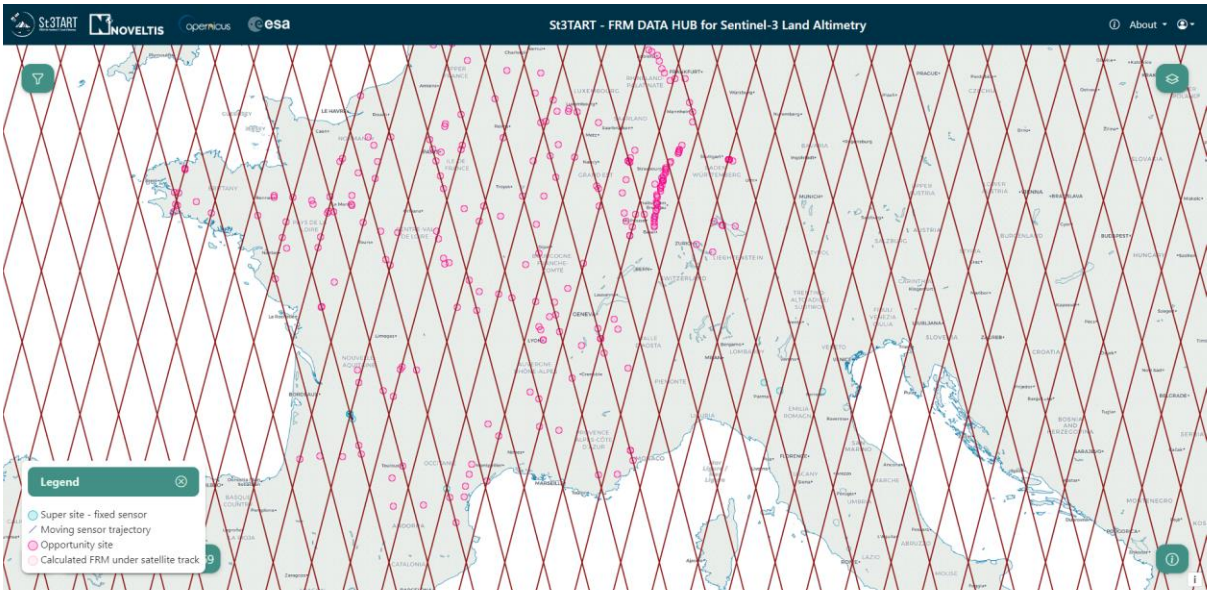
These have been discussed in detail indicating strategies adopted for data collection and validation in the scenarios of interest. It has been reminded that FRM are not directly comparable with Thematic Data Products. To ensure comparability with a specific measurements, post processing is needed. Metrological analysis implies the assessment of related uncertainties.

St3TART tools include SCalSIT:



and the FRM Data Hub (Unified data format: NetCDF with specific attributes):

Summary of Session 1:
Technical issues in coastal altimetry



Centralising the access to FRM measurements, the FRM Data Hub aims to federate the Cal/Val community to share FRM measurements in a free and accessible manner with fully characterised and documented FRM processing and measurements.

Recommendations for Hydrology

- Importance to deploy instruments managed and maintained by the project to ensure the operationality of Cal/Val Super Sites.
- Consider the "multi-mission" aspect to determine Super Sites, to share costs.
- Importance to have Super Sites representative of different measurement configurations.
- Deploy as many Super Sites as possible.
- Also rely on existing in situ networks from different countries to increase the number of opportunity sites to provide statistical analysis of Sentinel-3 performance over inland water.

Recommendations for FRM:

- Analysis of uncertainties is quite complex. "FRM metrological traceability document", written in collaboration with NPL, could be a good template to be used on other projects.

The Cryo-TEMPO Coastal Ocean Thematic Data Product: A CryoSat-2 Regional Product for Ocean Applications

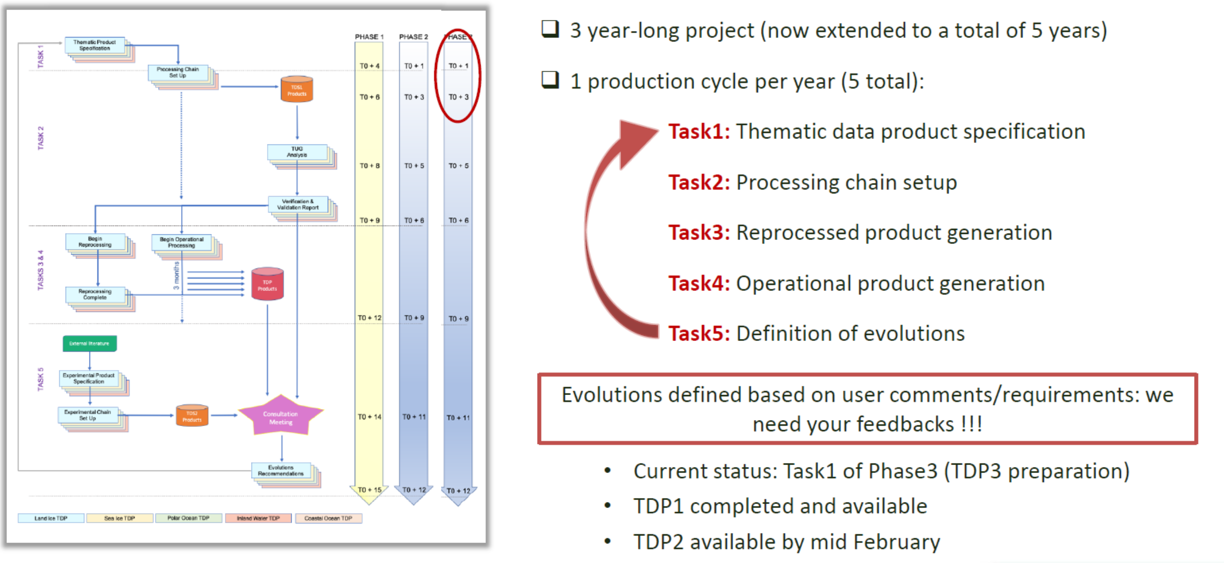
F. Nencioli, S. Dinardo, T Zilio, A. Deguze, A. Sanchez Roman, A. Pascual, S. Labroue and J. Bouffard

CryoSat-2 achievements in the Coastal Ocean have been summarised. The main aim of the Cryo-TEMPO project is to develop agile, robust, state of the art CryoSat-2 products dedicated to five Thematic Areas (Land Ice, Sea Ice, Polar Ocean, Coastal Ocean, Inland Waters).

The Cryo-TEMPO Coastal Ocean TDP have been discussed. Created from L1B and L2, 20 Hz product, GOP baseline-C product. Full CryoSat-2 mission covered; new observations updated monthly. Two main access points:

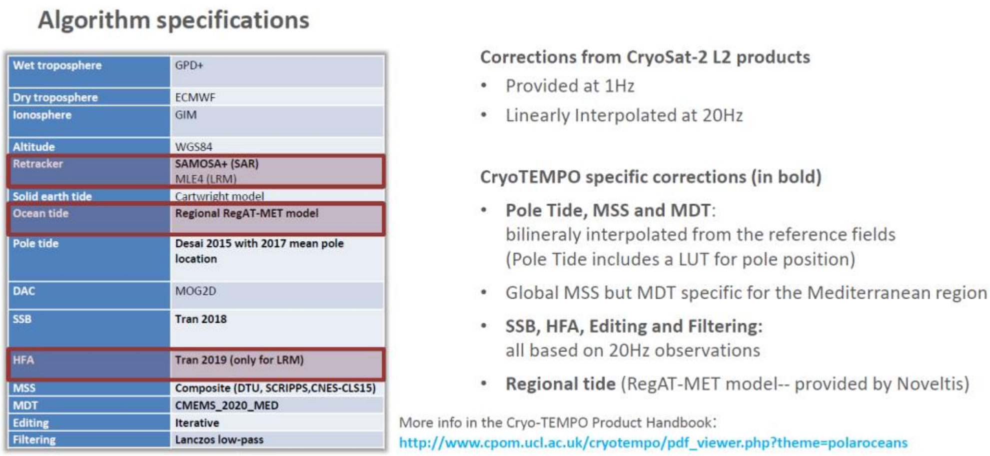
- The ESA CryoSat science server: https://earth.esa.int/eogateway/missions/cryostat/data
- The Cryo-TEMPO web portal http://www.cpom.ucl.ac.uk/cryotempo/index.php?theme=coastaloceans

In terms of production cycle:



and algorithm specifications:

Summary of Session 1: Technical issues in coastal altimetry

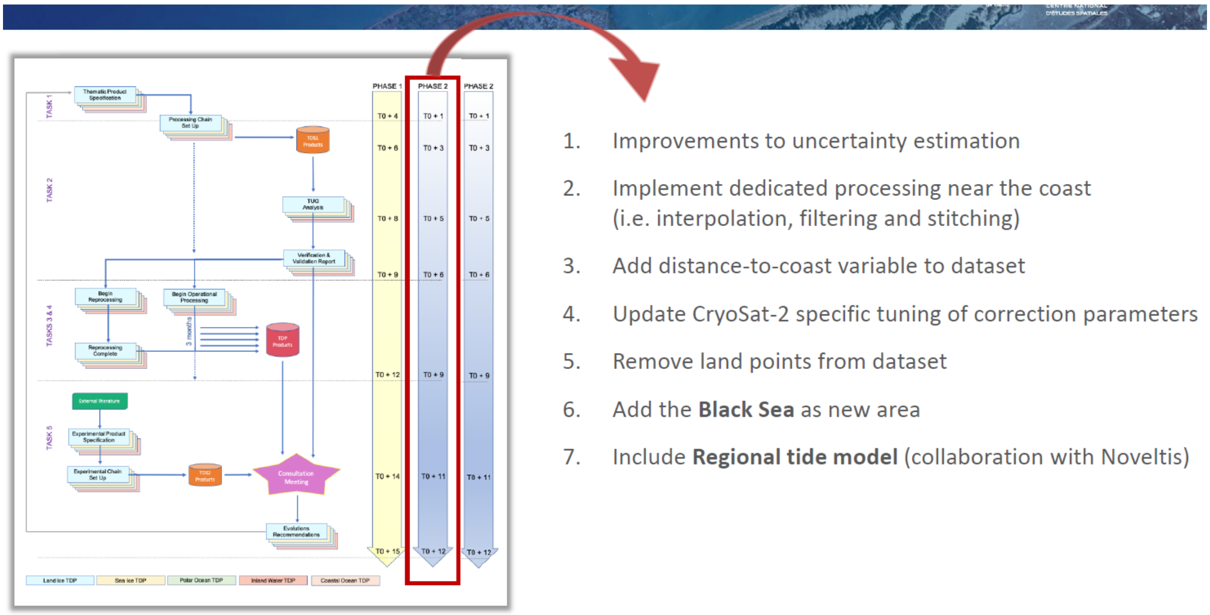


Wet troposphere	GPD+
Dry troposphere	ECMWF
Ionosphere	GIM
Altitude	WGS84
Retracker	SAMOSA+ (SAR) MLE4 (LRM)
Solid earth tide	Cartwright model
Ocean tide	**Regional RegAT-MET model**
Pole tide	**Desai 2015 with 2017 mean pole location**
DAC	MOG2D
SSB	**Tran 2018**
HFA	**Tran 2019 (only for LRM)**
MSS	**Composite (DTU, SCRIPPS,CNES-CLS15)**
MDT	**CMEMS_2020_MED**
Editing	**Iterative**
Filtering	**Lanczos low-pass**

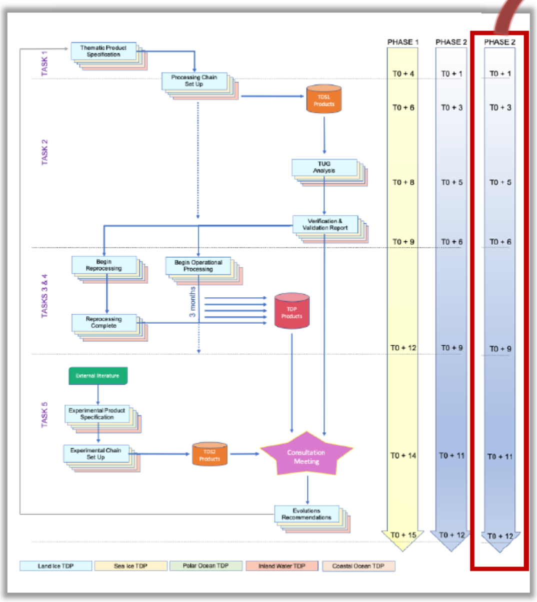
In particular, the Python implementation of the SAMOSA+ algorithm is freely available on GitHub: https://github.com/cls-obsnadir-dev/SAMPy

The correction for the correlation between significant wave height (SWH) and range errors available in TDP1 has been discussed.

Evolutions planned for phases 2 & 3 are the following and have been discussed in detail:



Summary of Session 1: Technical issues in coastal altimetry



1. Include SarIn observation (range only; no phase)
2. Extend domain to North-East Atlantic
3. Assess altimeter mode SSH bias in the Atlantic
4. Further refine correction parametrizations

Conclusions:

- CryoSat-2 observations remain underutilised in oceanography despite the advantages of SAR technology.
- Dedicated Cryo-TEMPO regional coastal product in the Mediterranean Sea.
- Initial comparison with in-situ observations shows analogous or better performance than existing satellites.
- Still room for improvements in the near shore region (<5 km from the coast).
- Iterative cycle to improve Cryo-TEMPO products each year.
- User feedbacks will be an integral part of the process to further improve the product performance near the coast.

Outlook and recommendations

- Dedicated (agile, robust) processing chains are important for testing state of the art solutions in coastal regions, but they need to be assessed:
    - Round robin projects (each with their own flavour of dataset/ diagnostics).
    - Define a common dataset and set of diagnostics to be used as benchmark?

Comparison with Tide Gauges:

- Should move away from distance from the TG to pair altimetry and in-situ.
- Due to complex coast morphology close distances might be dynamically very far (and vice versa).

Oceans Radar Altimetry With MAGAL Constellation

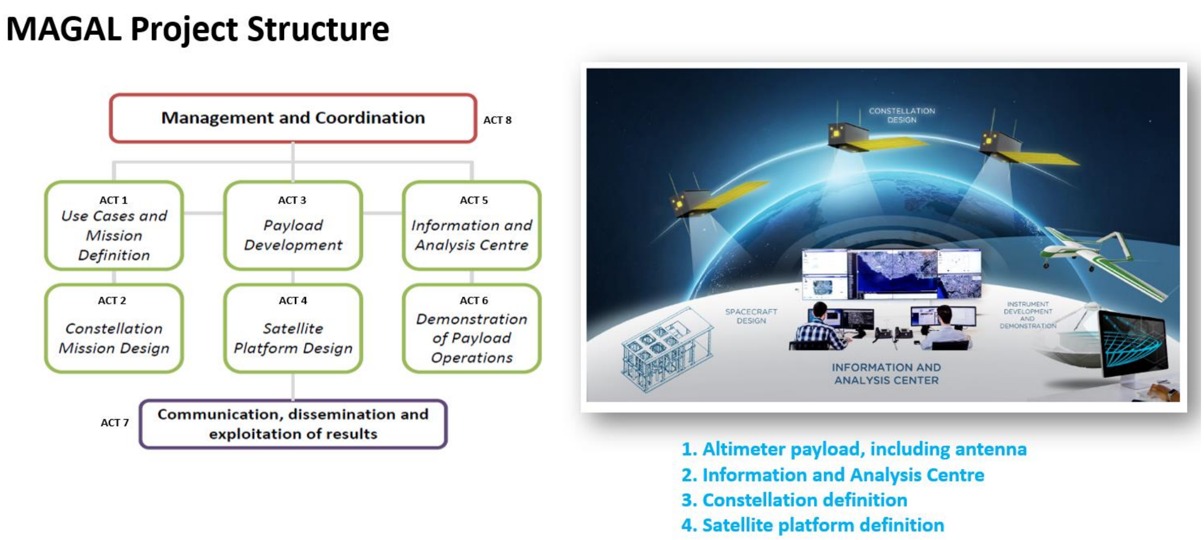
Marques A., Lázaro C., Fernandes M.J., Melo J., Guerra A., Arantes M., João A., Martins J. P., Pires N., Figueiredo P. V., Coelho V., Carvalho N., Cecilio C., Martins A., Mashtakov Y., Lima P., Fort B., Tapley B.

The MAGAL Project (1/7/2020 - 30/6/2023) has been presented (https://projects.efacec.com/magal/). Objectives:

- Development of a cost-effective, small satellite platform to reduce launch and operational costs.
- Development of a custom radar altimeter solution, with lower power consumption, assuring data quality and reliability.

Proof of concept: Can an innovative technological concept such as a constellation of small satellites with radar altimeters, not yet implemented to date, contribute to the future of Satellite Altimetry?

Project structure:



Use cases and applications:

Summary of Session 1:
Technical issues in coastal altimetry

MAGAL Use Cases and applications

- Sea Surface Topography
- Eddy Detection and Tracking
- Marine Debris Monitoring
- Inland Water Levels

Use cases require to:

- Improve the current temporal sampling: 10 to 5 days
- Maintain the current spatial sampling: interleaving MAGAL tracks with those of operational satellite altimetry missions can improve spatial sampling
- Maintain measurements accuracy and resolution
- Have precise satellite location and orbit maintenance

⇨ **Business plan with key products and cases to be exploited by MAGAL identified**

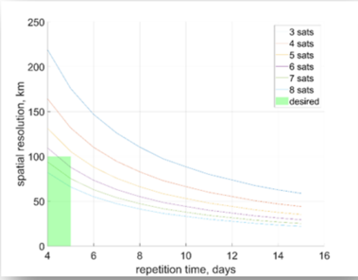
- ⇨ **Fisheries**
- ⇨ **Marine protected areas fulfilling European requirements directives**
- ⇨ **Natural disasters**

Orbital parameters:

Constellation Orbital Parameters

- **Mission science requirements frozen**
- **Constellation orbit defined**

Type of orbit	Sun-synchronous (SSO ≈ 98°)
Orbit Altitude	≈ 500 km
Expected Duration	Up to 3 years
Orbital Period	≈ 90 minutes
Revisit Period	5 days
# Satellites	6 Satellites

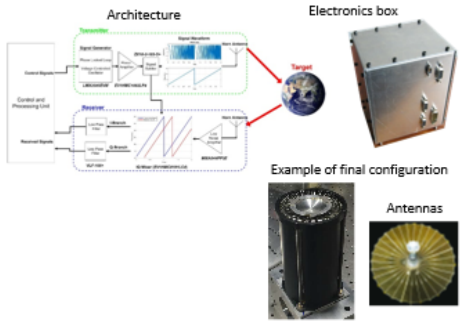


- **Exact ground track repetition Orbit**
- **1 orbital plane with all 6 satellites**
- **Temporal sampling: 5 days**
- **Spatial Sampling at Equator: ~88 km**

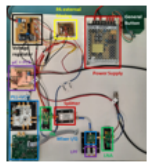
Under MAGAL project, no ground link neither control centre is required. Regarding the development of the radar:

Payload developments

- Radar altimeter (RA): developed by EFACEC and IT Aveiro, **miniaturized; expected accuracy of a single measurement after dedicated processing: 2-3 cm.**
- **Ku-band (13 GHz)**
- RA architecture is based in FMCW (Frequency Modulated Continuous Wave) to **minimize its power consumption.**
- RA communicates with MAGAL satellite through CAN bus protocol.
- **RA measurements at 20 Hz rate.**
- RA provides its Received Signal Strength Indicator (RSSI), as backscattering coefficient.
- RA with **range profile (FFT of distance measurement) at 1 Hz.**
- Local storage of range profile data; if required, loss-less data compress could be used.
- Radar altimeter will use primarily military/automotive industry components.
- RA with **1.5U of envelope, 3 kg of mass,** and **<20 W power consumption.**
- Deployable dish antenna.



Radar Altimeter	
Distance Rate	20 Hz
Range Profile	> 100 m
Range Profile Rate	1 Hz
Accuracy	< 20 cm
Power Consumption	< 20 W
Envelope	1.5U
Mass	<3 kg



RF Breadboard Blocks

10

Detailed information has been provided about payload, link budgets, orbit & pointing, data centres & products, launching studies and preliminary results.

Outlook and Recommendations:

- MAGAL aims at developing a cost effective, small satellite platform to reduce launch and operational costs, and a custom RA solution, with lower power consumption, compatible with small satellites.
- As a constellation of **6 satellites**, MAGAL will increase the density of sea surface topography measurements, enabling more data for altimetry products, when used in synergy with other missions, in coastal areas and over mesoscale features.
- MAGAL constellation should be considered an augmentation complement for the baseline altimetry missions (Sentinel-3 & -6MF and Jason series).
- Being developed in the "new space" concept, it reduces largely its deployment and launch costs, allowing several constellations to fly at the same time.
- MAGAL is a conceptual design, aiming to set the baseline for a future constellation, representing a competitive solution for altimetry data worldwide.
- Satisfying power and size requirements are the main engineering and design challenges in the case of a small satellite with a radar altimeter.
- Main limitation: Ku band antenna.
- Follow-up project to prove the concept.
- Looking for flying opportunities for a single satellite to demonstrate its performance.

- Require 2-3 years for development of flying radar altimeter and its antenna, manufacture and test the full satellite.

- Looking for financial support for production and launch costs.

- MAGAL constellation architecture can bring future Oceans monitoring to everyone, making the forecast and associated services/products more precise and in “real time”.

Towards validation of SWOT and new coastal processing algorithms: An altimetry and water level gauge case study in the Bristol Channel and Severn Estuary area

Dougal Lichtman, A. Shaw, C. Banks, F. M. Calafat, C. Gommenginger & P. Bell.

SWOT and the SWOT-UK project was introduced. The project aims at:

- Validating SWOT data with in-situ data and numerical models for water level spatial variability and marine-fluvial interactions by assembling a dataset of quality-controlled ground and satellite data of water level, slope and river discharge. Airborne and shipborne surveys during the SWOT 90-day daily validation phase to complement existing observations.
- Investigating SWOT performance in coastal and estuarine settings (SWOT is not designed for these environments and they are challenging)

The peculiarities of the Bristol Channel and Severn Estuary were reported. Huge tidal range (>14 m), strong currents and a tidal bore in the upper reaches. Waves (H_s) can reach over 7 m at the western limit but are small upriver. Areas are well gauged and covered by both Sentinel-3 and CryoSat-2 and two new GNSS-IR systems to be deployed.

The GNSS-IR for water level and waves was introduced and the role of the HYDROCOASTAL datasets & retrackers for investigations in the Bristol channel was detailed.

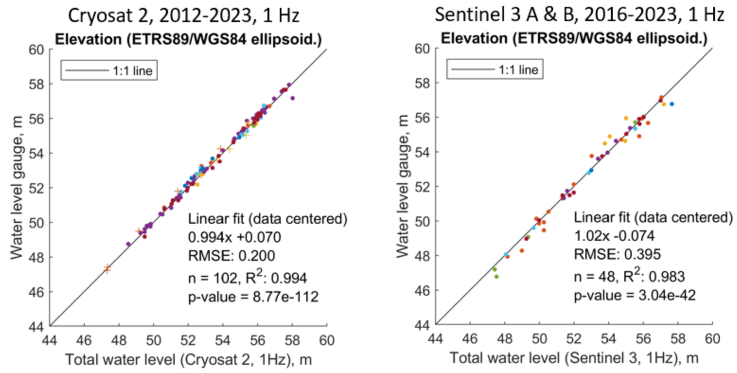
- Validation strategies were introduced. In particular, this area is challenging for tidal models as they give different results (e.g., ±1m FES2014 vs POLpred at mid-Bristol Channel).
- Total water level is used in the comparison (tide + surge), no correction for tide or air pressure (1 Hz, 20 Hz needs more work) and 6 km radius is imposed to match TWL gauge and satellite data. Standard QC flags can remove coastal data:

  Corrected Range = Range + Wet Tropo. + Dry Tropo. + GIM Iono.

  Total Water Level = Altitude - Corrected Range - Solid Earth Tide - Pole Tide - Sea State Bias

Some results were discussed, also in relation to shallow waters, coastal dynamics and morphology:

Summary of Session 1:
Technical issues in coastal altimetry



Data as far East as Severn Bridge, SWOT nadir. Data as far East as Epney.

Conclusions:

- A system has been set up to obtain near-real time data during the SWOT 90-day validation phase.
- Looking at water levels and slopes along and across the estuary.
- The altimeter data seems to show interesting coastal hydrodynamics.
- The 1 Hz altimeter data are consistent with multiple water level gauges.
- Working on the 20 Hz altimeter data analysis.
- Will be looking at the river hydrology data as well the ocean data.
- Looking forward to getting SWOT data for nadir and KaRin.

Outlook and Recommendations

- Synergetic use of data from multiple platforms and sensors to sample fast-changing processes in coastal regions.
- Promote constellations of small satellites to improve temporal sampling in the coastal zone.
- Enable joint research projects with commercial satellite operators.
- Improving data access and support for different (commercial) platforms.

  Better co-location/timing of in situ instrument deployments with satellite passes for coastal projects.


Image: ESA

Session 2: Applications of coastal altimetry data

Co-chairs: Luciana Fenoglio and Stefano Vignudelli

Potential Applications of SWOT High-Resolution Sea Surface Height Observations to Studying the Coastal Impact of Sea Level Rise

L.-L. Fu et al.

The Surface Water and Ocean Topography (SWOT) mission's advanced wide-swath technology provides for high-resolution ocean and surface water topography measurements. An overview of SWOT potential applications, particularly beneficial for the coastal zone, was provided in anticipation of when the commissioned data will be released at the end of the commissioning phase, 14 months after launch, which took place on Friday, December 16, 2022, onboard a SpaceX Falcon 9 rocket launched from Space Launch Complex 4E at Vandenberg Space Force Base in California.

Statistical decompositions of coastal surface currents and sea surface heights and evaluation of their performance

Eun Ae Lee and Sung Yong Kim

Authors reminded that high-resolution high-frequency radar-derived coastal surface currents (km in space and hourly in time) are available. It is useful to convert them into (coastal) sea surface heights at the similar resolution for evaluation/validation of observations obtained from upcoming satellite missions (e.g., SWOT, Odeysea, COMPIRA etc).

They conducted Helmholtz (physical) and wave-vortex (spectral) decompositions on high-resolution regional ocean model (ROMS)-simulated surface currents. In particular, wave-vortex decomposition requires assumptions of isotropic and stationary processes to separate currents into balanced and unbalanced motions and can be conducted only in the wavenumber domain.

Formulation and components of the decomposition have been discussed in detail along with energy spectra.

Conclusions:

- The simulated and (observed) coastal surface currents do not exhibit an evident decomposition of balanced and unbalanced motions when wave-vortex decomposition is applied.
- Wave-vortex decomposition may not always be valid in coastal regions in which (1) the isotropy, spatial homogeneity, temporal stationarity, and statistical no-correlations of the current components may not be guaranteed, and (2) multiple geophysical driving forces (e.g., wind, tides, and low-frequency currents) are present.
- The stream function obtained from the Helmholtz physical decomposition can be used as a proxy for balanced motions when the variance in the vertical currents is weak, except for the near-inertial

variance, which can provide better insights and can be applied to the analysis of upper ocean dynamics, including the propagation of the unbalanced motions and the vertical and horizontal structures of ageostrophic currents.

Estuarine water level change from high resolution altimetry

L. Fenoglio, J. Chen, H. Uyanik, J. Staneva, B. Jacob, J. Kusche

Tidal rivers and coastal-to-land sites are mostly affected by climate changes and are at multi-risks (coastline retreat, flooding storms and river floods). The goal of this study is to monitor the river-to-ocean continuum from altimetry (water surface elevation, discharge, tides salinity fronts, extremes) understand the hydrodynamic processes and separate tidal and river discharge. It aims at:

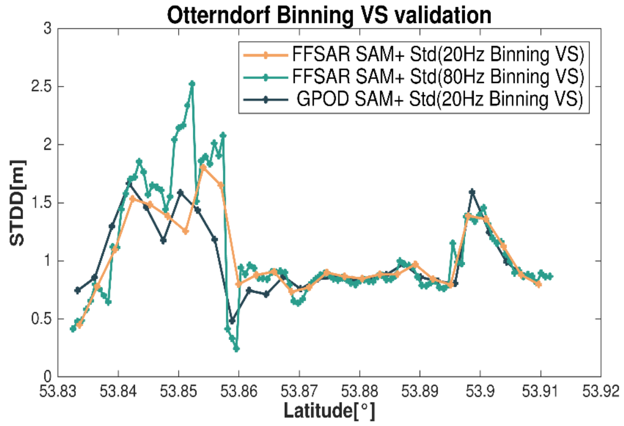
- Exploiting the new SAR- and the SWOT-altimetry data to improve estuarine/coastal analyses.
- Investigating models, in spatial resolution, and the memory of the model.
- Separating tides and discharge in the estuary.
- Understanding salinity fronts formation and evolution.
- Assessing the impact of river discharge on sea level and of sea level rise on extremes.

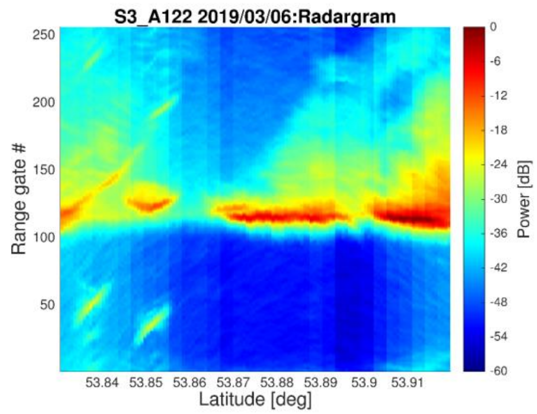
The Elbe Estuary and tidal river (70 km long, meso-tides 3-4 m range) was investigated. Authors focused on river plumes, discharge and tides interaction, contribution to sea level change, wind effect and air-sea interaction.

Measurements from altimetry and in situ (water height above ITRF) and river discharge were considered. Geodetic low-cost GNSS and GNSS-IR were also available. Auxiliary data were taken from river gauges (near real time), multi mission nadir altimeters, HR DTM and hydrodynamic models.

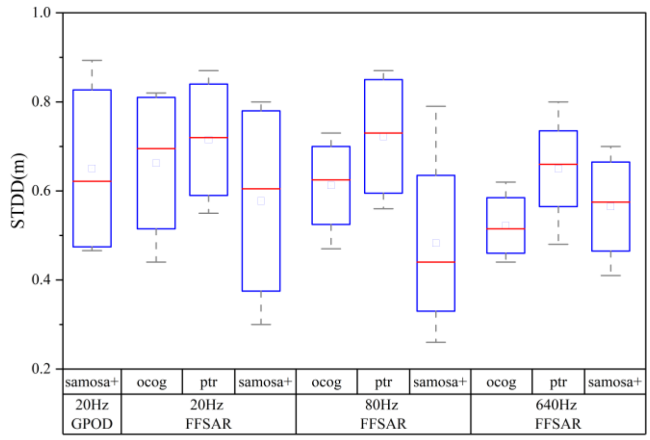
The adopted methodologies (Nearest Virtual Pass, HYDROCOASTAL, Binned overpass) and corrections applied to compute SSHA (all except DAC) were discussed. Results for Unfocused (EarthConsole® Altimetry Virtual Lab, https://earthconsole.eu/virtual-labs/) and Fully-Focused (CLS SMAP, https://github.com/cls-obsnadir-dev/SMAP-FFSAR) SAR were reported using OCOG, SAMOSA+, PTR at 20, 80 and 640 Hz.

The best results were obtained by FF-SAR data retracked with SAMOSA+. The land contaminates the altimeter signal in both UF- and FF-SAR, therefore, the signal from the middle of the waterbody is the most suitable for the investigation. The standard deviation difference at Otterndorf tide gauge (left) and the related radargram (right) are reported below:





In the next figure, the standard deviation difference at 4 TGs in the Elbe Estuary is reported. The binned point with the smallest standard deviation to the tide gauge is selected. The smallest STDD is 0.44 for FF-SAR SAMP and 0.62 for UF-SAR SAMP:



Median	0.62	0.70	0.72	0.61	0.63	0.73	0.44	0.52	0.66	0.58
Mean	0.65	0.66	0.72	0.58	0.61	0.72	0.48	0.52	0.65	0.57

Conclusions:

- Estuary and tidal rivers are challenging regions for nadir-altimetry.
- SAR Nadir-altimetry observes fine-scale changes in along-track (0.46 cm with FF-SAR & SAMOSA+ and 0.62 UF-SAR & SAMOSA+) with dedicated validation methodology.
- This is a challenging region for wide-swath missions.

Summary of Session 2: Applications of coastal altimetry data

Validation and Use of Altimetry Products in the Southwestern Atlantic Continental Shelf

Laura Ruiz-Etcheverry, M. Saraceno, L. Lago and M. Martinez

The Southwestern Atlantic Continental Shelf (SWACS) is one of the largest shelves in the world and hosts one of the most productive ecosystems. It is characterised by large tide amplitudes, from 6 to 0.5 m in the North.

The region has a significant impact on the balance of atmospheric CO_2 and therefore possible fluctuations may impact the climate. The dynamicity of the region, related to the circulation and sea level variability, has been so far mainly studied with numerical models.

Objective of the talk was to review the effort made by the group Southern Ocean PHYsical oceanogrAphy (SOPHYA) from University of Buenos Aires to validate and use altimetry products.

Knowing that the tidal amplitudes are large in the SWACS and it would be a possible source of error near the coast, the first approach was to validate the gridded all-sat altimetry data (AVISO) at seasonal scale. Authors selected the best 15 TG stations. The RMSD values between the seasonal cycle derived from gridded altimetry and in situ data from PSMSL (Permanent Service for Mean Sea Level, https://psmsl.org/) were lower than 2 cm, with a mean value of 0.61 cm. Correlation were high (within 0.89 and 0.9).

Authors explored possible altimetry corrections, such as tide and atmospheric effect, that might affect the altimetry data. As a case of study, the Río de la Plata estuary was chosen, which a shallow and dynamic region. They selected 8 models, regional and global, and compared the 5 main tidal constituents at two TG stations. FES2014 is the best model for the region, however, the magnitude is in the order of the M2 amplitude.

They also analysed the atmospheric correction since the Río de la Plata plume is highly dominated by wind and affected by storm surges. Authors selected the standard global model of DAC and two regional models in Rio de la Plata and observed that Mog2D captured the spatial variability of sea level, reporting a large variance at the upper estuary and a low variance at the mouth. However, it underestimated the magnitude.

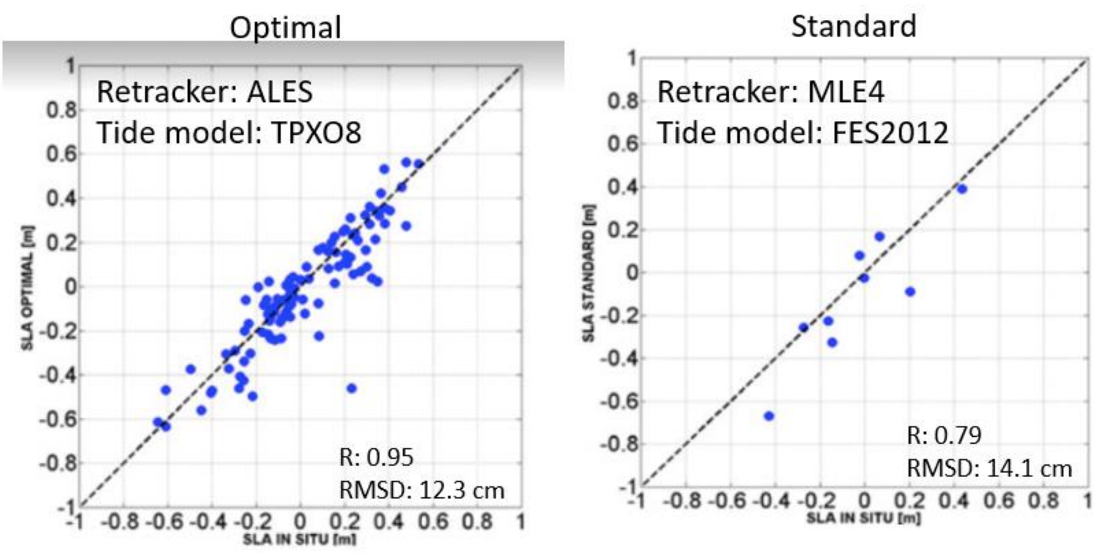
In an effort to understand the dynamics of the circulation at different temporal scales, several instruments along Jason track #26 and along 44.7º S were deployed thanks to the Franco-Argentinian project CASSIS (https://www.cima.fcen.uba.ar/malvinascurrent/en). Measured were pressure, conductivity, temperature, and velocity for about 1 year. The processing and the analysis of the data generated 3 PhD thesis, 1 master thesis and more than 10 articles.

The analysis of RSS (Root Sum Square) showed that FES2014 is the best model in the shelf, shelf-break and north of 42º S, where the tidal amplitude is smaller than the north. The Palma regional model was the best in the south and at the coast.
Authors also calculated the along shore transport with ADCP data and compared with gridded satellite altimetry. Good results allowed to expand the transport period from almost a year to 25 years.

The geostrophic velocity derived from along track data also correlated well with the in-situ data for periods larger than 10 days. However, the validation of sea level was not always good. It was observed that Mercator captures better SLA variabilities than gridded altimetry for scales lower than 10 days.

A validation was performed in the San Matias Gulf: Jason-2 data was compared with 22 months of in situ sea level near the coast. Authors analysed all the corrections applied to the satellite data, such as tides, finding that the TPX08 was the best tidal model to reproduce the main 5 tidal components, with an RSS value of 4.8 cm.

Two retrackers were also analysed: MLE4 and ALES. This latter recovered the 70% of the data. Finally, authors constructed a sea level time series by averaging the satellite SLA from both Jason-2 tracks and compared the best tide model and retracker with the standard ones, MLE4 and FES2012. The increased number of valid data, with the optimal options, and the improvement in statistics are clear:



Conclusions:

- FES2014 is the tidal global model that better represents the main 5 components in the SWACS. Except at the coast, south of 42º S and in the San Matias Gulf, where regional models are the best option, in particular Palma and TPX08.
- The global model for Dynamic Atmospheric Correction underestimates the sea level in the Río de la Plata estuary.
- The gridded multi-mission data represent adequately the seasonal scale.
- The gridded multi-mission data is also a good product to analyse the geostrophic transport in the north shelf for periods larger than 20 days. Except at 44.7º S, near the coast, where SLA variability is better represented by Mercator reanalysis for intra-seasonal scale.
- The use of ALES retracker in the San Matias Gulf at 1km from the coast improves significantly the percentage of valid along-track data.

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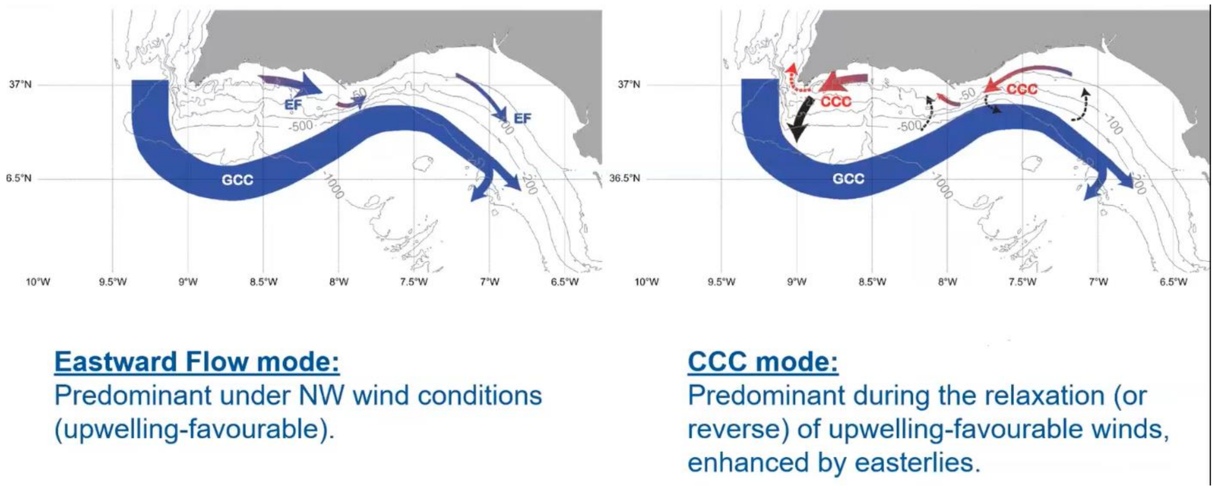
Detecting Coastal Flow Reversals Over the Gulf of Cádiz Using Multi-mission Altimetry Data

R. Mulero-Martinez, J. Gómez-Enri, E. Garel, P. Relvas, L. de Oliveira Júnior, R. Mañanes

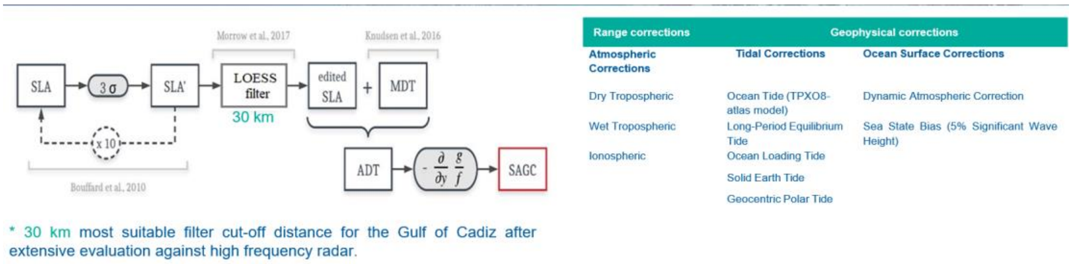
Authors presented a work related to the capability of altimetry data to detect coastal flow reversals over the gulf of Cádiz. The area of interest is explained including flows, mass exchanges and presence of eddies. The main circulation is characterised by a bimodal pattern. Circulation modes are 2 (Eastward Flow and CCC) and explained in detail.



Previous studies were cited. Altimetry was mainly used for detecting currents, small scale gradients and structures. Limitations lie in the selection of altimetry tracks (only normal-to-the-coast tracks were selected). Altimetry data edition to be improved. From a practical/operational point of view, this is an important limitation.

For the present study, Earth Console Altimetry Virtual Lab (https://earthconsole.eu/virtual-labs/) SARvatore for Sentinel-3A/B data were used (coastal zone profile, 80 Hz posting rate and SAMOSA++ retracker).

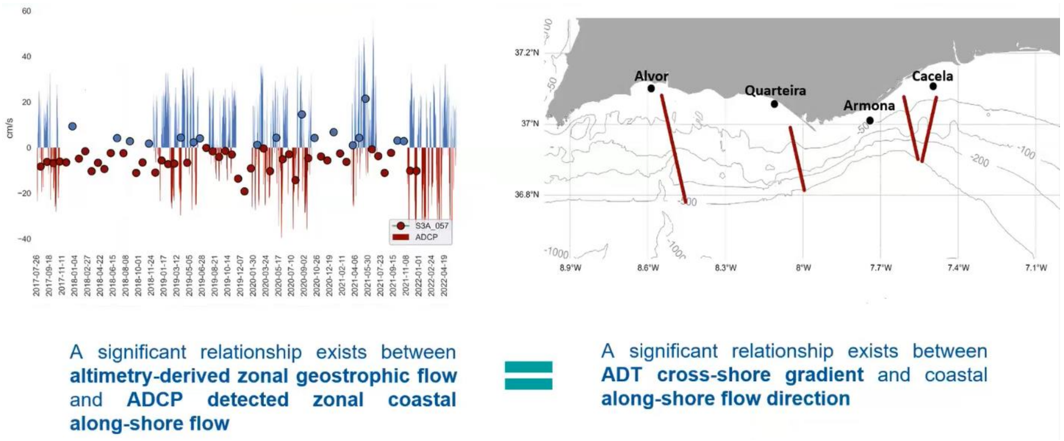
The data edition strategy was discussed:



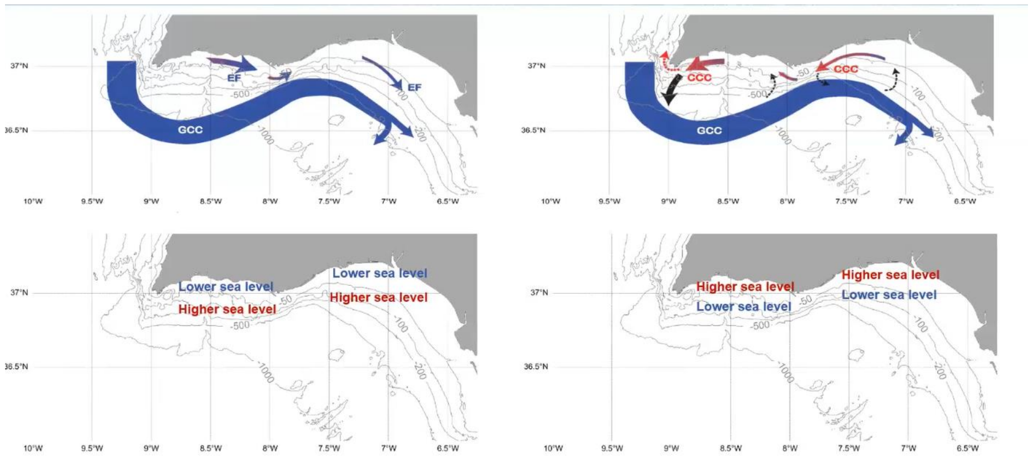
To use the geostrophic approximation in shallow water, the bottom friction must be considered, the adopted formulation was detailed. Authors compared ADCP data, 72h average velocities before the corresponding satellite pass, to altimetry-derived currents.

Results were the followings:

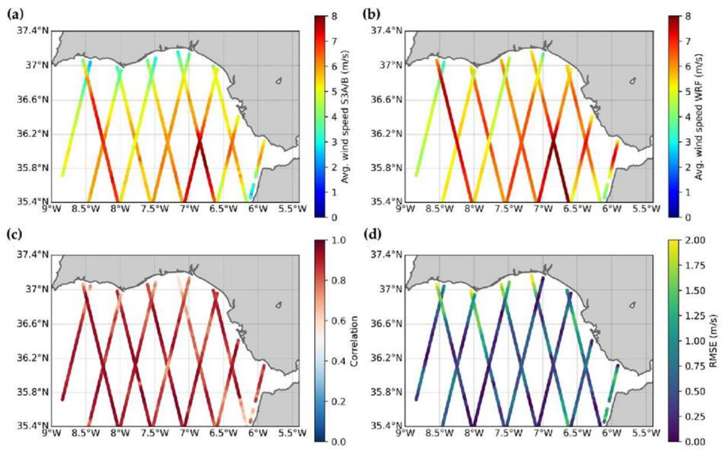
Summary of Session 2: Applications of coastal altimetry data

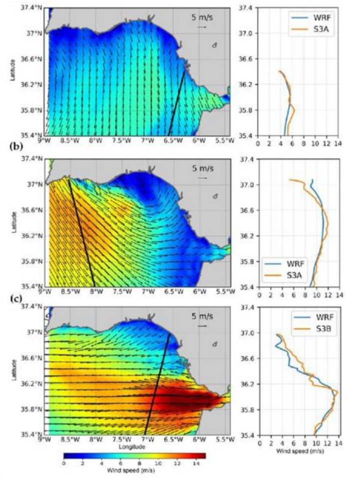


For the circulation:



Authors made a temporal analysis of the coastal circulation. Seasonal variability and wind effect over coastal circulation were investigated and preliminary results presented, also considering the WRF model using in situ and altimetry data. High-resolution wind models are essential to retrieve accurate information on surface circulation in synergy with altimetry-derived estimates:





Conclusions

- Current coastal altimetry data can be used to detect along-shore coastal flow reversals in the Gulf of Cádiz area, independently from any other observing system, as it has been statistically proven.
- Wind and bottom friction corrections play a critical role in obtaining realistic circulation results in coastal areas when using altimetry data.
- The preliminary results for the upwelling/non-upwelling seasonal variability agree with previous studies in the area (de Oliveira Júnior et al., 2022) as well as with an along-shore pressure gradient contributing to the coastal circulation.

On Assessing the Performances of Sentinel-3 Radar Altimetry in Sheltered Coastal Regions: Case-Study of the Grado-Marano Lagoon System in the Northern Adriatic Sea

Stefano Vignudelli, Francesco De Biasio and Ron Abileah

The northern Adriatic Sea is a laboratory for studying the land/sea continuum.

The objective of this study was to assess the Sentinel-3 radar altimetry dataset using the state-of-the-art products over the Grado Marano Lagoon acquired between 2019-2021 by using independent observations from the ICESat-2 lidar and from the Grado tide gauge to support the interpretation of the results.

The methodology was explained underlining that the radar altimetry processing involves three stages:

- First, coherent sums of bursts of individual echoes are done.
- Then, the radar range is estimated from the resulting signal.
- Finally, the range is translated to surface level.

Ranges are derived from S3B raw echo waveforms using two methods:

- Precise Inland Surface Altimetry (PISA) algorithm.
- ESA SAR Versatile Altimetric Toolkit for Ocean Research and Exploitation (SARvatore) from the Earth Console® ESA Altimetry Virtual Lab, using the “Inland Water High Posting Rate” product, retracked with SAMOSA+ (SAMOSA-2 tailored for inland and coastal water and sea ice).
- Both datasets are at 80 Hz: 1 observation every ~89 m.

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Differently from the SARvatore high posting rate product at 80Hz, the PISA algorithm identifies specular and quasi specular echoes using the radar cross section, and derives the range without any ad hoc retracking Abileah and Vignudelli, 2021, https://doi.org/10.1016/j.rse.2021.112580)

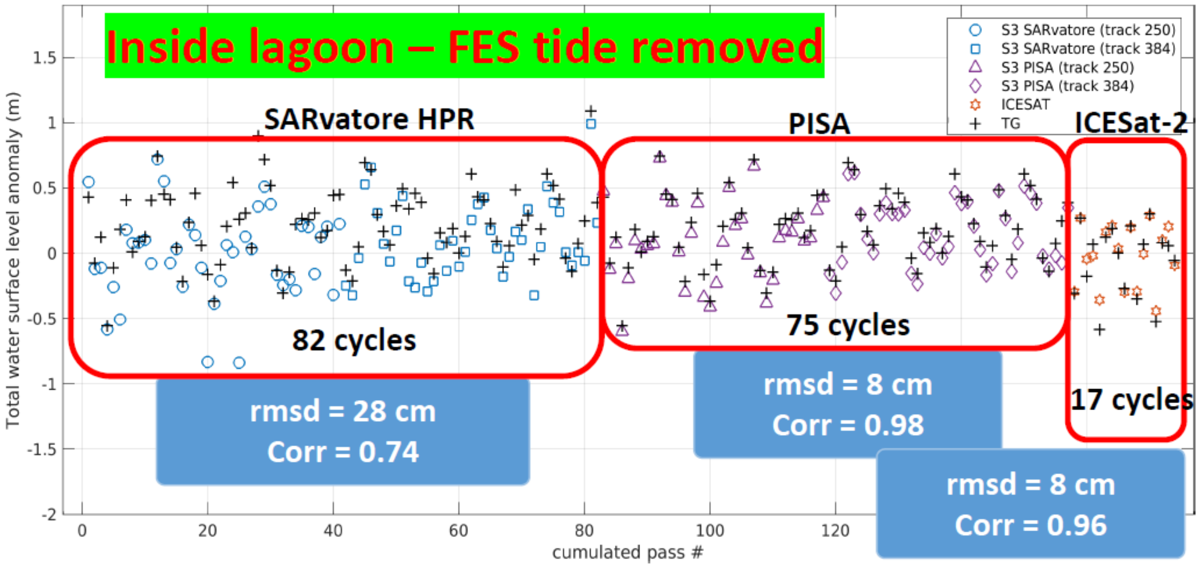
In agreement to what noted by authors in another talk belonging to session 1, waveforms acquired in Marano are specular and show a slight broadening of the peak into the 1st sidelobe (as also in Abileah and Vignudelli, 2021, https://doi.org/10.1016/j.rse.2021.112580)

Surface outliers have not been edited or removed.

Preliminary analyses at the Grado-Marano revealed several specular (and more quasi specular) echoes inside the lagoon and along the Ausa and Corno rivers, having width of 50 and 100 m, respectively. Specular echoes have a much higher SNR than Brownian water surfaces. High SNR translates to more ranging precision. With PISA, the range is estimated by finding the peak in the FFT output of 128 fast time echo samples. Having determined the range with PISA, surface level anomalies (SLAs) are computed using ancillary information taken from the SARvatore dataset. A discussion on acquired data followed.

The impact of the geophysical corrections on the surface water levels within the lagoon was evaluated. Dynamic Atmospheric Correction (DAC) is the second source of level variability. Astronomical tides (from FES2014 model) are the first. Residual SLA includes currents, residuals pressure effects not corrected by instantaneous IB (typical of Mediterranean basin) and halo and thermosteric effects. The inverted slope of the tide between the two tracks matches the expected latitudinal variability of tides with the pass direction.

The comparison of time series of ALT-TG (observed levels averaged pass by pass) showed that there is a clear consistency between the three satellite products: PISA and ICEsat-2 have much lower RMS difference than SARvatore. PISA uses only specular and quasi specular bursts. SARvatore uses all bursts independent of the surface reflectivity. This explains the difference in RMSD.



$$rmsd = sqrt\left(\sum_{k=1}^{N(passes)} \frac{(mean(ALT_k) - (mean(TG_k))^2}{N}\right)$$

When individual observations were compared, bursts inside the lagoon were more accurate than bursts outside the lagoon: sea state is more complex offshore. Detailed analyses were presented.

Conclusions:

- Overall, the results of the comparisons are promising and will be revisited with the novel HYDROCOASTAL dataset.
- ICESat-2 is another independent data set that can be used to validate the radar altimetry products.
- Further analyses are necessary to investigate the physics of echoes and how they relate to surface types and wind conditions.
- Specular echoes are less: what is better, to have one precise measurement or many measurements of lower precision?
- Specular and quasi specular echoes are precious for coastal altimetry: could they be the key to exploiting altimetry in sheltered coastal sea regions like never before?
- We propose the Marano Grado Lagoon as a cal val site for the Sentinel-3B, Sentinel-6 and ICESat-2 missions, a laboratory where a better understanding of radar reflectance at the sea is facilitated, thanks to existing infrastructures and structured logistics.

Session 2: Applications of coastal altimetry data (cont'd)

Co-chairs: Matea Tomic and Anrijs Abele

An assessment of conventional and retracked Sentinel-3 data with implications for an updated coastal mean sea surface with associated errors in Norway

Matea Tomić, Kristian Breili, Christian Gerlach and Vegard Ophaug

The study proposed a validation of conventional and retracked Sentinel-3 data. It included:

- Investigation of temporal (SLAs) and spatial (MDTs) variability of sea level observations.
- Conventional and ALES-retracked Sentinel-3A/B.
- Validation data: 23 permanent + 40 temporary tide gauges.

This will serve as a preparatory step for computing a new mean sea surface for the Norwegian coast.

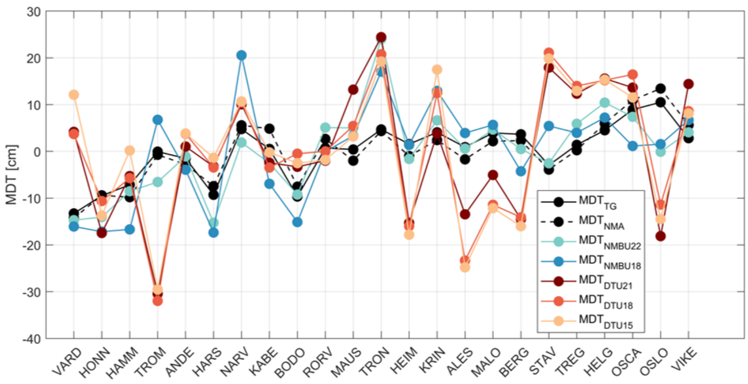
In the validation of SLAs, an optimum radius was defined as the distance from tide gauges where the correlation between altimetry and tide gauge observations starts to decrease. In the validation of MDTs, EOT11 and NMA tide models were used to evaluate MDT from conventional and ALES datasets.

The attention was then devoted to the determination of the coastal MSS: A preliminary version of NMBU22 coastal MSS model with associated errors was presented. It is the updated version of the NMBU18 model using SAR(In) data from Sentinel-3A, CryoSat-2 and Ka-band data from SARAL/AltiKa (2010-2017). NMBU22 is augmented with CryoSat-2 and Sentinel-3A/B data (2010-2021).

A 'Remove-restore" approach was adopted (MSS = MDT + N):

- Geoid model – NKG2015
- Data-Interpolating Variational Analysis (DIVA) gridding tool
- MDT surface + formal error field

Results were presented including the following:



MDT - TG	MIN [cm]	MAX [cm]	MEAN [cm]	STD [cm]	RMS [cm]	ρ
NMA	12.7	19.7	15.4	2.1	15.5	0.95
NMBU22	6.4	36.3	17.0	5.8	17.9	0.77
NMBU18	7.2	32.5	16.7	7.3	18.2	0.76
DTU21	-31.7	19.4	-1.5	14.4	14.1	0.15
DTU18	-33.8	22.1	-1.9	14.7	14.5	0.14
DTU15	-30.0	24.9	-0.5	15.5	15.2	0.03

Conclusions:

- Similar performance of ALES and conventional observations.
- More observations from the conventional dataset closer to tide gauges to:
  - Compare the resolution of ALES and NMA coastlines.
  - Test local ocean tide corrections in the coastal zone and in fjords.
- Preliminary version of NMBU22 coastal MSS – improvement over NMBU18MSS:
  - Calibration of the formal error field is necessary.

Origin of Sea Level Changes on the Shelf of the Northwest Atlantic from Sentinel-3A SRAL

Anrijs Abele, Sam Royston, Jonathan Bamber

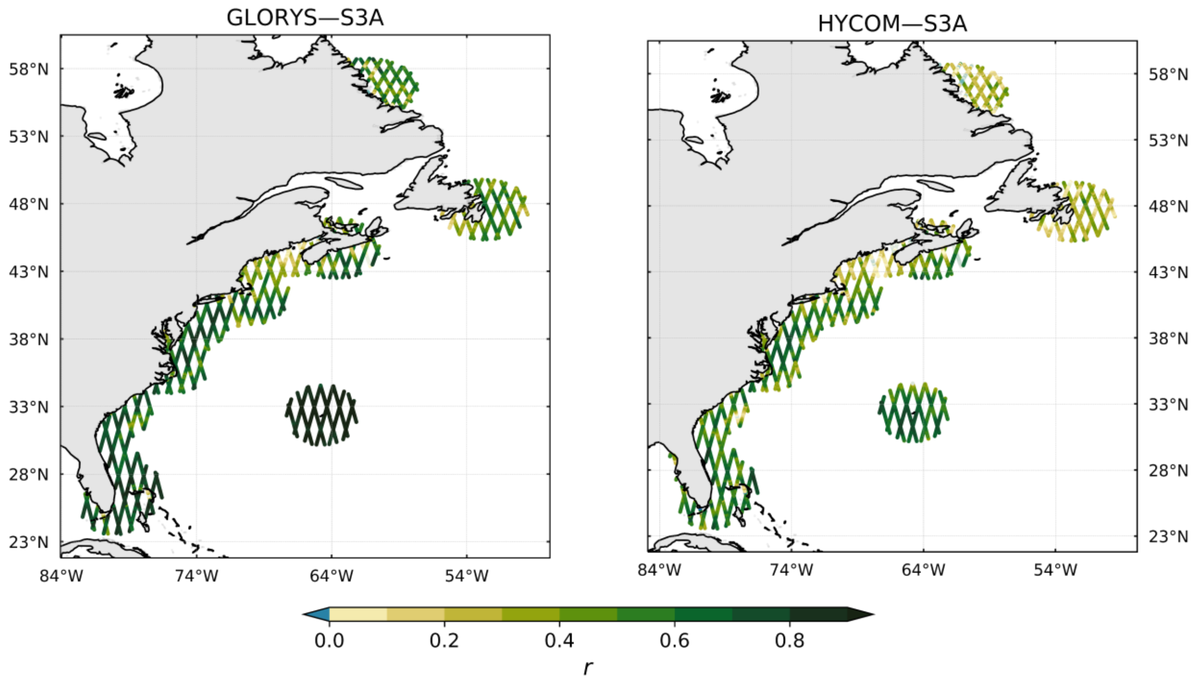
Sea level over the shelf is affected by coastal dynamics. These are less understood than open ocean dynamics and highly variable by location. The reliability of global reanalysis is questionable over the shelf. Until recent times, the coast was typically out of the scope for conventional, pulse-limited altimeters. However, long-term measurements are usually made and available at the coast (tide gauges, proxy measurements).

The talk addressed the following points:

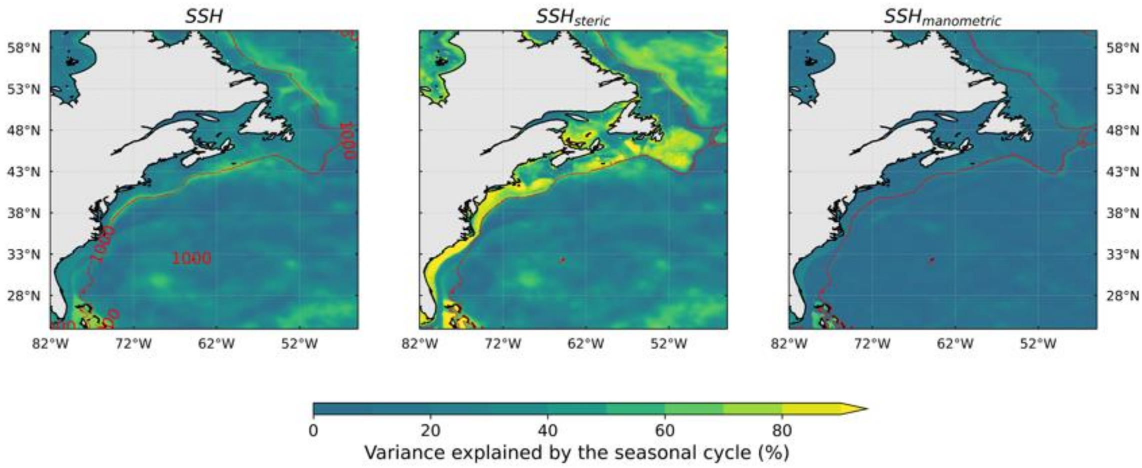
- What are the main patterns of sea level variability in the coastal zone of the Northwest Atlantic?
- What are the sources of modelled/observed variability?
- Where does the altimeter-observed sea level variability match the reanalysis?
- How does the sea level anomalies propagate over the shelf?

The region of interest is the Northwest Atlantic: between 82°W and 45°W, 24°N and 60°N. Focus is on a short time (2016–2020). 21 tide gauge stations are available (UHSLC hourly research quality data, MOG2D dynamic atmosphere correction, VLM ULR6A removed) plus along-track 1 Hz Sentinel-3A SRAL altimetry data limited to 250 km from each tide gauge, retracked with and without SAMOSA++ & ALES coastal retrackers. Corrections applied were discussed in detail. Reanalysis (GOFS3.1, GLORYS12) for the whole domain was also considered. Sea level components were explained in the definition of the methodology including the consideration of empirical orthogonal functions (EOF) and the variance explained.

The model-altimetry comparison reported very good results:



High correlations (>0.9) over the open ocean. GLORYS outperforms HYCOM/GOFS, especially at higher latitudes. Several results about the seasonal cycle:



and the EOF were also reported:

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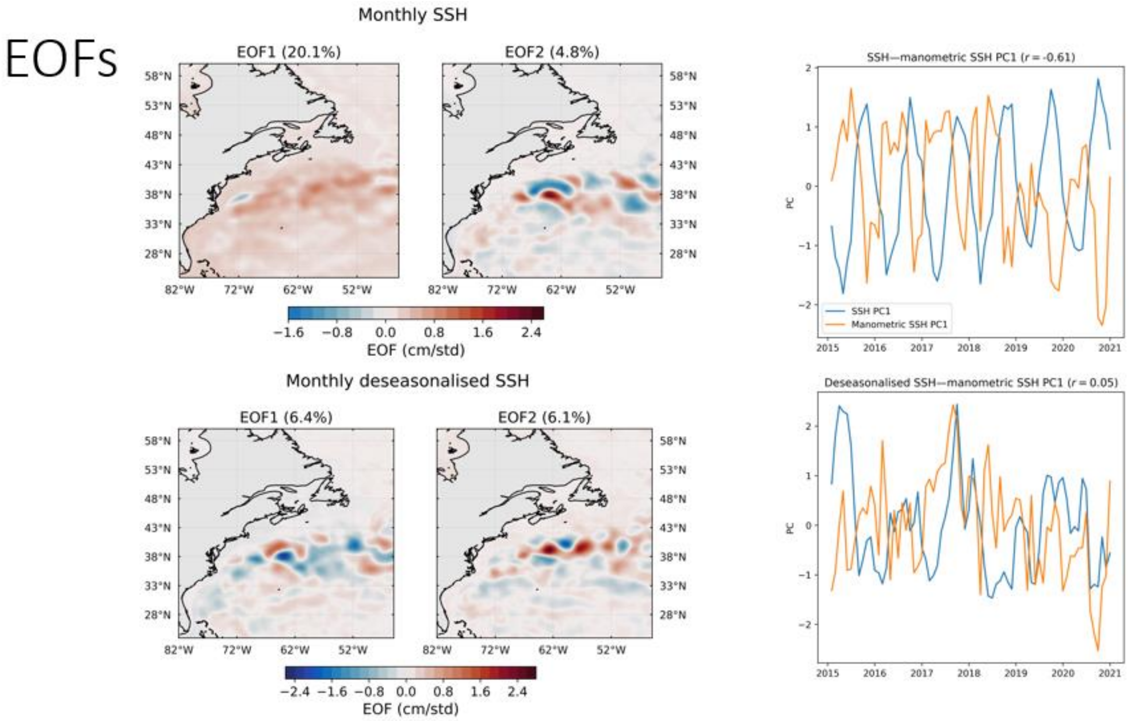


Conclusions:

- Steric SSH on the shelf is dominated by the seasonal signal.
- Manometric SSH is mostly unaffected by the seasonal cycle, except in the open ocean.
- Steric signal dominates SSH. The first EOF matches seasonal cycle.
- Sentinel-3A SRAL and tide gauges reproduce patterns shown by the GLORYS12 reanalysis.

Assessment of Sentinel-6A Data in a Complex Macrotidal Semi-enclosed Sea (Pertuis Charentais, France)

Y.-T. Tranchant et al.

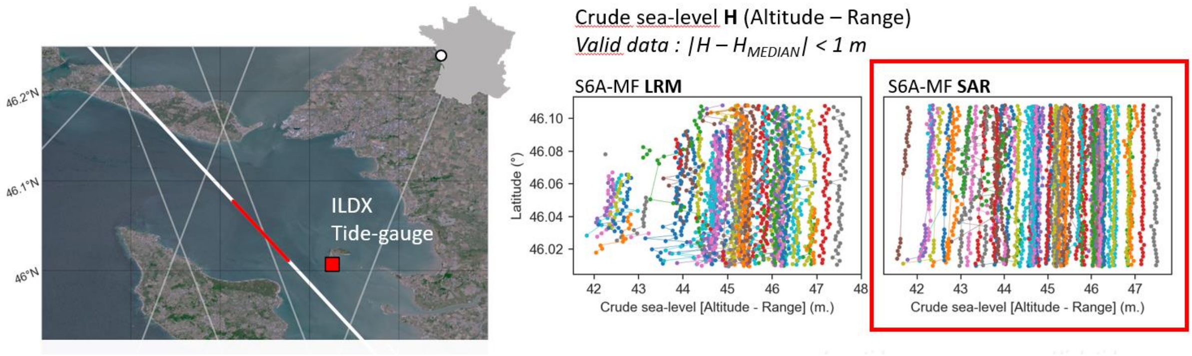
This talk added to the work presented in:

- *Contribution of innovative GNSS sea level mapping system to the exploitation of coastal altimetry data: Application in the Pertuis Charentais area and the Noumea Lagoon (Chupin C., 2022)*

- *Towards a better use of coastal altimetry: contributions of hydrodynamic modelling and new GNSS techniques (Tranchant Y.T., 2022)*

The Pertuis Charentais sea region was described in detail, in situ & altimetry data are available (including the sea-level observatory on Aix Island - ILDX) and both a microtidal regime and large intertidal mudflats are present.

Some results from Sentinel-6 Michael Freilich were given:



The objective of the talk was about linking the ILDX TG to S6A-MF SAR measurements. Standard GDR product (F07) was considered. No retracking, no optimal coastal geophysical corrections were applied. Numerical modelling and a marine surface drone were considered for the evaluation of S6A-MF SAR sea-level data in the region.

3 days of SSH mapping were conducted with PAMELI, an autonomous drone equipped with the Cylopée system (a combination of GNSS antenna and acoustic altimeter). This was done to support the geoid extraction from PAMELI SSH measurements by doing GEOID = SSH – DT with $DT = DT_{BUOY} + \triangle DT_{MODEL}$. The Gradient of Dynamic Topography (△DT) between the GNSS buoy and the position of the PAMELi USV was corrected by using a high resolution hydrodynamic model. These gradients can reach several cm/km in the region.

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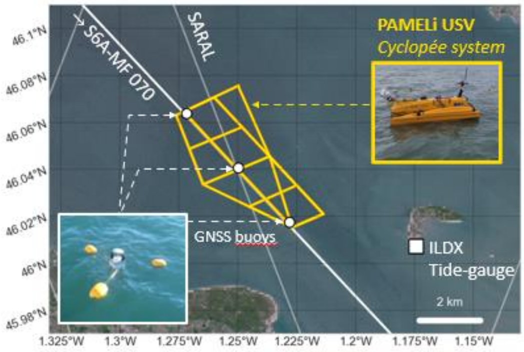
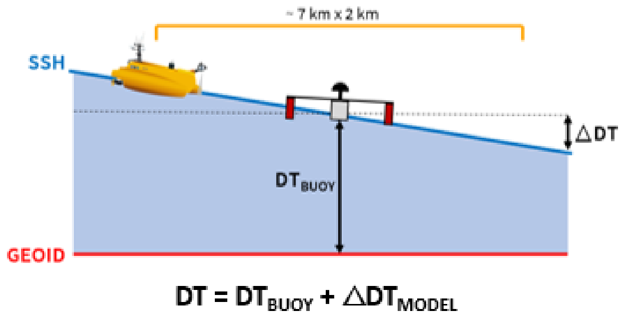




This led to an evaluation of 1.3 cm/km of geoid slope in the along-track S6A direction. Comparison with geoid/MSS models were presented. A link between ILDX TG and cartography was established through repetitive buoy static sessions.

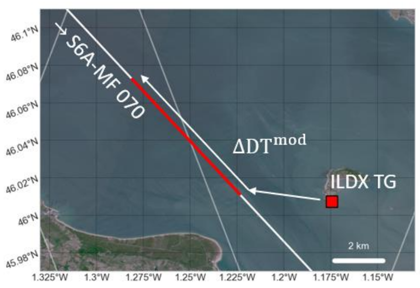
This represents:

- A validated methodology to extend spatially our geoid mapping capabilities in macrotidal coastal areas.
- A useful dataset for the assessment of actual and future MSS/geoid models in the region.

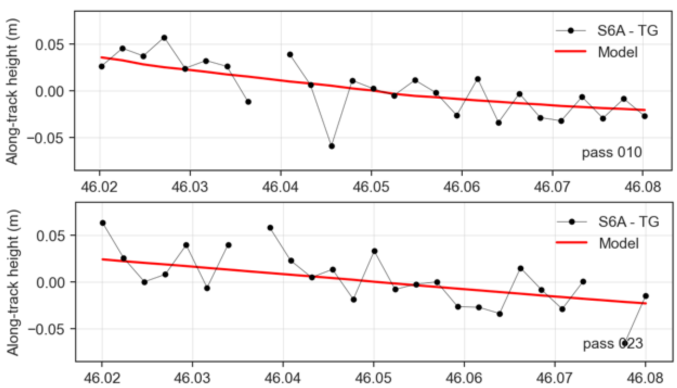
Future planned extensions are foreseen, away from nadir altimetry tracks, to fill gaps and get ready for SWOT large swath observations (for the later science phase)

More can be found in a dedicated poster "GNSS Survey for Geoid Mapping in a Macrotidal Sea Involving Marine USV, Buoys and Hydrodynamic Modelling (Pertuis Charentais, France)" presented at this workshop and in the paper Chupin et al., 2020.

The second objective of the talk focused on the modelling of fine-scale gradients of dynamic topography along-track and toward the ILDX TG by the implementation of the regional hydrodynamic model SCHISM 2DH (Zhang et al., 2016). The model was described and results in relation to Sentinel-6MF passages (20 Hz data) were presented:



$$\Delta DT^{mod} = DT^{mod}_{S6A_{20Hz}} - DT^{mod}_{TG}$$



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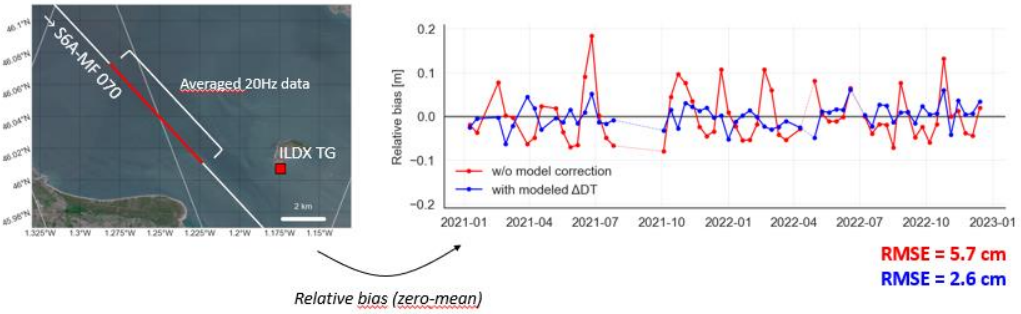
These were not good all the time.

Difference of TWLE (including oceanic tide and DAC) between S-6MF 20 Hz data and tide gauges was also presented and the SWH spatial pattern induced by wave dissipation throughout propagation on shallower water was discussed and could possibly explain a persistent along-track SSB gradient.

In the end, the relative bias (zero-mean) between S-6MF SAR and ILDX TG sea-level data, computed by averaging all valid S-6MF 20 Hz sea-level measurements at each passage, with and without gradients of dynamic topography, was presented:



Conclusions:

- Successfully implemented a methodology to link altimetry measurements to coastal TG in the challenging macrotidal coastal area of Pertuis Charentais.

- Numerical modelling and GNSS mapping techniques play a key role.

- An ideal playground for assessing range retracking algorithms and optimised geophysical corrections.

- The SSB slope feature will be furthered investigated.

Summary of Session 2: Applications of coastal altimetry data

CryoSat: Mission Status and Future Challenges over the Coastal Zones

A. Di Bella, J. Bouffard, T. Parrinello

A report was given on CryoSat-2 mission status. After almost 13 years the SIRAL-A performance are within requirements. Preparatory activities are ongoing for SIRAL-B. Questions marks are the mission extension until 2025 and operation beyond 2025. All monitoring parameters show that SIRAL is fit to operate until 2034 with the redundant side still available.

Data Portfolio include L1/L2 ICE & OCEAN DATA, CRYO-TEMPO EOLIS and the new CRYO-TEMPO products.

CryoSat processors for ocean applications have been discussed in detail underlining the excellent agreement with reference ocean missions. The mission is very well suited for oceanographic applications, from coastal & mesoscale to large scale & climate signals. The new COP Baseline D will include:

- Mode dependent bias reduction.
- Upgrade to SAMOSA v2.5 for SAR & SARIn.
- Improved SSB, wind speed and sigma0.
- Upgraded surface type mask, models and corrections…

Test Data Set to QWG is planned in Q3 2023. Transfer to operation in Q3/Q4 2023.

The Cryo-TEMPO Coastal Ocean Product focuses on the Mediterranean Region and includes SAMOSA+ retracker estimates. More information can be found in the CAW13 talk *"The Cryo-TEMPO Coastal Ocean Thematic Data Product: A CryoSat-2 Regional Product for Ocean Applications".*

Higher-level products and integration include the:

- SMOS-CryoSat L4 Sea Ice Thickness products (https://smos-diss.eo.esa.int/oads/access/).
- Copernicus Marine Service/ECMWF: https://data.marine.copernicus.eu/

ESA activities including CryoSat-2 data (improved for specific research purposes):

- **Baltic+ SEAL** (http://balticseal.eu/data-access/) including data retracked with the ALES+ SAR retracker.
- **HYDROCOASTAL** (https://www.satoc.eu/projects/hydrocoastal/hydrocoastal_data1.html) including CryoSat-2 data evaluated with several prototyped retrackers.
- **FFSAR-COASTAL** (https://www.satoc.eu/projects/ffsar/) including CryoSat-2 data evaluated with a Fully-Focused SAR processor.

The CAW poster by Carret et al., "*Contribution of CryoSat-2, multi-mission synergies and AI methods to observe coastal current intrusions over the North-Western Mediterranean Sea"* was also advertised.

In view of future missions, CRISTAL will continue the work performed by CryoSat-2 with some interesting additions. These are presented in the CAW talk by Cipollini et al., "*Dual-band altimetry from the Copernicus CRISTAL mission: Its capabilities for coastal altimetry".*

Future Challenges in the Polar Coastal Zone were reported.

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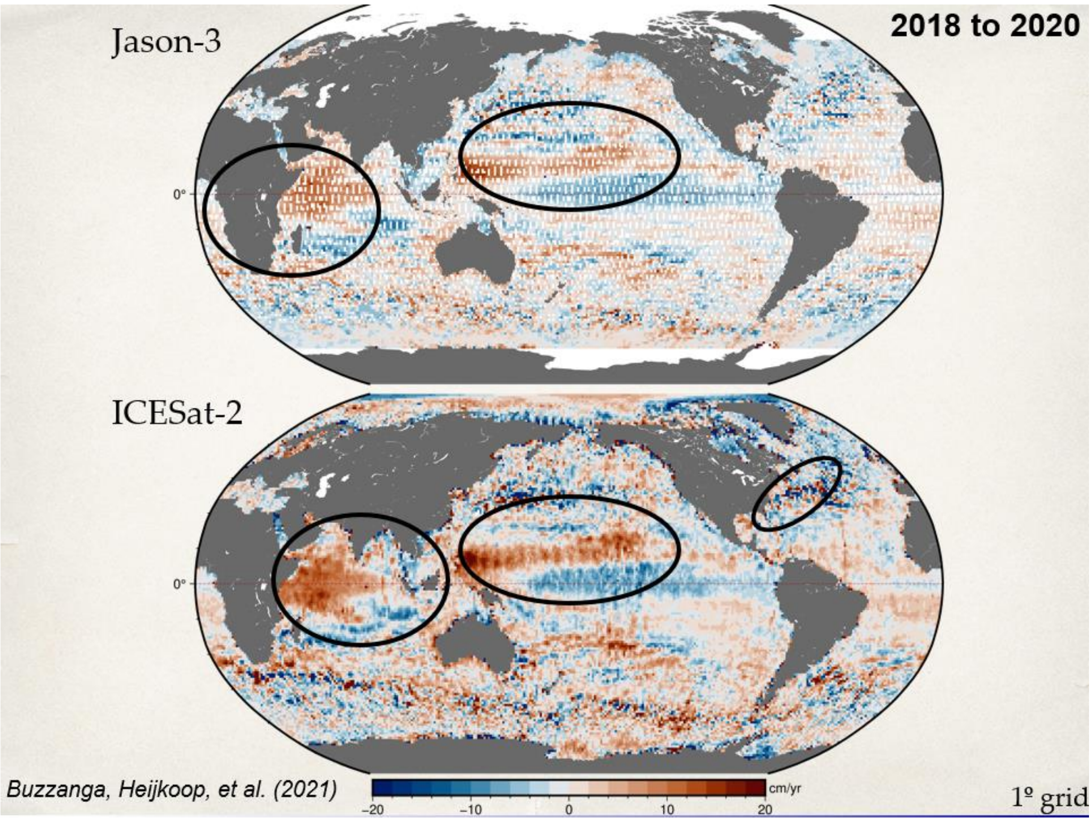
Conclusions:

- CryoSat in orbit for almost 13 years and is doing very good!
- Dedicated coastal products, continuously evolving.
- Coastal zone beyond sea level: CryoSat contribution to polar coastal altimetry.
- New challenges ahead, limited in situ validation data (FRM).
- Paving the way for CRISTAL.

An ICESat-2-based Assessment of Coastal Sea-level Trends and Variability

Brett Buzzanga, Ben Hamlington, Angelica Rodriguez

The talk introduced sea level rise and the altimetry & laser altimetry systems in the coastal zone. ICESat-2 key features were described and results against Jason-3 presented (see Buzzanga, et al., 2021, https://doi.org/10.1029/2020GL092327):



As well as results against tide gauges:

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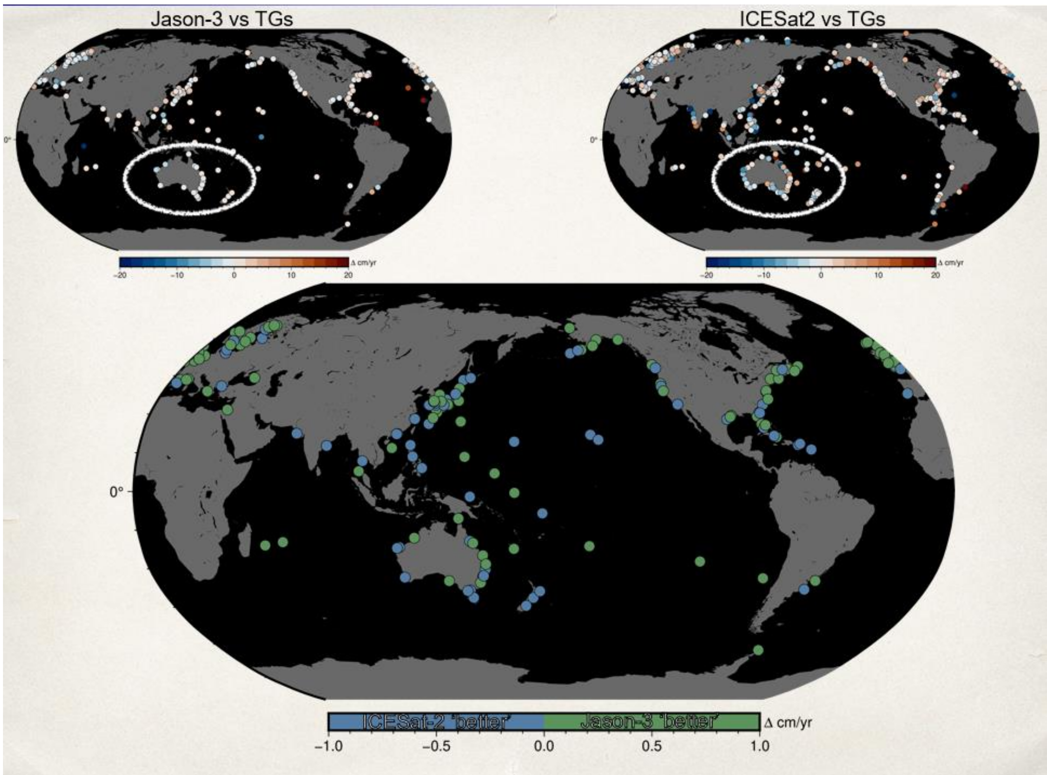


The North Atlantic drift and other similar analyses were presented using ICESat-2 data underling the importance of sampling a tide gauge data daily to correctly recover the linear rate from measurements.

Conclusions:

- ICESat-2 is filling data gaps in the radar altimetry record.
- Full instrumental suite helpful for process-based understanding.
- Could we derive temporal sampling strategies for coastal sea-level?

Many references are reported in the presentation for interested readers.

Session 2: Applications of coastal altimetry data (cont'd)

Co-chairs: Claire Maraldi and John Wilkin

Development of regional high-resolution hydrodynamic models in estuarian regions: The Seine and Elbe cases

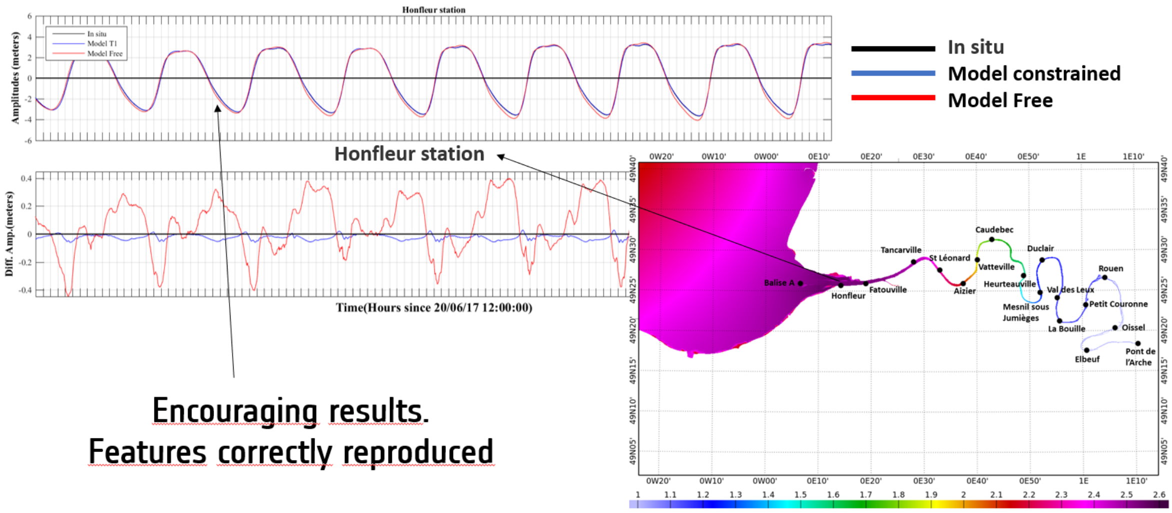
Ramiro Ferrari, Ergane Fouchet, Mathilde Cancet, Florent Lyard, Edward Salameh, Benoît Laignel, Luciana Fenoglio-Marc, Nicolas Picot, Pierre Féménias, Jean-Christophe Poisson.

The influence of the ocean (tides + surge) can be observed in the river water height from the river mouth up to hundreds of kilometres upstream. The interactions between the ocean flow and the river flow can produce distortions in the high-frequency variations of the water level measured in estuarine regions, especially in areas strongly influenced by ocean tides. In this context, hydrodynamic models are essential to remove the aliased high-frequency dynamical signals due to the ocean tide and storm surge from the satellite altimetry measurements (e.g., Sentinel-3 and SWOT) over estuarine regions, to obtain high quality data.

The importance of high frequency data from gauges and high-resolution models was remarked to support altimetry in these investigations. The formulation was explained along with high-resolution modelling requirements underlining parameters that contribute to the uncertainty budget of altimetry Cal/Val in estuarine areas.

Modelling activities on the Seine estuary were then discussed in the frame of St3TART. The T-UGOm model was adopted as an unstructured grid ocean model. Bathymetry & Coastline data were compared highlighting no significant differences (Univ. Rouen/LEGOS bathymetry and coastline were chosen). Tide gauge assimilation was discussed in relation to the configuration of the ocean model parameters (viscosity, bottom friction, bottom rugosity, lateral friction, etc.).

Good results were reported:

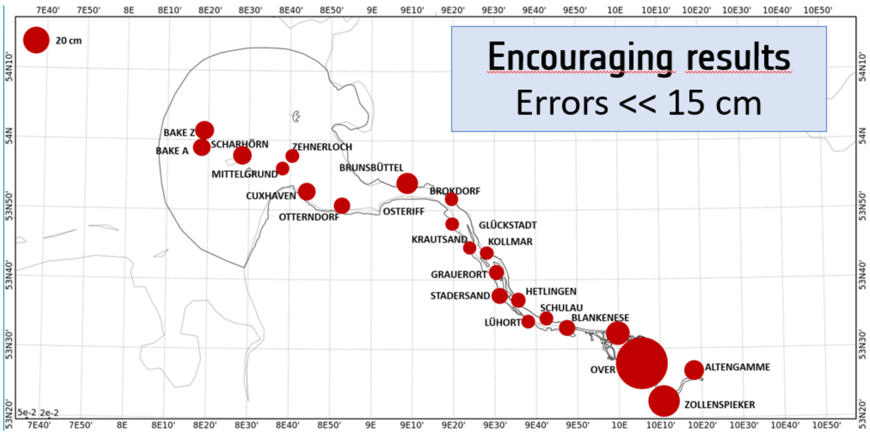


Frequency of tide gauges assimilation plays a key role, relaxing it, the error increases.

Similarly, modelling activities on the Elbe estuary were then discussed reporting good results:

Optimal Model configuration

Viscosity, bottom friction, bottom rugosity, lateral friction, etc.



Accuracy test of tide gauges assimilation is in progress.

Conclusions:

- These experiences showed encouraging results.
- Cal/Val requires to assimilate tide gauges (Seine experience).
- Based on the knowledge and experience gained in this work some other complex and challenging regions for Cal/Val activities could also be investigated.

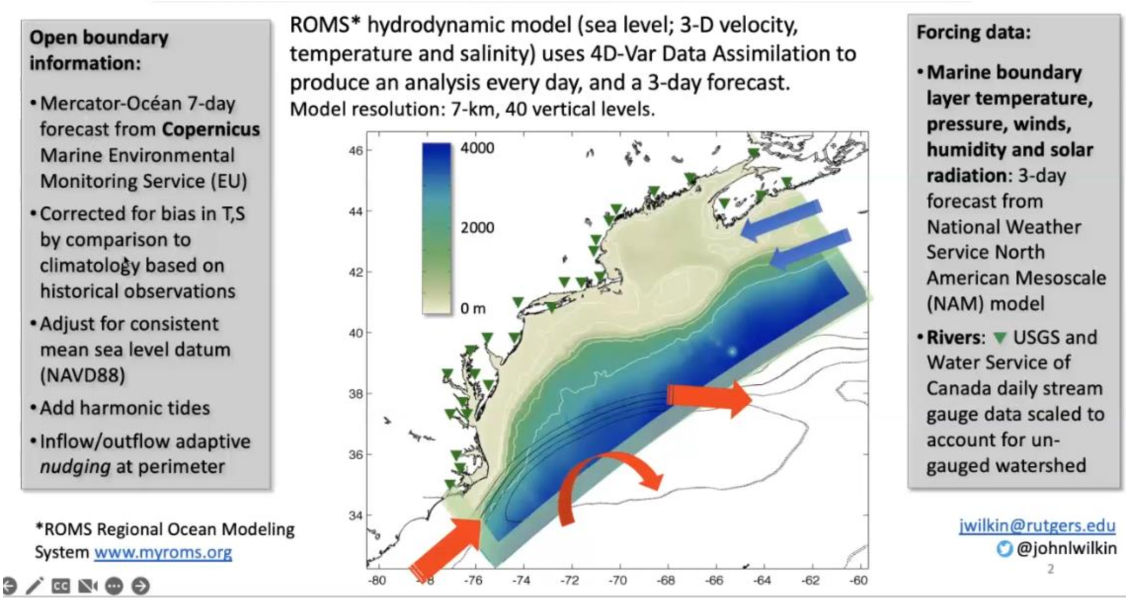
Regional ocean modeling with data assimilation for improving Mean Dynamic Topography and sea level variability forecasting in the coastal ocean

J. Wilkin, J. Levin E. Hunter and H. Arango

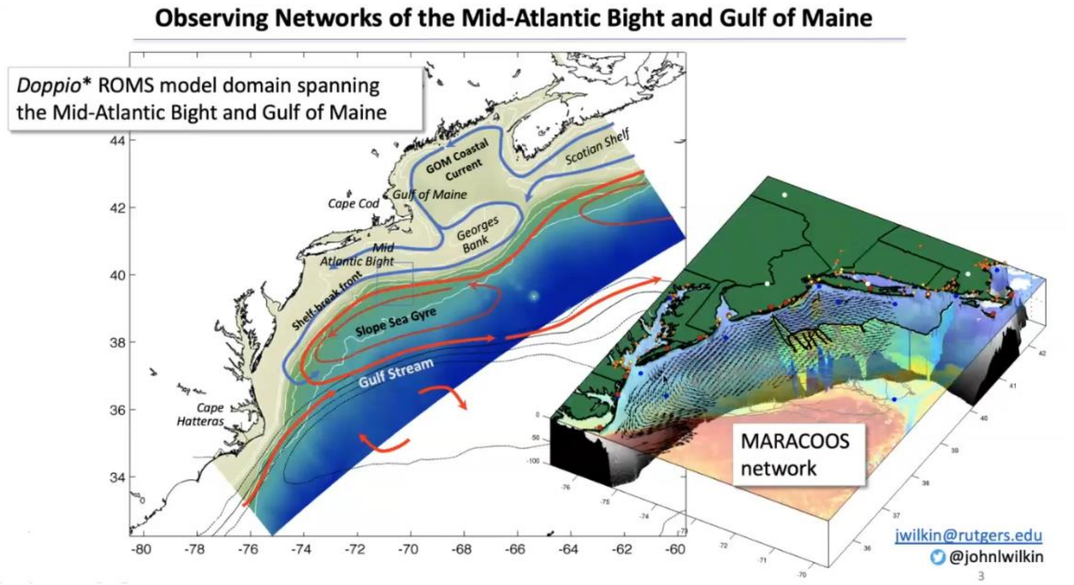
The talk reported about sea level assimilation in forecasting systems covering the East coast of United States.

The region of interest was introduced and the Doppio ROMS model adopted (www.myroms.org):

Summary of Session 2: Applications of coastal altimetry data



The general southwest flow, streams and gyres in the area were discussed. Quite strong inflow from coastal shelf. Regional observing systems are available:



From 2015 to a few months ago an array system of mooring was present, and data were mostly assimilated in real time. A constellation of satellite is also available capturing data over region. Observation of bottom temperature are available daily from ships.

Everyday assimilation is made using 300.000 observations. Authors started from the AVISO MDT and improved it using data assimilation from a climatological model (using climatological inputs, constrained with observations).

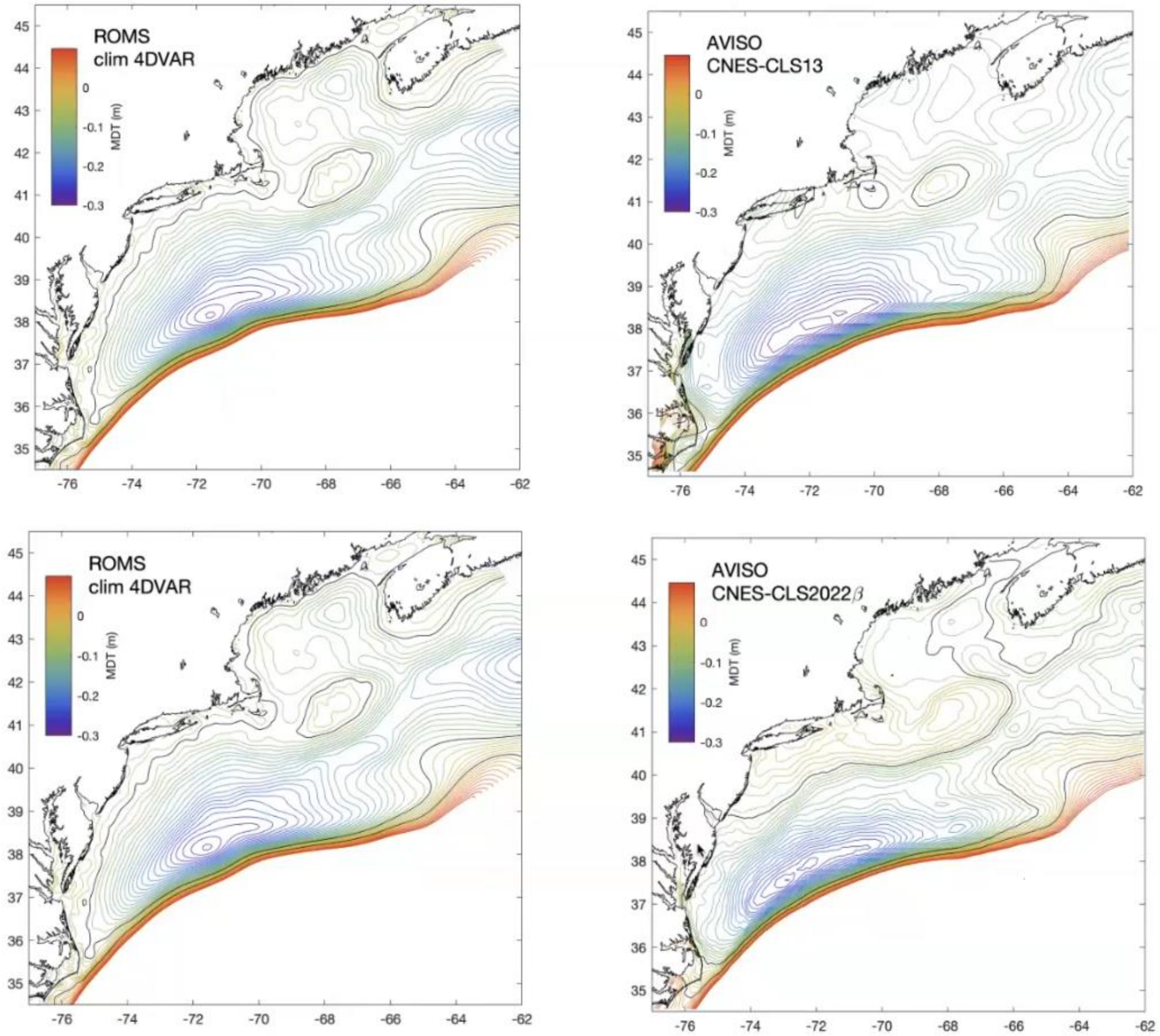
Moreover, the main seasonal climatological analysis is used:

- To correct biases in the Mercator-Ocean open boundary data.

- As MDT to combine with altimeter SSHA to get total sea level for assimilation.

The climatological analysis was presented in detail. System of geostrophic coastal currents demands MDT contours largely parallel to coasts. Recirculation on Georges Bank in Gulf of Maine basins was shown. Across-shelf sea level gradient is consistent with observed south-westward mean currents. Gyre circulation setup was evidenced.

Geostrophic flow into the coast was reported in comparing ROMS to AVISO CNES-CLS13 & CLS2022:



- CLS13: No Scotian Shelf or Gulf of Maine coastal Current.
- Weak across-shelf MDT gradient in Mid-Atlantic Bight.
- Many contours of geostrophic flow crossing the coastline.

Progress has been made by CLS models, but results are still better, and more usable, for ROMs for this very extended shelf especially up to the coast.

The pre-processing of altimetry data (SSH) is then discussed:

- Conventional mesoscale altimetry: high-frequency signals are removed by applying tide, inverse barometer (IB), and Dynamic Atmosphere (DAC) corrections.
- Here: these dynamics are in the model, so none of these high-frequency "corrections" were applied.
- However: to prevent small phase errors in the tide (resolution is low for a tidal model) from impacting SSH model minus data misfit, the altimeter tide signal was modified:

  - SSH is de-tided (GOT4.10, Ray 2013), and then a tide was added back from harmonics of a free run.

  - Modelled-observed SSHA misfit should then be dominated by non-tidal dynamics.
- MDT: to the tide-modified SSHA authors added their MDT from the climatological DA analysis so that modified SSHA observations and bias-corrected Mercator open boundary conditions were consistent.

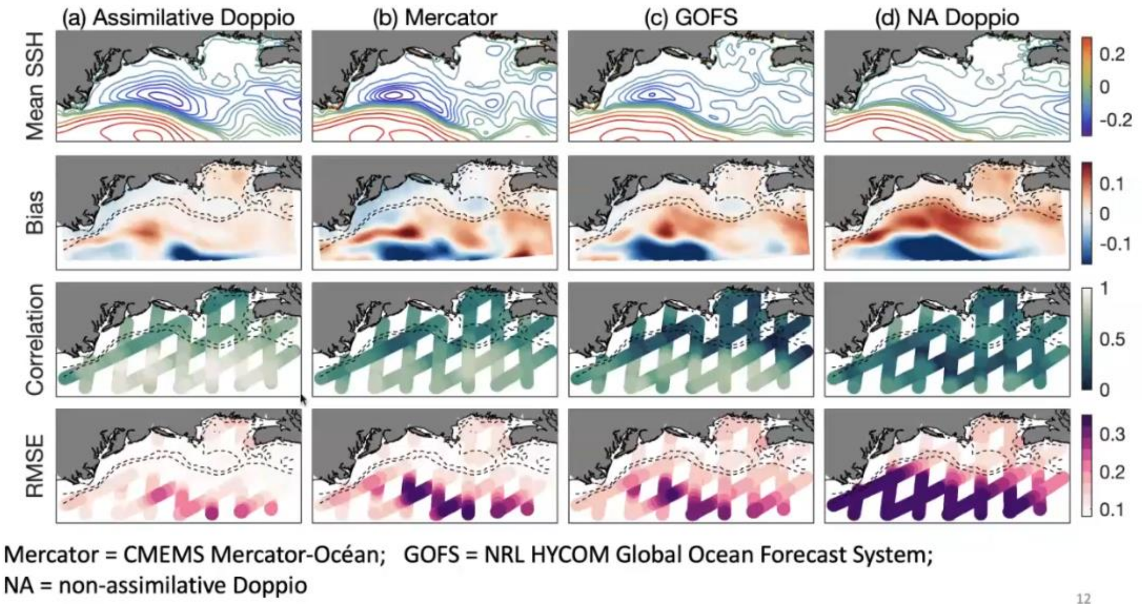
  - Accurate coastal MDT means that altimeter SSH can be used to within ~10 km of coast.
- To be useful as boundary conditions for estuary models and studies of coastal inundation, authors applied a uniform offset so that sea level datum is close to North American Vertical Datum 1988 (NAVD88).

Moreover,

- Observation error: ROMS 4D-Var assumes observation errors are uncorrelated in space and time
  - authors assumed ± 4 cm.
- Time covariance: in conventional altimeter analysis, e.g., AVISO optimally interpolated and gridded SSHA, information is projected in time with an explicit time covariance function:
  - time covariance is, presently, not an option in ROMS 4D-Var Observation Operator.
  - to compensate, observations were repeated on every model time step (6 min) in a ± 1.5-hour interval centred on true observation time.
  - this suppressed the generation of spurious surface gravity waves at $\sqrt{gh}$
- Error model: A posterior analysis of observation, background and estimation errors (following Desroziers et al. 2005) confirmed the error hypotheses are self-consistent.

Then model comparisons for assimilated altimeter sea level were presented:

Summary of Session 2: Applications of coastal altimetry data



The improvement with the assimilated Doppio is clear. RMSE is still present at the centre, due to gulf variability. Squared coherence was also presented for sea level and velocity at selected sites in the domain, including the Gulf of Maine. The improvement of coherence following the assimilation of coastal SSH was presented.

15 analyses were also made looking at the interannual mesoscale variability. The model matched bottom temperatures observations (eMOLT lobster traps time series). A very dramatic warming was reported.

Bottom temperature observations from fishing fleets data were compared to the models reporting again the good performance for Doppio.

Data are available at:

> Wilkin, J., Levin, J. (2022). Outputs from a Regional Ocean Modeling System (ROMS) data assimilative reanalysis (version DopAnV3R3-ini2007) of ocean circulation in the Mid-Atlantic Bight and Gulf of Maine for 2007-2021. SEANOE. https://doi.org/10.17882/89673

Conclusions:

- Rutgers *Doppio* forecast system down-scales global model; assimilates satellite and local in situ data.
- Uses 1-Hz along-track nadir altimetry (all satellites) to within ~10 km of coast.
  - *from RADS data base – multi-mission consistency and data format uniformity*
- Uses regional MDT from model with climatological mean forcing that assimilates mean observations.
  - *while CLS MDT has improved 2013 -> 2018 -> 2022, it is still unphysical in northeast U.S. shelf seas.*
- SSHA pre-processing retains high frequencies (no IB or DAC) but adjusts for (potential) tidal inaccuracy.
- Assimilation is by ROMS RBL-4D-VAR *Restricted B-preconditioned Lanczos 4D-Variational:*
  - *observations are used at their observation time and position.*

- *observation and background (model) error assumptions validated by posterior consistency checks.*

- Data assimilation significantly improves performance in the mesoscale.
- Intrinsic skill is high for high frequencies not captured by altimetry.
  - *well configured regional ROMS with accurate meteorological forcing and daily river inflows.*
- Operational monitoring of altimeters (and all observations) with ERDDAP control panel.
- 7 TB of open access outputs (15-year reanalysis hourly outputs; operational 3-day forecasts).

Coherent modes of coastal sea level variability from altimetry and tide gauge observations

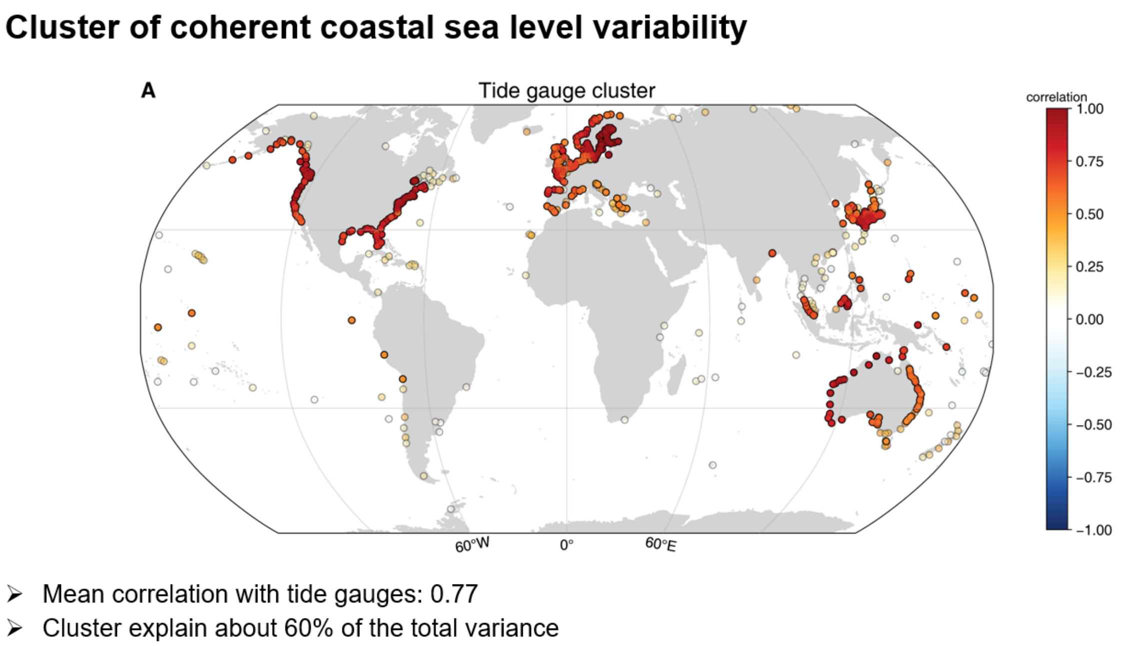
Julius Oelsmann, Francisco M. Calafat, Marcello Passaro, Chris Piecuch, Kristin Richter, Anthony Wise, Felix Landerer, Caroline Katsman, Chris Hughes, Denise Dettmering, Florian Seitz, Svetlana Jevrejeva

The talk started discussing the across-shore correlations w.r.t. coastal SLAs.

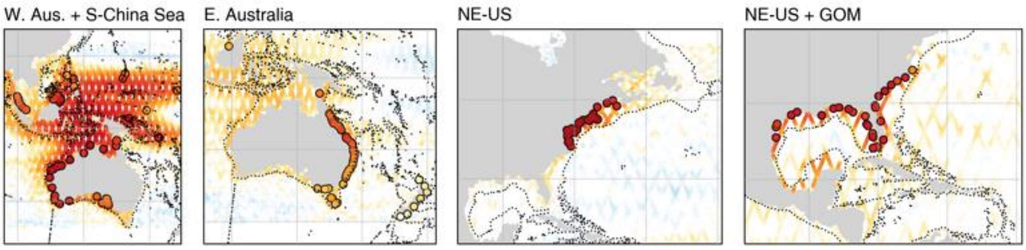
Research questions are:

- What are the regions of coherent coastal sea level variability?
- What are the cross- and along shore correlation length scales of coastal sea level variability?

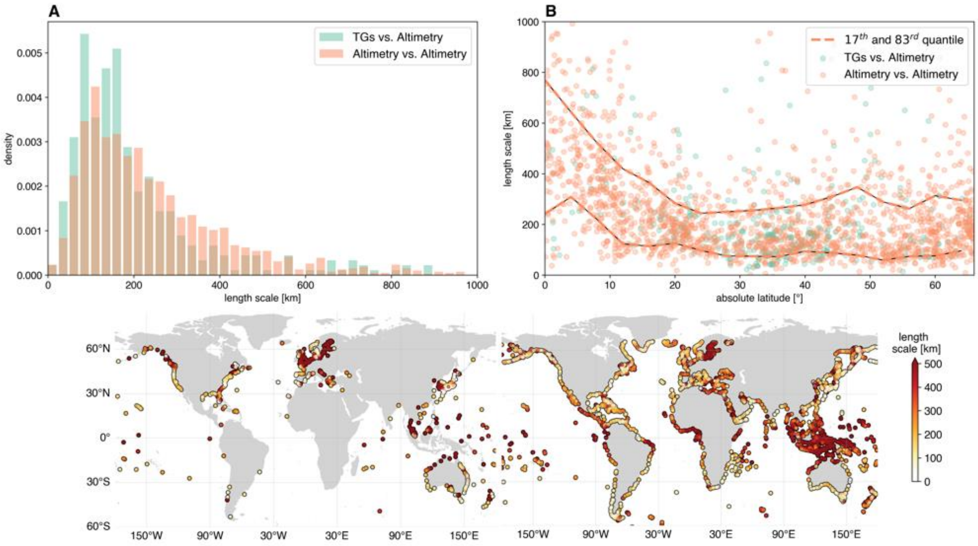
To answer the first question, tide gauge clusters were identified using Bayesian mixture models:



Correlation of cluster time series with detrended + deseasoned tide gauges and altimetry data (J1-J3) was investigated for the period 2002-2020 including coastal retracking (ALES). Strong influence of bathymetry on correlation structures.



Moving the attention to the second research question, across-shore correlation length scales were evaluated after describing the methodology:



Authors noted there is an overall dependency on the Rossby radius of deformation but also a strong influence of local coastal properties and drivers on the across-shore correlation structure.

Conclusions

- Coastal regions can be clustered into groups of coherent SL variability explaining a large fraction of the variance (60%).
- The across-shore correlation length scales are approximately proportional to the Rossby radius of deformation.
- This indicates the relevance of coastal dynamics causing such correlation structures.
- Over narrow continental shelves, across-shelf correlation length scales of processes are poorly resolved by current gridded products.
- Clues that coastally trapped waves cause large along-shore correlation length scales (up to 10,000km), however with large regional variations.

Summary of Session 2:
Applications of coastal altimetry data

Wind as driver of sub-annual Sea level anomalies on South Brazil and Patagonian Shelf

Marie-Christin Juhl, M. Passaro, D. Dettmering, M. Saraceno

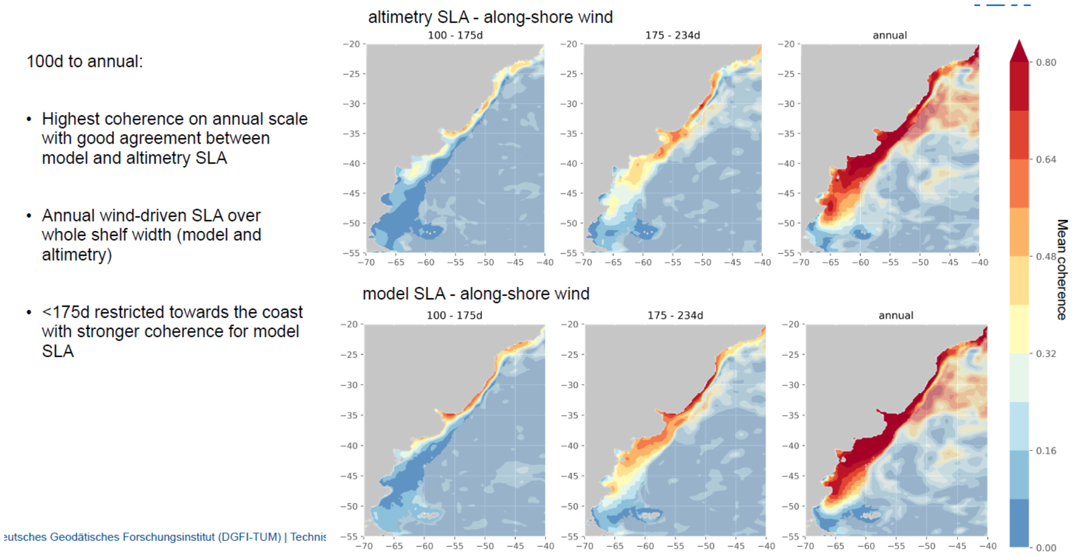
The Patagonian shelf is the largest continental shelf in the southern hemisphere. Previous studies showed that wind is an important driver of sea level anomalies (SLA) on parts of the Southwestern Atlantic Continental Shelf on annual scale. For coastal and shelf regions shorter temporal timescales get more important.

Objectives of the study were the following:

1. Is high-frequency SLA variability driven by the wind? In which frequencies and regions?
2. To what extent can gridded altimetry reveal high-frequency SLA on the continental shelf?

Data (SLA gridded L4 products from CMEMS & L4 wind speed components from scatterometers) were introduced in the frame of a methodology in which the magnitude squared coherence was used to obtain agreement of two time series depending on frequency. EOF-analysis was also performed.

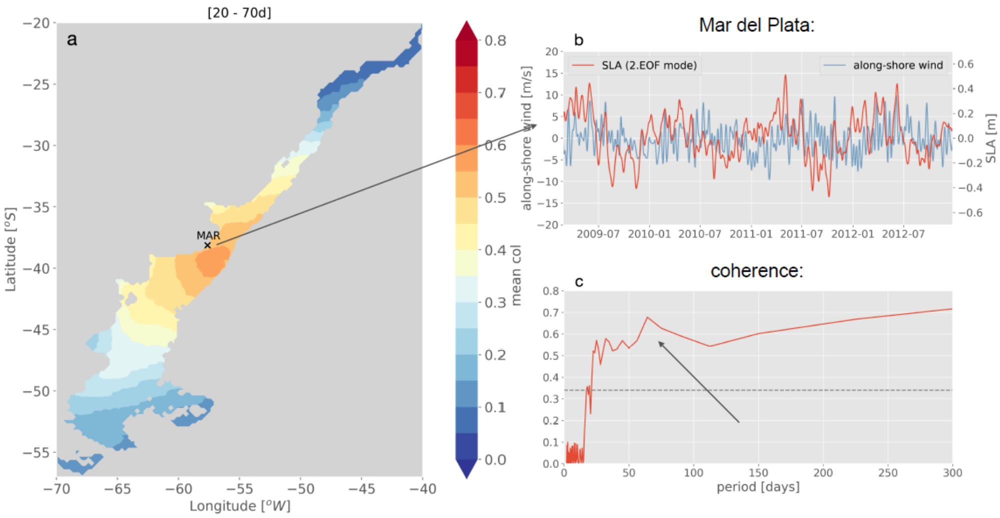
Coherence between SLA and wind was presented, as an example:



Coherence between wind and geostrophic velocity was also discussed. Along shore wind drives across-shore ocean mass transport, pressure gradient causes geostrophic current velocity and part of shelf circulation driven by wind through geostrophic adjustment.

The EOF analysis led to the decomposition of SLA into "modes of variability".

2. EOF mode SLA describe 10% of variability on the shelf. It shows good agreement with along-shore wind (corr. 0.6). Best agreement off the coast of Mar del Plata (spatial) and ~70 day (temporal).



Model vs. gridded altimetry SLA was also investigated.

Conclusions:

1. Is high-frequency SLA variability driven by the wind? In which frequencies and regions?

   - Yes, wind-driven SLA in all frequency bands (>1/20d), most notable along the Brazilian and Uruguayan coast and dominating annually.

2. What is the capability of gridded altimetry to show these high-frequency SLA on the continental shelf?

   - Coherence with the wind is notably higher for model SLA than altimetry SLA for 20d to 100d. The wind-driven variability below 20d is fully suppressed in the gridded altimetry product.

Summary of Session 2: Applications of coastal altimetry data

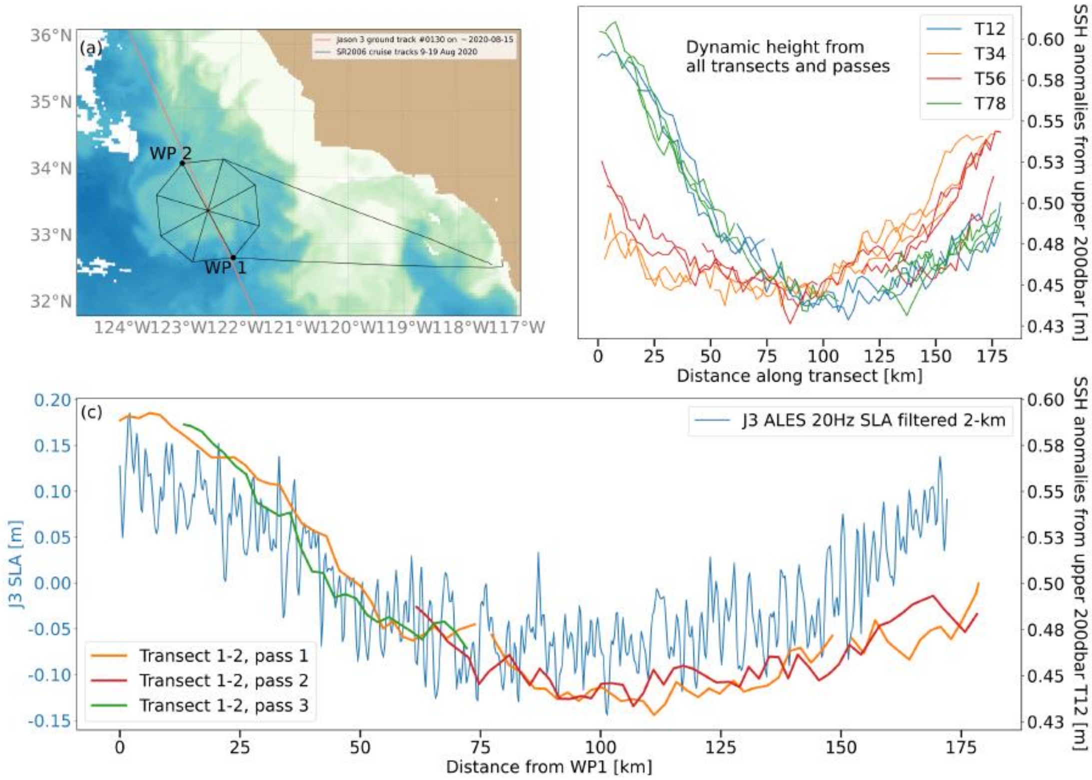
Coastal-to-open Ocean Exchange Processes in the California Current System from altimetry, ADCP and HFR data

Saulo M. Soares, Sarah Gille, Teresa Chereskin, Marcello Passaro

The goal of the study was to:

- lay the foundation for robust estimation of cross shore/shelf fluxes of heat, salt, mass, and carbon using high resolution altimetry.
- Investigate the role of meso- and submeso-scales (<100 km) eddies in geostrophic balance.

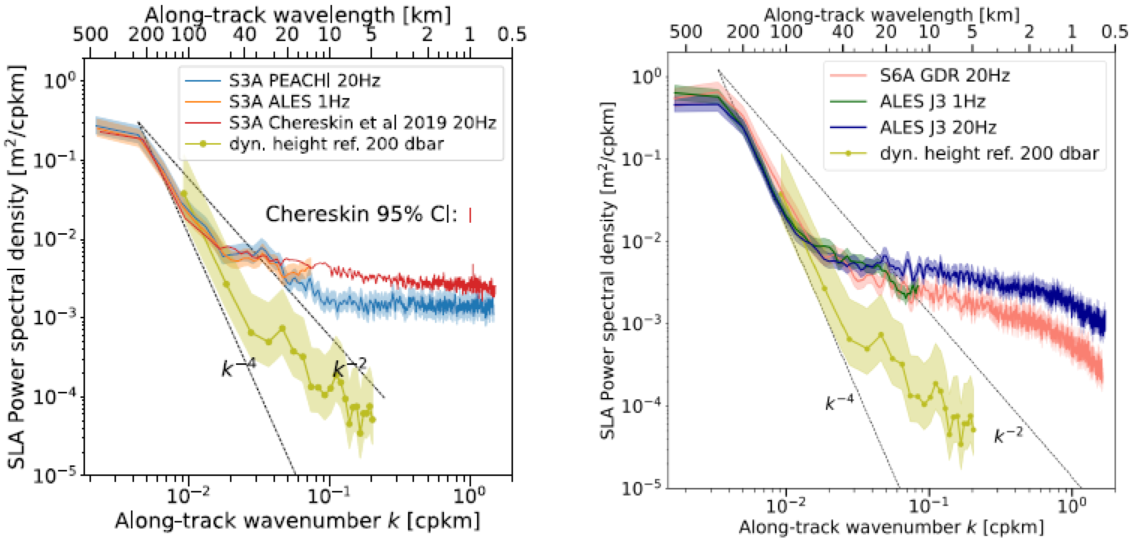
The California current system (CCS) and central coast of California are the selected study sites. Examples of exchanges driven by offshore eddy were presented and an example of the capability of altimeters to capture the smaller features linked to the cross-shelf exchanges was reported:



An array of observation is available in the area of investigation including Jason-3, Sentinel-6MF and Sentinel-3A tracks. Cruise tracks and HFR data are also available.

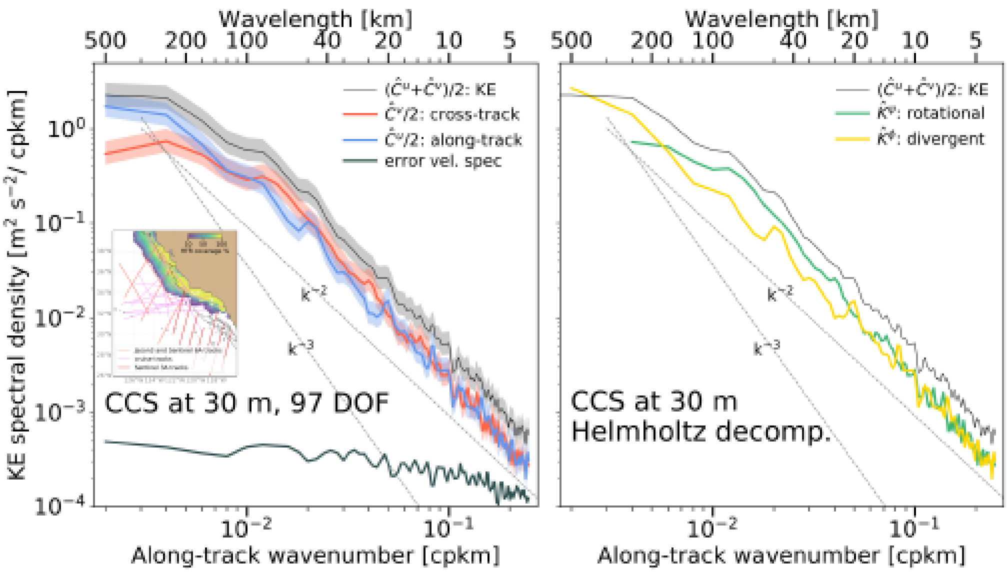
Power spectral densities from various systems & retrackers were compared.

Summary of Session 2:
Applications of coastal altimetry data



In a successive analysis, High-frequency Doppler radar currents were analysed in view of constraining height estimates. Frequency vs wavenumber spectra of offshore HFR currents were investigated. Helmholtz decomposition was applied to study divergent and rotational components.

Acoustic Doppler Current Profiler results were compared to divergent and rotational components providing a consistent matching:



To conclude, shelf and slope were studied with HFR data. Very similar results were obtained, more refined due to higher number of periods of good data.

Summary of Session 2: Applications of coastal altimetry data

Conclusions

- Altimetry and in situ steric heights diverge at scales < 60 km.
- The white plateau in radar altimetry is consistent with instrument noise, as previous studies have inferred. The nature of this noise merits further scrutiny.
- At sub mesoscales (<100 km), divergent (ageostrophic) energy is at least as large as rotational (only potentially geostrophic) energy. This divergence is not dominated by the internal tide band, suggesting it will not close the variance gap between steric height and altimeter.
- These modest internal tide contributions suggest that unbalanced processes are not the primary challenge in extracting the balanced SSH from altimeter data.
- Authors hypothesise that aliased surface gravity waves pose challenges for radar altimetry at scales shorter than ~60 km.
- Both surface and internal/tide wave challenges are expected to grow as the nearshore is approached.

Joint Estimates of Coastal Sea-Level Trend and Vertical Land Motion in the Northern Gulf of Mexico

C K Shum, Shangdao Wang, Chungyen Kuo, Wen-Hau Lan

An algorithm for the joint estimate of tide gauge adjusted vertical motion and sea-level reconstruction was presented:

[E0] $$S_i(t) = S_i(t_0) + v(t-t_0) + a\frac{1}{2}(t-t_0)^2 + \sum_{i=1}^{m} \alpha_i \sin\left[\frac{2\pi}{P_i}(t-t_0)\right] + \beta_i \cos\left[\frac{2\pi}{P_i}(t-t_0)\right] + \varepsilon_t$$

[E1] $$S'(\lambda_i,\varphi_i,t) = S(\lambda_i,\varphi_i,t) + Gh(\lambda_i,\varphi_i,t)$$
$$or \ = S(\lambda_i,\varphi_i,t) + \dot{u}_{i1}(\lambda_i,\varphi_i,t)$$
$$\Delta SL = g_a(\lambda_i,\varphi_i,t) - S'(\lambda_i,\varphi_i,t)$$
$$\Delta SL = offset + Drift(t-t_0) + \sum_{i=1}^{12}\left(A_i \cos(2\pi f_i t) + \Phi_i\right) + SSHSlope \cdot d + \varepsilon$$

Where Offset is a constant intercept term at time t_0; Drift is the altimeter instrument drift; A_i, f_i, Φ_i are the amplitude, frequency and phase of i^{th} harmonic parameters; *SSHSlope: SSH slope* with across track distance *d*; ε is residual error

[E2] $$g_{i1}(\lambda_i,\varphi_i,t) = S_i(\lambda_i,\varphi_i,t) + \dot{u}_{i1}(\lambda_i,\varphi_i)(t-t_0)$$
$$g_{i2}(\lambda_i,\varphi_i,t) = S_i(\lambda_i,\varphi_i,t) + Gh(\lambda_i,\varphi_i)(t-t_0)$$

[E3] $$g_c(\lambda,\varphi,t) = \sum_{k=1}^{M} \alpha_k^a(t) EOF_k^a(\lambda,\varphi)$$

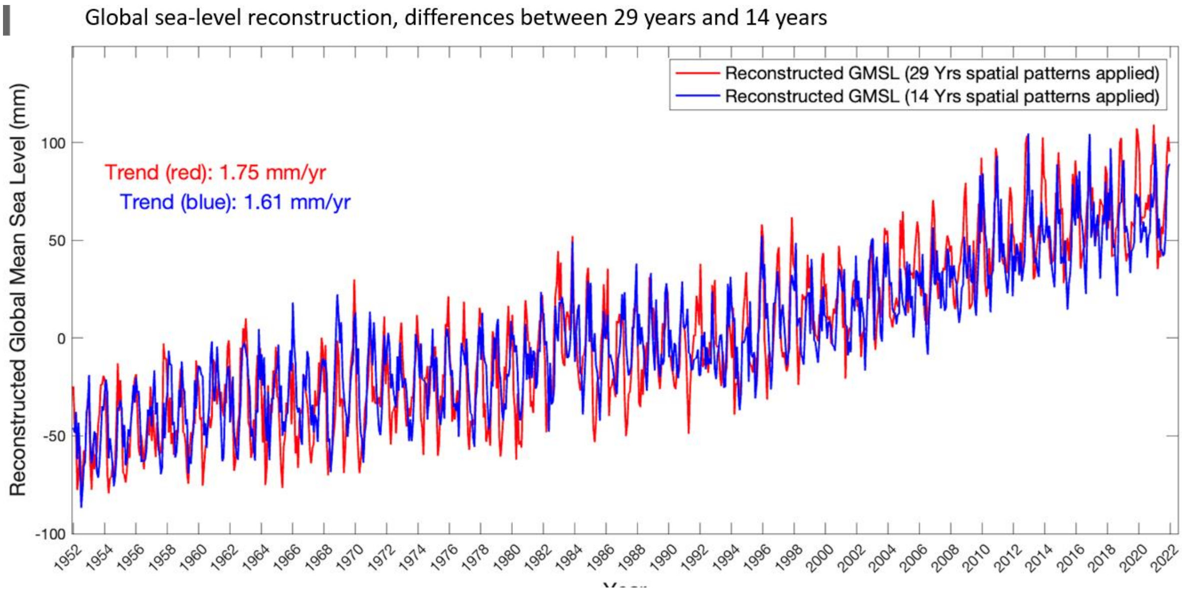
[E4] $$g_{i1}(\lambda_i,\varphi_i,t)_{i=1\ldots N} = \sum_{k=1}^{M} \alpha_k^{r_i}(t) EOF_k^a(\lambda,\varphi)$$

[E5] $$\dot{u}_{i21}(t-t_0) = \sum_{k=1}^{M} \alpha_k^{r_i}(t) EOF_k^a(\lambda,\varphi) - S_i(\lambda_i,\varphi_i,t)$$

$$r\dot{S}_{ji} = \dot{S}_j(\lambda_j,\varphi_j) - \dot{S}_i(\lambda_i,\varphi_i) = (\dot{u}_i(\lambda_i,\varphi_i) - \dot{u}_j(\lambda_j,\varphi_j)) - (\dot{g}_i(\lambda_i,\varphi_i) - \dot{g}_j(\lambda_j,\varphi_j))$$

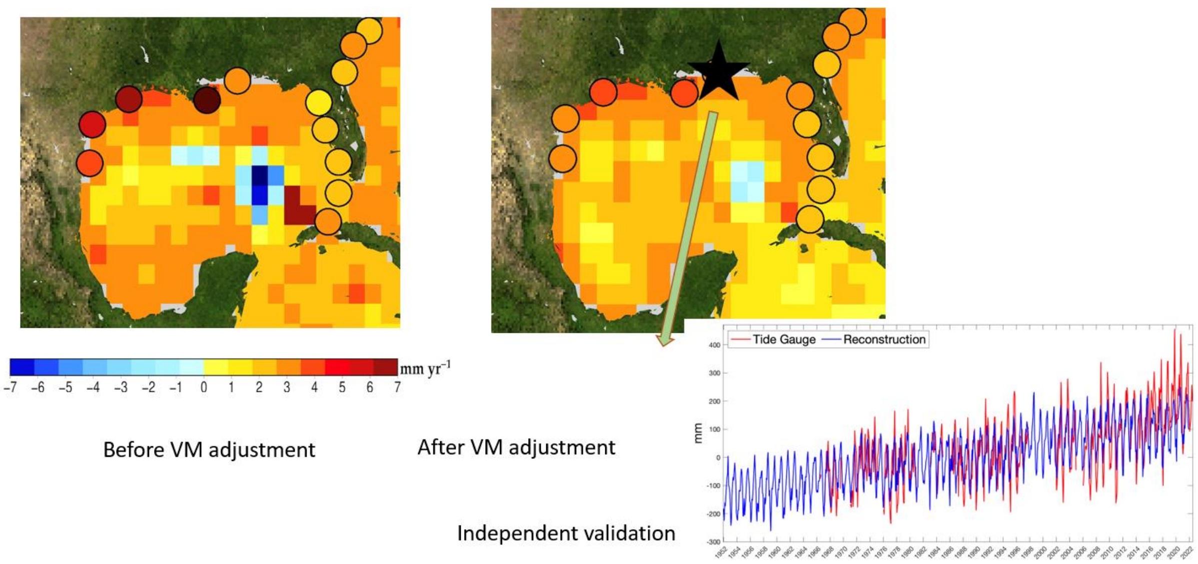
$$\begin{bmatrix} y_1 \\ z_0 \end{bmatrix}_{(n+l)\times 1} = \begin{bmatrix} A_1 \\ K \end{bmatrix}_{(n+l)\times m} \xi + \begin{bmatrix} e_1 \\ e_0 \end{bmatrix}, \quad \begin{bmatrix} e_1 \\ e_0 \end{bmatrix} \sim \left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \sigma_0^2 P^{-1} = \Sigma\right)$$

and results of Global sea-level reconstruction discussed reporting the following trends:



GPS data (ULR7a, NGL14) were compared to the iterated vertical land motion and GIA (ICE5G, VM2) data discussing vertical land motion residuals and correlation.

The impact of vertical land motion adjustment was evaluated in several case, as for example in:



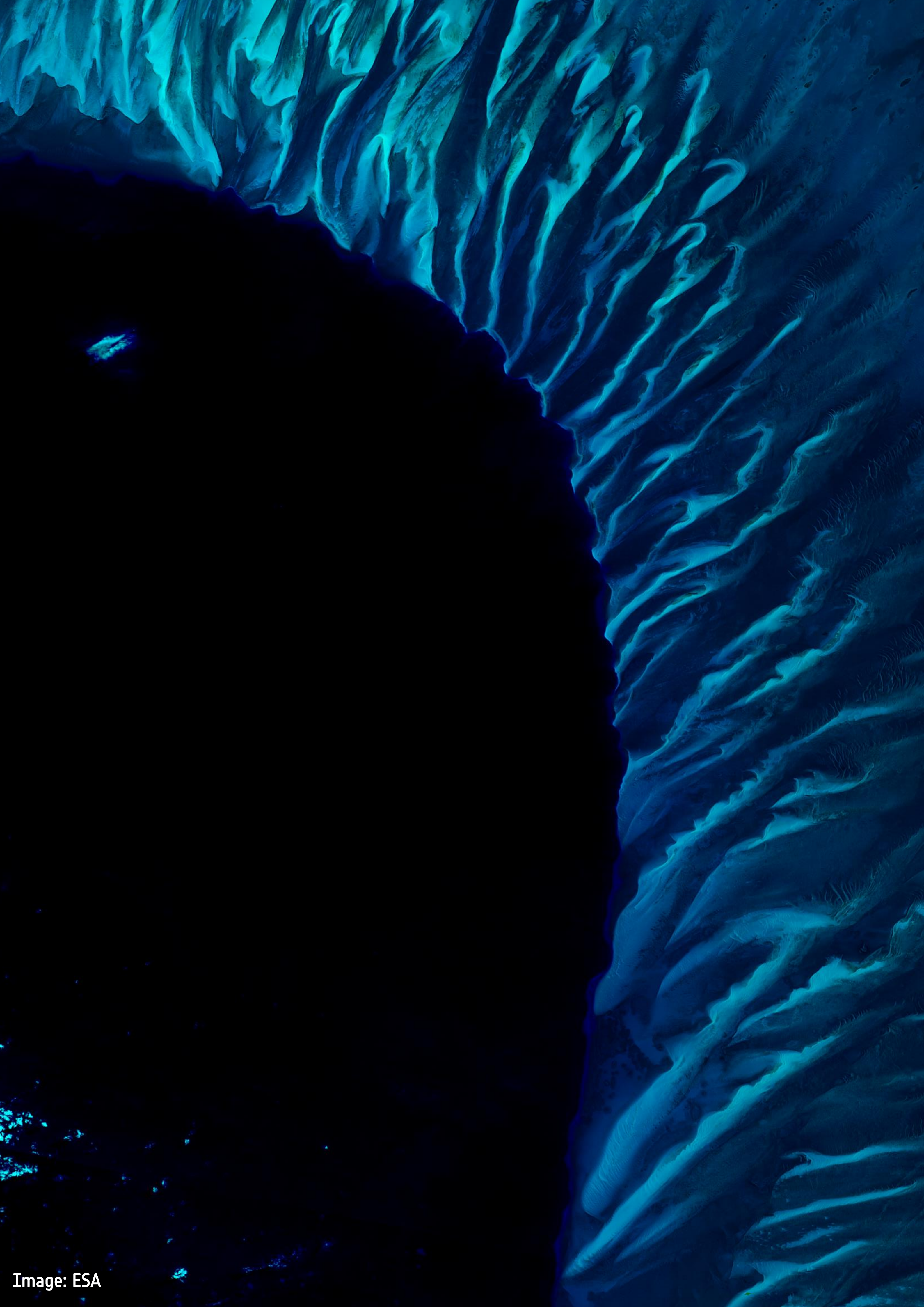


Image: ESA

Session 3: Synergistic, Climate Studies & Operationalisation

Co-chairs: Nicole Delpeche-Ellmann and Guoqi Han

Altimetry-observed shelf-edge currents off western Canada

Guoqi Han, Nancy Chen

Objective of the study were:

- To use satellite altimetry for monitoring interannual variations of near-surface flow on the shelf edge and continental slope off British Columbia.

- To improve knowledge on interannual and alongshore variations of the near-surface flow.

As a background information, a large-scale circulation pattern was evidenced. Seasonal wind patterns were described:

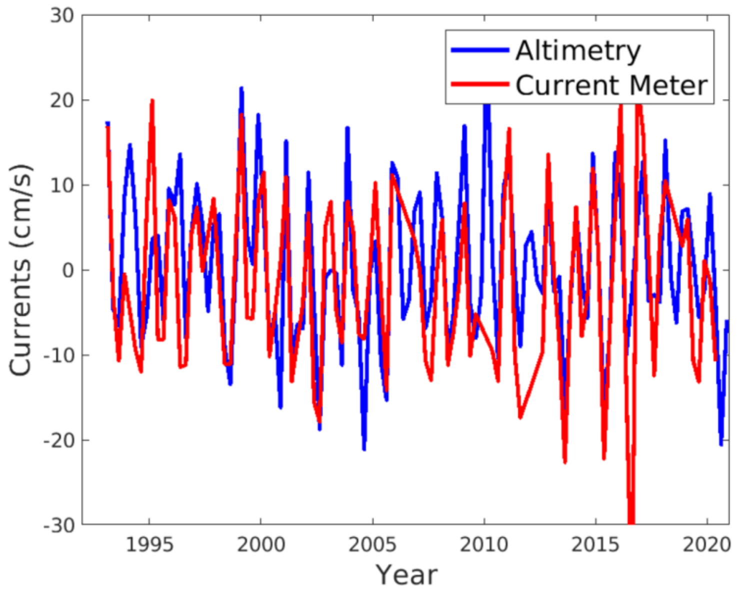
- Winter, downwelling winds off British Columbia.

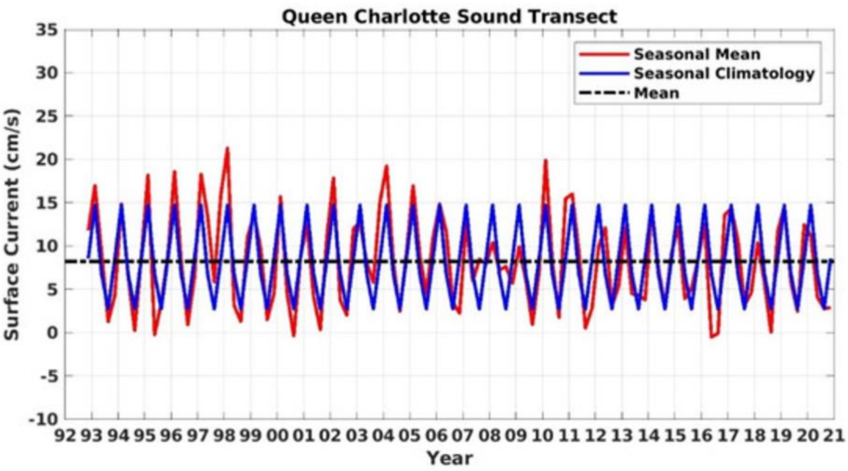
- Summer, upwelling winds off Vancouver Island.

The adopted method considers:

- TP/Jason along-track SLAs over 1992-2020 from RADS.
- Geostrophic surface current normal to track (Han et al., 2014) which is a good proxy for the along-shelf current.

Several transects are reported detailing the current magnitude and the seasonal cycles.





- Mean current: poleward, 8 cm/s
- Seasonal cycle: range 12 cm/s, poleward year round
- Notable interannual variations

EOF were studied to investigate Alongshore Current Anomalies. Seasonal current anomalies were correlated with buoy winds off Vancouver Island and off Oregon. Alongshore Wind Anomalies were reported. The first EOF mode is not significantly correlated with PDO or Nino3.4 index. Factors are:

- Significantly correlated with the alongshore wind anomalies.
- El Nino/La Nina, PDO, and their interactions
  - Wind stress patterns
- Large current anomalies during EL Nino and La Nina years.
- But not statistically significant with PDO or Nino3.4

Conclusions

- The study showed the utility of satellite altimetry for monitoring shelf-edge flow off Western Canada.
- The surface shelf edge currents correspond to both regional winds off West Vancouver Island and remote winds off Oregon.
- Large episodical current anomalies during the El Niño and La Niña years.

Summary of Session 3: Synergistic, Climate Studies & Operationalisation

Accurate Dynamic Topography by Satellite Altimetry and Marine Geoid Model

Majid Mostafavi, Nicole Delpeche Ellmann, Artu Ellmann

Authors reminded that Dynamic Topography (DT) represents a realistic quantification of ocean dynamics than SSH:

- Geodetic Approach by Tide Gauge (TG), Satellite Altimetry (SA), etc., with respect to a geoid model (equipotential surface of the earth).

- Oceanographic Approach using a mathematical hydrodynamic model (HDM), often referring to undisclosed datum.

Problems are that:

1) SA data need to be validated to retrieve accurate DT against in situ data;
2) TGs are valid nearshore and don't represent offshore DT and
3) Reliable reference vertical datum is needed.

Solution proposed: Hydrodynamic Model Level (HDM) can be used to validate offshore satellite altimetry data and high-resolution geoid can be used as the static datum.

The study aimed to:

- Develop a method to determine accurate DT from HDM, TG, and SA data.

- Use the method to validate DT data and SA performance.

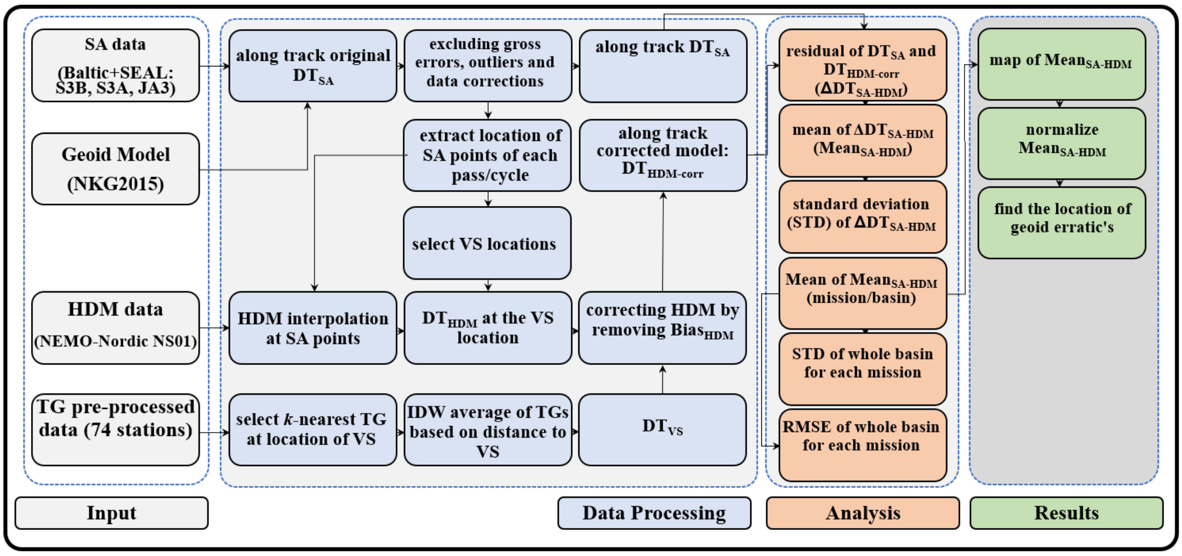
- Determine the problematic area by the synergy of different DT sources.

- Specify persistent and semi-persistent problematic areas using multi-mission SA data.

Methodology involved the usage of a high-resolution geoid (regional geoid model Baltic Sea NKG2015, res. 1 km), being the EGM 2008 (res. ~9 km) too coarse. Baltic+ SEAL ALES+ and ALES+SAR re-tracked data have been adopted resulting in better performance with respect to L2 standard products.

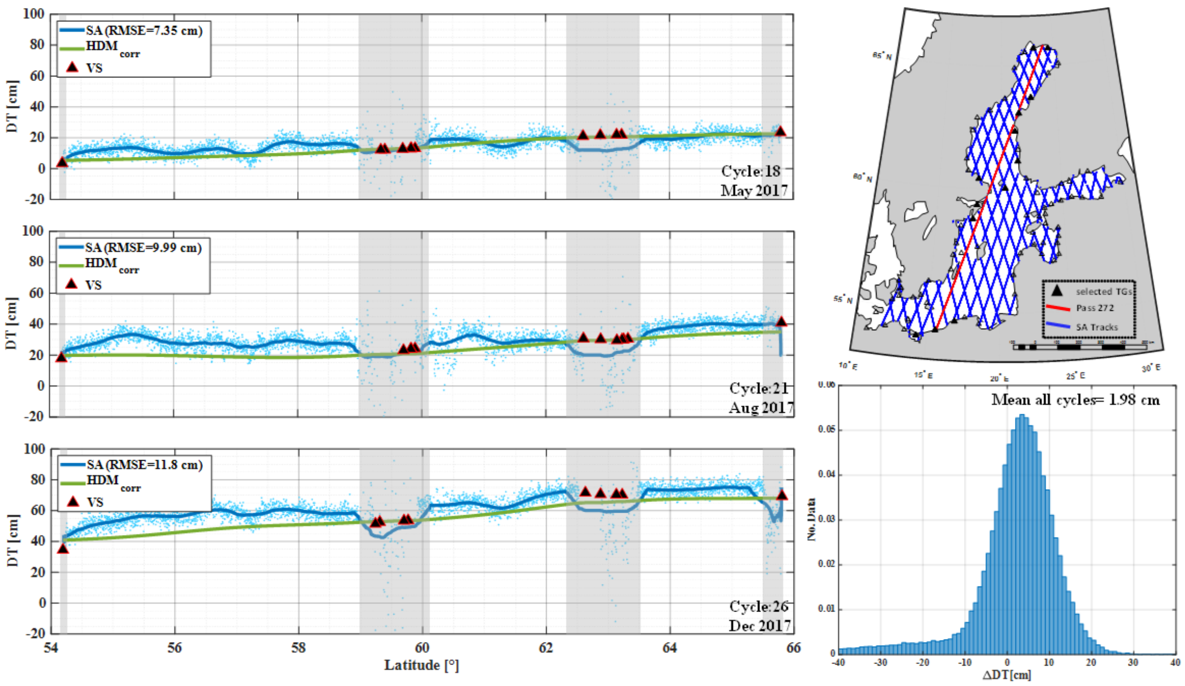
The HDM correction was explained in detail with its formulation along the criterium for Satellite Altimetry data evaluations.

The full methodology is reported here:

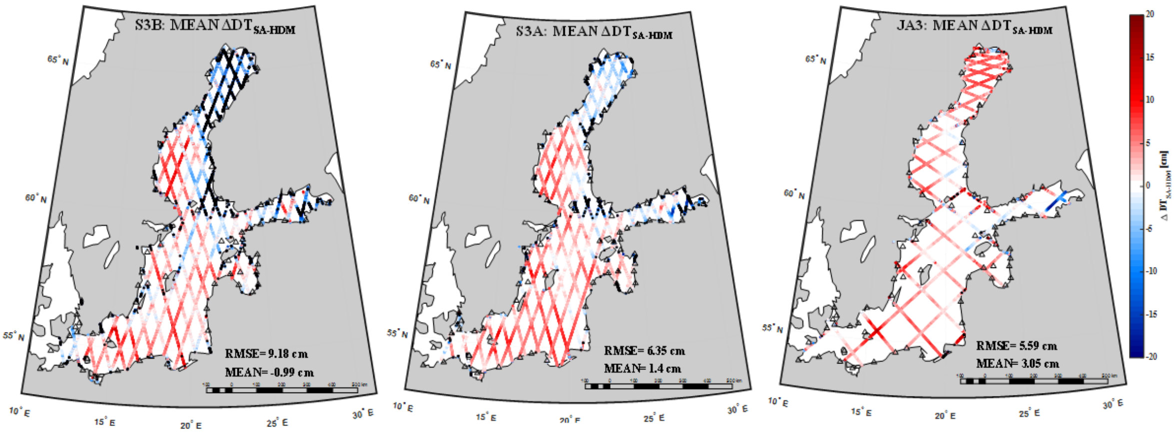


For the case study, the Baltic Sea including 74 TGs was selected. The various vertical datums and the adopted geoid, vertical uplift & hydrodynamic models were introduced. Sentinel-3A, Sentinel-3B, Jason-3 along-track 20 Hz ALES+ & ALES+SAR retracked data from Baltic+ SEAL (2016-2019) was considered.

The comparison of Sentinel-3A pass #272 dynamic topography DT_{SA} (blue dots) with the TG corrected HDM (green line) for 3 cycles (representing different seasons) in 2017 is reported below. The altimetry dynamic topography moving average is denoted by the blue solid line, the grey zones show masked near coast and land areas and the triangles denote locations of virtual stations.



Standard deviation between altimetry missions and hydrodynamic model was also discussed. RMSE was evaluated, and problematic areas identified:



Conclusions

- Core component utilized to determine accurate instantaneous DT: access to a high-resolution quasi-geoid model (incl. NKG2015).
- Accurate sea level variability is obtainable by utilizing the geoid rather than MSS model.
- Discrepancies between HDM and SA were in the range of ±20 cm with a STD of 10 cm and RMSE of ~9 cm (for S3B) and ~6 cm (S3A and JA6) over Baltic Sea.
- Large STD values over complex parts of the Baltic Sea at coastal (presence of the archipelagos and small islands) and sub-arctic areas.
- The synergy of the different datasets (geoid, SA, TG, and HDM) can reveal inconsistency between datasets and improve the reliability of them.
- Multi-mission SA comparison can identify the persistent problematic areas due to:
  - sea-ice (sub-artic area).
  - TG issues (such as inadequate/incorrect correction applied, zero-level problems, etc.).
  - geoid model-related problems (e.g., in the eastern part of the Gulf of Finland), etc.

Forecasting Of Absolute Dynamic Topography By Utilizing Machine Learning With Synergy Of Satellite Altimetry Data

Nicole Delpeche-Ellmann, Saeed Rajabi-Kiasari and Artu Ellmann

Reliable and accurate sea level forecast is a key component for:

- Safe navigations, coastal protection, geo-hazards management, climate change, and alarming coastal city flooding.
- Operational forecasting systems and planning decisions.

Machine learning can assist with forecasting and prediction especially with huge data sets and non-linearity characteristics of input data such as sea level. It takes input data to learn best hypothesis (out of many) to compute predictions/forecast of a target variable by minimizing a loss function (while updating weights). ML can be supervised, unsupervised or reinforcement learning.

Important components:

- Input data: Identifying relevant data for irrelevant uses computer resources and creates noise.
- Map Hypothesis: Computational complexity vs statistical properties (e.g., linear, deep learning.
- Loss function: Minimum errors.

Various machine/deep learning models developed to forecast sea levels:

- Convolutional Neural networks (CNNs).
- Recurrent Neural networks (RNNs).
- Long short-term memory (LSTM).

Input data were identified as one of most important components. Challenges with various sea level data sources (e.g., tide gauges, satellite altimetry, hydrodynamic models) were discussed underlining dissimilar spatio-temporal resolutions (SA and TG). High-resolution geoid is a key component in linking sources and providing a realistic and consistent vertical datum.

A corrected hydrodynamic model (HDM) has been made available for the Baltic Sea region:

- Bias corrected by using 73 TG stations and interpolation methods.
- Validated by Baltic+ Seal SA data.
- Linked with high-resolution NKG2015 geoid model.

Benefits of absolute dynamic topography:

- More realistic and accurate sea level forecasting.

- Conformity with all countries.
- Can lead to a better ocean circulation estimation.

Two general approaches for sea-level forecasting:

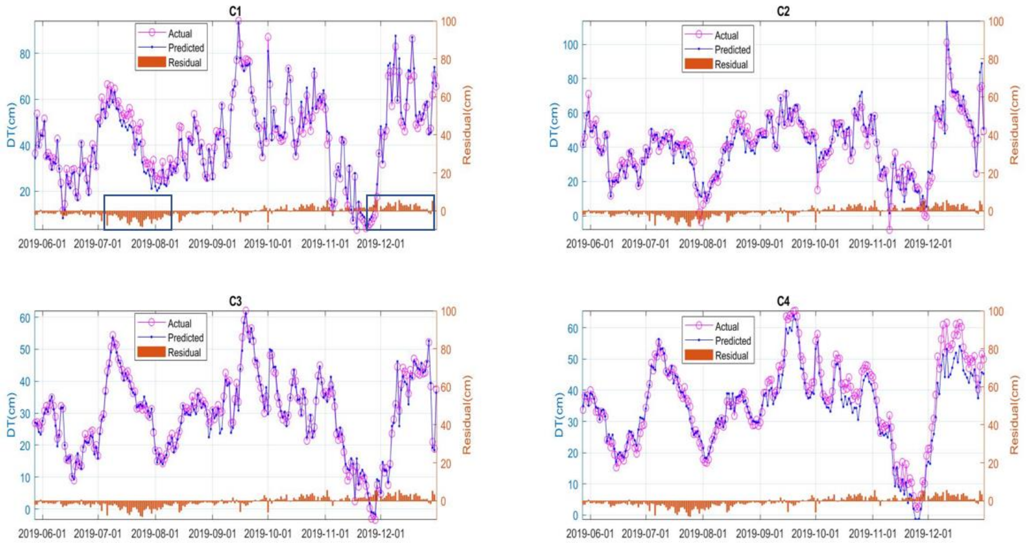
- Autoregressive models:
    - Based on the historical measurements of the observations (here sea level).
    - Current available autoregressive model, one day ahead with R=0.90.
- Physical models
    - Based on physical/hydrometeorological variables.
    - Current available physical model forecasts sea level, one week ahead with R=0.85.

Objective of the study is to integrate both methodologies via hybrid modelling. Study gap:

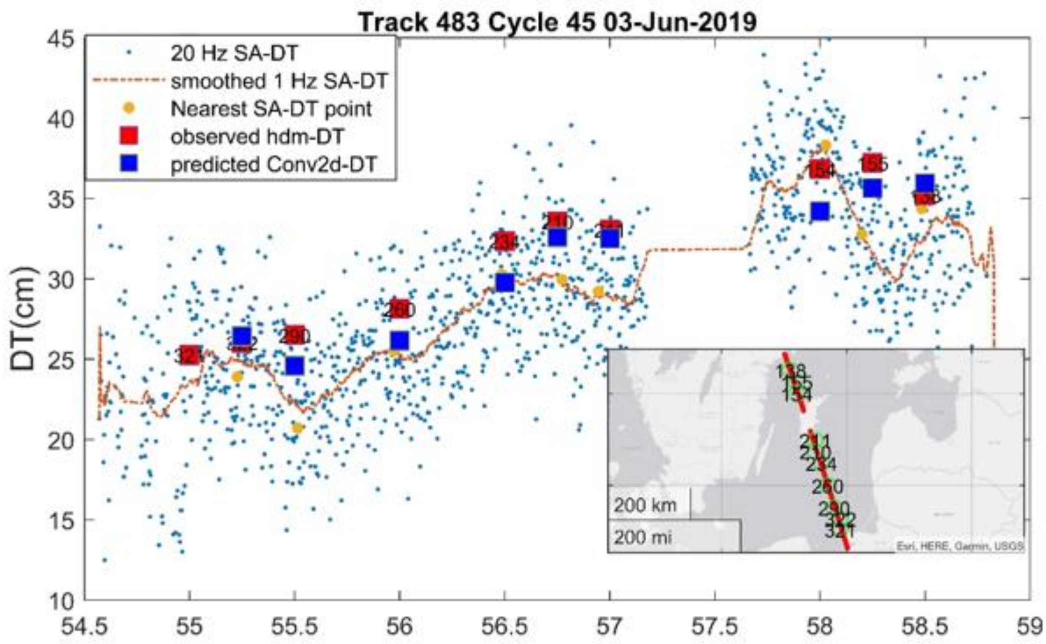
- Previous studies have more relied on using ML for relative sea-level prediction (e.g., SLA or extremes).
- The literature is still limited for absolute sea-level predictions (SSH or DT).

The discussion highlighted the study regions and the input datasets. In the selected framework, 80% of data was used train and build the model. 20% was used to test and check performances. Authors performed a forecast of the DT field using a multivariate one-day ahead 2D convolutional neural network (Conv2d). An external validation with SA-DT for various tracks (after applying satellite corrections and referencing to Geoid) was performed.

Spatial correlation coefficients were discussed along with the forecasting performance of Conv2d model:



The presentation ended discussing the validation with satellite altimetry-dynamic topography data for several tracks including the following:



Conclusions & Future works

Using a Multivariate Convolution Neural Network to forecast Dynamic Topography:

- Statistical analysis showed R^2 over 0.9, RMSE of 4.7 cm both for training and test sets.
- Based on the spatial RMSE plot, higher discrepancies were observed in the south-eastern Baltic (RMSE of 10 cm).
- External validation with along track-SA: confirmed agreement by RMSE<5 cm.
- Still for some tracks, auhtors observed smoothed daily DT (e.g. 614 and 711).

Future studies

- Forecasting of a longer time span (e.g., 7 days).
- Use of higher spatial resolution.
- Inclusion of other input sources (e.g., river discharge).

This study used satellite altimetry for the validation phase of our model. Instead it can also be included as model inputs in future solutions.

SESSION 3: Synergistic, Climate Studies & Operationalisation (cont'd)

Co-chairs: Marie-Isabelle Pujol and Julius Oelsmann

Toward Higher resolution Level-3 altimeter sea level products

M.-I. Pujol & DUACS team, A. Sánchez Román, G. Dibarboure, M-H. Rio

The presentation introduced a 5-Hz (~1.2 km) L3 altimeter product. This product is expected to answer the users' need & Copernicus Marine Service requirements:

- *"Toward higher resolution model in open ocean and coastal areas: model resolution increased by a factor 3 or more in the post 2025 period".*

  → need higher resolution altimeter products to constraint them (P-Y Le Traon, OceanPredict 2019).

- For regional applications/models.

- Downstream applications: marine safety; biogeochemical activity; research activities.

Moreover, it could be of interest for coastal areas applications (excluding littoral).

The L3 5 Hz processing methodology was described in detail (posting rate, corrections, quality control…)

L3 5 Hz are then compared with L3 1 Hz altimeter products. Higher data availability in coastal areas with L3 5 Hz data compared to L3 1 Hz: 80% data availability up to ~5 km from the coast (~10 km for L3 1 Hz) and no significant degradation of the SLA variance when approaching the coast compared to L3 1 Hz.

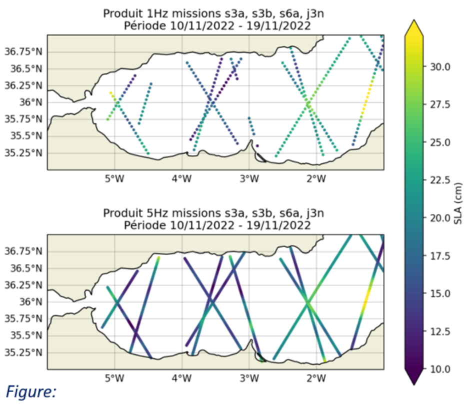


Figure:
Example of L3 1Hz and 5Hz altimeter measurement in Alboran Sea

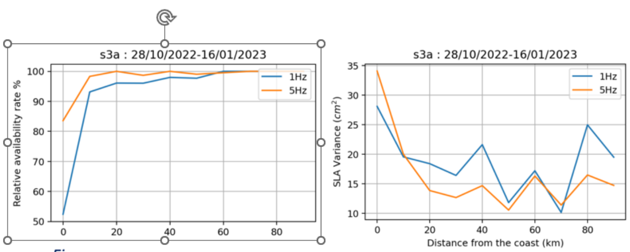
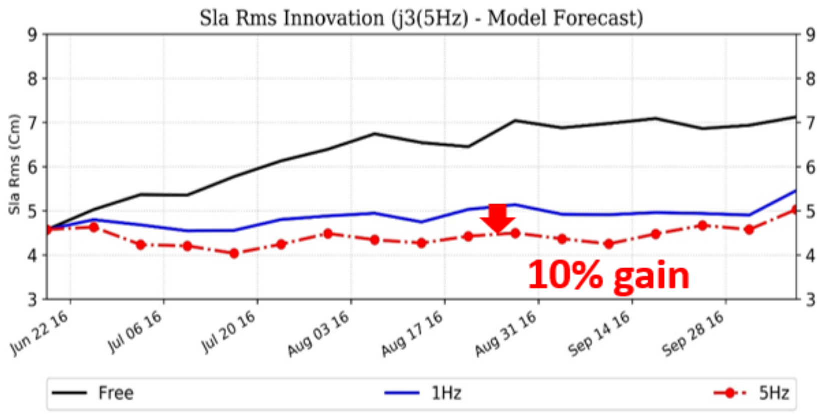


Figure:
Data availability rate and SLA variance near the northern Spanish coast (Unit: % of theoretical expected measurements; cm²)

Validation results also showed an improved consistency with tide gauge measurements and new insights into the altimeter spectral content with Sentinel-3A.

An example of assimilation in numerical models was presented, demonstrating improved model performances:



SLA innovation temporal evolution (difference between observation and model forecast) for model free run (black) and model assimilated with 1Hz (blue) or 5Hz (red) altimeter measurement

RMS of the difference between model output and HF radar observations also decreased when using the 5 Hz product, that also allowed to better resolve coastal eddies:

Conclusions & perspectives:

Altimeter L3 along-track products at 5 Hz (~1 km) posting rate are now available through the Copernicus Marine Service:

- NRT production for European Seas since November 2022.
- Production for Global Ocean in preparation (targeted in Nov. 2023).

➔ Dedicated to regional applications. Nevertheless, could also be of interest for coastal applications (> 5 km near coast)

➔ Do not hesitate to test them and give your feedback (content, quality, sampling, …): always valuable to improve the products!

R&D continue with CNES:

- DUACS-RD Samples V3 Global Ocean version, including improved processing, soon available.

- Make the link with other projects, e.g.:

  - New coastal-dedicated project in collaboration with CTOH and NOVELTIS to prepare specific coastal 20 Hz product: samples V1 soon available (c.f. F. Birol's presentation on the first day of the Workshop).

  - Cryo-TEMPO (ESA): improved SAR processing for coastal/regional applications (c.f. F. Nencioli's presentation given on the first day of the Workshop)

- SWOT: use Nadir ASAP; work on-going to define the processing for KARIN measurement.

- New mapping methodologies: multiscale/multivariate/multi-captor; IA.

➔ Prepare possible future evolution of the Copernicus Marine Service production.

The relationship of Mean Sea Level Anomalies and Extreme Water Levels along the European Coasts

Tomás Fernández-Montblanc, Jesús Gómez-Enri, Prof Paolo Ciavola

Authors discussed coastal hazards and coastal risk underlining the aftermath of recent coastal extreme events.

The understanding of each single component of the extreme total water level (ETWL) and its spatial and temporal patterns shall improve the preparedness and coastal adaptation measures to reduce the impact of coastal flooding specially in a climate change context.

Authors aimed to:

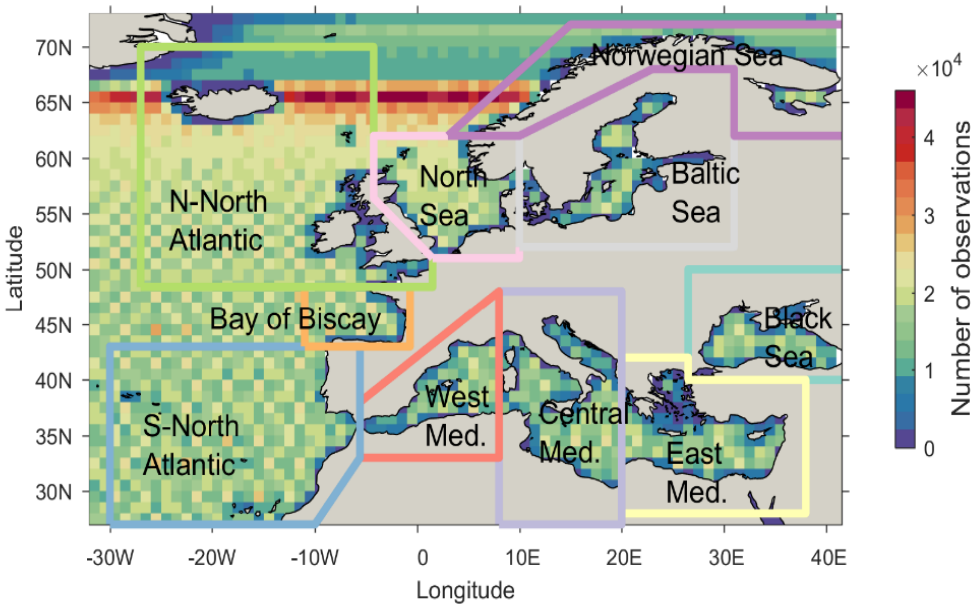
- Analyse the contribution of the seasonal cycle of the Monthly MSL (derived from multi-mission radar altimetry) to the extreme water levels.

- Analyse the high frequency signals (surges and tides) contribution to the ETWLs.

- Perform a comparison of ETWLs detected with satellite altimetry with a coastal extreme storm impact database at a pan-European scale.

Selected sea level datasets (SLA, CMEMS, L3, Mog2D model DAC, FES2014 Tide model) and storm impact database (coastal flood extreme event (CFEE) database) were discussed along with the adopted formulation. The study area is the following:

Summary of Session 3: Synergistic, Climate Studies & Operationalisation



Investigated are the seasonality of the annual cycle of the average monthly mean sea level (AMMSL) in the study area from 1993 to 2016 and the interannual variability. Attention was devoted to both:

- the spatial pattern of the relationship between the storm impact database and
- the AMMSL & Monthly MSL anomalies along the European coastline.

Conclusions

- Non-significant correlation between the AMMSL and the monthly frequency of the Coastal flood extreme event.
- The average monthly fraction of component variance of MMSL presents significant values of positive correlation in the Central Med (r = 0.59), North Sea (r = 0.60) and Baltic Sea (r = 0.75).
- The relationship of MSL anomalies indicates a significant and positive correlation with coastal flood extreme event in the Central Med., S-North Atlantic, North Sea and Baltic Sea.
- These regions show with largest inter-annual variability where MSL anomalies are mainly driven by atmospheric and meteorological forcing (North Sea), prevailing wind and the water exchange with other catchment (Baltic Sea, Adriatic Sea).
- The role of MMSL should be considered either for the comprehensive analysis of the past extreme event, or future projection of coastal flooding extreme event.

Summary of Session 3: Synergistic, Climate Studies & Operationalisation

Vertical land motion reconstruction reveals nonlinear effects on relative sea level

Julius Oelsmann, Marta Marcos, Marcello Passaro, Laura Sanchez, Denise Dettmering, Florian Seitz[1]

Challenges in estimating vertical land motion were highlighted:

- Pointwise VLM observations are limited in time and space.

- Several processes cause nonlinear VLM or regional non-GIA VLM (tectonic activity, mass loading changes, human induced VLM).

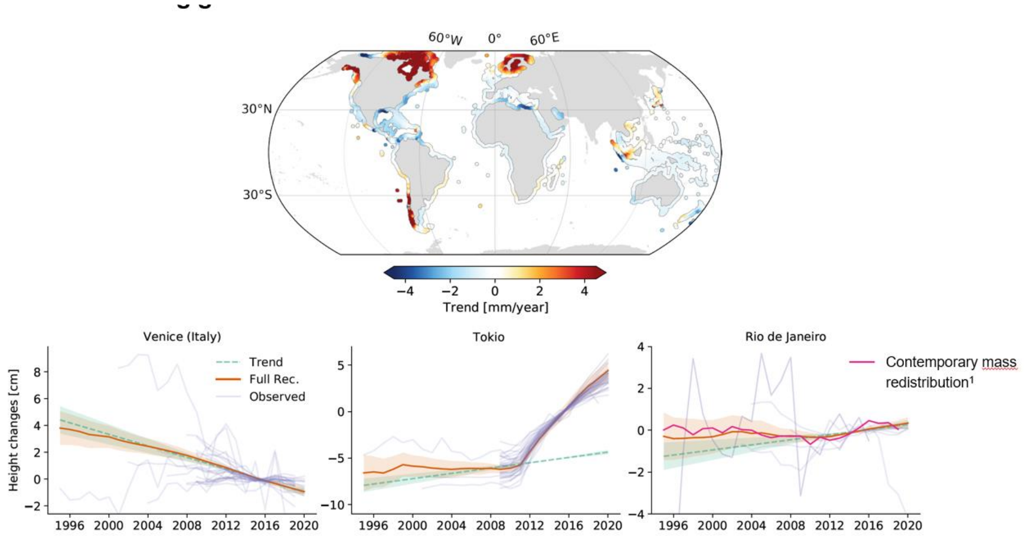
- Previous studies incorporated limited assumptions of VLM processes (i.e., GIA VLM) and limited observational constraints.

10.957 GNSS time series, 713 altimetry minus tide gauge time series for the period 1995 – 2020 were considered.

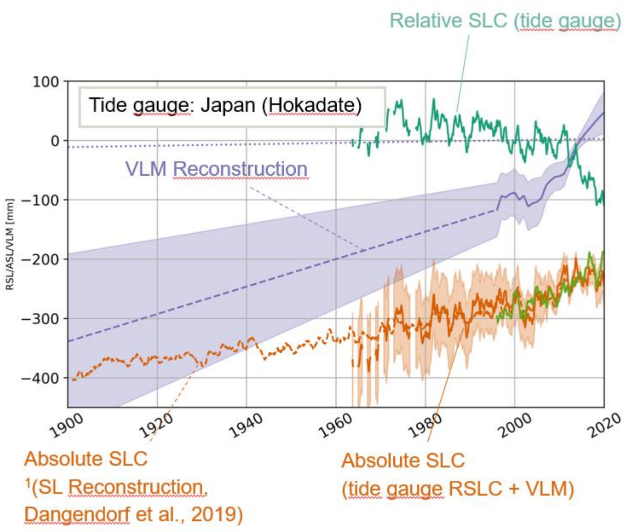
Authors aimed at understanding the effect of VLM on contemporary and future relative sea level change by reconstructing time- and space-resolving VLM.

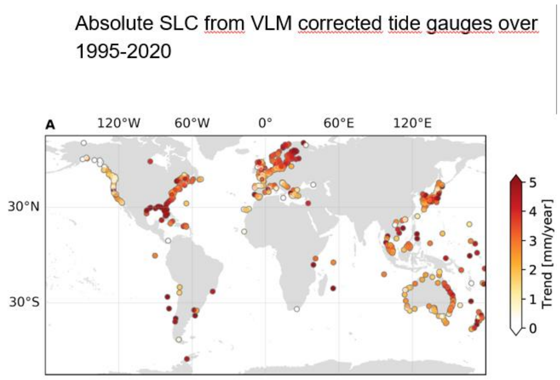
An example reconstructing time- and space-resolving vertical land motion was presented through a Bayesian Principal Component Analysis (Height changes = linear trend + present-day variability + noise) coupled with Trans-dimensional regression.

An example of Non-linear VLM along global coastlines is given below:



Then the contribution of VLM to contemporary regional sea level change was investigated by authors.





Conclusions:

- High regional VLM variability (e.g., due to tectonic activity, local effects, etc.) increases uncertainties in regional sea level projections, which should be accounted for in coastal planning.
- VLM reconstruction provides enhanced understanding of non-GIA and non-linear VLM effects on coastal sea level change.
- Low station density/temporal coverage contributes to VLM uncertainties.
- Further investigations are required to find optimal solutions to account for (non-linear) regional VLM in SL reconstructions.

Sea-Level Change Along the Norwegian Coast Between 2003 and 2018 From Satellite Altimetry, Tide Gauges, Hydrography, and Satellite Gravimetry

F. Mangini, A. Bonaduce, R. Raj, L. Chafik, L. Bertino

Mass component of sea level was discussed. Sea-level change due to changes in ocean mass are locally due to the exchange of water between land and ocean and to the redistribution of water within the ocean.

Objective of the talk was to infer the wind contribution to mass component of sea-level variations. Focus was on the Norwegian coast in the period from April 2002 to April 2019 (monthly data).

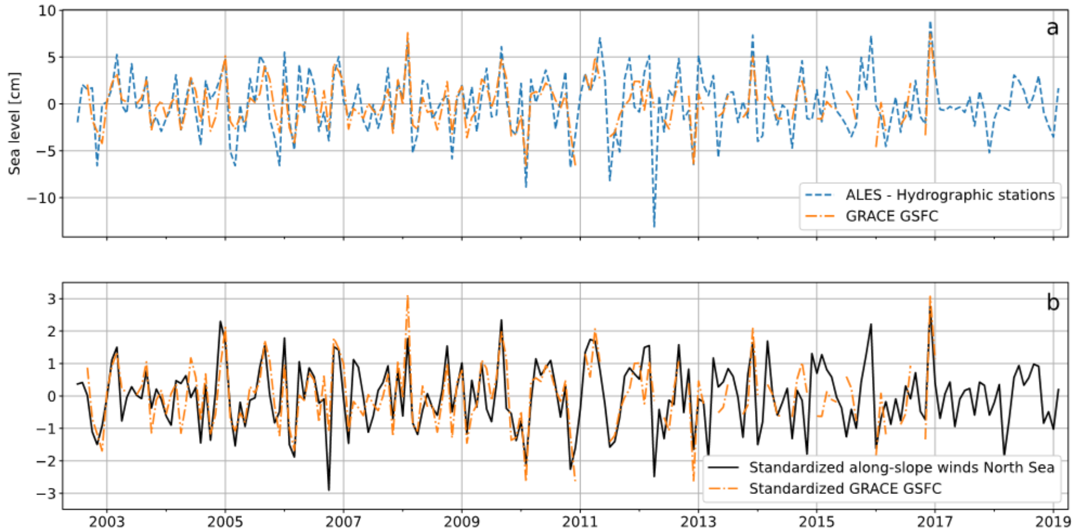
For robustness, two sets of estimates were considered: remote sensing & in situ observations.

In the first set of estimates, satellite altimetry data (1-Hz, ALES retracked data) and hydrographic data were considered. At each hydrographic station, this equation was evaluated: mass sea level = sea level - steric sea level.

Advantages of the approach: Sea level is centred at each hydrographic station and the approach is applicable to other regions. Limits: instruments capture small-scale spatial variability.

In the second set of estimates, GRACE and GRACE-FO data were considered (monthly values of gravity field around the Earth). These data return the mass component of the sea level but present issues in coastal area.

Local winds were evaluated at intra-annual timescales. Peculiarities of the scenario of interest were underlined. Results were then presented:



Conclusions:

- GRACE and satellite altimetry + hydrographic stations:
    - captures physical signal along coast of Norway.
        - consistent results.
    - resembles local and remote along-slope winds.
        - useful to quantify their contribution.

- Can we use GRACE to understand sea level variations in other regions of the World?

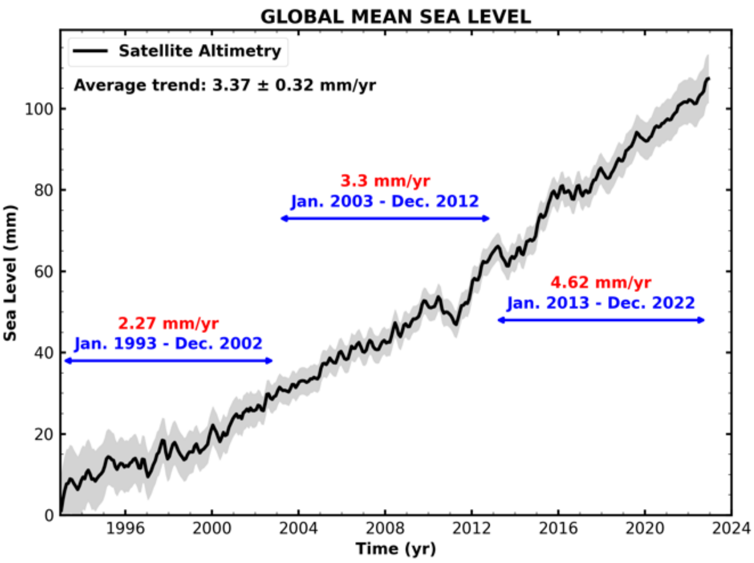
SESSION 3: Synergistic, Climate Studies & Operationalisation (cont'd)

Co-chairs: Guoqi Han and Laura Ruiz-Etcheverry

Sea level along the world's coastlines can be measured by a network of virtual altimetry stations

A. Cazenave et al.

An overview was given on Natural and climate-relates phenomena. Complex processes impacting sea level at the coast were reviewed. Sea level rise at the coast is related to global mean rise, regional trends and small-scale coastal processes. Global mean sea level trends are accelerating:



Global regional trends were shown, and the following effects were related to small-scale processes:

- Shelf currents
- Small-scale eddies
- Atmospheric forcing & wind stress
- Wind-waves
- Density changes in river estuaries & deltas
- Changing tides
- Climate modes

Can we construct long-term coastal sea level time series using past altimetry missions?

The ESA Climate Change Initiative Coastal Sea Level Project (Phase 2: 2023-2024) was presented. Objective: Reprocessing of the Jason-1/2/3 altimetry data in the world coastal zones to answer the question: Is coastal sea level rising at the same rate as in the open ocean?

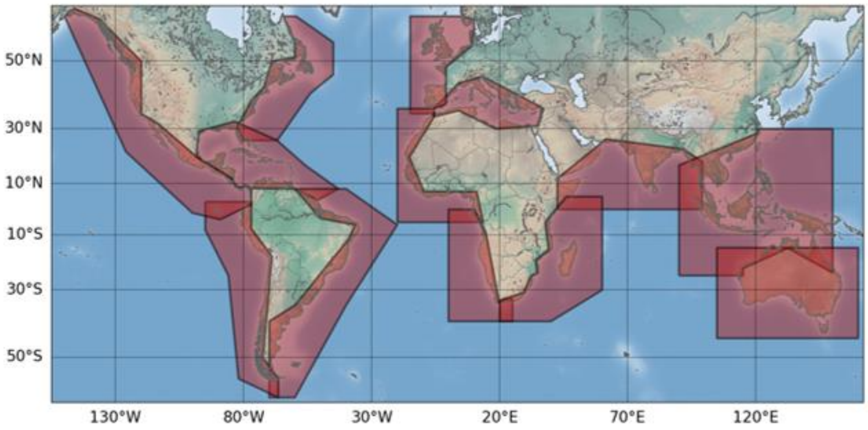
Summary of Session 3:
Synergistic, Climate Studies & Operationalisation

A Reprocessing of along-track data from the Jason altimetry missions in the world coastal zones was performed (retracking of radar waveforms + improvement of the geophysical corrections). The focus is on coastal trends.

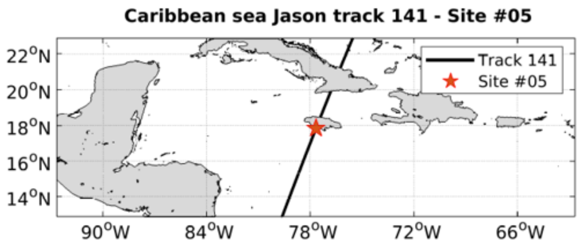
ALES (Adaptative Leading Edge Sub-waveform) retracking and associated sea state bias were used in the frame of the X-TRACK processing system (20 Hz estimates). The temporal coverage is of 18 years (Jan 2002 to Jan 2020).

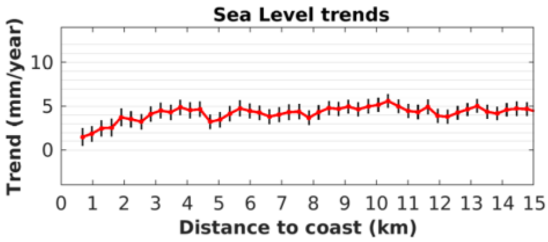
The methodology included both the selection of valid data between 0 and 20 km from the coast at numerous coastal sites as well as a strict editing (based on trend errors, % of missing data, trend continuity between successive 20 Hz points, …) to remove outliers.

Studied regions were the following:



Examples of results obtained with this new reprocessing were given, for instance:



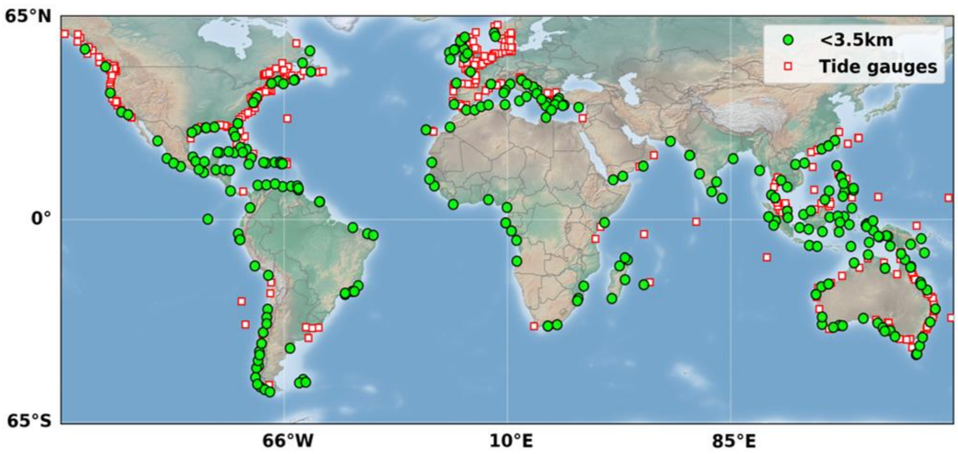


The distance (km) to the coast of the 1st valid point along the satellite track allowed the team to introduce the concept of 'virtual' coastal altimetry station:

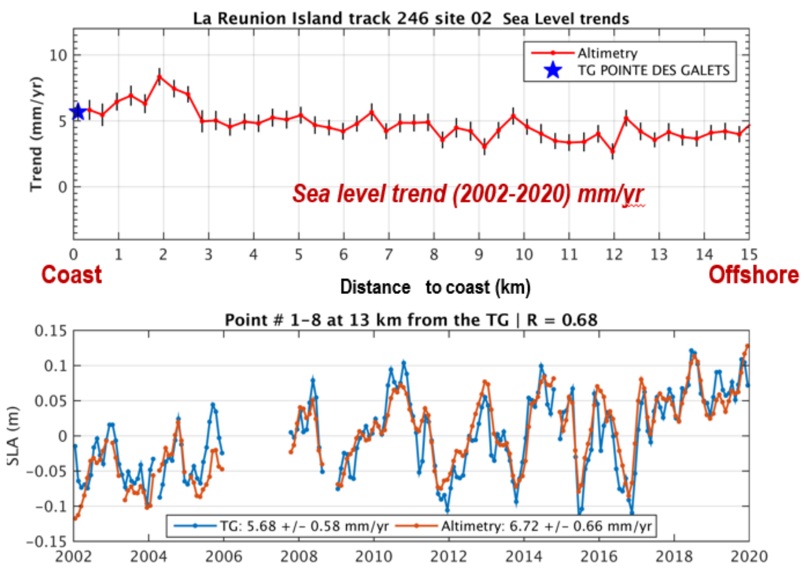
- 756 virtual stations at a distance of <6 km from the coast including 271 virtual stations at distance of <3.5 km from the coast.

The comparison between available tide gauges and virtual stations was also presented:

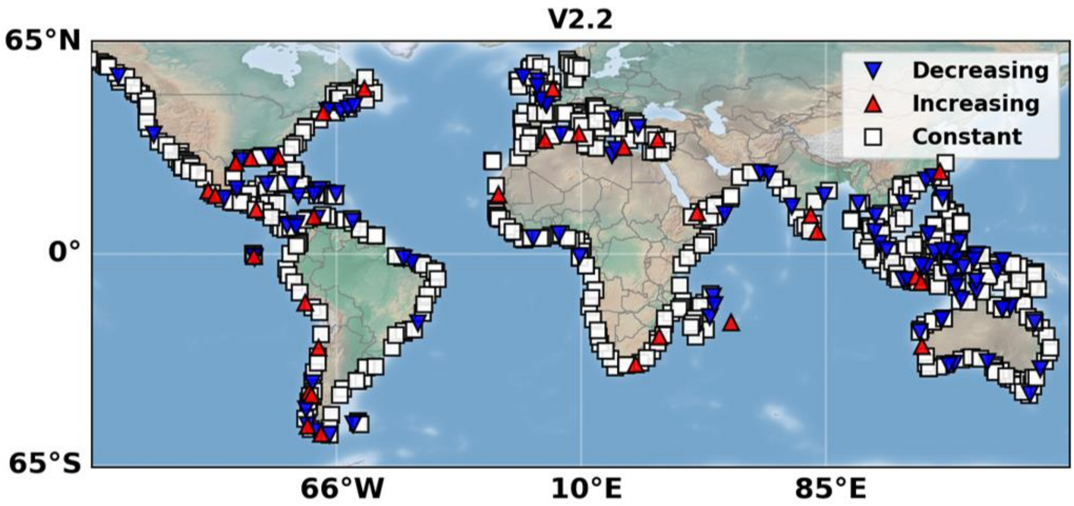
Summary of Session 3: Synergistic, Climate Studies & Operationalisation



Altimetry-tide gauge comparison at La Réunion Island



The coastal trend behaviour close to the coast was compared to offshore.



Sea level trends at the coast:

- 90%: Constant trend from offshore to the coast.
- 10%: Increasing or decreasing trend in the last 4-5 km to the coast compared to offshore.

Many examples were shown.

Data (V2.2, January 2023) can be accessed on the SEANOE website (https://doi.org/10.17882/74354). Data products and processing are described in:

- Benveniste J. and the Climate Change Initiative Coastal Sea level Team, Coastal sea level anomalies and associated trends 2 from Jason satellite altimetry over 2002-2018, *Nature Scientific Data*, 7, 357, https://doi.org/10.1038/s41597-020-00694-w, 2020.
- Cazenave, A., Gouzenes, Y., Birol, F. et al. Sea level along the world's coastlines can be measured by a network of virtual altimetry stations. Commun Earth Environ 3, 117 (2022). https://doi.org/10.1038/s43247-022-00448-z.

Objectives of Phase 2 of the project will be to:

- Extend the coastal sea level time series at virtual stations.
- Assess the impact of new altimeter geophysical corrections (FES2022 ocean tide model) and perform a new processing using the 'Adaptive' retracking.
- Better character coastal trend errors related to both data processing and the climate variability (influence of climate modes).
- Quantify small-scale coastal processes at sites where the sea level trend differs from offshore.
- Demonstrate the usefulness of this new coastal sea level product for past sea level reconstructions.

Dual-band altimetry from the Copernicus CRISTAL mission: Its capabilities for coastal altimetry

Paolo Cipollini, Franck Borde, Kristof Gantois, Günther March, Jérôme Bouffard, Cristina Martin-Puig, Salvatore Dinardo

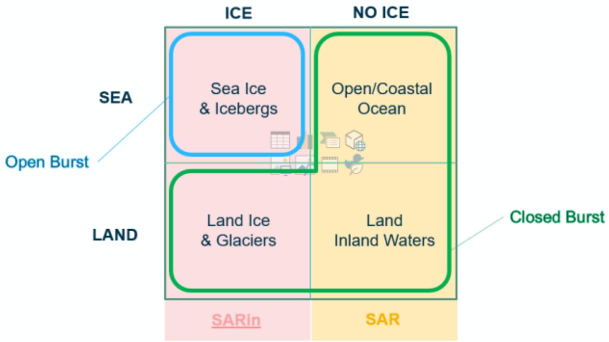
CRISTAL will be an operational altimetry mission for the Cryosphere which builds on the heritage of CryoSat-2 (coverage up to 88 degrees latitude). Primary objectives: sea ice, icebergs, land ice, glaciers. Improvements w.r.t. CryoSat-2 have been discussed:

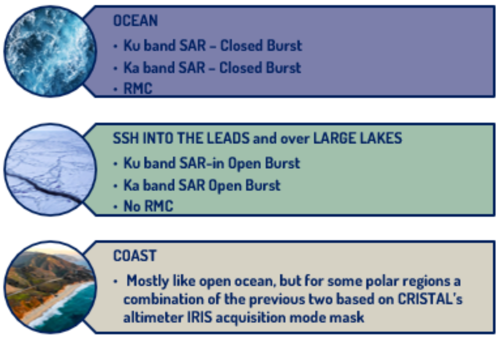
- Dual-frequency Ku/Ka SAR altimeter: Ku is interferometric, Ka added to measure snow layer.

- Increased bandwidth: 500 MHz in both Ku and Ka.

- Increased interferometric baseline (1.17 m → 1.33 m) and reduced Angle of Arrival (AoA) uncertainty (<23 arcsec).

- Open burst mode → improved azimuth (along-track) resolution (enabling proper Fully Focused SAR) & range precision over specific targets:





- Flexible open loop/closed loop tracking everywhere.

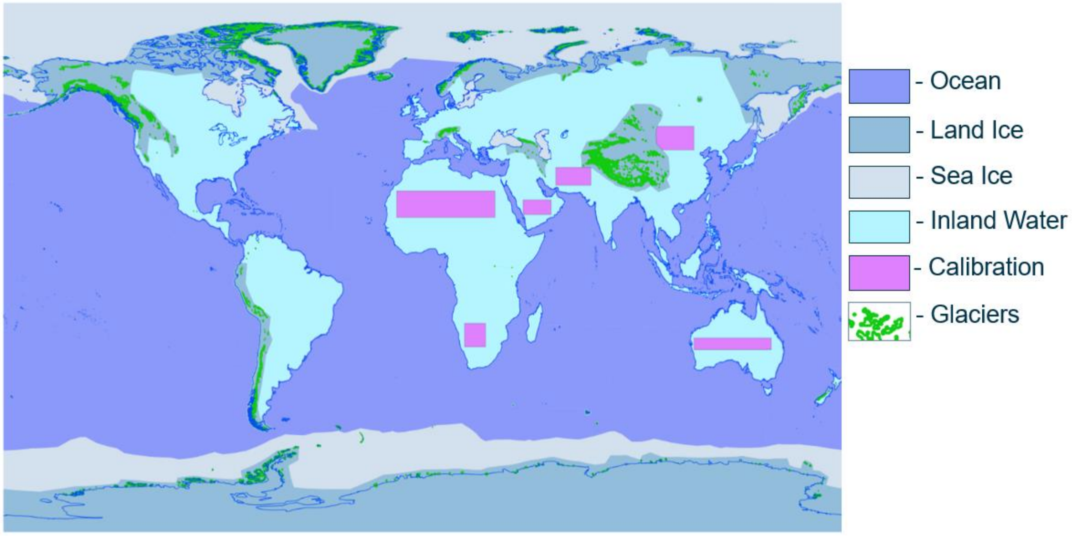
- Includes the AMR-CR (Advanced Microwave Radiometer for CRISTAL), provided by JPL and inherited from Sentinel-6MF AMR-C:

  - Allowing wet tropospheric correction of altimeter measurements.
  - High frequency channels (HRMR) with small footprints (<4 km) for coastal areas (also useful for ice classification/snow parameters).

- Full coverage of hydrological targets.

- EUMETSAT will generate operational global ocean products: ocean, coastal and SSH into the leads and over large lakes.

The mode mask has been presented:



The advantages of SARin (open burst) over sea ice and for polar coastal oceanography were also discussed. The interferometric mode for Coastal Altimetry provided with CryoSat-2 improved results in the coastal zone by using angle of arrival & the coherence waveforms. CryoSat-2 has a reduced BRF in SARin, with CRISTAL many more echoes will be collected.

Authors are seeking the engagement and feedback from the polar and oceanographic communities to exploit the simultaneous Ku/Ka measurements for novel science. For instance, how the dual-band capability is expected to enable new investigations in the marginal ice zone and in the coastal zone.

The ongoing development and design parameters were then discussed.

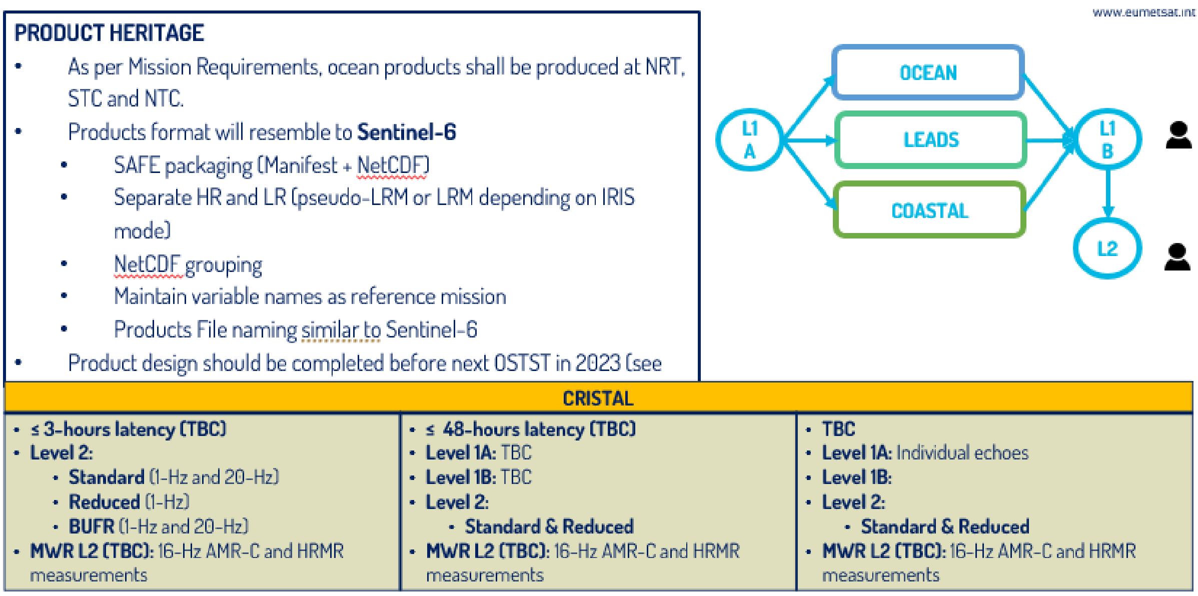
Another first of this mission is the equal exploitation of the Ku and Ka band for oceanography. Neither serves as a secondary band. Instead, the strengths of both are exploited to enrich the products, e.g., with an improved ionospheric correction, rain flagging, etc.

Orbit parameters are the followings:

Inclination	Altitude	Cycle
• 92 Degrees	• 683.62 Km	• 367 days
Sub-cycles	• 2, 5, 7, 12, 19, 31 and 112 days	

Thematic L1b ocean processors will be implemented.

Products will be the following:



CRISTAL-A is scheduled for launch in late 2027.

Baltic SEAL: New insights into the mean and variability of the sea level in the Satellite Altimetry era

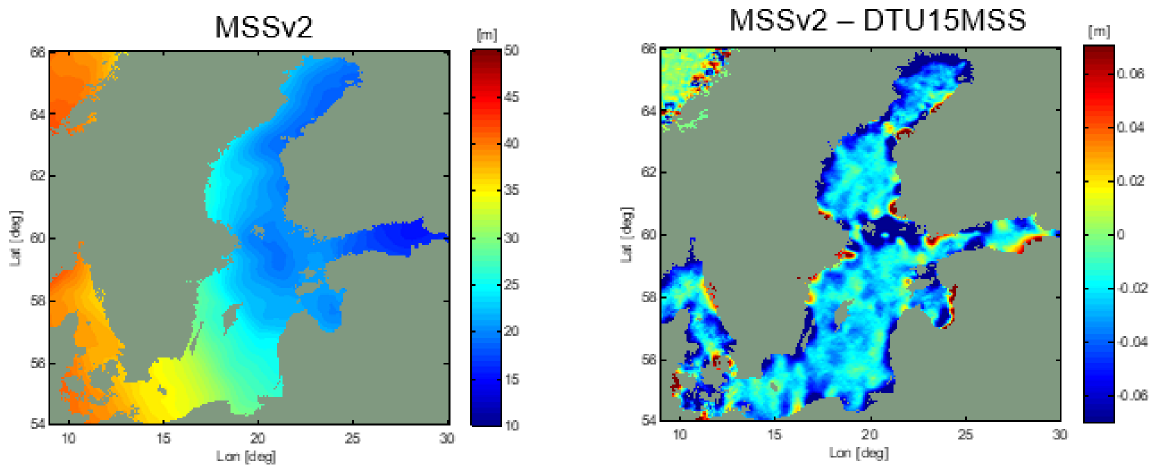
Marcello Passaro, Felix L. Müller, Julius Oelsmann, Adili Abulaitijiang, Ole B. Andersen, Emma Chalençon, Denise Dettmering, Michael Hart-Davis, Jacob L. Høyer, Laura Rautiainen, Ida M. Ringgaard, Jani Särkkä, Rory Scarrott, Christian Schwatke, Florian Seitz, Kristine Skovgaard Madsen, Laura Tuomi, Marco Restano, Jérôme Benveniste

The Baltic+ Sea Level (BALTIC SEAL) project team aimed at generating novel multi-mission sea level (MMSL) along-track and gridded products. This was needed because previous products did not include information from the sea-ice covered surface and from the coastal zone.

This was done by improving algorithms (unsupervised waveform classification, retracking), geophysical adjustments & corrections, radar techniques (Delay-Doppler Altimetry) and multi-mission cross-calibration & gridding. The Baltic Sea is the perfect laboratory for satellite altimetry (challenging coastlines, sea-ice coverage, small scale variability).

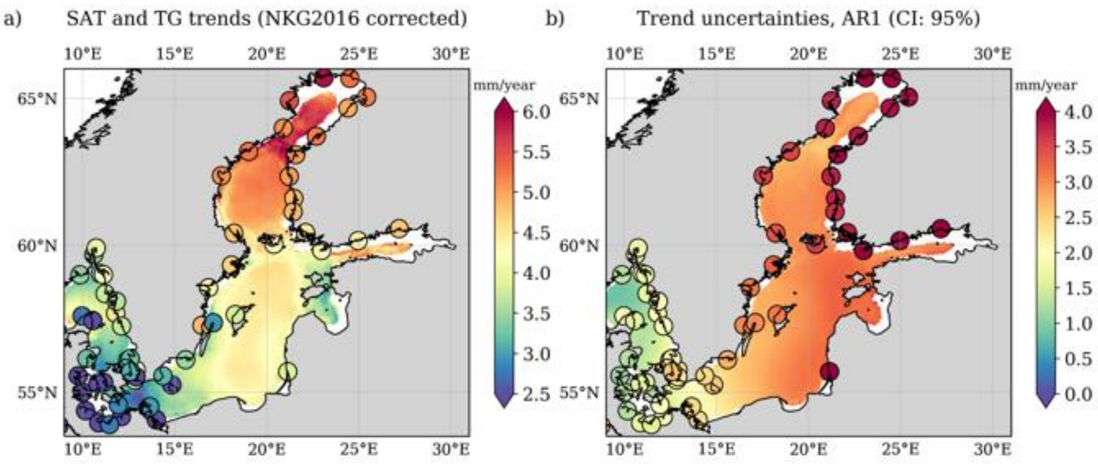
Validation steps were discussed. SAR and optical images were used for validating the classification of data and tide gauges were considered for the validation of sea level products.

A Mean Sea Surface for the Baltic Sea was developed. Major improvements were observed near the coast also thanks to the inclusion of dedicated quality flags.



Moreover, the Mean Dynamic Topography resulted more homogenous towards the coast.

Trends, including uncertainties, and annual cycles were also evaluated showing an increasing sea level across the whole basin:



Spatial gradients were investigated in relation to the North Atlantic Oscillation (NAO) and a correlation of 0.7 was reported in the bay of Bothnia.

- A 3-day experimental gridded product was also developed for the identification and analysis of storm surge events. This could be useful for providing the initial state of sea level before a surge event, to more accurately predict the surge through models.

Products and documentation are available via the Baltic SEAL website: http://balticseal.eu/. Python scripts are also available to help users exploring the Baltic+ SEAL products.

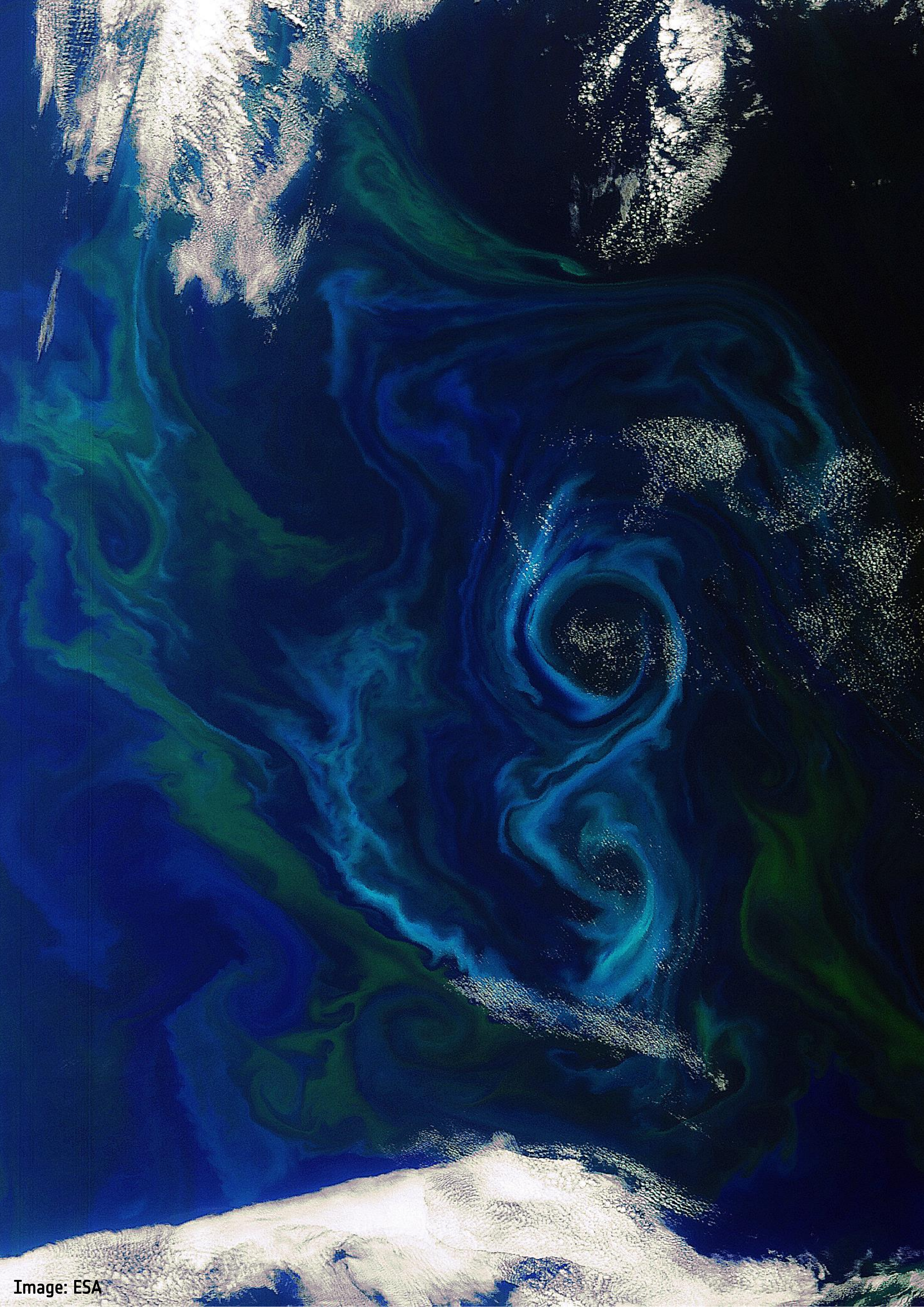


Image: ESA

Session 4: Wave & Wind

Co-chairs: Sonia Ponce de León and Lotfi Aouf

On the assimilation of directional wave spectra in coastal wave model: Upgrade of CMEMS-IBI

L. Aouf, L. Louis, A. Dalphinet, C. Toledano, M. Sotillo, R. Aznar

The study aimed at:

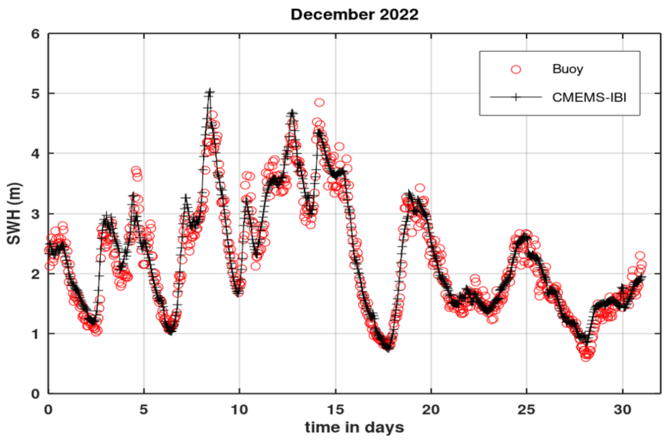
- Upgrading the CMEMS-IBI wave system with the assimilation of directional wave observations from CFOSAT.
- Improving IBI wave products: relevance of wave directionality for CMEMS Coastal users (wave submersion warning, wave overtopping and flooding…).
- Better describing wave coupled processes to IBI-PHY ocean circulation model.
- Preparing the IBI-wave reanalysis with 1/36° resolution and DA of satellite Wave observations (Envisat, Sentinel-1 and CFOSAT).

In the framework of the Copernicus Marine Service (CMEMS), the IBI-MFC (Iberia-Biscay-Ireland Monitoring and Forecasting Centre) regularly delivers complete ocean information for the IBI area covering the European Atlantic façade:

- Data for Blue (ocean physics and waves) & Green (biogeochemical) ocean components.
- High resolution models & coupling components.
- Observations ingested through Data Assimilation schemes (for analysis & reanalysis production).
- Product quality assessed (consistent science-based products).

The performance of CMEMS-IBI-WAVE system following a recent update with SWIM spectral DA are discussed:

Summary of Session 4:
Wave & Wind



Benefit of directional wave spectra from CFOSAT/SWIM in coastal areas was shown and discussed in the frame of data assimilation. Model runs have been described as follows:

- Wave model MFWAM in CMEMS-IBI configuration with grid size of 5 km and spectral resolution of 24 directions and 30 frequencies.

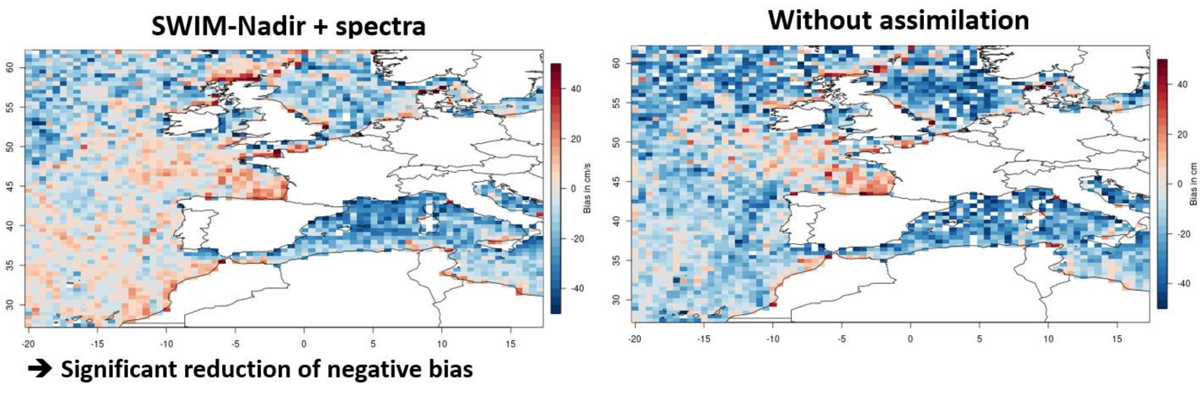
- Nested in CMEMS-global waves, which provides boundary conditions.

- Hourly wind forcing from IFS-ECMWF atmospheric system.

- Several models run with assimilation of SWIM wave Spectra (beam 10°) and SWH (1hz) from nadir and control run to evaluate the impact. Run with IBI surface currents forcing has also been performed. Period of study January-June 2022.

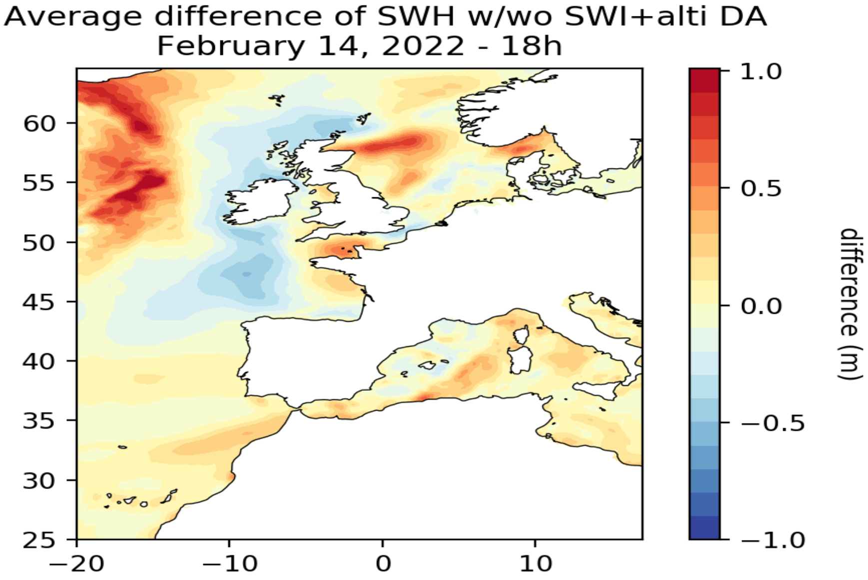
- Validation with independent altimeters data and buoys provided by CMEMS in situ TAC.

Results, including assimilation, showed a better slope particularly for high SWH and improved normalised RMSE by roughly ~10.4%. As an example, the impact of the SWIM wave spectra and SWH assimilation (January-February-March 2022) was discussed in this figure:



Summary of Session 4: Wave & Wind

The impact of hourly surface currents in IBI ocean area was showed as well as the spectral analysis during the Eunice storm (Mid-February 2022). The difference on SWH is clear:



A comparison on the assimilation of SWIM spectra only and the assimilation of both SWIM spectra and nadir altimetry SWH was also discussed. Thanks to SWIM directional wave spectra a significant reduction of SWH bias particularly in the range of long swell (10-16 sec) was presented.

Improved results were reported for many regions.

Conclusions:

- The assimilation of SWIM directional wave spectra has shown a significant improvement of integrated wave parameters in IBI ocean regions (operational in CMEMS since November 2022).

- The use of SWIM directional observations induces a better scaling of wave energy and dominant wave period, particularly on storm tracks in North-East Atlantic.

- The DA of SWIM spectra and nadir SWH enhances the impact in the forecast period and ensures reliable integrated parameters during the 2–3-day forecast.

- Using hourly surface currents forcing in CMEMS-IBI improves small scale wave-currents interactions and induces better integrated wave parameters (particularly in the channel and coastal Iberian Peninsula).

Satellite Altimetry-Based Calibration of the Nearshore Wave Model SWAN and Assessment of Spectral Wave Climate in the Black and Azov Seas

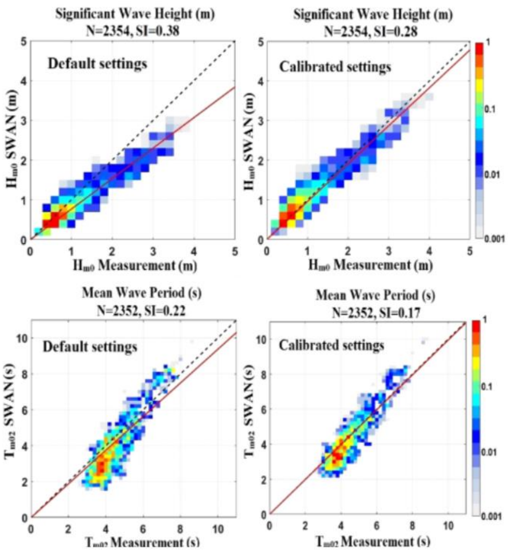
Khalid Amarouche; A Akpinar; S Myslenkov

The spectral wave climate assessment in the Black and Azov Seas (WSPEC_BAS) project was presented. Project is still ongoing.

Objectives of the project:

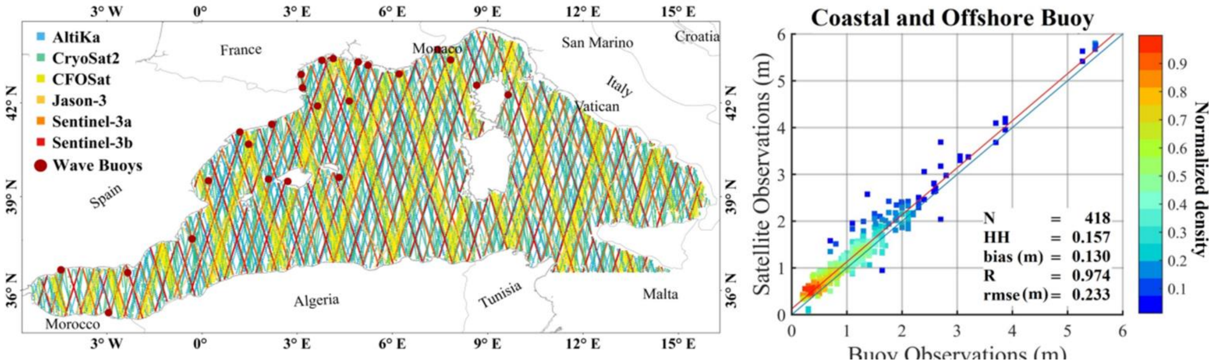
- Implementation of an operational spectral wave model.
- Long-term Wave Spectra database for the Black and Azov seas.
- Detailed assessment of the spectral wave climate considering Uni-model and Multi-modal wave systems.
- Wave storm assessments based on spectral information.

Waves in the sea are composition of different waves (having different frequencies and directions). The only way to understand them is to use the spectral analysis. To analyse the spectral wave climate, authors use models. Some models exist for global investigations, WWIII and SWAN were used in this study. Setting and calibrating parameters is very important. The accuracy of the model is highly dependent on this and on the specific investigated area. Error statistics in the Black Sea were reported:

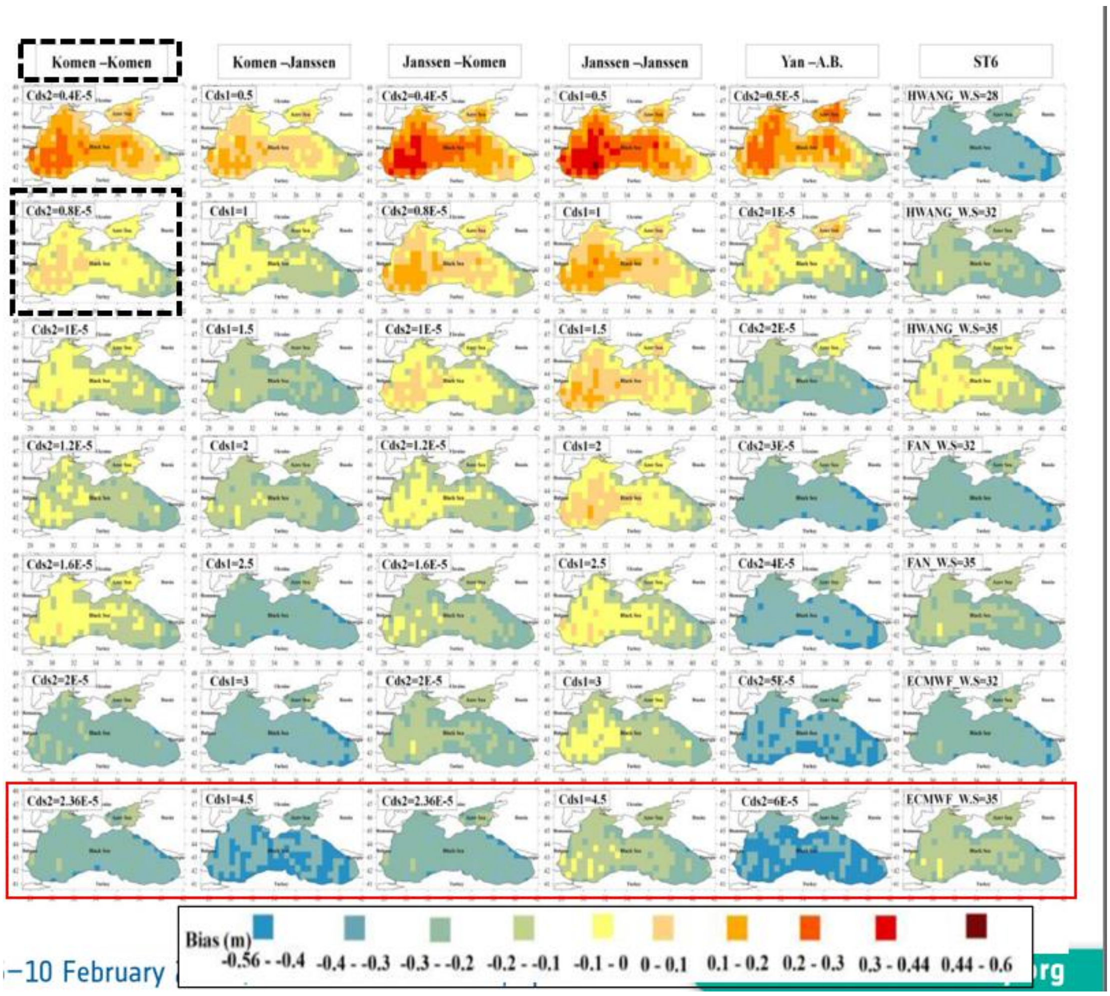


Before and after calibration the improvement is clear.

It is necessary to have a balanced model to have good results everywhere and not only at specific locations. Copernicus operational multi-mission altimeter database products were used to calibrate wave spectral models (GO_L3_SWH_NRT_SM) over the whole region. It was not possible to validate satellite observation as they have no matching points in the Black Sea with buoys, so the only way was to use the Mediterranean Sea (24 buoys, 418 matching points). Results were good:



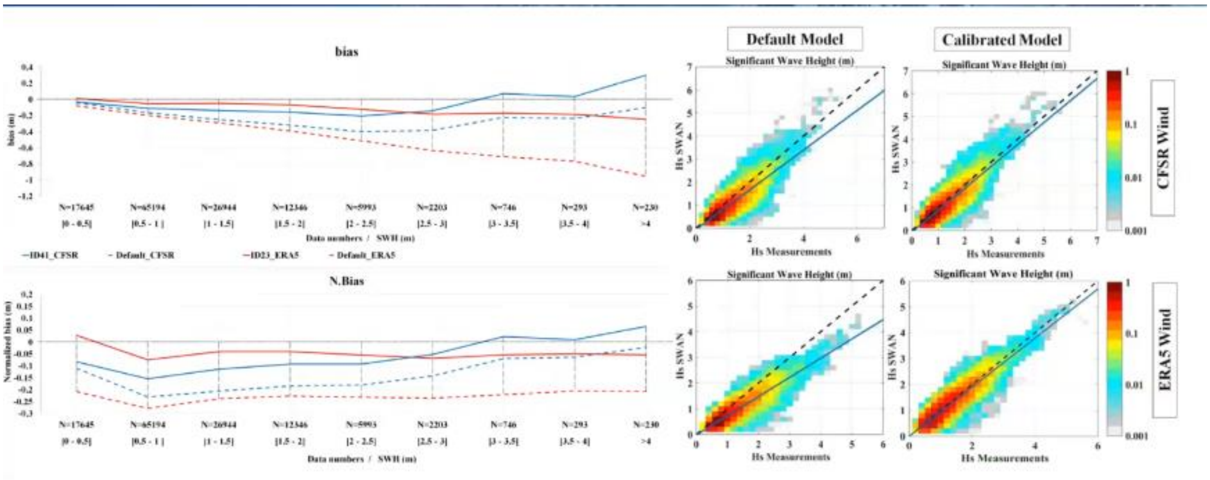
Moreover, results by calibrating the SWAN model parameters were presented discussing the bias:



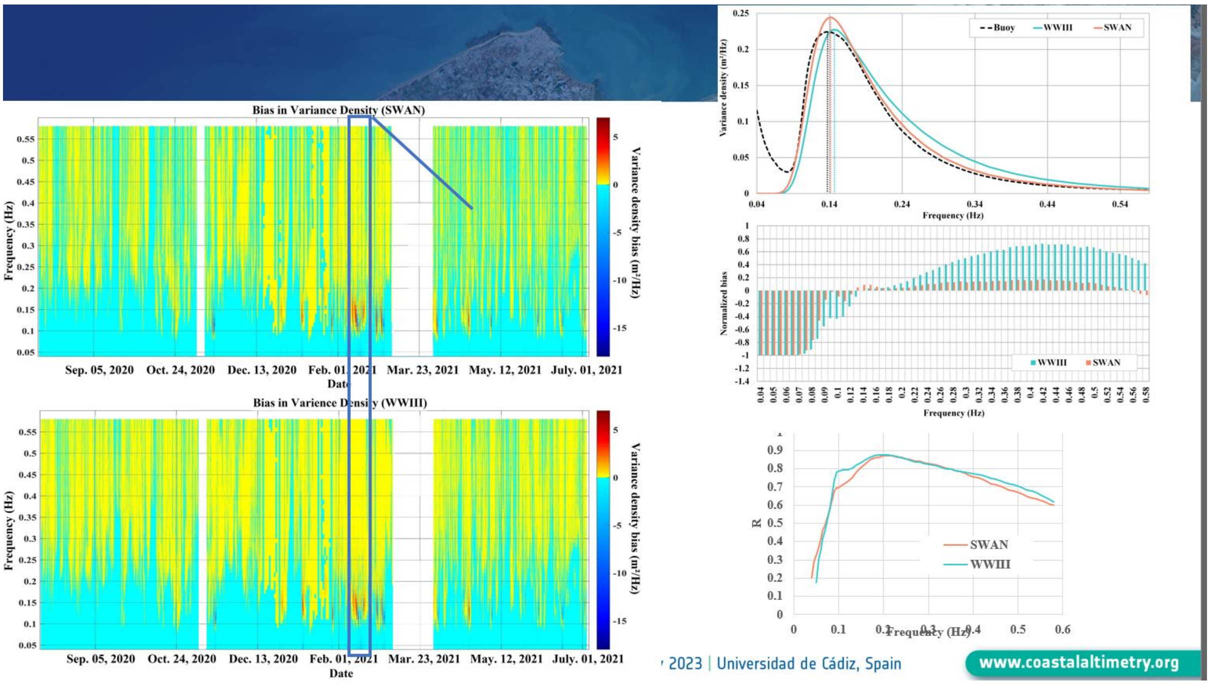
Default mode is the last line reporting the worst results. Controlling the dissipation (CdS coefficient) improved the results (other lines). Also, wind inputs were checked: ERA5 data give a better correlation than CFSR. This causes the bias in the wave model above.

The difference between calibrating with buoys or altimetry data was also showed. By using all altimetry data, only by setting a specific parameter we can obtain good results.

Here another comparison using different wind data:



To validate models using spectral data, buoys data are used. By evaluating both models, bias in time can be seen:



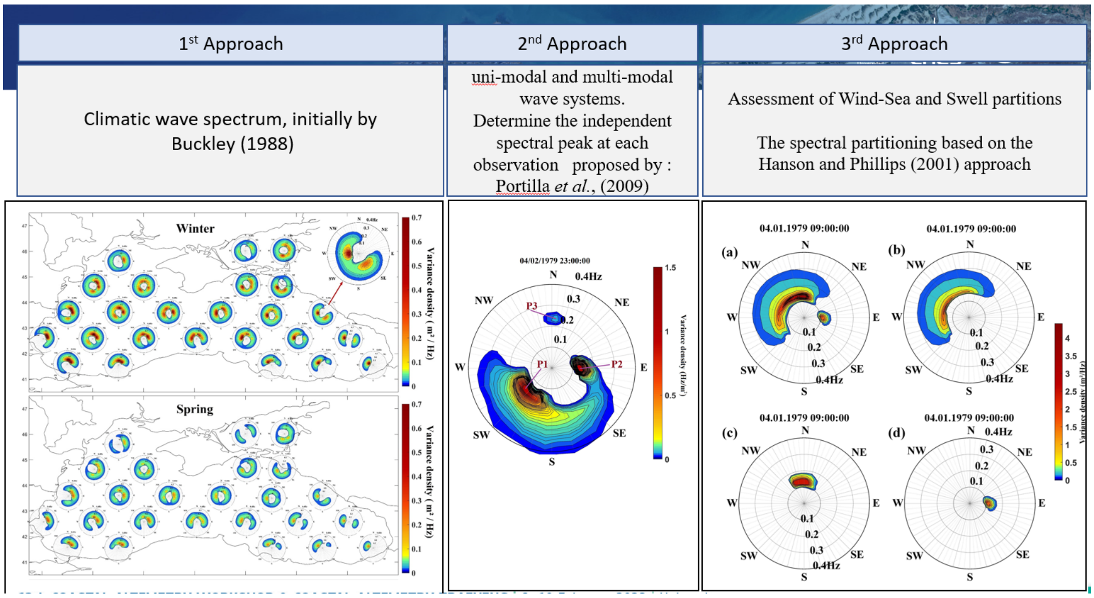
In most measurements, the bias was close to zero except for winter. This was due to a shift; the wind data was probably not reliable all the time. Measurements from buoys were differently overestimated by the two models. Other results were shown.

Authors uses the method by Björkqvist et al. 2016 to correct the overestimation.

Summary of Session 4: Wave & Wind

Comparing the 2D spectra, measurements showed some correspondence in defining the peak. Some mismatching was highlighted, due to the complexity of locations, therefore, the grid resolution has to be improved for models.

The final objective of the project is to provide a database analysed using 3 approaches:



Using the second approach they determined the number of wave spectra & independent spectral peaks and accuracies. The contribution of sweels was investigated in the various regions. Evaluation of trends and wind directions was presented.

Conclusions

- Calibration of the wave spectral model based on altimetry observations allowed a significant improvement of the wave model accuracy in estimating the significant wave height.

- Calibration of spectral wave model based on SWH obtained from altimetry data is not necessary to provide good accuracy in estimated wave spectra in the coastal location, and validation against spectral measurements is recommended.

- The new CFOSAT spectral observation may be a future alternative to calibrate the spectral models. However, those data are currently not validated for the Black Sea and cover a short period and a limited area.

- Noting that long-term trends and changes in wind-sea and swell may have opposed directions, the spectral wave partition should be separately considered for the climate change and trend analysis studies.
- Wave climate studies based on bulk wave parameters can provide wrong information related to the trend and change in the wave climate at some location.
- It is now crucial to promote the development of more complete wave data atlases that incorporate spectral wave climate descriptions.

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Assessment of renewable wave energy resources in the French façade coastal zone using high-resolution altimetry products

Sonia Ponce de León, Marco Restano, Jérôme Benveniste

Wave energy conversion technology is another sustainable energy source to supply energy offshore far from the grids and support the development of the Blue Economy.

Many studies were listed, their impact is twofold as they confirm:

- That the wave energy resource is significant and worth harnessing as a serious energy contributor.
- That specific areas in the world have better resources than others.

For the wave power assessment in the French façade coastal zone, the CCI Sea State dataset (https://climate.esa.int/en/projects/sea-state/) & the ESA Altimetry Virtual Lab (former GPOD/SARvatore) products including SAMOSA+ retracker estimates were used (https://earthconsole.eu/altimetry-virtual-lab/).

Objectives

- Investigate the feasibility of satellite altimetry-based assessments of wave renewable energy potential in the French façade.
- Use the homogenised multi-mission altimeter (Ku-band) data "Sea State Climate Change Initiative" of the European Space Agency to estimate a map of the wave power.
- Estimate the wave power along the coast, taking advantage of the high-resolution satellite altimetry data products from the Sentinel-3 mission, and using the improved retracking algorithm SAMOSA+ (Dinardo et al., 2018, Dinardo 2020).

The empirical model of Gommenginger et al. (2003) was employed to estimate the wave period, required for the estimation of the wave power density from the Ku-band radar altimeter significant wave height and the radar backscatter coefficient.

The method was validated with different wave buoys along the French and Iberian Peninsula. 10 missions are considered in the CCI Sea State database: Topex-Poseidon, Envisat, ERS-1, ERS-2, GFO, SARAL/AltiKa, Jason-1, Jason-2, Jason-3, CryoSat-2.

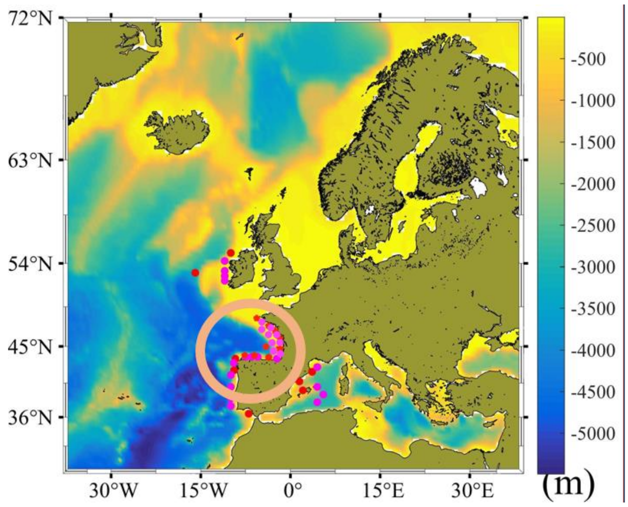
Ocean current data for the region under analysis was taken from MERCATOR Ocean (IBI):

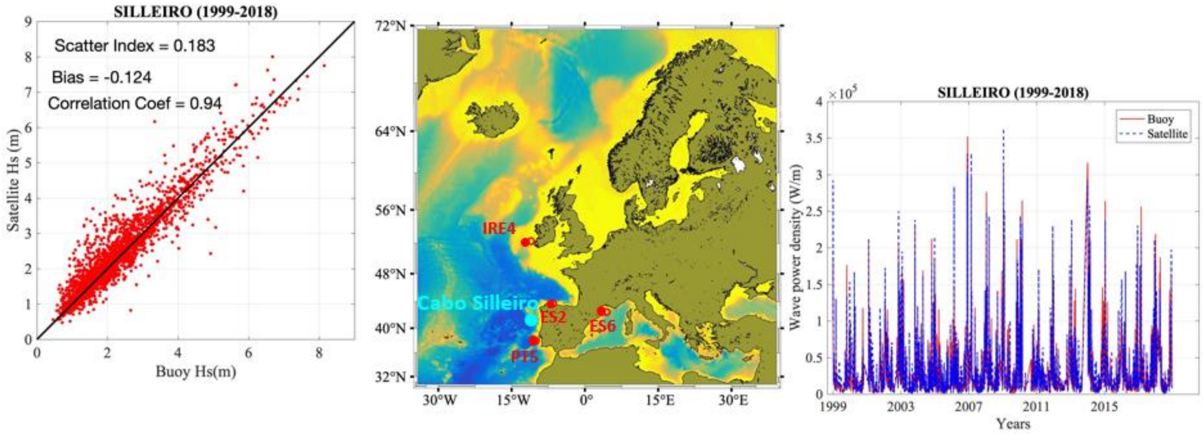
- IBI_ANALYSISFORECAST_PHY_005_001 product.
- spatial resolution: 0.028 degrees.
- since: 2019-05-04 to present.
- Temporal resolution: hourly mean, daily mean, monthly mean,15-minutes mean.

Summary of Session 4: Wave & Wind

The wave power formulation was discussed. The method implies the use altimetry data. SWH is directly from the altimeter and it also necessary to estimate the zero-crossing period T_z using altimetry data adopting the method developed by Gommenginger et al. (2003).

The validation of the selected method was made at wave buoy's locations (red circles) & at locations used for the assessment of wave power from altimeters included in the ESA CCI Sea State datasets (magenta circles) (1991 - 2018).

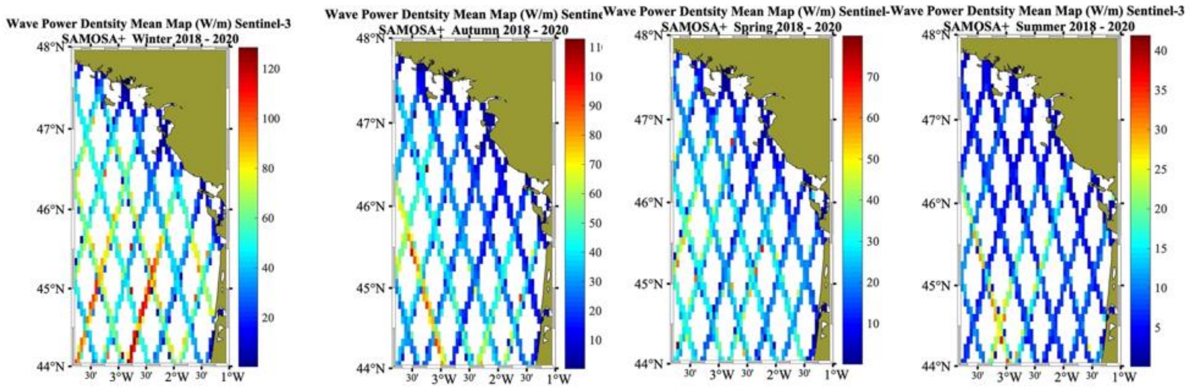




Several results were presented also summarising the yearly mean wave power (W/m) at various locations and comparing to wave power estimated only by using satellite altimetry data.

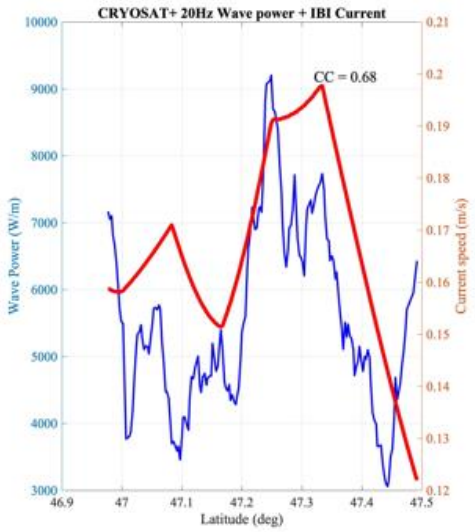
Then the Sentinel-3 SAMOSA+ dataset was introduced along with filtering approaches to eliminate outliers in the coastal zone. Seasonal wave power density mean maps were presented:

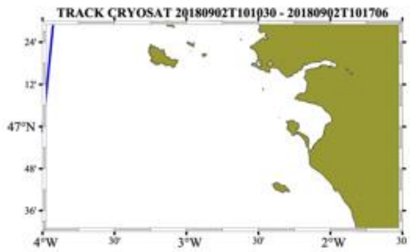
Summary of Session 4:
Wave & Wind



An example was shown also with CryoSat-2 products.

The presentation ended discussing the along-track evolution of wave power in relation to currents:





Conclusions:

- The different characteristics of the chosen locations show some correspondence between variability and mean wave power which is an important information in putting together a marine renewable energy strategy for any jurisdiction.

- These results obtained using ESA Sea State CCI data do not provide information very near the coast where the wave energy recuperation machines could be installed.

- The local energy available depends on bathymetry and wave-current interaction. Data closer to the coast are required, for this reason Sentinel-3A/B altimeter data processed with the coastal SAMOSA+ retracker by the ESA Altimetry Virtual Lab hosted in the EarthConsole® will be adopted.

- The method will be extended to other coastal locations worldwide. The investigation is still under development to compare Sentinel-3 high-resolution altimetry products obtained with different retracking strategies (official SAMOSA2 & AVL SAMOSA+).

Future work:

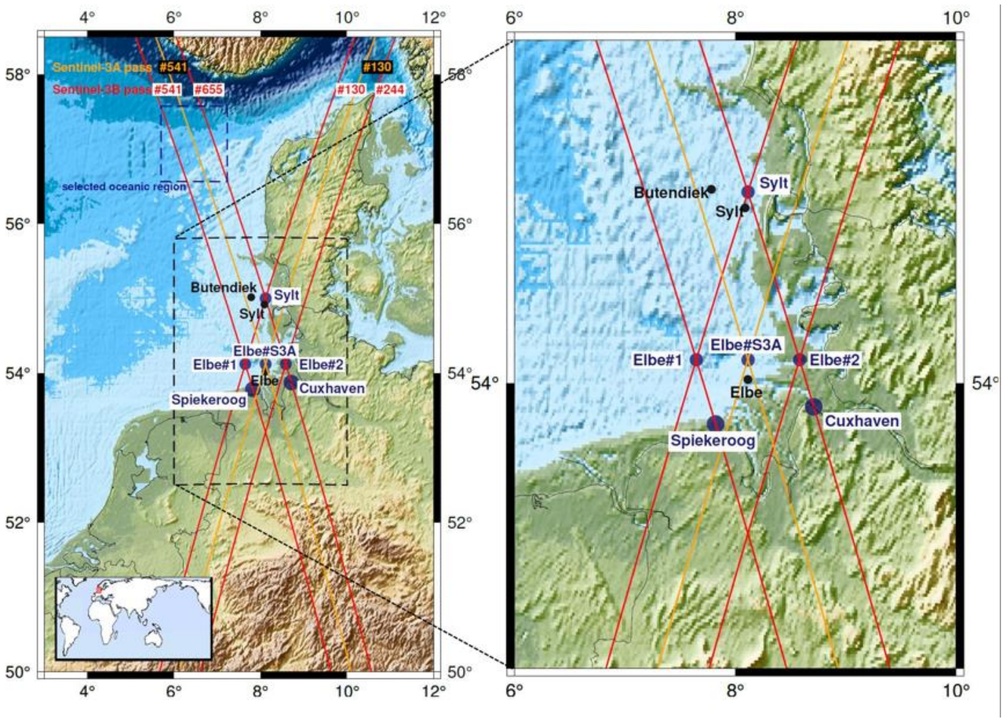
- Investigate the improvement in the wave power estimates near the coast using new retrackers.
- Perform wave power assessments in other regions with this method.
- Investigate the effect 1) of the distance between the altimeter track and buoy and 2) of the length of the buoy record on the regression coefficients value (the altimeter data extraction is slow, so shorter extraction intervals are preferable).
- Investigate the effect of the interpolation method on the regression coefficients in the wave power estimates.

Improving estimates of significant wave height in coastal zones from Sentinel-3 SAR altimetry using a data driven method (RiwiSAR-SWH)

Junyang Gou, Mohammad J. Tourian, Omid Elmi

The estimation procedure of SWH in altimetry was discussed detailing the characteristics of Unfocused SAR processing. A data inversion approach was discussed to estimate SWH using simple features from SAR waveforms.

An oceanic region was considered including 4 virtual stations nearshore and 2 virtual stations at the coastlines. SAMOSA+ estimates provided good performance.

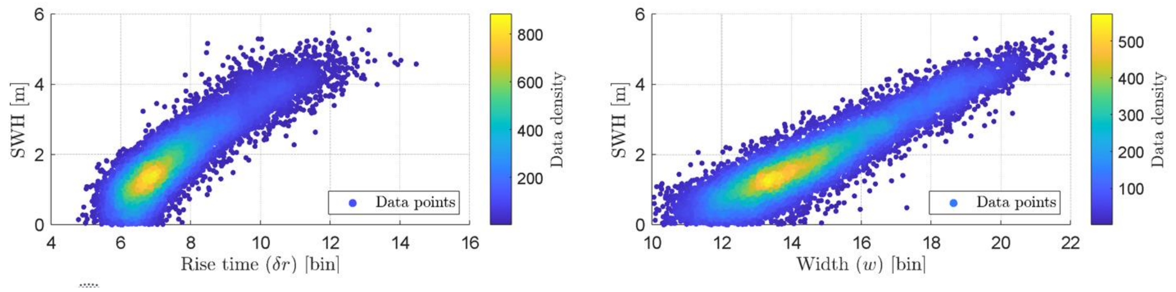


Summary of Session 4:
Wave & Wind

The idea behind the adopted data driven approach (RiwiSAR-SWH) is to extract two essential features from the altimetry waveforms based on the oceanic region:

- The rise time based on the 4-beta model.
- The width from the OCOG retrackers.

These have opposite linear behaviours.

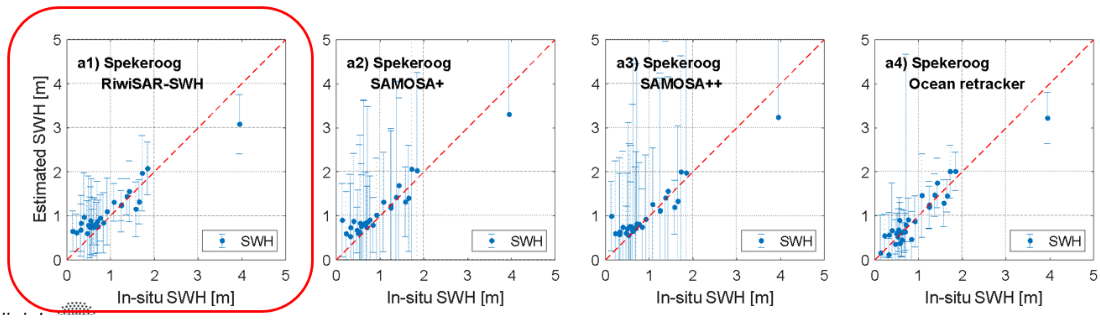


The SAMOSA+ SWH was used as a reference and the formulation explained underlining how the rise time is useful in the coastal zone, where the contamination impacts the trailing edge, and the width cannot be correctly estimated.

Validation was performed in both median and individual sense. Results were compared to SAMOSA+ & SAMOSA++. For Spiekeroog:

- **Relatively homogenous environment**
- Comparable median estimates
- Outperform other candidates by:
  - Individual measurements
  - Number of valid estimates

Method	RMSE_m	RMSE_i	Valid ratio
RiwiSAR-SWH	0.31	0.77	96%
SAMOSA+	0.28	1.92	85%
SAMOSA++	0.28	2.45	84%
Ocean	0.24	0.95	82%



Moreover, the new approach offers better performances (40% improvement) close to coastlines:

- RiwiSAR-SWH: correct estimates at 1 km offshore.
- Others (SAM+, SAM++, SAM2/Official Products): correct estimates at 1.8 km offshore.

For the area of Cuxhaven, RiwiSAR-SWH performed very well providing closest measurements at 1.1 km offshore, where other retrackers failed.

Conclusions:

- Data-drive model: RiwiSAR-SWH
    - Provide reliable SWH estimates without considering the complicated physical model.
- Better performance in the coastal zones
    - Better RMSE (asses both precision and accuracy).
    - Robust against non-standard waveforms.
    - Provide reliable SWH estimates staring from around 1 km offshore (more than 40% improvement)
- Applicable globally for all types of SAR waveforms
    - With necessary readjustments of the model.
    - Potential application for inland water altimetry.

- For more information, please check the publication on *Advances in Space research*: https://doi.org/10.1016/j.asr.2021.12.019.

Synergy between in situ and high-resolution model data to validate high resolution significant wave height altimeter measurements in the coastal zone

Guillaume Dodet, Grégoire Mureau, Mickaël Accensi, Yves Quilfen

Authors reminded that:

- Sea states present strong spatial gradients over the inner shelf, which are poorly resolved by conventional altimetry.
- SAR altimetry, with finer resolution and higher SNR, offers a great opportunity to improve our knowledge on coastal sea state variability.
- In situ wave buoys represent the gold standard for assessing the quality of altimetry SWH measurements. A large majority of wave buoys are in the coastal zone.
- Recent studies (e.g., Nencioli and Quartly, 2019; Jiang et al. 2022) have demonstrated the high sensitivity of Sentinel-3A validation results to buoy coastal settings.

Summary of Session 4: Wave & Wind

Objective of the talk was to exploit high-resolution wave model and novel altimeter-buoy data pairing methods to investigate the performance of Sentinel-3A 20 Hz SWH data (PLRM, SAR, LR-RMC) in the coastal zone.

The adopted methodology was the following:

- Altimetry data were filtered using swh_ocean_qual = 0, distance to coast > 0km, SWH > 0.2m. Outlier filtering applied.

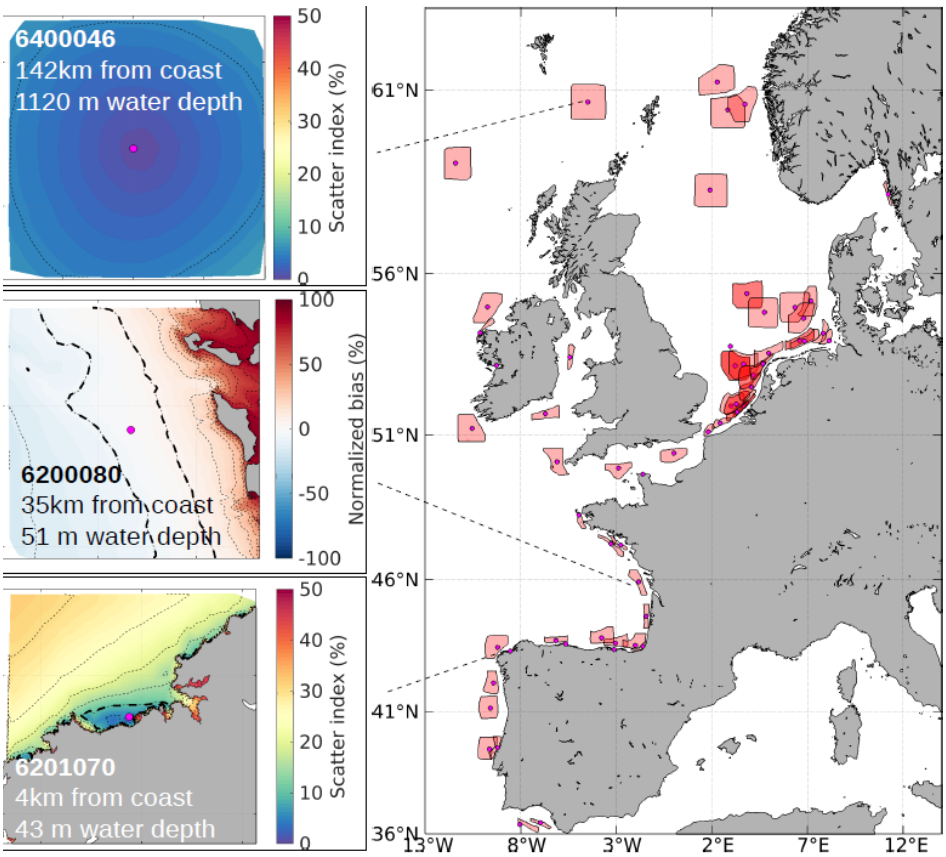
- In-situ CMEMS data were near real time hourly SWH observations (http://www.marineinsitu.eu/). Buoy selection: distance to nearest S3A track < 20km. 70 buoys identified with distance to the coast between 2 and 250 km.

- Wave model data were WW3 Resource CODE hindcast (1992-2021), details on the model were also provided.

Buoy spatial representativeness and data pairing methods (static @ 100/50/20 & 5 km, polygon and dynamic including a Dynamic adjustment) were discussed in detail before presenting results:

- SWH variability around coastal buoys:

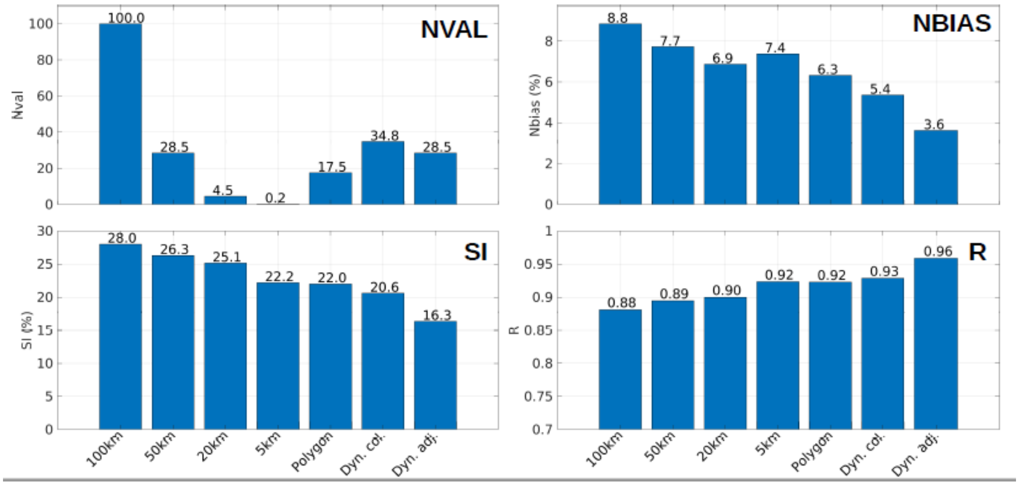
    - Buoy representativeness areas (BRA) presented strong heterogeneities in size and shape. Overall, BRA varied over 3 orders of magnitude (from 10 km^2 to ~10,000 km^2)



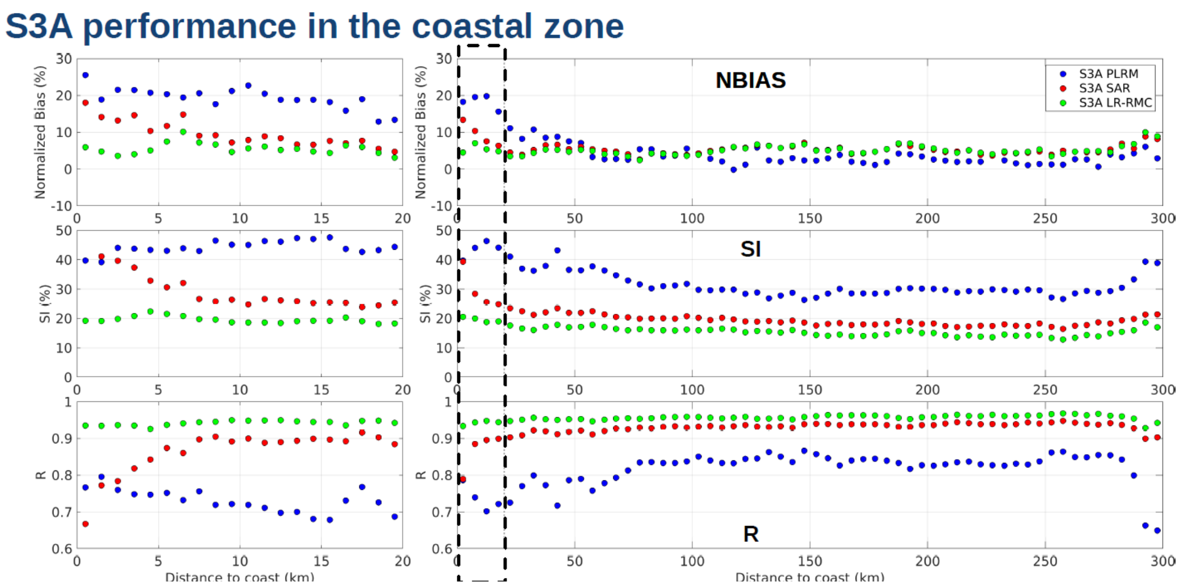
Summary of Session 4:
Wave & Wind

The main factors driving coastal sea state variability were water depth, coastline geometry, bathymetry gradients, tidal currents, and wind gradient.

The sensitivity to data pairing methods was then inferred in terms of Nval (number of samples), Nbias (normalised bias), SI (scatter index), R (correlation coefficient). For Results obtained with S3A SAR 20 Hz SWH:



Sentinel-3 altimetry performance in the coastal zone was also discussed for various processing modes:



Conclusions:

- Strong anisotropic SWH variability in the coastal zone, related to wave interactions with bathymetry, currents and winds, significantly impair comparisons between altimeter and in situ data.

- Dynamic data pairing methods enhanced with high-resolution model results improve the robustness of validation results in the coastal zone.

- Sentinel-3A SAR measurements show significant improvements with respect to PLRM measurements, in particular within the 20km coastal strip.

- Higher proportion of low sea state measurements in the coastal zone explain part of the radar altimeter performance reduction (not only the coastal backscatter heterogeneities).

- LR-RMC processing, currently implemented in Sea State CCI products, present very stable results from offshore up to 1km from the coast, with SI < 20% and R > 0.95.

Outlook and Recommendations

- Reference SWH in situ dataset is required for assessing coastal altimetry performance.

- Spatial representativeness error is a significant source of error in coastal altimetry performance analysis and should be systematically investigated as part of the uncertainty budget.

- Global coastal high-resolution (unstructured or multi-grid) wave modelling is a prerequisite to foster the evaluation and exploitation of coastal altimetry SWH data at global scale.

- Impact of sea state variability and wave groups on radar echoes at the scale of the footprint should be investigated to better constrain the Sea State Bias correction.

Ocean waves observation from space: Complementary approach from nadir, CFOSAT-SWIM and SAR wave mode systems

Annabelle Ollivier, Adrien Nigou, Victor Quet, Charles Peureux, Romain Husson, François Soulat, Marine De Carlo, Fabrice Ardhuin, Alice Dalphinet, Lotfi Aouf

Remote sensing observations of waves can provide different kind of information:

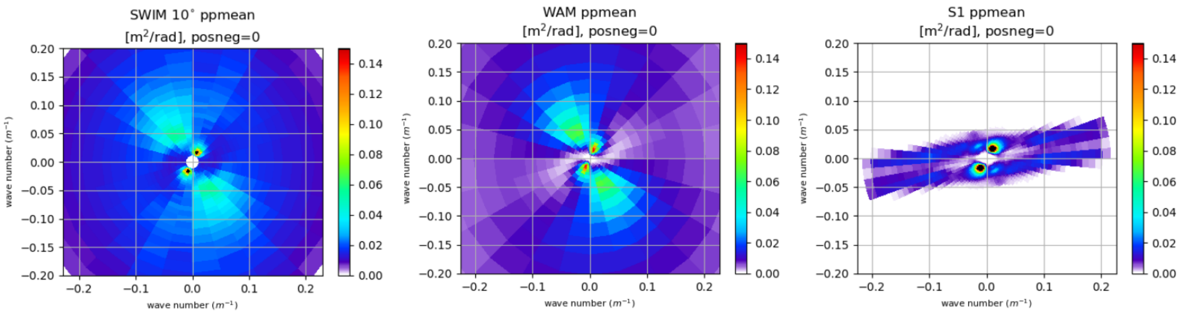
- Nadir altimetry Hs estimation or
- Wave spectra (Hs, Wavelength, direction, and partitions):
    - From Sentinel-1 wave mode
    - From SWIM / CFOSAT

Each technique has complementary advantages but also limitations that can be pushed forward to:

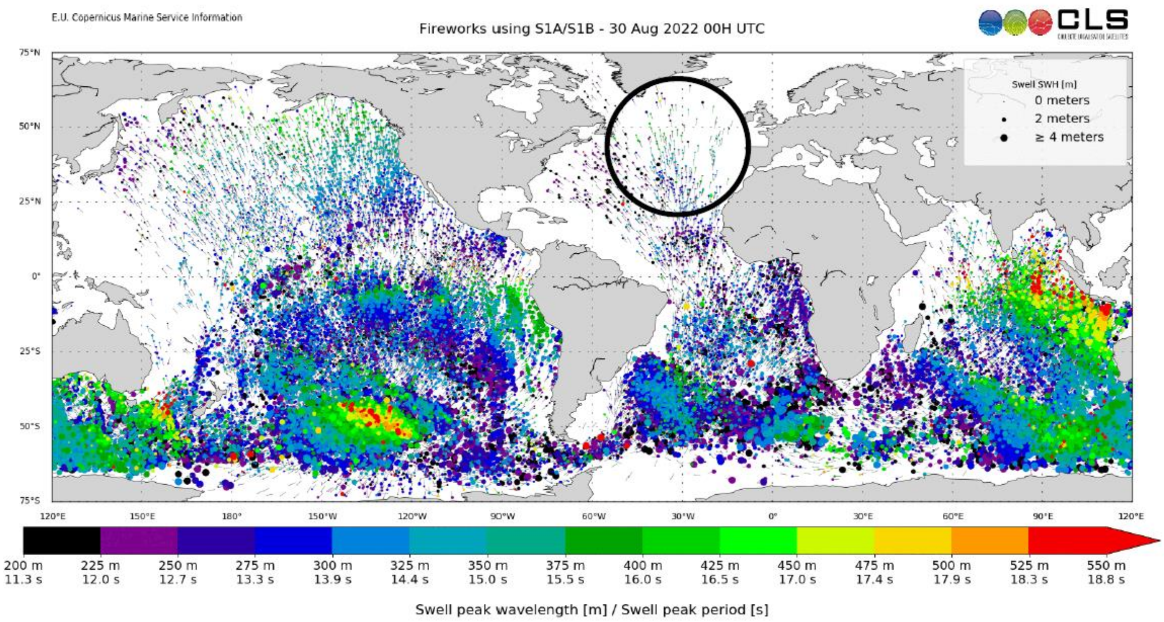
- Get closer to the coasts.
- Characterise more exhaustively the waves.

- Get uncertainty associated to the data.

Scales observed with SWIM, Sentinel-1 and nadir altimetry were compared in this study showing global coverage. Compared to SWIM, Sentinel-1 misses some areas mainly near coasts and North Atlantic. CFOSAT spectra were reviewed in the coastal zone. Unlike Sentinel-1 (affected by cut off) almost blind to wind seas, CFOSAT catches both wind seas and swells between 30 and 500 m wavelength. Mixed sea example for SWIM, WAM and Sentinel-1: (averaged over 10º/10º boxes) were showed symmetrising all spectra to consider the SWIM ambiguity in the direction (at 180º).



Excellent results were obtained by merging swell information from CFOSAT and Sentinel-1:



Fireworks products (L3 CMEMS since 2018) were built from S1 only. Since end 2021, they include CFOSAT and enabled to catch storms in the North Atlantic where S1 never does. Data are available here http://satwave-report.cls.fr/.

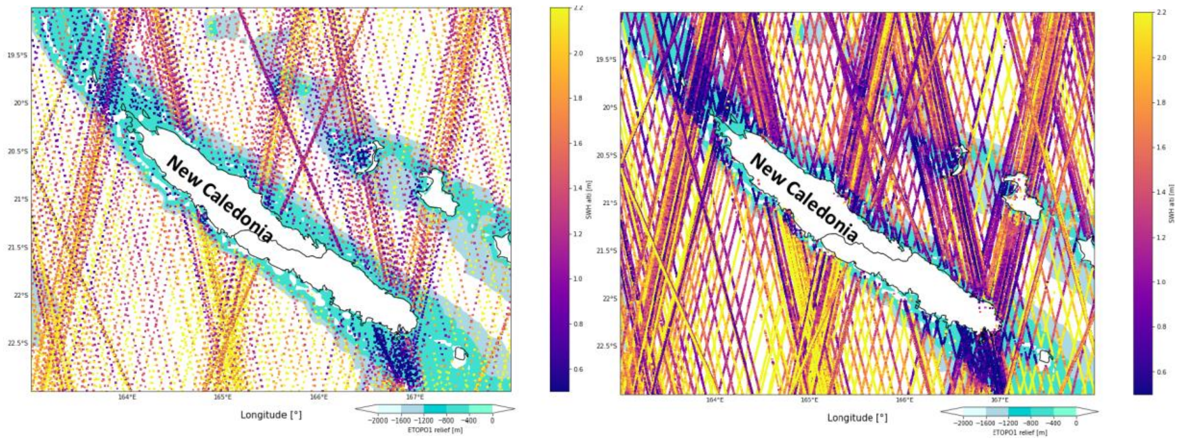
Nadir altimetry 5 Hz L3 WAVE demonstration products were presented. Missions provided as demo products over one year: 2021 (CFOSAT nadir, Jason-3, AltiKa, HY-2). Soon, Envisat 11 years (on ESA portal, FDR4ALT project).

Data available at:

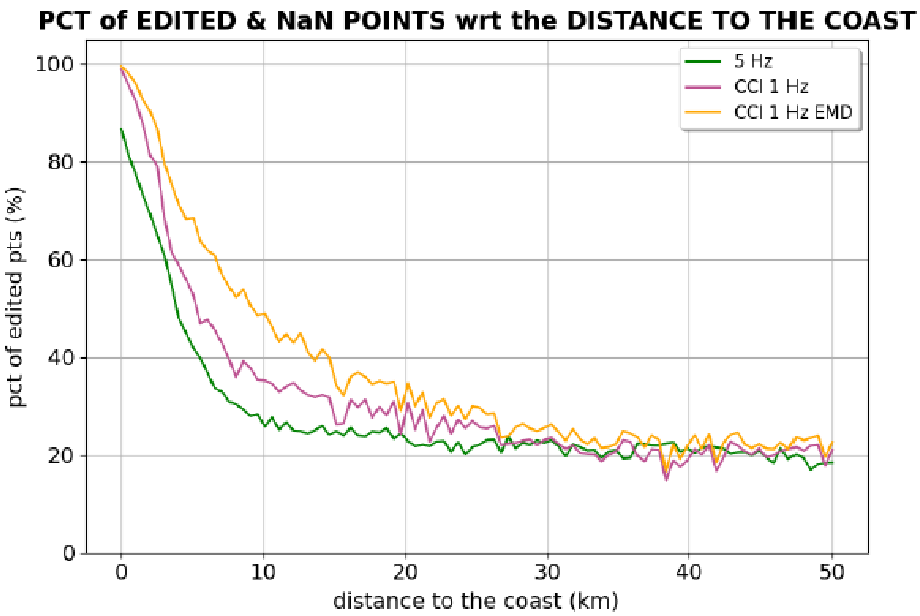
Summary of Session 4: Wave & Wind

https://www.aviso.altimetry.fr/en/data/products/windwave-products/

This product improves (right plot, below) the current operational 1 Hz CMEMS/ CCI along track SWH (left plot, below). Better coverage is obtained near coasts and inside lagoons.

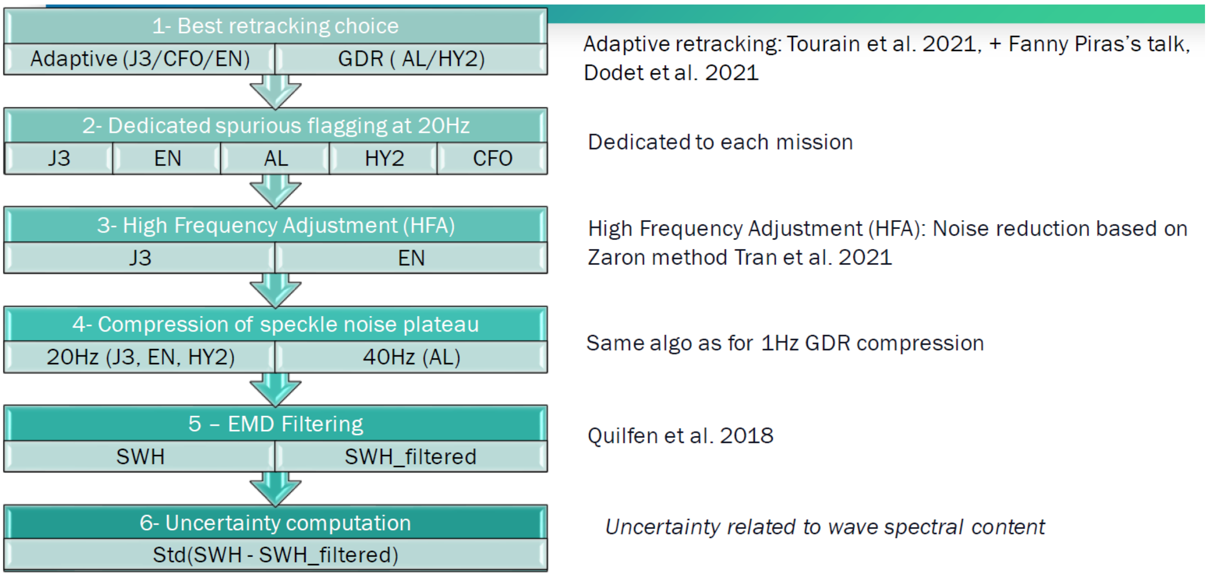


Globally, it offers 20% more valid data below 20 km:



Summary of Session 4: Wave & Wind

The 5-Hz processing recipe was detailed:



Additional comparisons to 1 Hz products were also reported. The estimation of uncertainties was also discussed and related to the local spectral distribution of waves. Indeed, wave groups contribute to small scale fluctuations in altimeter wave heights, explaining 50% of the standard deviation below 70 km.

Waves variability under 70 km was investigated with CFOSAT products. The uncertainty is higher for swell areas, where spectrum is directional.

Conclusions:

Nadir altimetry 5 Hz products:

- Get closer to coasts.
- Associated with an uncertainty field based on geophysical understanding of the variability below 70 km.

SWIM full spectrum products:

- Get more information than just the total Hs: direction, wavelength and partitions.

Combined SWIM/S1 fireworks (L3-CMEMS)

- Propagate swell information apart from the mission track until coasts.


Image: ESA

Acknowledgements

The authors would like to warmheartedly thank the Members of the Organising Committee, the Members of the Scientific Committee, the session co-chairs and the lecturers of the Coastal Altimetry Training.

The authors would like to also warmheartedly thank the people involved in the logistic organisation Riccardo who still didn't get his suitcase back from the airline, Ezgi and all the ESA Conference Bureau, as well as Federica, Giorgia and Ornella from the ESA Earth Observation Graphic Bureau for the workshop graphics.

Also, warm thanks are extended to our host Prof. Jesús Gómez-Enri, to the Universidad de Cádiz and to the students who helped run everything smoothly.

ESA has funded the event, with support from CNES and all the Organising Committee Member's institute for their effort invested in the shaping of the workshop.

Appendix: List of session co-chairs

Opening session: Jérôme Benveniste

Session 1: Florence Birol, David Cotton, Clara Lázaro and Francesco Nencioli.

Session 2: Luciana Fenoglio, Stefano Vignudelli, Matea Tomic and Anrijs Abele, Claire Maraldi and John Wilkin.

Session 3: Nicole Delpeche-Ellmann, Guoqi Han, Marie-Isabelle Pujol, Julius Oelsmann and Laura Ruiz-Etcheverry.

Session 4: Sonia Ponce de León and Lotfi Aouf.

The long list of Organising and Scientific Committee Members can be found at https://www.coastalaltimetry.org