Report of the

Ocean Surface Topography Science Team Meeting

Puerto Rico Convention Center, San Juan, Puerto Rico, USA

Tuesday, November 7, 2023 - Saturday, November 11, 2023

Edited by

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1 Executive Summary

The Ocean Surface Topography Science Team (OSTST) Meeting was held in San Juan, Puerto Rico, USA, from November 7, 2023, through November 11, 2023. Due to COVID-19 pandemic restrictions, this was the first in-person OSTST meeting held in the US since 2019. The primary objectives of the meeting were to address specific issues on the reference series of altimetry missions (TOPEX/Poseidon, Jason-1/2/3, Sentinel-6), including algorithm and model improvement, Cal/Val activities, merging with other altimetric satellites (CryoSat-2, SARAL/AltiKa, Sentinel-3, CFOSAT, SWOT), and preparation for other future missions.

In addition to the technical and science sessions, the meeting included the Sentinel-6 Validation Team (S6VT) meeting (chaired by the Project Scientists) and splinters on Coastal Altimetry and on CFOSAT. A new splinter session entitled "Synergies between Argo, GRACE, and Altimetry" was created this year to address the synergies between these observing systems, their uncertainties, and any technical issues that can impact the estimation of the sea level change and its components. Online forums, introduced for the 2020 virtual meeting, were available during and until the next OSTST meeting. All of the presentations from the plenary, splinter, and poster sessions are available on the AVISO website:
https://ostst.aviso.altimetry.fr/programs/2023-ostst-complete-program.html.

Sentinel-6 Michael Freilich (Sentinel-6 MF), launched on 21 November 2020 from Vandenberg Air Force Base (now Space Force Base, VSFB), has and successfully completed its commissioning and entered routine operations on schedule one year later. As mentioned, it succeeded Jason-3 as the Reference Mission on 7 April 2022 when Jason-3 vacated the reference orbit. The first full mission reprocessing of products was released on 28 July 2022, another full reprocessing was completed in July 2023.

Jason-3, which was launched on 17 January 2016, continues its extended mission and is fully operational with all redundant systems available. It completed a longer than initially planned 15-month tandem phase with Sentinel-6 MF (hereafter S6MF), which allowed for calibrations of both the primary and redundant instruments on S6MF. On 25 April 2022 it began operations in an orbit that optimally interleaves ground tracks with S6MF. A second tandem phase with Sentinel-6 MF has been requested for early 2025.

Sentinel-3A and -3B were launched in February 2016 and April 2018, respectively. Much like past missions in the reference orbit, a tandem phase with a separation of 30 seconds between the two satellites was performed to provide cross-calibration. Subsequently, Sentinel-3B was placed in a nominal orbit that is 140° out of phase with Sentinel-3A and both missions now provide sea level measurements along high inclination tracks as part of their routine operations. A full mission reprocessing of altimetry Level 2 products was completed in 2023.

CFOSAT was launched on October 29, 2018, with scatterometers to detect both wind and wave conditions. After both a validation workshop and the first science team meeting in July and September 2019, respectively, data has been publicly released as of February 2020. The next

CFOSAT Science Team meeting will be held in Nanjing, China (November 28-30, 2023). The second full reprocessing of SWIM data in version 6 is completed, all data from 25 April 2019 to the current date are now available. Version 7 of reprocessing will be available in 2024.

The Surface Water and Ocean Topography (SWOT) mission was launched from VSFB on December 16, 2022. The primary instrument on SWOT, KaRIn, is the first space-borne wide-swath altimetry instrument, capable of high-resolution measurements of the height of water in the ocean and freshwater bodies. After commissioning and initial calibration, beta products have been made available to the science team in August 2023. The first images from SWOT were released, and the first results are showing great promise for the instrument capabilities (see NASA and CNES news).

Finally, presentations on the status of other planned, proposed, and existing missions were given, including the Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) and Sentinel-3 Next Generation Topography. After discussion of these missions and other issues concerning altimetry, the OSTST adopted (among several others detailed in the full report) the following **recommendations**:

- **Sentinel-6 MF Extended Operations Phase Orbit:** In light of that fact that user needs remain very high for altimetry observations complementary to the reference mission, the OSTST recommends extending operations of Sentinel-6 MF, assuming it remains in good health, beyond the time when Sentinel-6B has become the reference mission. Specifically, the OSTST recommends:
    1) Moving Sentinel-6 MF to an exact repeat orbit with the same characteristics as the reference orbit, except for a phase difference of 163° along the orbit, either ahead or behind Sentinel-6B, resulting in an interleaved ground-track to the reference orbit. (Jason-3 currently flies 163° behind Sentinel-6 MF).

	Reference	Interleaved
Semi-major axis (km)	7714.4278	
Eccentricity	0.000095	
Nodal period (s)	6745.72	
Repeat cycle (days)	9.9151	
Longitude at Equator for pass 1	99.9242º	98.5069º

    2) The project adopt the same data availability requirements as expressed in the EURD (R-U- 00460/490/500/515/520/570/573/576) for the Extended Operations Phase of Sentinel-6 MF (See table below), with the understanding that Sentinel-6B operations will be prioritised over Sentinel-6 MF. These requirements are as follows:

	NRT	STC	NTC
ALT L1		95% within 36h (HR: 90%) *R-U-00490*	95% within 60d (HR: 90%) *R-U-00515*
ALT L2	90% within 3h (HR: 85%) *R-U-00460*	95% within 36h (HR: 90%) *R-U-00500*	95% within 60d (HR: 90%) *R-U-00520*
MWR L2	90% within 3h *R-U-00570*	95% within 36h *R-U-00573*	95% within 60d *R-U-00576*

- **Jason-3 Orbit Change:** The OSTST endorses the current plan to move Jason-3 to a Long Repeat Orbit immediately after the conclusion of a second tandem with Sentinel-6 MF. This 371-nodal-day long repeat orbit should be the same as the one occupied by Jason-2. The first two LRO cycles should be phased such that Jason-3 will interleave the two Jason-2 LRO cycles, each shifted by 2-km. This will result in a systematic 2-km global grid combining Jason-2 and Jason-3 LRO data. The OSTST also recommends two additional LRO cycles that revisit the Jason-2 LRO ground tracks to fill in gaps and reduce mean sea surface errors.
- **Climate Quality Accuracy in Future Missions:** The OSTST notes that to achieve accuracy in global and regional sea level change as detailed in GCOS requirements, it will be necessary to maintain and continue to improve accuracy of orbital determination systems, such as those achieved using a combination of SLR, DORIS and GNSS. The OSTST has demonstrated that three tracking systems (GNSS, DORIS and SLR) are necessary to achieve maximum accuracy on the determination of regional sea level trends, and it strongly recommends that such accuracy be maintained in the design of Sentinel-6C. The OSTST also noted that accuracy of the Climate Data Record requires continued maintenance or improvement of the terrestrial reference frame, which also relies on these tracking systems. Finally, requirements on other aspects of the altimetric measurement system must also be maintained or continue to improve.
- **Synergies with Argo and GRACE:** Argo plays a critical role in numerous cross-cutting climate-related science topics important to the altimetry, GRACE and broader science communities. In light of Deep Argo's ability to rapidly expand observations of the ocean below 2000 m, resolve variations of temperature and salinity over the full- ocean depth, and close regional and global sea level budgets, the OSTST recommends substantially increased support for the OneArgo Program. Added resources are needed to expand the array to include global implementation of Deep Argo and increased coverage by Core Argo in polar regions and marginal seas.
- **Altimetry Product Evolution:** The OSTST recommends that agencies study the performance of the three latency products, NRT, STC and NTC with an aim toward understanding if all three still meet user needs, or if their performance and latencies should be redefined or adjusted. This should be considered across all platforms.

- **Potential Gap between CryoSat-2 and CRISTAL:** The OSTST recommends studies to address which satellites, airborne operations, or other assets might help fulfill scientific needs for high-latitude ocean and ice elevation measurements during a potential gap between CryoSat-2 and CRISTAL. The OSTST also recommends minimizing the probability of a gap by extending CryoSat-2 operations through at least 2028 and avoiding delays in the launch of CRISTAL to the extent possible.
- **Integrity of the Altimetry Constellation and Instrument Function:** In light of ongoing efforts to launch a large number of communications satellites in orbits close to the 1336 km altimetry constellation, the OSTST recommends that agencies take steps to determine and establish sufficient margins that will safeguard altimetry missions in both reference and polar orbits from collision, debris and interference with their passive and active instruments.

2 Opening Plenary

The Ocean Surface Topography Science Team (OSTST) held its meeting in San Juan, Puerto Rico, USA, from November 7, 2023, through November 11, 2023. On behalf of the Project Scientists (Severine Fournier, NASA; Josh Willis, NASA; Pascal Bonnefond, CNES; Eric Leuliette, NOAA; Remko Scharroo, EUMETSAT; Alejandro Egido, ESA), Severine opened the meeting and presented the agenda and explained the logistics. In particular, she reminded the team of the addition of online forums. The forum is available until a new one for the next OSTST will be set-up, it can be accessed (after login) at: https://ostst.aviso.altimetry.fr.

Severine announced that Alejandro Egido is replacing Craig Donlon as the ESA Project Scientist.

2.1 Program and Mission Status

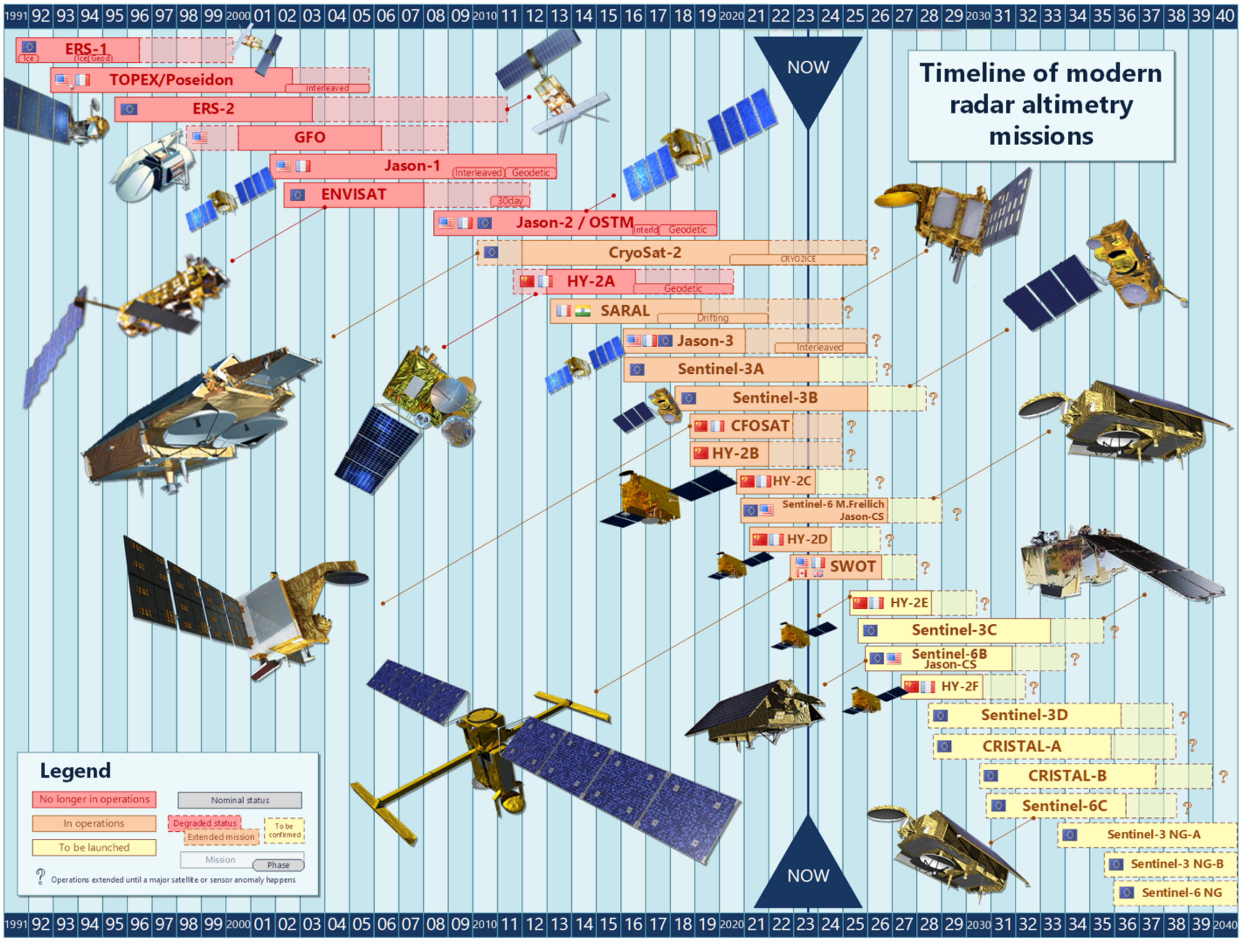


Figure 2.1-1: Altimetry missions' timeline as of August 2023 [source: Aviso+ (2022). Timeline of modern radar altimetry missions. https://doi.org/10.24400/527896/A02-2022.001 version 2023/08].

The program managers presented the status of altimetry and oceanographic programs at NASA (Nadya Vinogradova-Shiffer), CNES (Annick Sylvestre-Baron, NOAA (Eric Leuliette), EUMETSAT (Estelle Obligis), and ESA (Jérôme Bouffard).

Nadya Vinogradova-Shiffer (NASA HQ) gave a summary of the NASA Ocean Physics Program, highlighting the satellite and airborne missions NASA is involved in as well as the Sea Level Change Team in addition to the OSTST. She also noted the successful launch of the SWOT mission and preliminary outstanding SWOT observations. She reminded the audience of the upcoming NASA SWOT science team call which deadline is December 15, 2023, and the upcoming NASA/NOAA OSTST call that will come out on February 14, 2024.

Annick Sylvestre-Baron (CNES) summarized the CNES Ocean Program, which includes support of Sentinel-6 MF, Sentinel-3, SWOT, and HY-2 as well as Jason-2 and -3. Annick also noted the successful launch of the SWOT mission and the impressive first results. She mentioned the SWOT Adopt-a-crossover consortium. She also noted that SARAL/AltiKa received a 1-year mission extension for operation through the end of 2024, allowing a very good overlap with SWOT for at least 2 years. She acknowledged the 10-year anniversary of the SARAL/AltiKa. CFOSAT also received an extension through the end of 2024. The CFOSAT Science Team, which consists of 22 projects from 13 countries was also renewed for the period from 2023 to 2027 and the next CFOSAT ST meeting will be held in China November 28 through 30, 2023. She reminded the audience of the upcoming CNES/EUMETSAT OSTST call that will come out in April 2024.

Estelle Obligis (EUMETSAT) presented the status and outlook of the Oceanography Services for EUMETSAT. Estelle noted that EUMETSAT delivers services ranging from research and development to operational, and that the scope of services was increasing beyond Physical Oceanography to environmental and climate monitoring and weather prediction. She noted the growing integrated stream of marine products that EUMETSAT is in charge of including wind vectors, sea ice parameters, surface temperature and fluxes, sea surface height, waves and wind speed, and ocean color. She presented the EUMETSAT mission planning highlighting the altimetry missions, including the current and upcoming Copernicus missions that will ensure continuity of altimetry observations until 2050. Finally, Estelle noted an upcoming hydrological applications from satellite observations workshop in 2024 due to the increased interest of EUMETSAT member states. EUMETSAT is also preparing a mandatory altimetry program to be approved by council in 2026. Estelle also provided an update on the OST Virtual constellation white papers; the final document will be delivered to the Committee on Earth Observation Satellites management by mid-2024.

Eric Leuliette (NOAA) provided a status update on the NOAA Jason/Sentinel-6 Program Status. NOAA continues to support PIs as part of the OSTST and is planning to maintain its support to the 2025-2028 Team with a joint NOAA/NASA ROSES solicitation coordinated with CNES/EUMETSAT TOSCA. Eric noted that the National Environmental Satellite, Data, and Information Service (NESDIS) was reorganized in August 2023, the Laboratory for Satellite Altimetry is now in the STAR Ocean Topography and Cryosphere Branch. Eric also highlighted the NOAA CoastWatch web site and data portal, designed to help people find, choose, access, and use satellite data in applications and decision-making for ocean, coastal, and fresh waters. He also noted that the third International Operational Satellite Oceanography Symposium organized by EUMETSAT and NOAA and hosted by the Korea Hydrographic and Oceanographic Agency (KHOA) was held in June 2023.

Finally, Jérôme Bouffard (ESA) provided an update on the ESA Program. Jérôme noted the FDR4ALT project that is currently reprocessing ERS-1,-2, and ENVISAT altimeter data for consistency across missions; the data will be released by the end of 2023. He also noted that CryoSat-2 and SMOS continue to produce sea level and soil moisture/ocean salinity observations, respectively; both their operations have been extended until the end of 2025. CIMR is targeted for launch in 2028 and will observe sea ice, sea surface temperature and other variables. He highlighted different ESA Cal/Val activities and ESA CCI projects including the sea level budget closure, river discharge, lakes and sea ice projects. Jérôme announced that an international altimetry meeting to celebrate the 30-year anniversary of altimetry will be held in Montpellier, France on September 2-7, 2024.

On behalf of the Project Managers, Christophe Ferrier (CNES) reviewed the status of the Jason-3 mission. In April of 2022, after S6MF was recognized as the official reference mission, Jason-3 was moved to the interleaved orbit, with ground tracks spaced halfway between the reference mission tracks. The satellite is in excellent health with nominal performance of all instruments and systems and with all redundant systems still available. The annual Cal/Val reports can be found on the AVISO website. A second tandem mission with Sentinel-6 MF has been requested for the beginning of 2025 and the Project team remains ready to support such a move. The OSTST should discuss and make a recommendation regarding the future of Jason-3 after the second tandem mission. In the event that the satellite was to suffer any serious degradation, it would be moved to a graveyard orbit and to a disposal orbit in case of an emergency.

Carolina Nogueira Loddo (EUMETSAT) and Pierre Féménias (ESA) provided an overview of the Sentinel-3 Marine Mission. The Sentinel-3A & 3B altimeters continue to perform well and all marine data is meeting all accuracy, availability, and timeliness requirements. There was a major issue affecting the ground segment in late April and May 2023, but all data were recovered. Full mission reprocessing is completed with a consistent baseline between Sentinel-3A and 3B. Future reprocessings will provide improvements to polar and coastal data. In a second talk on Sentinel-3, Pierre Féménias (ESA) discussed the Sentinel-3 Land Mission. Pierre noted that the Sentinel-3A and 3B products are fulfilling all requirements over inland waters, land ice and sea ice. A full mission reprocessing of altimetry Level 2 products was completed during the second quarter of 2023 and made available. Finally, he noted that Sentinel-3C and 3D are ready to take over from 3A and 3B to extend the time series.

Remko Scharroo (EUMETSAT) gave an overview of the Sentinel-6 MF mission on behalf of all the project and program managers. Julia noted that Sentinel-6 MF is continuing the operational ocean altimetry services provided by Jason-3 until April 2022 in synergy with those of Sentinel-3. The satellite continues to meet all science and operational requirements and has demonstrated excellent on-orbit performance. A power cut affecting one of the ground stations in June 2023 resulted in 4 passes lost; a server problem caused missing critical auxiliary files in late June/early July 2023. A new baseline followed by a full mission reprocessing was completed earlier in 2023. A new baseline will be implemented early 2024. Julia also noted that Sentinel-6B will be removed from storage in mid-October 2024, with launch planned for November 2025 on a SpaceX Falcon 9 from Vandenberg. She noted the addition of a third ground station, to complement Fairbanks and Kiruna capability during tandem and dual operations of Sentinel-6 MF and Sentinel-6B. Finally, a third satellite, Sentinel-6C is now part of the Copernicus long term scenario. Industrial studies are ongoing to assess technology obsolescence and to enhance the value of the Sentinel-6 missions for the user community.

Lotfi Aouf (MeteoFrance) provided an overview of the China-France Oceanography Satellite (CFOSAT), which provides global scale observations of surface wind and wave spectral properties. While both instruments continue to perform, the antenna of the scatterometer has stopped rotating in December 2022, which is impacting the surface wind retrieval and will necessitate an adaptation of the ground processing. The second full reprocessing of the SWIM data was completed in 2022, a new version will be implemented in 2024. CFOSAT data are used operationally in wave forecast models and their use in coupled models is in preparation. Lotfi showed impressive images from CFOSAT of the high waves generated by the Ciaran storm at the coast in November 2023. The maximum wave height recorded was more than 21.3 meters.

An update on the SWOT mission was provided by Lee Fu (NASA). The SWOT mission was successfully launched on December 16, 2022. The satellite was in an initial 1-day repeat orbit for Cal/Val purposes before moving to the scientific 21-day repeat in July 2023. This scientific orbit provides global coverage with minimal gaps. Thanks to the SWOT's KaRIn instrument, we can get SSH observations in 2 dimensions at 2km and lower resolution for the first time. A first look at the data shows that SWOT observations exceed the mission's requirements. Many lakes and rivers that were never observed from space before are now uncovered. A beta version of the data was made available to the science team in August 2023, the data will be publicly available by the end of 2023. The mission science team will be renewed in 2024, the last in-person science team meeting was held in September 2023 in Toulouse, France. The next one will be held in June 2024.

Alejandro Egido (ESA) gave a presentation on the upcoming set of satellites slated to extend the Sentinel-3 record for all topography variables, called Sentinel-3 Next Generation Topography (S3NG-T). The primary objective for S3NG-T will be to guarantee continuity of Sentinel-3 topography measurements from 2030 through 2050 while providing enhancement, with secondary objectives to provide new products such as wavenumber spectra and gradient products. Hydrology is now a primary objective of the mission, which was not the case for Sentinel-3. The preliminary concept consists of two dedicated large satellites carrying wide-swath (Ka band) and nadir altimeters (Ku and C band), together with a microwave radiometer and precise orbit determination instruments. The first launch is planned for 2032.

Cristina Martin-Puig (EUMESAT) discussed the status of the CRISTAL satellite mission. CRISTAL, a Copernicus Expansion Mission will expand the legacy of CryoSat-2, with improved performance in the polar and ocean regions. It will include a dual-frequency Ku/Ka SAR altimeter, with the Ku being interferometric. Because both Ku and Ka band altimeters are primary instruments, the dual frequencies will be exploited to provide improved corrections and flagging, resulting in significant product improvements. Also, a passive microwave radiometer (similar to the one on Sentinel-6 MF) will allow for retrieval of a wet tropospheric correction for oceanic and polar measurements. The first objective of the mission is to retrieve high quality measurements of sea ice, snow depth and land ice. A secondary objective is to provide high-quality measurements of sea surface height over the ocean. CRISTAL-A is on track for launch in late 2027, with CRISTAL-B to be launched near the end of CRISTAL-A mission. CRISTAL will be the first high latitude operational mission providing high resolution measurements.

2.2 Other reports and issues

In addition to the programmatic and mission talks, additional talks discussed developments with the Argo array of profiling floats, presentation of discussion topics for consideration by the splinters, a presentation of an initiative to rethink new storytelling approaches to sea level rise and an invited special talk from the Director of the Caribbean Center for Rising Seas, part of the Puerto Rico Science, Technology & Research Trust.

Nathalie Zilbermann (Scripps) gave a presentation on Argo, its relationship to satellite altimetry and its scientific importance to close the Earth Energy Imbalance and the Sea Level budget. She discussed accomplishments of the Argo array and described a new effort called OneArgo, which represents an expansion of the existing array to cover the deep ocean and polar oceans, as well as adding biogeochemical observations. She also gave some recommendations to the OSTST on the use of Argo data following the discovery of manufacturing issues affecting some Argo floats. Unfortunately, the Argo program is facing some challenges as resources have not been secured to implement OneArgo causing the Argo system to be in net decline. Widespread support for OneArgo was voiced during open discussions, and as in 2022, a recommendation was adopted by the OSTST regarding expansion of Argo. See Recommendations in the Executive Summary and Conclusions for details.

On behalf of the other Project Scientists, Eric Leuliette (NOAA) presented discussion topics for consideration by the splinter sessions. These included:

1) future planning for Jason-3 after the second tandem phase with Sentinel-6 MF that was requested,
2) revising the climate requirements on future reference missions (S6 and S6 Next Gen) including the number of tandem phases and possible changes in the intermission bias and stability requirements,
3) the future of the OSTST, considering the increasing number of missions and instruments, the diversity of communities (oceanography, coastal, geodesy, hydrology, cryosphere), and the climate impacts from travel.

Details of the discussion topics can be found in the online presentation.

Josh Willis presented Space Stories, a think tank for US based creatives and technologists to rethink new storytelling approaches to sea level rise. This initiative is organized by Garage Stories and consists of masterclasses that are being held during the month of November 2023 with 15 participants spread in 5 teams. The winning team will have the opportunity to present their concept at JPL in 2024.

Finally, Fernando E. Pabón Rico, the Director of the Caribbean Center for Rising Seas, part of the Puerto Rico Science, Technology & Research Trust was invited to speak about climate issues that are impacting the island of Puerto Rico. Puerto Rico has about 3 million inhabitants and faces several climatic issues, including devastating impacts from hurricanes (with a hurricane season stretching over 6 months every year), sea level rise, and droughts. While Puerto Rico has a lot of outdated infrastructure, it has the most advanced environmental regulations in the Caribbean. Fernando explained the economically, socially, and geographically urgent task that is to make good decisions to help the communities facing climatic challenges with a long-term vision. One of the goals of the Caribbean Center for Rising Seas is to work with partitioners and the public to change urban development practices, update building codes, zoning and land use regulations, and spread the knowledge and understanding of sea level rise and flooding to the public.

3 Poster Sessions

Two poster sessions were conducted on Wednesday and Thursday and the posters were on view during the coffee breaks throughout the entire meeting. Links to the posters are available on the meeting website: https://ostst.aviso.altimetry.fr/programs/2023-ostst-complete-program.html.

The posters were grouped into the following categories:

- Application development for Operations [9 posters]
- CFOSAT [4 poster]
- Coastal Altimetry [4 posters]
- Instrument Processing (Measurement and retracking) [3 posters]
- Instrument Processing (Propagation, Wind Speed and Sea State Bias) [0 poster]
- Outreach, Education & Altimetric Data Services [1 poster]
- Precise Orbit Determination [0 poster]
- Regional and Global CAL/VAL for Assembling a Climate Data Record [14 posters]
- Science Results I: Climate Data Records for Understanding the Causes of Global and Regional Sea Level Variability and Change [3 posters]
- Science Results II: Large Scale Ocean Circulation, Variability and Change [2 posters]
- Science Results III: Mesoscale and Sub-Mesoscale Oceanography [15 posters]
- Science Results IV: Altimetry for Cryosphere and Hydrology [6 posters]
- Sentinel-6 Validation Team (S6VT) Meeting [2 posters]
- Synergies between Argo, GRACE, and Altimetry [1 poster]
- The Geoid, Mean Sea Surfaces and Mean Dynamic topography [7 posters]
- Tides, internal tides and high-frequency processes [8 posters]

4 Forum Only Session

An online forum was available during the entire duration of the meeting. All presentations and posters are available on this forum: https://ostst.aviso.altimetry.fr/index.html#forum_section

The forum-only presentations were organized as follows:

- Application development for Operations [0 presentation]
- CFOSAT [1 presentation]

- Coastal Altimetry [2 presentations]
- Instrument Processing (Measurement and retracking) [2 presentations]
- Instrument Processing (Propagation, Wind Speed and Sea State Bias) [1 presentation]
- Outreach, Education & Altimetric Data Services [0 presentation]
- Precise Orbit Determination [5 presentations]
- Regional and Global CAL/VAL for Assembling a Climate Data Record [5 presentations]
- Science Results I: Climate Data Records for Understanding the Causes of Global and Regional Sea Level Variability and Change [1 presentation]
- Science Results II: Large Scale Ocean Circulation, Variability and Change [2 presentations]
- Science Results III: Mesoscale and Sub-Mesoscale Oceanography [4 presentations]
- Science Results IV: Altimetry for Cryosphere and Hydrology [3 presentations]
- Sentinel-6 Validation Team (S6VT) Meeting [0 presentation]
- Synergies between Argo, GRACE, and Altimetry [1 presentation]
- The Geoid, Mean Sea Surfaces and Mean Dynamic topography [1 presentation]
- Tides, internal tides and high-frequency processes [1 presentation]

5 Splinter Sessions

The splinter sessions were organized as follows:

Wednesday, November 8:

- Instrument Processing (Measurement and retracking) [7 Oral talks]
- Precise Orbit Determination [8 Oral talks]
- Instrument Processing (Propagation, Wind Speed and Sea State Bias) [7 Oral talks]
- Outreach, Education & Altimetric Data Services [5 Oral talks]
- The Geoid, Mean Sea Surfaces and Mean Dynamic topography [Round Table]

Thursday, November 9:

- Regional and Global CAL/VAL for Assembling a Climate Data Record [12 Oral talks]
- Coastal Altimetry [6 Oral talks]
- Application development for Operations [Round Table]
- Synergies between Argo, GRACE, and Altimetry [6 Oral talks]
- Tides, internal tides and high-frequency processes [Round Table]
- Sentinel-6 Validation Team (S6VT) Meeting [10 Oral talks]

Friday, November 10:

- Science I Results: Understanding and Quantifying Regional and Global Sea Level Budgets [6 Oral talks]
- CFOSAT [Round Table]
- Science Results II: Large Scale Ocean Circulation, Variability and Change [8 Oral talks]

- Science Results III: Mesoscale and Sub-Mesoscale Oceanography [7 Oral talks]
- Science Results IV: Altimetry for Cryosphere and Hydrology [6 Oral talks]

Links to the presentations are available on the meeting website:
https://ostst.aviso.altimetry.fr/programs/2023-ostst-complete-program.html.

5.1 Application development for Operations

Chairs: Deirdre Byrne, Gerald Dibarboure, Gregg Jacobs, Carolina Nogueira Loddo

5.1.1 Summary

The Application development for operations splinter consisted of a poster session and a roundtable discussion. The posters presented are listed below:

1. The Global Water Monitor: Operational Monitoring of Lakes, Wetlands, and River Reaches for Resources and Hazards; Birkett et al. (https://doi.org/10.24400/527896/a03-2023.3695).
2. Assessing Tropical Cyclone Intensity Forecasts Using the NOAA Next-Generation Enterprise Ocean Heat Content Algorithm; Byrne et al. (https://doi.org/10.24400/527896/a03-2023.3727).
3. A near global improved gridded multi-mission daily SLA product slightly beyond real time; Jensen et al. (https://doi.org/10.24400/527896/a03-2023.3839)
4. Seasonal Prediction of Harmful Algal Blooms Caused by Karenia brevis on the West Florida Shelf Using Satellite Altimetry Data; Liu et al. (https://doi.org/10.24400/527896/a03-2023.3789).
5. Status in the development of the CRISTAL Marine Data Centre; Moreau et al. (https://doi.org/10.24400/527896/a03-2023.3865).
6. NOAA Jason-3 Products; Richardson et al. (https://doi.org/10.24400/527896/a03-2023.3680).
7. Jason-3 Near-Real Time Products Latency from October 2022 to October 2023; Richardson et al. (https://doi.org/10.24400/527896/a03-2023.3681).
8. Multiparameter Mesoscale Eddy Tracking Products for Operational Use; Roman-Stork et al. (https://doi.org/10.24400/527896/a03-2023.3733).
9. Physically-consistent mapped altimetry products on user-customizable grids; Wortham et al. (https://doi.org/10.24400/527896/a03-2023.3796).

5.1.2 Splinter Discussion Points and Recommendations

The round table discussion was handled through several seed questions on data availability and applications, user services and communication, and product contents. The round table was co-chaired by Carolina Nogueira Loddo (EUMETSAT), Josh Willis (NASA), Heather Roman-Stork (NOAA), Pierre Femenias (ESA) on behalf of the official co-chairs.

5.1.2.1 Data Availability and Applications

The use of small satellites/cubesats to monitor high frequency events, e.g. in coastal zones, inland waters has been questioned, as well as applications that could benefit from such measurements and its benefits. With the understanding that higher temporal frequency sacrifices accuracy, several points were considered:

- CubeSats were brought up with respect to “Future Mission Scenarios” as they are smaller, cheaper etc, but several questions were raised on the acceptable reduced

accuracy and ongoing studies on accuracy, repeatability, use for cross-validation etc. They could be considered as a complement to a strong, reliable, stable constellation; but should not replace any stable mission.
- Regarding accuracy, 10 cm accuracy for inland water is considered acceptable, whilst 1 m is not useful for inland applications.
- In terms of benefits, high latitudes with fast hydrological changes would benefit from these missions and daily temporal resolution would be good for hydrology. It was recalled that CNES has a phase 0 with a SMASH constellation for hydrology.

Chinese altimeter missions were also discussed, considering that L2 OGDR products from 3 missions (HY-B, -C, -D) are distributed by EUMETSAT via EUMETCast Europe and terrestrial. As far as is known, their performance is good. In particular, the NRT and STC products might add some much-desired coverage. The splinter questioned the interest in these new sources of altimetry data:

- Need clarity on the access to and use of data from the Chinese HY-2 missions (3 planned) – from a viewpoint of quality assurance and importantly – the legal side of this with respect to any integration or use-of by the US scientists, especially the US government agencies; (NASA has rules, NOAA likely does as well, so it would be nontrivial for either agency).
- EUMETSAT is distributing the L2 data to Europe; nevertheless, it's still not simple within Europe to get access to L2 data (EUMETSAT has to greenlight it). If there is a recommendation from the community to receive these data, EUMETSAT can talk to the Chinese agency about making it happen.
- Copernicus has L2P, L3 along-track calibrated with Jason-3.
- Meteo-France gets the data from EUMETSAT and uses it.

There is a strong need for altimeters over polar oceans and the potential gap between CryoSat-2 and CRISTAL is a cause for concern. CryoSat-2 is reaching the end of its life and there is a big risk in a few weeks related to the switchover of the Side B controls. The CRISTAL community is pushing for the launch not to be delayed, a recommendation from OSTST to extend CryoSat-2 will make it easier for the CRISTAL community and possibly extend CryoSat-2 funding. It was clearly expressed that the **end users want continuity more than accuracy**, which would justify the funding for system upgrades etc. This topic was considered relevant and to a formal recommendation/appreciation at the end of the OSTST meeting (***Potential Gap between CryoSat-2 and CRISTAL***).

In the context of Copernicus Sentinel-3 (S3) Next Generation Topography missions (S3 NG Topo), ESA is proposing to make a switch from profiling radar altimetry to a combination of swath + profiling altimetry, perhaps by the mid-2030's i.e., taking the initiative to follow-on the SWOT instrument format. A time gap between SWOT and the next SWOT-format mission is possible. Although SWOT swath data are not yet part of operational products or climate data records, one can expect in the future, swath data would be included in these, and in order to include SWOT, continuity with future missions would be required. How best to close this gap?

5.1.2.2 User Service & Communication

In terms of user information, there is recognition that despite the effort from the different agencies to communicate in a simpler way, the information is frequently spread out in too many places. Tailored/simplified products to use with fewer things to explain are appreciated by end users, i.e. products that are easier to use, with fewer parameters, and information on the uncertainty parameter. It was noted that too much information can be overwhelming or intimidating. Similar theme to outcomes of Operational Satellite Oceanography Symposium meetings (push for sensor agnostic products, including uncertainty).

The product portfolio is wide, with a variety of SSHA, Wind and Wave L2/L2P/L3 products; with the 1Hz and 20Hz in the L2 products and 5Hz in L3 products (coming soon, before the end of 2023). The agencies should better communicate to the end-user about the different products available.

It would be useful to inform the community about evolutions related to NRT/OGDR and STC/IGDR, without spamming people with too many emails. It was suggested to provide clear information through the data access websites.

5.1.2.3 Products Contents

Given the recent improvements in the performance of NRT/OGDR products, a question was raised regarding the value of STC/IGDR for applications. NRT products have a good orbit, and the dynamic atmospheric correction was recently added, so the gap between NRT and STC is in theory smaller than it used to be. The following thoughts were shared:

- Many people are likely unaware that the NRT product has reached this point.
- If the difference between NRT/STC is proven to be negligible, it would make sense to consider issuing NRT products only for new missions such as CRISTAL.
- Some people within the OSTST want to continue STC products, e.g.:
    - The Copernicus Global Land Service (CGLS), which is a component of the Land Monitoring Core Service (LMCS) of Copernicus, the European flagship programme on Earth Observation (*https://land.copernicus.eu/global/themes/water*).
    - Sentinel-6 MF STC products are currently used for ENSO (El Niño-Southern Oscillation) detection and prediction.

It was suggested that the agencies should perform studies to characterize any differences in performance between NRT/OGDR and STC/IGDR, including comparison of SSH calculations as well as overall data coverage to compare the performance of the two products. This topic was considered relevant and suggested as a formal recommendation/appreciation at the end of the OSTST meeting (Altimetry Product Evolution).

5.2 CFOSAT

Chairs: Lotfi Aouf, Danièle Hauser, Joanna Staneva, Doug Vandemark

5.2.1 Summary

The CFOSAT session during the OSTST meeting was scheduled as a poster session, and because of the proximity of the science team meeting (28-30 November), the participation was smaller in comparison with 2022. Only 5 abstracts were received, including 4 poster presentations and 1 forum only presentation.

The poster presentations were moderately well attended. Two poster presentations concerned the impact of the assimilation of reprocessed SWIM wave spectra from the upgraded algorithms of Level 2 (IPF-6.02) from Aouf et al. (https://doi.org/10.24400/527896/a03-2023.3822) and the use of SWIM nadir sea level data in multi-missions data in order to improve geostrophic current estimation (Jenn Alet et al.; https://doi.org/10.24400/527896/a03-2023.3788). We had also a poster presentation from Aouf et al. (https://doi.org/10.24400/527896/a03-2023.3880) on the use of SWIM directional spectra to validate a bi-static spectral retrieval processing for the Harmony mission from the ESA EE-11 (Earth Explorer) program.
A very interesting presentation from Tran et al. (https://doi.org/10.24400/527896/a03-2023.3879) has shown the improvement of Sea State Bias (SSB) for sea level anomaly altimetry missions by using off-nadir wave spectra from CFOSAT mission.
Another poster from Kleinherenbrink et al. (https://doi.org/10.24400/527896/a03-2023.3748) concerns the implementation of artificial intelligence algorithm to provide maximum wave height from SWIM nadir. The results show a very good agreement with buoys and open a good perspective for rogue waves operational forecast.

Unfortunately, we had no participation for the round table of CFOSAT session because of the session being scheduled at the same time as the Sentinel-6 Validation Team session.

5.3 Coastal Altimetry

Chairs: Florence Birol, Brett Buzzanga, Joana Fernandes, Clara Lazzaro

5.3.1 Summary

The first talk, "Review of Satellite Altimetry for Ocean and Coastal Applications for Societal Benefit" was presented by Vardis Tsontos (https://doi.org/10.24400/527896/a03-2023.3849). Continuity of satellite altimetry observations that are the product of successful partnerships between international space agencies for more than three decades has yielded an important long-term data record of essential climate variables over the ocean, coasts, and land. These have enabled a growing number of practical, decision support applications involving operational government agencies and the private sector, an overview of which was the focus of the presentation. Representative classes of applications discussed included: coastal hazards related to storm surge, flooding and sea level rise in support of spatial planning for resilience and disaster mitigation; tropical cyclone forecasting for early warning and emergency response; coastal circulation and wave model-based systems for marine safety and navigation; and marine fishery and biodiversity conservation applications related to potential fishing zone advisories, by-catch mitigation and marine protected area design. It is expected that higher spatial resolution, wide-swath coverage closer to coastlines from SWOT will further catalyze such applied uses. The importance of multi-mission EO and in-situ data integration also with modelling approaches and interactive web-based tools increasingly available via coastal observing system portals for the delivery of synthesis information products and scenario exploration by stakeholders and the broader community was emphasized.

Fernando Niño gave the second talk on "FDR4ALT new coastal products for the ERS / Envisat missions" (https://doi.org/10.24400/527896/a03-2023.3782). The FDR4ALT project ran between October 2019 and July 2023, and was part an ESA project in the scope of the European Long Term Data Preservation Program (LTDP+), striving to provide fundamental data records for the Envisat and ERS-1 and ERS-2 altimetry missions. The ocean/coastal thematic data product (TDP) provides a seamless transition between the open ocean and the coast and is available for high-frequency data (20hz). The product description can be found at https://www.fdr4alt.org/. For the product definition we undertook a round robin analysis of different combination of altimetric corrections (retrackers: ice-2, mle3 and adaptive, wtc: radiometer, gpd+, era5; tides: fes2014, got4.10, fes2014regional, iono: gim, bifrequency, mss: cnescls15, combined_cnes/dtu). Validation was done with along-track, and map-based analysis, as well as with tide-gauges for which the level-3 x-track reprojected product was created. Data availability, as least as good as standard 1Hz data, but can be improved if using GPD+ (the product uses the radiometry WTC). Very good agreement with tide gauges in the 5 validation regions, and the data provides better quality when using regional tide solutions (NEA & MedSea). A new product including GPD+ and regional Arctic tide is in the works on the FDR4ALT Follow-On project.

Faugère et al. (https://doi.org/10.24400/527896/a03-2023.3825), explore the potential of ICESat-2 to measure sea level in the coastal zone. There is an overall consistency between

ICESat-2 and Cryosat-2 in the open ocean and coast. Local biases at coast, likely due to tidal and/or mean sea-surface mismodeling, can lead to systematic errors manifesting as large sea level anomalies visible in ICESat-2 and SWOT as seen in the Strait of Ormuz and Canadian Fjords. SWOT and ICESat-2 should be used in conjunction to minimize biases in each.

Aouf et al. (https://doi.org/10.24400/527896/a03-2023.3868) show recent improvement in wave forecast at regional and coastal scales from data assimilation of multi-mission 5 Hz significant wave heights (SWH). First, they show that SWH decrease induced by changing bathymetry is well captured by 5 Hz processing of CFOSAT-nadir, Jason-3, SARAL/AltiKa, and HY2B. Next, they use the MFWAM wave model for the Iberian-Biscay-Ireland regional configuration with a grid size of 5 km and spectral resolution of 24 directions and 30 frequencies. Incorporating the 5 Hz data via assimilation into the models substantially improves the model estimates of wave heights. They also find a 10 cm improvement in regional (North Atlantic and Mediterranean Sea) bias (an improvement of ~40%), particularly for SWH > 7 m. They use drifting buoys from the SUMOS campaign to investigate small scales, and similarly find a decrease in bias. For SWH > 4 m, model bias is reduced from -21 cm without data assimilation to -8 cm with multi-mission data assimilation. This offers promising perspectives for operational coastal wave models as only CFOSAT-nadir is currently providing NRT 5 Hz SWH.

The presentation “Impacts of using different atmospheric models on altimeter-derived Sea Level Trends”, by Joana Fernandes (https://doi.org/10.24400/527896/a03-2023.3739), focused on the analyses of various numerical weather models from ECMWF, evaluating their accuracy and stability for the purpose of estimating the wet path delay (WPD) of satellite altimetry measurements, with focus on their impact on sea level trends. Due to its low precision, ECMWF operational model should not be used before 2004. After this date, it has significant discontinuities, which in some regions introduce trend errors that can exceed 1 mm/yr, over periods of 7-8 years. The most relevant impacts are over the periods of the Jason-2 mission (phase A) and over the period of Jason-3 (phase A) and Sentinel-3A missions. Overall, ERA5 is the best compromise between precision and stability and should be adopted for climate studies, whenever WPD based on observations are not available, such as coastal and inland water regions.

The last talk “Satellite Altimetry Sea Level Height and Related In Situ DART® and Tide Gauge Products Stewardship and Comparison Study in NOAA/NCEI” was given by Yongsheng Zhang (https://doi.org/10.24400/527896/a03-2023.3699). The NOAA National Centers for Environmental Information (NCEI) provides near real-time and delayed-mode product distribution, archive services, and long-term data stewardship for the OSTM/Jason-2 and Jason-3 products. The NCEI Hazards Group also hosts an archive of high-resolution water-level data as part of the US National Tsunami Hazards Mitigation Program (NTHMP), including over 300 NOAA/NWS Deep-ocean Assessment and Reporting of Tsunamis (DART®) records, tide gauge records from NOAA “tsunami-ready” network maintained by the NOAA/NOS Center for Operational Oceanographic Products and Services (CO-OPS), water level data from the Pacific Tsunami Warning Center (PTWC), and the National Tsunami Warning Center (NTWC). The representativity of the DART® bottom pressure observations was investigated, by comparing them to the satellite altimeter and coastal tide gauge water level data. Using cross-spectral and wavelet analysis, and direct comparison with coastal tide gauge records, it was found that the DART® Sea Surface Height Anomalies (SSHA) agree with the altimeter SSHA and coastal or island tide gauge records in regions with high atmospheric dynamics. These regions include the North Pacific Ocean along Japan, the Aleutian Islands and Alaska, the Hawaii Islands, the West Atlantic along the US East Coast, and the Caribbean Basin. The results of applying the Jason-3 Interim GDR SSHA data in tracking the Tsunami wave, which was triggered by the volcano eruption in Tonga on January 15, 2022, has also been presented. It is demonstrated that satellite altimeter tracks are the unique observations and very helpful for tracking the propagation of the front of the tsunamis.

Dodet et al. (https://doi.org/10.24400/527896/a03-2023.3768) seek to better monitor wave transformation as energy progresses from deep water across the barrier reef-lagoon system. As very few observing systems are currently capable of this, they here show a preliminary assessment of Sentinel-3A (S3A) capacity to measure significant wave heights (Hs) at the south-west lagoon of New-Caledonia. First, S3A Hs is used to validate the SCHISM-SWAN coupled wave model during the onset of a tropical cyclone. Tidal modulation of Hs was well reproduced but peak Hs was underestimated, likely due to unrealistic wind forcing. Next, empirical mode decomposition was used to denoise 20 Hz Hs by estimating a noise threshold from the first mode and applying this to subsequent modes. Analyzing 49 tracks during 2016-2020, they find three distinct regions of wave transformation: slowly decreasing Hs (20%) from deep water to ~8km above reef; strong Hs (50%) decrease from ~8km above reef to reef top; Moderate Hs variability within the lagoon. Local winds dominate Hs within the lagoon. Offshore in-situ measurements of Hs correlate well with S3A, but not within the lagoon due to distance between in-situ measurements and S3A ground tracks. S3A and simulated Hs offshore and in the lagoon present consistent trends but significant differences in magnitudes that require further investigations.

Timmermans et al. (https://doi.org/10.24400/527896/a03-2023.3808), address two questions: 1) can we use the altimetry to learn more about the spatial properties of sea state variability using in situ sites at the coast; and 2) can we use those findings to better exploit in situ records to better understand how uncertainties affect analyses based on multiple collocations, e.g. through different sampling approaches? Using moorings along the US West Coast, they find that even at offshore deep-water sites, where sea state conditions are often assumed to exhibit considerable spatial homogeneity, changes in summary statistics (such as mean bias) on spatial scales ~20 km. They also find a relatively large bias at station 46246 in the Northeast Pacific. At nearshore sites, the sampling approach (i.e., the radius around the in-situ site used to collect altimeter measurements) heavily influences the uncertainties. They assess agreement between Jason 3 and moorings using 4 different approaches for both a 25 km and 75 km radius around the buoy: track median estimate; adaptive filtering (selecting only measurements with a long-term coherence > 0.98); single nearest 1 Hz to buoy; median of 3 nearest 1 Hz to buoy. For 25 km, full track median and nearest 3 Hz are the same, while filtering increases the correlation and reduces bias but at expense of samples, indicating strong spatial sea state gradients. At higher values of Hs, Jason-3 appears to underestimate in all cases. Using 75 km radius generally decreases performance. A 13-month period of Jason-3 agrees well that of Sentinel-6 MF low resolution, which in turn are very similar to the findings from the 5-year Jason-3-year record. Sentinel-6 MF high resolution exhibits a sea-state dependent bias in both offshore and nearshore. It may be stronger nearshore, although the results are affected by quality control issues nearshore and not evaluated for statistical robustness.

Buzzanga et al. (https://doi.org/10.24400/527896/a03-2023.3819) explore the use of ICESat-2 for estimating global mean sea surface (MSS). To assess the stability of the MSS, they compute the variance of dynamic ocean topography (DOT) in 25 km boxes around tide gauges. They find no spatial bias in the residual between the ICESat-2 and the tide gauges. They then compute the MSS from ATL12 sea surface height in 25 km grid cells and interpolate to 1 min resolution to compare directly with the global MSS product DTU21 estimated from the constellation of radar altimeters. They find excellent agreement (mean difference of 0.1 m). They perform a regional analysis over Tuvalu, a Pacific Island nation under extreme threat from sea-level rise. They find slight discrepancies that warrant further investigation.

Ferrer et al. (https://doi.org/10.24400/527896/a03-2023.3711) presented a poster on “FFSAR data radargram exploitation for improving the altimeter retracking performance in coastal zone”. Currently, coastal altimeter processing cannot provide highly accurate and precise measurements without removing potentially valuable outliers. This study introduces a method to extract features from Sentinel-6 MF FF-SAR data radargrams using a point clouds classifier (based on a statistical distribution analysis of the σ_0 radar intensity values) to accurately locate the ocean targets within complex coastal environments. Compared to a shapefile-based approach that uses a static coastline that does not include natural phenomena such as tides or storms, the new method reduces noise in both the SSH and SWH noise in the 4-5 km band. It enhances understanding of specular points behavior and distribution, providing improved placement of the radargrams for better detection of ground and ocean back-scatterers.

Juhl et al., presented a poster on “On the potential of mapping sea level anomalies from satellite altimetry with Random Forest Regression” (https://doi.org/10.24400/527896/a03-2023.3794). In this study, the authors utilized Random Forest Regression to estimate daily sea level anomalies (SLA) based on a 1-year along-track SLA data to build the training dataset. The method employed SLA means, weighted means, and standard deviations, at various spatial and temporal neighborhoods, as predictors in the estimation of unknown SLA values on a set of grid points. Validation using tide gauge data (GESLA) revealed a 10% higher correlation with tide gauge records, compared to Copernicus Marine Service (CMEMS) products. While CMEMS SLA products are optimized for spatial mesoscale studies, the authors' methodology enhances sea level variability characterization, particularly in coastal zones. The authors highlight the potential of this strategy for implementing operational Copernicus products on regional scales.

Martinez et al., presented a poster on “High spatial and temporal resolution hydrographic data collected by Southern Elephant Seals in a wide continental shelf” (https://doi.org/10.24400/527896/a03-2023.3703). This study analyzes in situ data from CTD sensors installed on 5 elephant seals that crossed the Argentine Continental Shelf in October

2019. Two distinct regions, north and south of 42°S, are identified based on temperature and salinity data acquired along the trajectories. North of 42°S, warmer and saltier waters from San Matias Gulf are found. In situ data correlates well with satellite sea surface temperature, revealing Malvinas Water and other water masses. High spatiotemporal resolution of in situ data shows gradients associated with a seasonal front developed north of Peninsula Valdes. Elephant seal speed correlates with tidal currents in the north, revealing potential for bathymetry chart error detection using maximum seal depth.

5.3.2 Splinter Discussion Points and Recommendations

Few discussion points were brought up during the session:

- Whenever observations are not available, ERA5 reanalysis wet path delay estimates should be adopted for climate studies (e.g., to estimate sea level trends).
- ICESat-2 and SWOT should be used in conjunction to explore biases in each.
- Mean sea surface and ocean tide models need to continue to be improved for better understanding of coastal sea level.
- More near real time 5 Hz significant wave height products should be made available and ingested into operational coastal wave models to reduce biases.

5.4 Instrument Processing: Measurements and Retracking

Chairs: Francois Boy, Phil Callahan, Jean-Damien Desjonqueres, Alejandro Egido, Marco Fornari, Cristina Martin-Puig, Walter H.F. Smith

5.4.1 Summary

Summary LR and Calibrations

Some efforts are still on-going with the calibration and the retracking of LRM echoes especially to improve Sentinel-6 MF data.

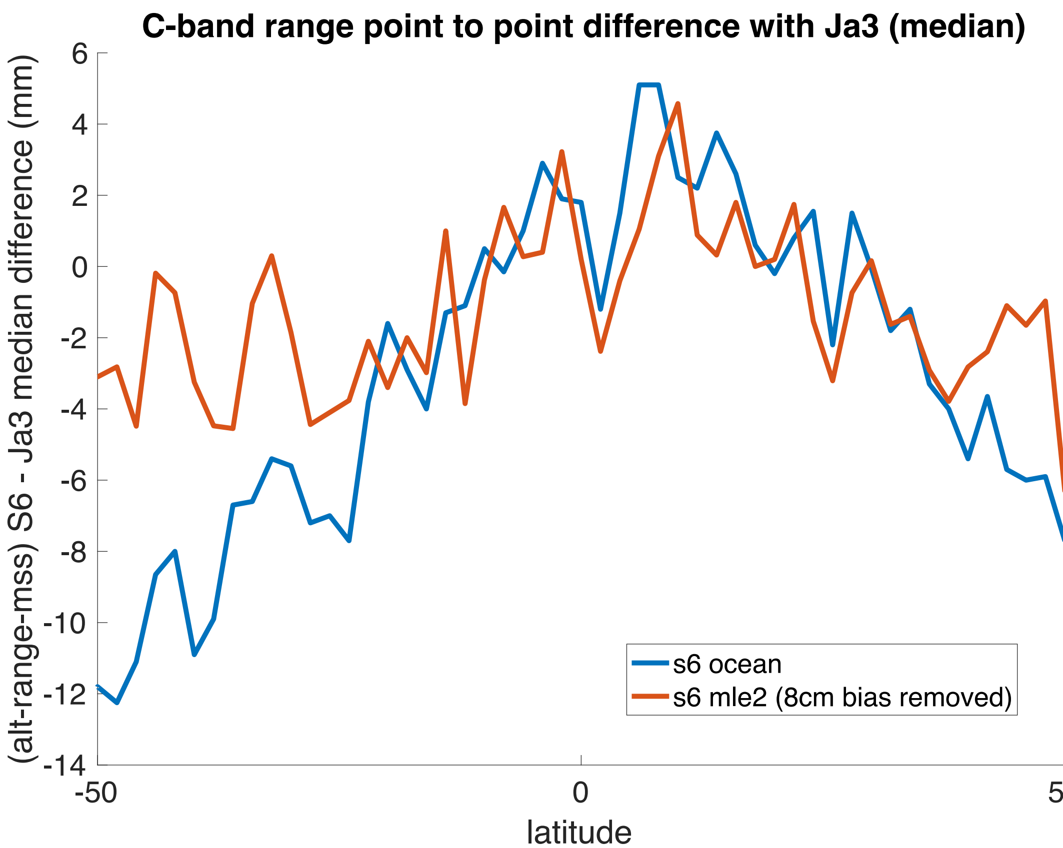


Figure 5.4-1: Jason-3 vs Sentinel-6 MF difference for height measurements derived from product ocean retracker (blue) and with a dedicated MLE-2 retracker (red).

Sentinel-6 MF C-band data present significant differences when compared with Jason-3. These differences are believed to originate with Sentinel-6 MF not Jason-3. Sentinel-6 MF C-band is noisier than for Jason-3 which makes it more challenging to process. However, algorithm changes could mitigate this. In particular, the implementation of a numerical MLE-2 retracker (Desjonquères et al., https://doi.org/10.24400/527896/a03-2023.3874, Figure 5.4-1), suppressing the Significant Wave Height C-band estimation, could improve both the noise level and agreement with Jason-3.

Using an appropriate noise model, the FastAdaptive retracking (Mangilli et al., https://doi.org/10.24400/527896/a03-2023.3780, Figure 5.4-2) would provide an optimized solution for Sentinel-6 MF LRM echoes processing. It is also a numerical retracker and therefore takes into account the altimeter Point Target Response and over all would be beneficial to the Sentinel-6 MF mission. It would ensure a good stability thanks to the use of the PTR and would not be affected by the high Pulse Repetition Frequency generating some pulse-to-pulse correlation for the LRM echoes. The FastAdaptive algorithm, while slower than the current operational numerical retracker is computationally efficient and it should be compatible with the development of a medium-term operational processor (i.e., a few years from now).

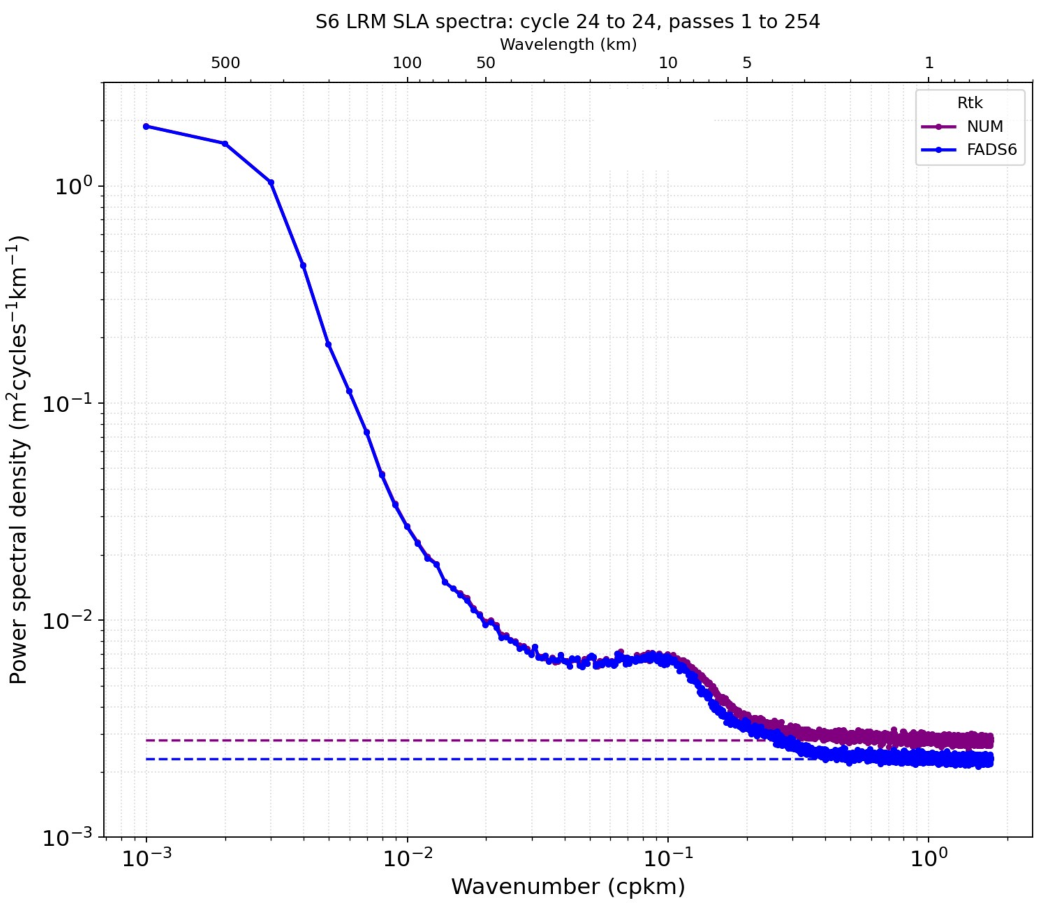


Figure 5.4-2: Sentinel-6 MF Sea Level Anomaly spectra derived from the product (purple) and from the Fast Adaptive algorithm (blue)

Results from the altimeter calibrations for the Copernicus altimetry missions (García et al., https://doi.org/10.24400/527896/a03-2023.3844) demonstrate compliance with mission requirements. Parameter evolution can be different from a mission to another one (Table 5.4-1) but without impact on data after calibration compensation. In particular, the slope of the power drop for Sentinel-6 MF at the beginning of the mission was higher than for previous missions, but it has decreased since then and has no detected impact on the derived geophysical estimations.

Calibration Parameters Drifts	Delay mm/year	Power dB/year	Width mm/year	USO mm/year
EnviSat	+ 1	– 0.15	+ 0.1	+ 3.3
CryoSat-2*	– 0.2	– 0.13	– 0.00	+ 0.5
Sentinel-3A	– 0.1	– 0.21	– 0.28	+ 3.7
Sentinel-3B	+ 0.5	– 0.24	– 0.03	+ 2.0
Sentinel-6	– 3.4	– 0.55	– 0.34	– 4.7

Table 5.4-1: Synthesis of instrumental drifts estimated from on-board calibrations.

A different approach for calibrating raw echoes has been developed, using the complex cal1 range impulse response (Dinardo et al., https://doi.org/10.24400/527896/a03-2023.3864). Such approach can compensate the raw echoes for any instrumental distortions and ease the retracking. However, this approach can only be used when processing raw waveforms (SAR) and not the onboard-generated LRM data, as that would require a deconvolution which has proved to be difficult in the past.

Summary SAR:

More and more applications emerge from the use of Fully-Focused SAR on the Sentinel-6 MF mission:

T. Moreau et al. (https://doi.org/10.24400/527896/a03-2023.3803) presented an optimal configuration of this processing for different surface types (for example the application of azimuth windowing for specular surfaces, see Figure 5.4-3) and a series of applications.

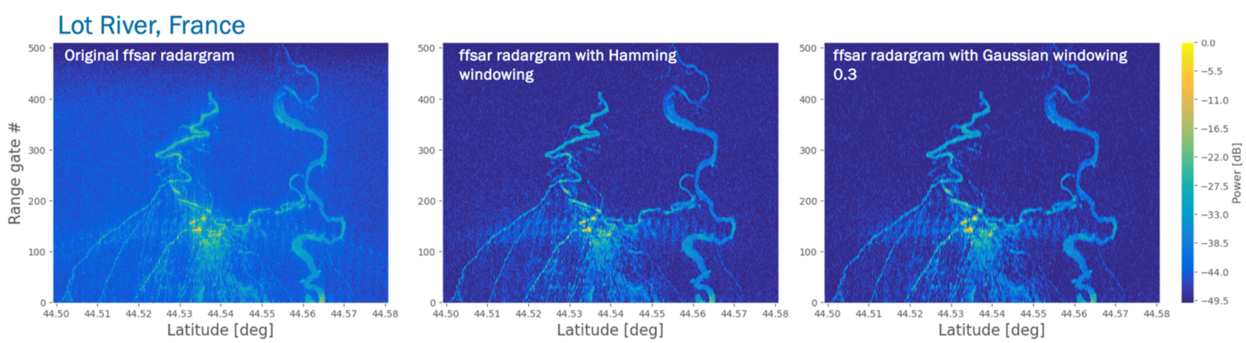


Figure 5.4-3: Application of azimuth windowing to FFSAR processing over inland waters (S6-MF)

In hydrology, exploiting the 2D FFSAR radargram, it is now possible to identify the river's features emerging as bright curves from the darker surroundings and it appears possible to retrieve water surface height even when the river is observed off-nadir (Desjonquères et al., https://doi.org/10.24400/527896/a03-2023.3875 and Daguzé et al., https://doi.org/10.24400/527896/a03-2023.3801 in poster session, Boy et al., https://doi.org/10.24400/527896/a03-2023.3781 in hydrology session).

In the open-ocean, swell waves signatures are observed as amplitude modulation in the FF-SAR radargram that can be used to derive 2D spectra featuring characteristics such as period, amplitude and direction of the swell waves. This year, Altiparmaki et al. (https://doi.org/10.24400/527896/a03-2023.3754) exploited the so-called azimuth cutoff in SAR altimetry to determine the vertical velocity variance of the ocean surface under moderate conditions. Then, Kleinherenbrink et al. (https://doi.org/10.24400/527896/a03-2023.3742) presented an extension of the Altiparmaki et al work. Cross-spectral analysis is studied to remove at least two of the four spectral ambiguities (Figure 5.4-4).

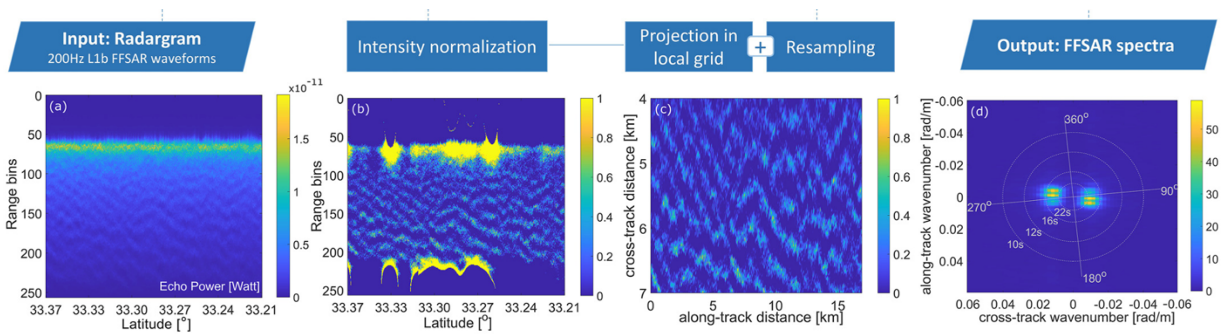


Figure 5.1-4: Processing steps to estimate wave spectra from FFSAR waveforms (Sentinel-6 MF).

- Regarding sea ice leads, T. Moreau showed another example of possible applications using FFSAR. S6-MF imagery processing can provide valuable information on lead/floe detection and coverage. C. Buchhaupt et al. (https://doi.org/10.24400/527896/a03-2023.3678) proposed a new numerical stack retracker scheme adapted for sea-ice surfaces for the Sentinel-3 UFSAR mode. He demonstrates an improvement of the backscattering power function to match sea-ice signals.

5.5 Instrument Processing: Propagation, Wind Speed and Sea State Bias

Chairs: Shannon Brown, Cristina Martin-Puig, Estelle Obligis

5.5.1 Summary

This splinter had no poster and 7 oral presentations:

- 1 about mapping methods, this one was wrongly attributed to this splinter and was moved to session Science III.
- 1 about sea state bias.
- 6 about wet tropospheric correction.

	Est. Unc. [cm]
SSB3	2.0
SSB4	2.0
SSB4 + velocity variance	1.9-2.0
SSB-VV - (no SWH)	2.5-2.7

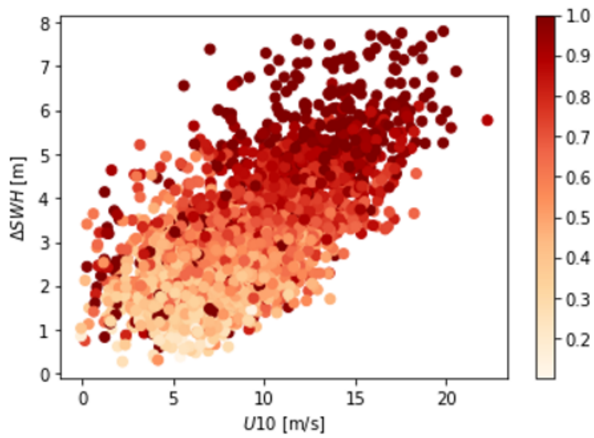


Figure 5.5-1: The table and figure show the very limited improvement of the sea state bias model.

Marcel Kleinherenbrink presented “Inclusion of the ocean's vertical velocity variance into the sea-state-bias correction” (https://doi.org/10.24400/527896/a03-2023.3747). The main conclusions of this study are (Figure 5.5-1):

- Including velocity variance has limited impact on SSB:
  - The auto correlation method is not robust enough.
  - The model data is not accurate enough.
- For swath altimeters:
  - Model data might help to reduce the SSB uncertainty.
  - ACF method on S3-NGT spectra probably yields better results.
- Looking forward:
  - Use machine-learning approaches on SAR spectra and waveform parameters.

Pedro Aguiar presented “Improved algorithms for the wet tropospheric correction over coastal regions: application to the Sentinel-3 mission” (https://doi.org/10.24400/527896/a03-2023.3726). The main conclusions of this study are (Table 5.5-1):

- The WTC retrieval over coastal regions is still a challenging process.
- The use of the open-ocean UP3S0 algorithm with modified inputs significantly improved the retrieval errors in the WTC.

- Moreover, the developed coastal algorithms, with the same modified inputs, further improved the WTC retrieval errors, from ~16 cm to 3.3 cm close to the coast.
- All the results shown are in line of agreement with the comparison against the ERA5 model.
- More work needs to be done to further improve the retrieval errors and meet the requirements for coastal altimetry applications (e.g., technological improvements on the radiometer and altimeter sensors).

Algorithm	Algorithm Description	0-5 km		
		Mean	RMS	RMS improv.
Op. 3I	Open-ocean Sentinel-3A operational algorithm, MWR TBs and SRAL σ_0	-14.1	16.2	-
O2C UP3S03	Open-ocean UP3S0 algorithm, MWR TBs modified by LF and WPD classes, and SRAL σ_0 modified by DistCoast classes	-1.2	4.4	11.8
C2C UP2	Coastal algorithm, MWR TBs modified by LF and WPD classes, and SRAL σ_0 modified by DistCoast classes	-0.7	3.6	0.8
C2C UP4	Coastal algorithm, MWR TBs modified by LF and WPD classes, SRAL σ_0 modified by DistCoast classes, and SST_{skin} and γ_{800} from the ERA5 model	-0.5	3.3	0.3

Table 5.5-1: Mean and RMS of the differences $WPD_{GNSS} - WPD_{MWR}$ in cm, for the first class of distance from coast.

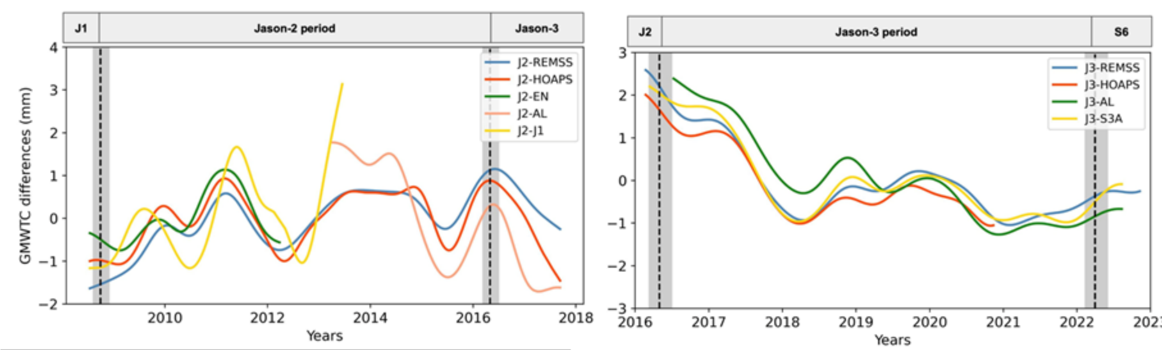


Figure 5.5-2: Comparisons between (left) CDRs, Jason-2, Envisat, SARAL/AltiKa and Jason-1 MWR WTC and (right) CDRs, Jason-3, SARAL/AltiKa and Sentinel-3A MWR WTC.

Anne Barnoud presented "Wet troposphere correction derived from water vapor climate data records" (https://doi.org/10.24400/527896/a03-2023.3729). HOAPS Vinterim and REMSS V7R2 water vapor climate data records show, in agreement with inter-mission comparisons (Figure 5.5-2):

- A drift of Jason-2 MWR WTC over 2009-2010 (about 2 mm in 2 years).
- A drift of Jason-3 MWR WTC over 2016-2018 (about 3 mm in less than 2 years).

Ralf Bennartz presented "Performances and benefits of a 1D-variational approach to retrieve the wet tropospheric correction: recent achievements for Sentinel-6 MF and Sentinel-3A and -

3B topography missions" (https://doi.org/10.24400/527896/a03-2023.3840). The main outcomes of this study are (Figure 5.5-3):

- Development of a 1Dvar method for WTC retrieval.
- Systematic comparison with neural network algorithms and model estimation.
- Proof of concept for Sentinel-6 MF in 3-TBs and 6-TBs configurations.
- Benefit of Synergetic use of Sentinel-3 MWR and SLSTR observations.

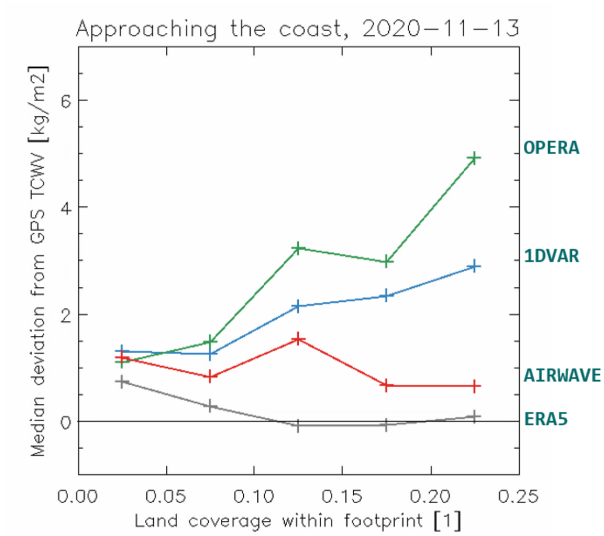


Figure 5.5-3: Median deviation from GPS TCW for different models as approaching the coast.

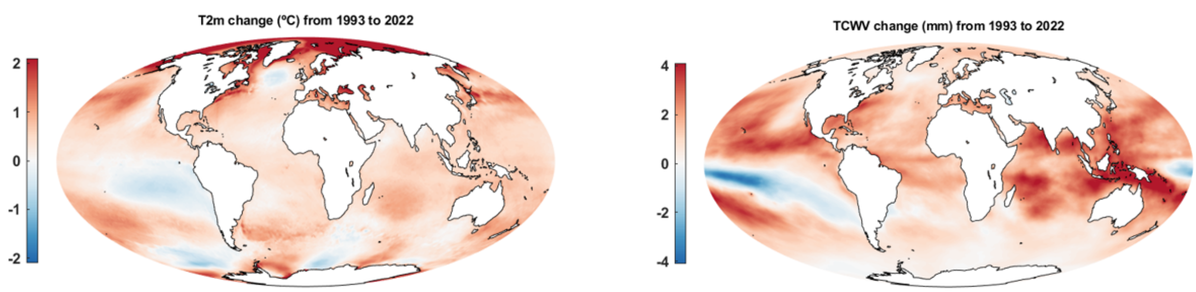


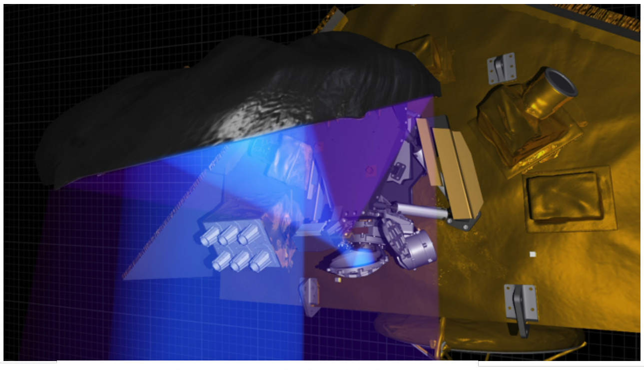
Figure 5.5-4: Global maps of (left) T2m change (global mean of +0.53 ℃, about 0.18 ℃/decade) and (right) TCWV change (global mean of +1.28 mm, about 0.43 mm/decade), from 1993 to 2022.

Telmo Vieira presented "How has global warming impacted the altimeter wet path delay over the altimetry record?" (https://doi.org/10.24400/527896/a03-2023.3784). The main outcomes of this study are (Figure 5.5-4):

- Over 1993-2022, WPD has increased at an average rate of 0.26 mm/year over the global ocean.
- Due to the global warming over these 30 years, this is a physical signal that should not be misled with any kind of drift.

Shannon Brown presented “Progress on the Wet Path Delay Correction: Historical, Current and Future” (https://doi.org/10.24400/527896/a03-2023.3701). The main outcomes of this study are (Figure 5.5-5):

- Sentinel-6 MF exhibiting climate quality calibration on NTC product due to new supplemental calibration system.
- No trends observed with uncertainty < 0.08mm/year over mission to date.
- Jason-3 long-term calibration updated and PD correction product available, appears to improve non-closure of sea level budget.
- Jason-2 GDR-F long-term calibration improved over GDR-D after 2017 (un-changed before).
- HRMR working well, shows promise for new applications for cryosphere altimeter missions, including CRISTAL.



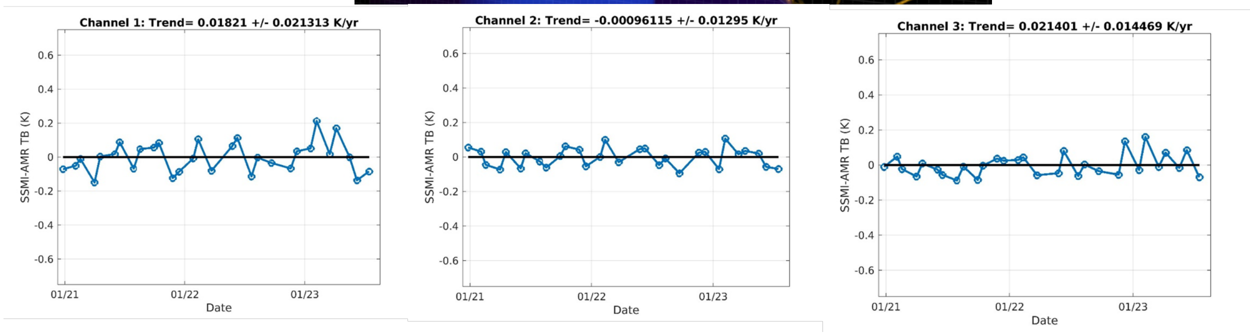


Figure 5.5-5: (Top) Model of the Sentinel-6 MF AMR instrument. (Bottom) Trends between SSMI and Sentinel-6 MF AMR brightness temperatures for the (from left to right) 18.7 GHz, 23.8 GHz, and 34.0 GHz channels.

5.5.2 Splinter Discussion Points and Recommendations

There was no specific discussion at the end of the meeting. But the chairs noted the very good progress made by the community in developing alternative methods for WTC retrieval and in developing stable WTC suitable for climatic applications.

5.6 Outreach, Education & Altimetric Data Services

Chairs: Hayley Evers-King, Jack McNelis, Vinca Rosmorduc, Margaret Srinivasan

5.6.1 Summary

Session oral presentations:

1. Raising awareness of SLA adjustments in the IMOS-Ocean Current website by Gabriela Pilo (CSIRO), David Griffin (CSIRO), https://doi.org/10.24400/527896/a03-2023.3707
2. A new dataset of relative sea level measurements created using Global Navigation Satellite System (GNSS) receivers by Andrew Matthews (National Oceanography Centre), Simon Williams (National Oceanography Centre), Chris Banks (National Oceanography Centre), https://doi.org/10.24400/527896/a03-2023.3777
3. CTOH products and altimetry applications over the ocean, coasts, and continental Surfaces by Fernando Niño (Legos / Univ. Toulouse, CNES, CNRS, IRD, UPS), Damien Allain (LEGOS / Univ. Toulouse, CNES, CNRS, IRD, UPS), Florence Birol (Legos / Univ. Toulouse, CNES, CNRS, IRD, UPS), Fabien Blarel (Legos / Univ. Toulouse, CNES, CNRS, IRD, UPS), Robin Chevrier (Legos / Univ. Toulouse, CNES, CNRS, IRD, UPS,), Wassim Fkaier (Legos / Univ. Toulouse, CNES, CNRS, IRD, UPS,), Benoît Laurent (Legos / Univ. Toulouse, CNES, CNRS, IRD, UPS), Fabien Léger (Legos / Univ. Toulouse, CNES, CNRS, IRD, UPS), Rosemary Morrow (Legos / Univ. Toulouse, CNES, CNRS, IRD, UPS), Oscar Vergara (Legos / Univ. Toulouse, CNES, CNRS, IRD, UPS), https://doi.org/10.24400/527896/a03-2023.3776
4. Altimetry Data on PODAAC by Jinbo Wang (Jet Propulsion Laboratory, California Institute of Technology, United States)
5. Altimetry Missions Applications Support: An international collaboration for the Jason-series, Sentinel 6 MF & SWOT by Margaret Srinivasan (JPL), Vardis Tsontos (JPL), Matthew Bonnema (JPL), https://doi.org/10.24400/527896/a03-2023.3872

Session posters:

6. SWOT Applications Working Group (SAWG) Report (2022-2023) by Vardis Tsontos (JPL), Margaret Srinivasan (JPL), Matt Bonnema (JPL), Santiago Peña-Luque (CNES) and Nicolas Picot (CNES), https://doi.org/10.24400/527896/a03-2023.3871

2022-2023 Highlights:

The session this year included fewer oral presentations than typical, and included talks focused on data products, a web page, and applications user support. No outreach and education or data center talks were presented. Also absent were any 'Showcase' presentations or data demonstrations. Figure 5.6-1 shows two speakers in the session, Gabriel Pilo (left) and Jinbo Wang (right).

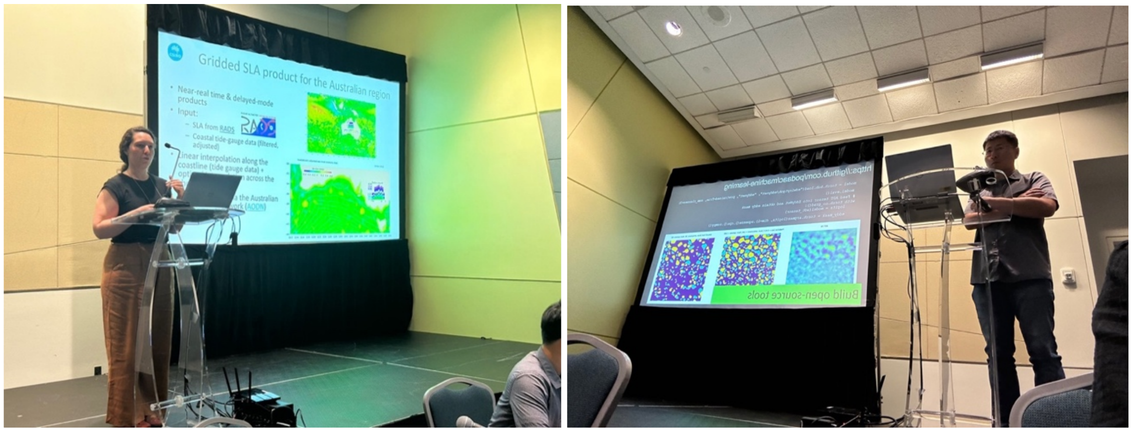


Figure 5.6-1: ODS Splinter photos; Left, Gabriela Pilo (CSIRO); Right, Jinbo Wang (JPL).

Data services and Operational Applications:

Talks this year focused on data services and operational Applications topics. Although some outreach activities were discussed, no talks were specific to outreach or educational activities. No student groups participated this year.

Data Services provide a method and process for exchanging information and linking projects and users for greater benefit from the wide variety of altimetry-derived available datasets. Gabriela Pilo (CSIRO; https://doi.org/10.24400/527896/a03-2023.3707) focused on data visualization service developed by the Australian Integrated Marine Observing System (IMOS), a joint collaboration of a number of academic and research organizations, for use by researchers and the general public for current and past current conditions in the ocean surrounding Australia. Examples illustrated various sea level heigh anomaly map options including coastal tide gauge data and several interpolation products.

Another presentation from the UK National Oceanography Center (NOC, Andrew Matthews, Simon Williams, and Chris Banks; https://doi.org/10.24400/527896/a03-2023.3777) highlighted a new dataset using global navigation satellite system (GNSS) receivers to measure relative sea level. NOC is now installing dedicated GNSS-IR receivers alongside traditional tide gauges. They introduced the 'Permanent Service for Mean Sea Level' (PSMSL) data portal which includes example notebooks, and their work on developing a mechanism to deliver near real-time GNSS-IR data to users.

Fernando Niño (LEGOS CNRS/CNES/IRD/University Toulouse III; https://doi.org/10.24400/527896/a03-2023.3776) provided an overview of the French Center for Ocean Topography and the Hydrosphere (CTOH) data products updates for ocean coastal and hydrology products, and plans for SWOT data when available.

Jinbo Wang (JPL) provided an update and overview of existing products and future plans for satellite altimetry data at the NASA Physical Oceanography Data Active Archive Center (PO.DAAC). Products and services for the Jason-series and SWOT missions, including new cloud access and processing systems and services were highlighted, as well as plans and examples of NASA's Open Data and open science initiatives.

The last talk in the session was presented by splinter Co-Chair Margaret Srinivasan (JPL; https://doi.org/10.24400/527896/a03-2023.3872) to outline efforts at NASA and JPL, along with international partners to enhance the use of the full time series of satellite altimetry data to support operational and applied uses of the data. Examples of a number of these user groups were highlighted.

The sole poster for the ODS Splinter was presented by Vardis Tsontos (JPL), Margaret Srinivasan (JPL), Matt Bonnema (JPL), Santiago Peña-Luque (CNES) and Nicolas Picot (CNES); https://doi.org/10.24400/527896/a03-2023.3871. It featured an annual report on the SWOT Applications Working Group (SAWG) rather than the listed topic of more general altimetry applications.

5.6.2 Splinter Discussion Points and Recommendations

- Future meeting topics:

Feedback from past meetings, data centers and projects continue to be relevant for the ODS splinter. In future meetings, the session would benefit from highlights representing all ocean and hydrology satellite altimetry mission data centers and projects, as well as highlights from science team activities related to outreach and educational activities at their institutions.

- Developing exchanges on outreach and training:

As proposed in the 2022 OSTST ODS splinter report, a workshop format on the training material and on outreach 'good practices' could benefit OSTST members and their colleagues and students. The Showcase element of the ODS splinter has traditionally been a quick and convenient way, using minimal or no slides, to share experiences and examples of outreach and educational activities and opportunities at OSTST members or outside institutions. We plan to promote this activity more strongly in the future.

- New Planned Efforts:

The focus of the outreach team for the coming years will be on climate (particularly including sea level rise) and hydrology education, public outreach, as well as on applications outreach for current and upcoming ocean altimetry missions—Sentinel-6B and beyond. The outreach team will compile a list of activities planned by current participants, identifying areas for collaboration. The anticipated elements of this focus (not withstanding new arising opportunities) will include:

1. SWOT education & public outreach
2. SWOT Applications focus on Early Adopters and other applied science users
3. Sentinel-6 MF and Sentinel 6B applications (including GNSS-related)
4. Training events, to include (with suggested audience):

a. Routine data access workflows/cloud use (data managers, new and established users)
b. Altimetry 101 (Early career scientists/engineers - attracting next generation to technical altimetry)
c. Specific applied uses (multi-mission) e.g. extreme waves, mean sea level, marine mammals, and fisheries (applied users/general awareness for policy makers etc.

5.7 Precise Orbit Determination

Chairs: Sean Bruinsma, Alexandre Couhert and Frank Lemoine

5.7.1 Summary

The POD session at the 2023 OSTST meeting included eight oral and five forum presentations. Four of the presentations focused on the reference altimetry missions (T/P, Jason-1/-2/-3, Sentinel-6 MF) with contributions from the CNES (Moyard et al., https://doi.org/10.24400/527896/a03-2023.3863), the CPOD (Fernandez et al., https://doi.org/10.24400/527896/a03-2023.3725), NASA/GSFC (Lemoine et al., https://doi.org/10.24400/527896/a03-2023.3866), and JPL (Conrad et al., https://doi.org/10.24400/527896/a03-2023.3842). Two presentations were made by Thales Aliena Space and CNES and addressed the performance of the new altimetry mission SWOT (Couhert et al., https://doi.org/10.24400/527896/a03-2023.3877; d'Este et al., https://doi.org/10.24400/527896/a03-2023.3772). Various complementary analyses were also shown on the effect of ITRF2020 for the POD of altimetry satellites (DGFI-TUM, Rudenko et al., https://doi.org/10.24400/527896/a03-2023.3719; CNES, Saquet et al., https://doi.org/10.24400/527896/a03-2023.3856), improvements in the modeling of Earth radiation pressure (CNES-IPGP, Nocet-Binois et al., https://doi.org/10.24400/527896/a03-2023.3869), time variable gravity field (CNES, Lemoine et al., https://doi.org/10.24400/527896/a03-2023.3882), direct Solar Radiation Pressure (CLS-CNES, Cherrier et al., https://doi.org/10.24400/527896/a03-2023.3851), and in using POD observations to empirically absorb residual SRP modeling errors (CLS-CNES, Katsigianni et al., https://doi.org/10.24400/527896/a03-2023.3688) and calibrate in-flight systematic GNSS measurement errors (CLS-CNES, Banos Garcia et al., https://doi.org/10.24400/527896/a03-2023.3850).

Mission	Gravity field	POD residuals		Xover residuals (cm)	Radial orbit RMS difference (mm)	
		DORIS (mm/s)	SLR (mm)		poef	std2300
TOPEX (930120-041101)	std2300	0.5125	**14.73**	**5.602**	**8.8**	----
	GRGS RL05	0.5125	**14.79**	**5.596**	**8.6**	3.3
Jason-1 (020115-090126)	std2300	0.3883	**0.758**	5.486	7.5	----
	GRGS RL05	0.3883	0.772	**5.483**	**7.2**	3.5
Jason-2 (080712-161002)	std2300	0.3906	7.09	5.292	6.2	----
	GRGS RL05	0.3906	7.09	5.292	6.2	2.8
Jason-3 (160217-230828)	std2300	**0.3911**	**5.85**	**5.166**	**6.1**	----
	GRGS RL05	**0.3909**	**5.81**	**5.157**	**5.9**	3.4

Table 5.7-1: Comparison of TOPEX-Poseidon/Jason-1/Jason-2/Jason-3 GSFC DORIS+SLR std2300 and std2300+CNES_GRGS_RL05 gravity field with CNES POE-F DORIS+GPS reduced dynamic orbits (Lemoine et al., https://doi.org/10.24400/527896/a03-2023.3866).

5.7.1.1 POD status

Both the Copernicus mission POD and CNES/JPL/NASA POD analyses are nominal. The current set of reference orbits agrees well with average radial RMS differences of 8-9 mm for TOPEX/Poseidon, 7-8 mm for Jason-1, 6-7 mm for Jason-2, 5-6 mm for Jason-3 (see Table 5.7-1). The NASA GSFC std2300 and the CNES POE-G series of orbits have switched to ITRF2020. The next set of CNES POE-G Standards will be deployed in 2024 first for Jason-3 and Sentinel-6 MF, before initiating the reprocessing for other missions.

5.7.1.2 SWOT

Thanks to the satellite development team and the stringent design constraints that were accounted for (despite the size of the spacecraft) to meet the POD needs of SWOT, the early inflight results show 3D and radial POD accuracies of < 1.2 and < 0.8 cm RMS, respectively. An accurate calibration of the GPS, DORIS, and SLR phase centers (and/or Center of Mass knowledge issues) owing to the yaw flips still has to be done. To this aim, independent DORIS-derived and GPS-based orbits will be useful to disentangle the CoM from phase center location errors and possible time-tag inconsistencies.

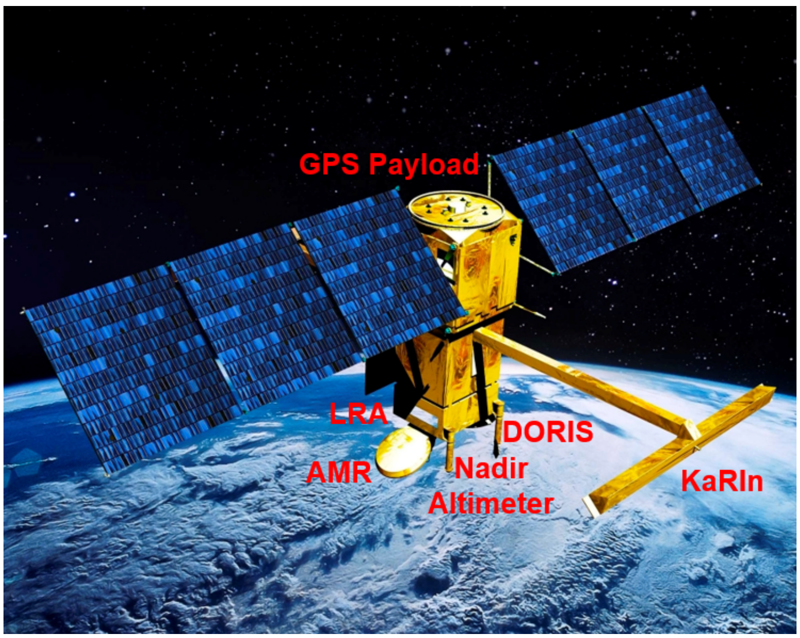


Figure 5.7-1: SWOT satellite and its POD instruments.

5.7.2 Splinter Discussion Points and Recommendations

5.7.2.1 Climate quality accuracy in future missions

Climate requirements on reference missions, such as Sentinel-6 and Sentinel-6-NG (Next Generation), imply new drift constraints on POD, especially at basin scales (for regional sea level rates detection and quantification). Stabilities of 0.1 mm/year per decade are now requested regionally in terms of orbit accuracy (Meyssignac et al., 2023). One can only recommend starting to derive regional radial orbit error budgets for the currently available solutions for the decadal time series J2-J3-S6, with groups willing to contribute to a common paper. This would provide a first assessment of the efforts left to reach this target.

In addition to this point, the OSTST wrote up this recommendation dedicated to the POD tracking observations: "To achieve accuracy in global and regional sea level change as detailed in GCOS requirements, it will be necessary to maintain and continue to improve accuracy of orbital determination systems, such as those achieved using a combination of SLR, DORIS and GNSS. The OSTST has demonstrated that three tracking systems (GNSS, DORIS and SLR) are necessary to achieve maximum accuracy on the determination of regional sea level trends, and it strongly recommends that such accuracy be maintained in the design of Sentinel-6C. The OSTST also noted that accuracy of the Climate Data Record requires continued maintenance or improvement of the terrestrial reference frame, which also relies on these tracking systems. Finally, requirements on other aspects of the altimetric measurement system must also be maintained or continue to improve."

5.7.2.2 Future ways for improvements

Meeting these new climate-driven needs will require that we tackle a variety of limitations that affect both the current dynamic and measurement models used in POD. A list of recommendations, which should be considered regarding this challenge for satellite altimetry, is detailed below:

- Satellite and orbit design: (i) Improve CoM knowledge; (ii) the stability of surface properties (related to radiation reflection, emission and absorption); and (iii) avoid a spacecraft design that introduces self-shadowing of different elements w.r.t to incoming radiation; (iv) Embark accelerometers to validate independently the macro models; (v) For the attitude law, design missions to include yaw flips and yaw steering attitudes to facilitate observation of errors in POD parameters.
- Tracking systems: (i) Better understand systematic errors and their impact on orbit stability (or their ability to observe it); (ii) Include multiple independent tracking techniques is essential; (iii) Improve the quality of the tracking techniques and the data that they provide; (iv) Support the densification of the SLR network, especially in the Southern Hemisphere.
- Geocentric motion: Include tidal, non-tidal (annual and semi-annual), interannual models and/or observations.
- Integrating equations of motion: Incorporate background measurement and dynamic model uncertainties into POD for altimeter satellites. It would be useful if these uncertainties were provided with these models, which is not always the case.
- Reference frames: Resolve inter-technique inconsistencies between the reference frame-defining parameters.

- Mass change observations by satellite: Support next generation gravity missions (Mass Change, MAGIC) to assure continuous observations. We need continuous observations of time-variable gravity provided by GRACE-FO like missions as an input for precise POD modeling.
- Last but not least: Satellite missions are not independent of each other; since users will incorporate all available data into their analyses. Thus, reaching these new targets for climate-driven goals for altimetry means that we should consider the requirements of complementary altimeter missions (other than the reference missions).

5.8 Regional and Global CAL/VAL for Assembling a Climate Data Record

Chairs: Pascal Bonnefond, Shailen Desai, Luisella Giulicchi, Bruce Haines, Eric Leuliette, and Nicolas Picot

Determining the random and systematic errors in the fundamental instrument observations and in the Level-2 geophysical data products is a continuing process that involves participation of both the project teams, dedicated validation teams (e.g. S3VT and S6VT), and the OSTST investigators. The principal objectives of joint verification are to:

1. Assess the performance of the measurement system, including the altimeter and orbit-determination subsystems;
2. Improve ground and on-board processing;
3. Enable a seamless and accurate connection between the current (Jason-3 and Sentinel-6 MF) and legacy (TOPEX/Poseidon and Jason-1,2,3) time series;
4. Enable the development of Level 3 and Level 4 products by an accurate analysis of any regional bias between the reference mission and the other flying altimeters (currently SARAL/AltiKa, Sentinel-3A & B, CryoSat-2, HY-2, and SWOT).

To succeed in these objectives, the general approach is to pool the talents and resources of the project and science teams. Engaging the science team in the continuous CALVAL effort has been one of the hallmarks of success for the TOPEX/Poseidon and Jason altimeter programs. The CNES and NASA research announcements have consistently emphasized CALVAL, recognizing that the science investigators conducting research in some of the most demanding applications (e.g., mean sea level) are often positioned to offer the most innovative CALVAL solutions.

During the first few months of each new mission, an intensive verification effort is conducted by all members of the Verification Team in order to verify the integrity of the system—and to perform adjustments where necessary—before starting the routine GDR/NTC production. However, the verification effort continues afterwards on a routine and permanent basis. These ongoing efforts are essential for understanding and minimizing regionally correlated errors, and for ensuring the integrity of the long-term climate record at the 1-mm/yr level.

CALVAL activities are conducted based on dedicated in-situ observations, statistics, cross comparisons between models, different algorithms and external satellite data. The studies go well beyond validation of the overarching error budget underlying the mission requirements. They focus particularly on the temporal and geographically correlated characteristics of the errors. Reduction of this class of errors is critical, since they are conspicuously damaging to estimates of ocean circulation and sea level. CALVAL activities also encompass issues related to data return, such as data editing and flagging. We also encourage CALVAL presentations on specialized topics, such as the characterization of SSH in Arctic Ocean sea ice leads, and the examination of the impacts of SWH, swell, and roughness on SSH data quality.

Because of the usual large number of contributions, the CALVAL splinter is separated into two parts:

1. Local CALVAL (focusing on bias estimates from in-situ measurements) and
2. Global CALVAL (focusing on relative SSH biases between different missions, the assessments of correction terms and error budget).

This year's Cal/Val sessions consisted of 12 oral presentations, 14 poster presentations and 5 forum only contributions. Presentations spanned calibration and/or validation results with in-situ or global methods from numerous missions ranging from TOPEX/Poseidon, Jason-1,2,3 and Sentinel-6 MF, Sentinel-3A and 3B, HY-2B, SARAL/AltiKa, CryoSat-2, and SWOT.

5.8.1 Summary of results from regional studies and in-situ calibration sites

Table 5.8-1. Absolute SSH bias values (in mm) for different missions and from the different calibration sites (using in-situ SSH measurements)

Mission	Bass Strait	Harvest	Corsica	Gavdos	Average
TOPEX-A MGDR†	+4	+7	+25		**+12**
POSEIDON-1		–11	+12		**0**
TOPEX-B MGDR†	+17	+6	+24		**+16**
Jason-1 GDR-E	+42	+12	+43	+41	**+34**
Jason-2 GDR-D	+15	+8	+16	+5	**+11**
Jason-3 GDR-F	–4	+14	+4	–2	**+3**
Sentinel-6 MF F08 (LRM MLE4, side A)	–6	+28	+4	–17*	**+2**
Sentinel-6 MF F08 (LRM MLE4, side B)	–4	+35	+9	–17*	**+6**
Sentinel-6 MF F08 (SAR (HR), side A)	–8		+8		**0**
Sentinel-6 MF F08 (SAR (HR), side B)	–7		+11		**+2**
Sentinel 3A BC_005 (SAR)			+15	–5	**+5**
Sentinel-3B BC_005 (SAR)				–5	**-5**

*Average from side A&B for Sentinel-6 MF at Gavdos

†TOPEX MGDR + orbit from GSFC + radiometer correction

The Harvest Platform operated as the NASA Prime Verification site from 1992 to 2022, when the instruments were powered off as the platform is prepared for decommissioning. Haines et al. (https://doi.org/10.24400/527896/a03-2023.3834) presented results from new observation systems designed to ensure continuity and preserve the historical record. Calibration metrics from GNSS buoys deployed near Harvest are competitive with those from the platform, except under high wave conditions (https://doi.org/10.24400/527896/a03-2023.3713). Preliminary results from a new tide gauge installed at Vandenberg Space Force Base demonstrate promise, emphasizing the stability of land as an advantage compared to the platform. Coupled with assets on Catalina Island, particularly a new dual-band transponder, (Desjonqueres et al., https://doi.org/10.24400/527896/a03-2023.3728), results from Harvest and vicinity will continue to provide insights on current and future altimetric systems.

Results from the dedicated facility at Corsica presented by Bonnefond et al. (https://doi.org/10.24400/527896/a03-2023.3710) showed stability in the Sentinel-6 MF bias with no major changes from baseline processor F06 to F08, except for the addition of Low-Resolution (LR) Numerical Retracking (NR). NR/LR shows a small improvement in SSH bias standard deviation (SSH bias lower by 3.7 mm for LR NR compared to MLE4). LR NR also provides better agreement with Jason-3 than MLE4. Validation using all overflying satellites over a 13-year period shows a good consistency (12.6 mm rms). A poster detailed the extension of the Corsica facilities to include SWOT cal/val (https://doi.org/10.24400/527896/a03-2023.3709) with very promising results for both the SWOT-Nadir SSH bias and comparisons with swath SSH from KaRIn.

The GNSS buoy array in the Bass Strait provided crucial insights into SWOT over the Fast-Sampling (1-day repeat) Phase (Watson et al., https://doi.org/10.24400/527896/a03-2023.3761). The results were complemented by additional findings presented during the Sentinel-6 Validation Team Meeting (https://doi.org/10.24400/527896/a03-2023.3760), providing a comprehensive understanding of intra-swath variability and the validity of corrections for Jason-3 and Sentinel-6 MF.

The ESA Permanent Facility for Altimetry Calibration (PFAC) includes a transponder installed in Crete at a crossover point of the Jason/Sentinel-6 and Sentinel-3 ground tracks, which continues to provide absolute calibration results focused on the altimeter range component of the measurement systems. Mertikas et al. (https://doi.org/10.24400/527896/a03-2023.3765) presented updated range and SSH bias results for monitoring Sentinel-3 and Sentinel-6MF. The uncertainty budget in Fiducial Reference Measurement (FRM) standards was elucidated, along with insights into the absolute calibration of the HY-2B mission in a poster (https://doi.org/10.24400/527896/a03-2023.3766).

For the tandem phase of Jason-3 (J3) and Sentinel-6 MF (S6MF), the intermission SSH bias from all sites agree at the few mm level (Figure 5.8-1). These results reflect the cancellation of common-mode errors due to the satellites flying over each site in formation. The overall average of +6.9 mm (S6 Side B higher than J3) is indeed very close to the comparable figure from global analysis (+7.2 mm) over the same time period. If the intermission SSH biases are computed instead from the entire calibration record for each site (not just the tandem phase), the results are somewhat less consistent, due primarily to Harvest. This site has experienced an unexplained uptick (starting in 2018), which renders Jason-3 SSH bias estimates from early overflights systematically lower than those from recent overflights. This puzzling feature is under investigation.

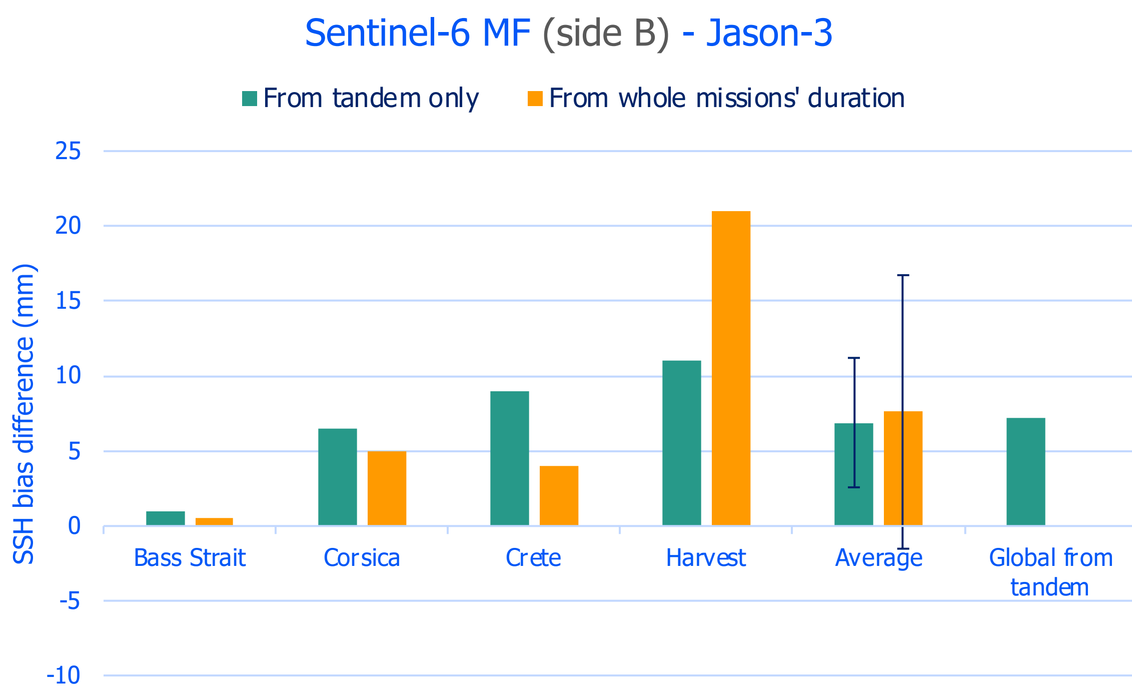


Figure 5.8-1. Intermission biases between Sentinel-6 MF and Jason-3 from the estimates of the absolute SSH bias at various calibration sites (Bonnefond et al., [Corsica], Haines et al. [Harvest], Mertikas et al. [Gavdos], Watson et al. [Bass Strait])

The accuracy of corner reflectors was highlighted in two presentations (Gibert et al., https://doi.org/10.24400/527896/a03-2023.3827 and Maraldi et al., https://doi.org/10.24400/527896/a03-2023.3791), demonstrating an equivalence to active transponders with high stability in the range and sigma0. The critical importance of site selection for the success of corner reflectors was emphasized.

Leuliette et al. (https://doi.org/10.24400/527896/a03-2023.3861) reported on the stability of sea level measurements from the altimeter constellation using selected gauge data from the University of Hawaii Sea Level Center (Figure 5.8-2). Sea surface heights from GDR-F Jason-3 and F08 Sentinel-6 MF Low-Resolution (LR) MLE4 retracker demonstrated no significant drifts, but challenges in comparing gauges with the S6MF LR Numerical Retracker (NR) were noted. A known error in F08 for low wave heights increases the variance in the residuals near some gauges. For the Sentinel-3 missions no significant drifts were detected in either SAR or PLRM products, and the Sentinel-3A SAR drift (BC_005) was reduced from BC_004. The 30-year reference mission/tide gauge comparison offered a comprehensive understanding of the stability of different missions. Matthews et al. (https://doi.org/10.24400/527896/a03-2023.3778) presented a poster on long-term sea level data from tide gauges from the Permanent Service for Mean Sea Level (PSMSL).

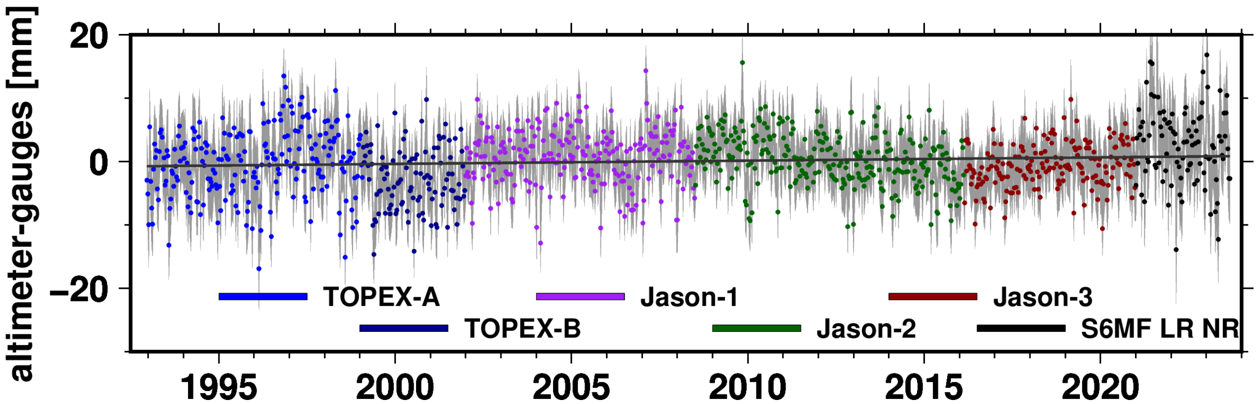


Figure 5.8-2. The altimeter minus tide gauge residuals from the 30-year reference series record are consistent with no drift (0.05 ± 0.8 mm/year, 95% CI) Leuliette et al. The higher noise in the Sentinel-6MF Low-Resolution Numerical Retracker residuals is attributable to the known error in low wave heights in Baseline F08.

The study by Lichtman et al. (https://doi.org/10.24400/527896/a03-2023.3809) focused on the validation of the Surface Water and Ocean Topography (SWOT) mission in coastal zones, using a case study in the Bristol Channel and Severn River-Estuary system. A merged Level 3 (L3) product, derived from the KaRIn swath and nadir altimeter data, has a resolution of 2 km. Adjustments were made to facilitate the comparison with water level gauges (WLG) and the results were compared to those from similar analysis using CryoSat-2 and Sentinel-3. Data from SWOT, CryoSat-2 and Sentinel-3 exhibited similar agreement to the WLG observations, demonstrating a slope close to 1:1 (in scatter plots) and an RMSE ranging between 0.2 to 0.4 m. The so-called noiseless data (SWOT L3 product) showcased the improvement achieved by removing data close to the shore.

Saraceno et al. (https://doi.org/10.24400/527896/a03-2023.3828) presented the PATASWOT experiment, where two moorings were deployed in the Argentine Patagonian Continental Shelf under the 1-day repeat track of SWOT during Fast-Sampling Phase. These moorings were equipped with Conductivity, Temperature, and Depth (CTD) recorders along with upper-looking current meters. Preliminary results from the experiment revealed disparities between CMEMS/AVISO gridded and along-track data patterns and observations from SWOT. Hovmöller diagrams suggest the propagation of a signal approximately 1 m/s towards the south. These findings emphasize the importance of real-world Cal/Val experiments in ensuring the accuracy and reliability of SWOT observations in dynamic coastal environments.

5.8.2 Summary of global validation studies

Nilsson et al. (https://doi.org/10.24400/527896/a03-2023.3755) presented global validations of the performance of the Jason-3 mission. Despite the change to the interleaved orbit, there was no major impact on the system's performance. An observed change in significant wave height (SWH), after the orbit shift, stabilized within one year. Overall, the Jason-3 mission demonstrated good system performance, a conclusion further supported by the findings presented by Flamant et al. (https://doi.org/10.24400/527896/a03-2023.3793).

Flamant et al. (https://doi.org/10.24400/527896/a03-2023.3793) presented the assessment of Jason-3 GDR-F mission performances over the ocean, demonstrating very good performances of the reference MLE4 Jason-3 GDR-F SLA. No visible degradation of products due to instrument aging was observed, and the new orbit had minimal impact on performance. Adaptive retracker outputs allowed for improvements, with SLA Adaptive data proving globally more valid than SLA MLE4 data. Taking into account valid points in both datasets, the adaptive solution exhibited superior performance over seven years (2016/02 to 2023/02), resulting in reduced variance (–0.13 cm^2) of along-track 1Hz SLA. This reinforces similar findings for Jason-2 from Roinard et al.

Piras et al. (https://doi.org/10.24400/527896/a03-2023.3811) presented the outstanding performances of the newly reprocessed ERS-1, ERS-2, and ENVISAT products, known as the FDR4ALT products. Clear improvements were evident compared to former datasets such as REAPER and ENVISAT V3.0. The Sea-Ice Thematic Data Products (TDP) performances have been published in Bocquet et al. 2023 and two additional papers (land-ice and the general project) are in preparation. Anticipated availability to end-users, along with associated documentation, was expected by the end of 2023.

Banks et al. (https://doi.org/10.24400/527896/a03-2023.3767) and Naeije et al. (https://doi.org/10.24400/527896/a03-2023.3771) focused on the ongoing validation and recent improvements to the ESA CryoSat Ocean Products. CryoSat-2 continues providing high-quality ocean data after more than 13 years. The unique orbit of CryoSat-2 provides complementary coverage to other altimetry missions, and the forthcoming Baseline D products are expected to provide further improvements.

Nencioli et al. (https://doi.org/10.24400/527896/a03-2023.3846) presented the validation of Sentinel-3A/B baseline collection BC_005 over the ocean. The recent full mission reprocessing ensures consistency from the mission's inception to the present (represented by data produced operationally). Geographically-correlated errors at the millimeter scale were effectively mitigated, resulting in improved overall SSHA performance. Reductions in cross-over SSHA standard deviation and the elimination of a small spectral bump were notable achievements. Enhanced long-term SSHA stability from both missions, which are now better aligned with the reference missions (Jason-3 and Sentinel-6 MF, see Figure 5.8-3) and in-situ tide-gauge observations.

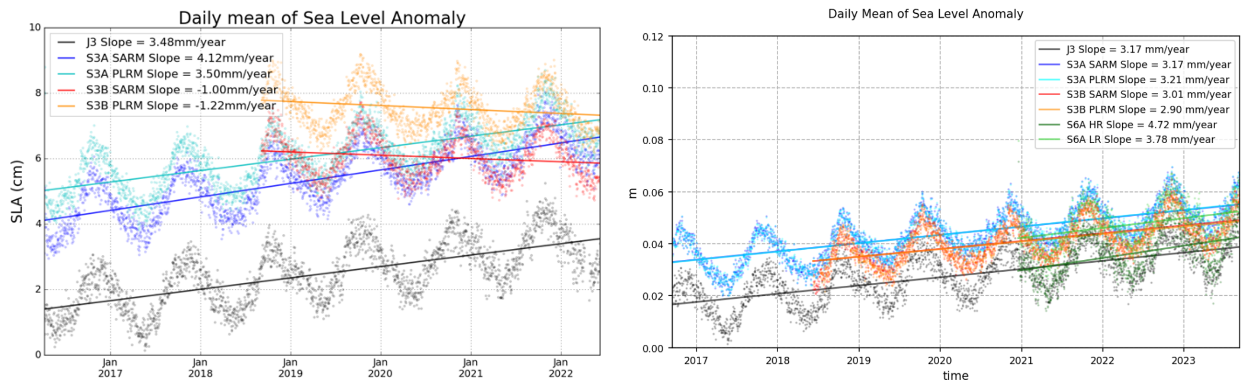


Figure 5.8-3. Global mean sea level computed from Sentinel-3 baseline collection BC_005 (right) are more consistent than BC_004 (left) for both Pseudo-Low Resolution Mode (PLRM) and SAR Mode (SARM) processing. Nencioli et al.

Kocha et al. (https://doi.org/10.24400/527896/a03-2023.3804) presented the results of the 30-year reprocessing of sea level anomaly data aimed at improving climate and mesoscale satellite data records. The DT2024 reprocessing showcased mesoscale improvements, particularly in coastal and polar regions, as well as the improved continuity of mean sea level. The global mean sea level (GMSL) of reference has been recomputed with the new standard L2+, with availability expected soon on AVISO in 2024. A higher resolution dataset (1Hz -> 20Hz) is also available (https://doi.org/10.24400/527896/a03-2023.3805), offering a more detailed assessment of sea level anomaly products. The presentation further detailed accessible platforms for downloading data and highlighted additional posters on related topics, including obtaining satellite data closer to in-situ data on wind wave Copernicus service products.

An assessment of reprocessed TOPEX GDR-F products from Forster et al., (https://doi.org/10.24400/527896/a03-2023.3833) revealed notable improvements in sea surface height anomaly (SSHA) estimation. The enhancements were attributed to updated geophysical models and an improved orbit solution, contributing to the largest improvement in SSHA performance. The application of numerical retracking proved instrumental in improving side-A range, significant wave height (SWH) stability, and mitigating hemispherical errors in both side-A and side-B. Additionally, improved consistency with the successor mission Jason-1 was observed, demonstrating better geographical correlation and significantly enhanced stability between TOPEX GDR-F and Jason-1 GDR-E (Figure 5.8-4). The consistency of the long-term trend was underscored, providing valuable insights into sea level rise impacts. Quet et al. (https://doi.org/10.24400/527896/a03-2023.3795) presented a poster on the estimation of the TOPEX side-A/B bias. and Beckley et al. (https://doi.org/10.24400/527896/a03-2023.3813) discussed the impacts of TOPEX GDR-F results on sea level rise estimates (Figure 5.8-5). Barnoud et al. (https://doi.org/10.24400/527896/a03-2023.3730) discussed improved consistency of long-term trends, for discussion on sea level rise impact in the framework of ASELSU project.

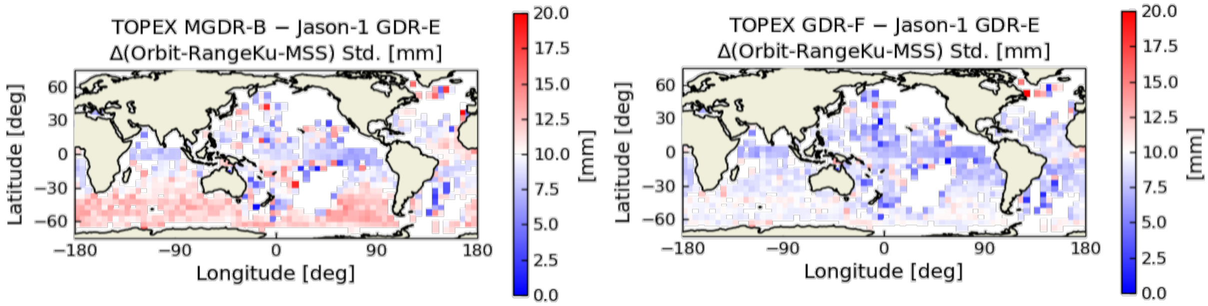


Figure 5.8-4. Improved consistency between TOPEX and Jason-1 during the tandem phase using GDR-F products (right) compared to MGDR-B products (left) from Forster et al.

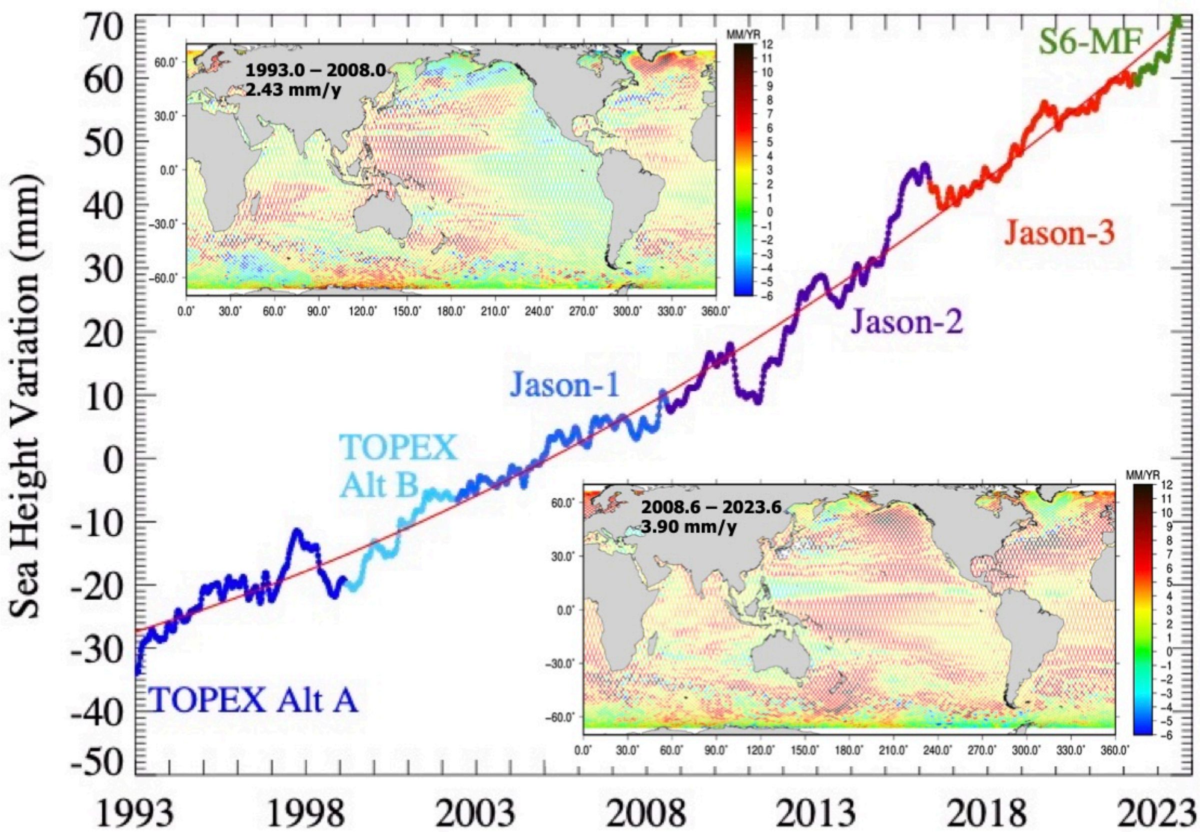


Figure 5.8-5. Global mean sea level variations from 1993 to mid 2023 are estimated (Beckley et al.) from TOPEX, Jason, and S6-MF (F08) altimetry based on GSFC std2006_cs21 orbits, TOPEX GDR-F data, and radiometer recalibrations. The red line is the quadratic fit to the SSH variations after removal of annual and semi-annual signal and application of GIA. The linear sea level rate is estimated at 3.14 mm/y ± 0.4 mm/y with an acceleration of 0.096 mm/y^2 ± 0.025 mm/y^2. Regional sea level rates are shown above (left inset) for the first 15-years and last 15-years (right inset) of the TOPEX/Jason/S6-MF sea surface height time series. The revised GMSL reduces the ocean mass budget misclosure during the GRACE Follow-On (GFO) era by ~40% (RMS reduction of 2.2 mm).

“The impact of reprocessing Jason-2 to GDR-F standards,” as presented by Roinard et al. (doi 10.24400/527896/a03-2023.3816), showcased very good performances of the reference Maximum Likelihood Estimation 4 (MLE4) Jason-2 GDR-F sea level anomaly (SLA). Taking into account valid data in both datasets, however, the adaptive retracker outperformed MLE4, resulting in reduced variances of SSH difference at crossovers (–0.5 cm^2) and along-track 1-Hz SLA (–0.7 cm^2). The findings underscored the potential for adaptive retracker solutions to enhance the overall quality and accuracy of altimetry data.

Philipps et al. (https://doi.org/10.24400/527896/a03-2023.3848) conducted a comprehensive global ocean data quality assessment of SARAL/AltiKa GDR-F products. Despite the mission being in its eleventh year and having spent over seven years in a drifting orbit, the performance remained excellent compared to Jason-2 and Jason-3. The assessment highlighted the mission's longevity and sustained high-quality performance in altimetry data acquisition.

Philip et al. (https://doi.org/10.24400/527896/a03-2023.3836) presented results indicating promising data quality for Haiyang-2D, aligning with the previous HY-2B and HY-2C satellites. The assessment positioned HY-2D as a strong candidate for potential integration into multi-mission products such as DUACS (Data Unification and Altimeter Combination System) and CMEMS (Copernicus Marine Environment Monitoring Service). The findings underscored the reliability and compatibility of HY-2D data for assimilation into operational ocean monitoring products.

5.9 Science I: Climate data records for understanding the causes of global and regional sea level variability and change

Chairs: Anne Barnoud, Ben Hamlington and Benoit Meyssignac

5.9.1 Summary

The session was evenly split between global and regional studies on trends and accelerations during the altimeter record. Across these presentations, there was a specific focus on three topics in particular: 1) improved estimation of the trends, accelerations and their uncertainties and implications for budget studies; 2) interpretation of the satellite altimeter trends and accelerations using model-based approaches; 3) local and regional studies on sea level trends with the objective of attribution to underlying processes. These three areas along with associated conclusions and key discussion points are described below.

As the satellite and in situ records have lengthened, the altimeter trends and acceleration both globally and regionally have evolved in terms of their estimate and uncertainty in that estimate. In turn, this has led to a refined understanding of the sea level budget on a range of spatial scales. Ablain et al. (https://doi.org/10.24400/527896/a03-2023.3721) provided an overview of recent results on the budget closure from an ongoing project dedicated to assessing the robustness of the observing system through a dedicated focus on detection of errors and characterizing uncertainties. A goal of this effort is to ensure consistency between observed variables of the climate system on global and regional scales during the altimeter record. While this work is ongoing, a framework has been established that combines effort from several work packages and ultimately provides a robust structure for ongoing evaluation of the budget (Figure 5.9-1). Initial results from this framework indicated progress in assessing and attributing errors and uncertainties. Additional presentations covered the improved estimates of global mean sea level (GMSL) (Mangilli et al., https://doi.org/10.24400/527896/a03-2023.3785) and evolution of trends and accelerations globally and regionally (Rodriguez et al., https://doi.org/10.24400/527896/a03-2023.3815). Mangilli et al. (https://doi.org/10.24400/527896/a03-2023.3785) demonstrated the use of a generalized least squares approach to trend and acceleration estimates of GMSL, providing a 15% improvement of the trend uncertainty and 20% improvement on the acceleration with respect to past estimates. Meanwhile, Rodriguez et al. (https://doi.org/10.24400/527896/a03-2023.3815) showed that regionally, some parts of the satellite altimeter trend map continue to evolve over time, with patterns in the Pacific Ocean still heavily linked to large-scale climate variability. In other ocean basins, trends are now tracking closely to the global average, indicating a narrowing of the range of regional trends as the altimeter record lengthens. All of these studies indicate an improving understanding of the trends and acceleration - along with their uncertainties - in the altimeter record as it extends beyond 30-years. This is an expected outcome based on past studies and emphasizes the importance of continuity.

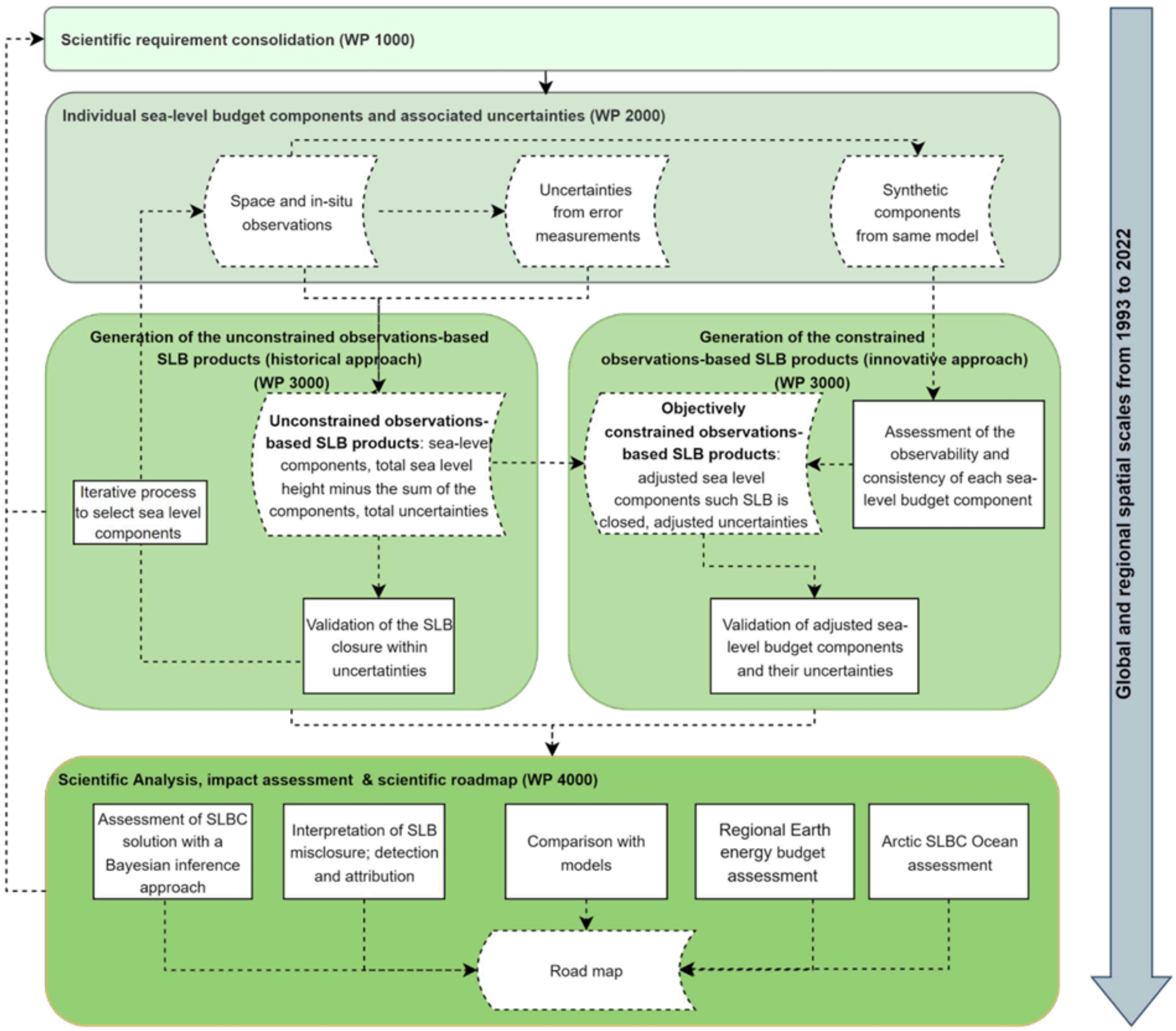


Figure 5.9-1: Framework for evaluating sea level budget closure during the satellite altimeter record on global and regional scales from the Sea Level Budget Closure CCI+ project (Ablain et al.).

A second theme of the session was the comparison of the pattern of sea-level rise from satellite altimetry to the patterns provided by climate models. Coats et al. (https://doi.org/10.24400/527896/a03-2023.3832) focused on understanding the role for internal variability in driving past and future ocean-dynamic sea-level changes in CMIP6 simulations. While some CMIP6 simulations have regional patterns of change that are a close match to the altimeter record, none are a good match globally. The focus of the work is on differences across the individual historical simulations and the role for internal variability, external forcing, and structural factors in driving these differences. A relationship is found between patterns of change in sea surface temperature (SST) and those in sea level, with a relationship found to common large-scale climate signals. Nerem and Fasullo et al (https://doi.org/10.24400/527896/a03-2023.3751) further investigated the differences between regional sea level from altimetry and climate model large ensembles, finding some agreement but key areas of difference between the observations and models. The forced response varies considerably between models, with the gradient across the Pacific in the altimeter pattern and area of particular disagreement (Figure 5.9-2). A key takeaway from this discussion was the importance of the observation-model comparisons in understanding the emergence of the forced response and the attribution of features in the altimeter trend pattern that persist in the 30-year record.

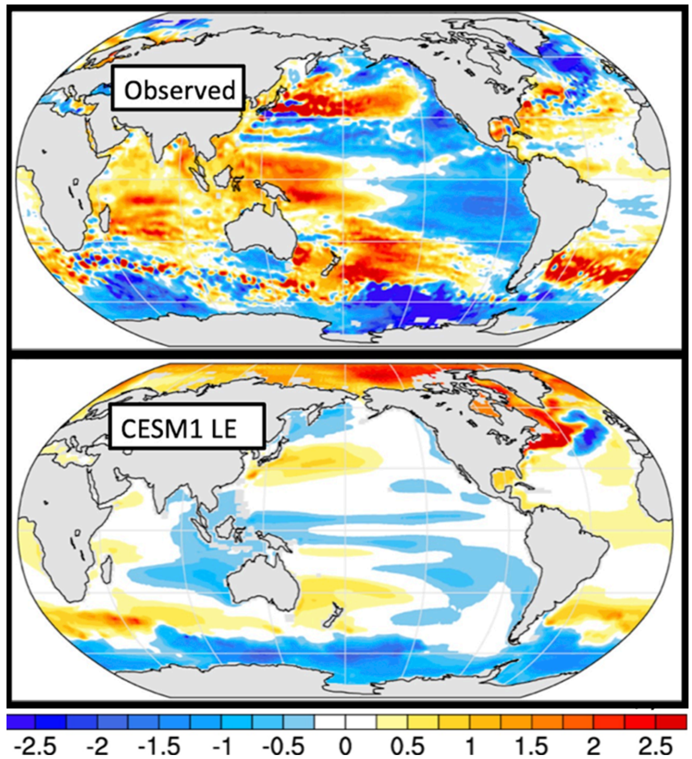


Figure 5.9-2: Comparison between satellite altimeter observed trend pattern (mm/year; global average removed) and estimated trend pattern from CESM1 LE. Similar results were found using CESM2.

The last topic of emphasis during the session was attribution of local and regional trends and accelerations in the satellite altimeter record. There were several presentations on this topic, covering sea level change in the southeast coast of the United States (Lee et al., https://doi.org/10.24400/527896/a03-2023.3690; Volkov et al., https://doi.org/10.24400/527896/a03-2023.3746), and contributions to sea level trends from Greenland both through gravitational, rotational, and deformational changes (Fenty et al., https://doi.org/10.24400/527896/a03-2023.3897) and time-varying discharge from rivers (Tajouri et al., https://doi.org/10.24400/527896/a03-2023.3692). Lee et al. used ECCO to highlight the forcing mechanisms of interannual sea level variations on the east coast of the United States, finding that offshore winds are a major factor causing incoherent interannual sea level changes between the northeast and southeast coasts (Figure 5.9-3). Volkov et al. (https://doi.org/10.24400/527896/a03-2023.3746) demonstrated the impact of the North Atlantic tripole on coast-flood risk along the U.S. southeast and Gulf coasts and shifting distributions of sea level change during the altimeter record. Finally, Tojouri et al. (https://doi.org/10.24400/527896/a03-2023.3692) found that the sea level response in the Beaufort Gyre Region is primarily driven by salinity variations in the upper 300 meters, mainly due to convergence of salinity changes by the main ocean circulation. This supports the idea of including freshwater discharge variability in forced ocean models to better represent regional sea level. The presentations on this topic again highlighted the need for continuity of the altimeter record and dedicated efforts to understand the changes that are occurring locally on a range of timescales and their physical drivers.

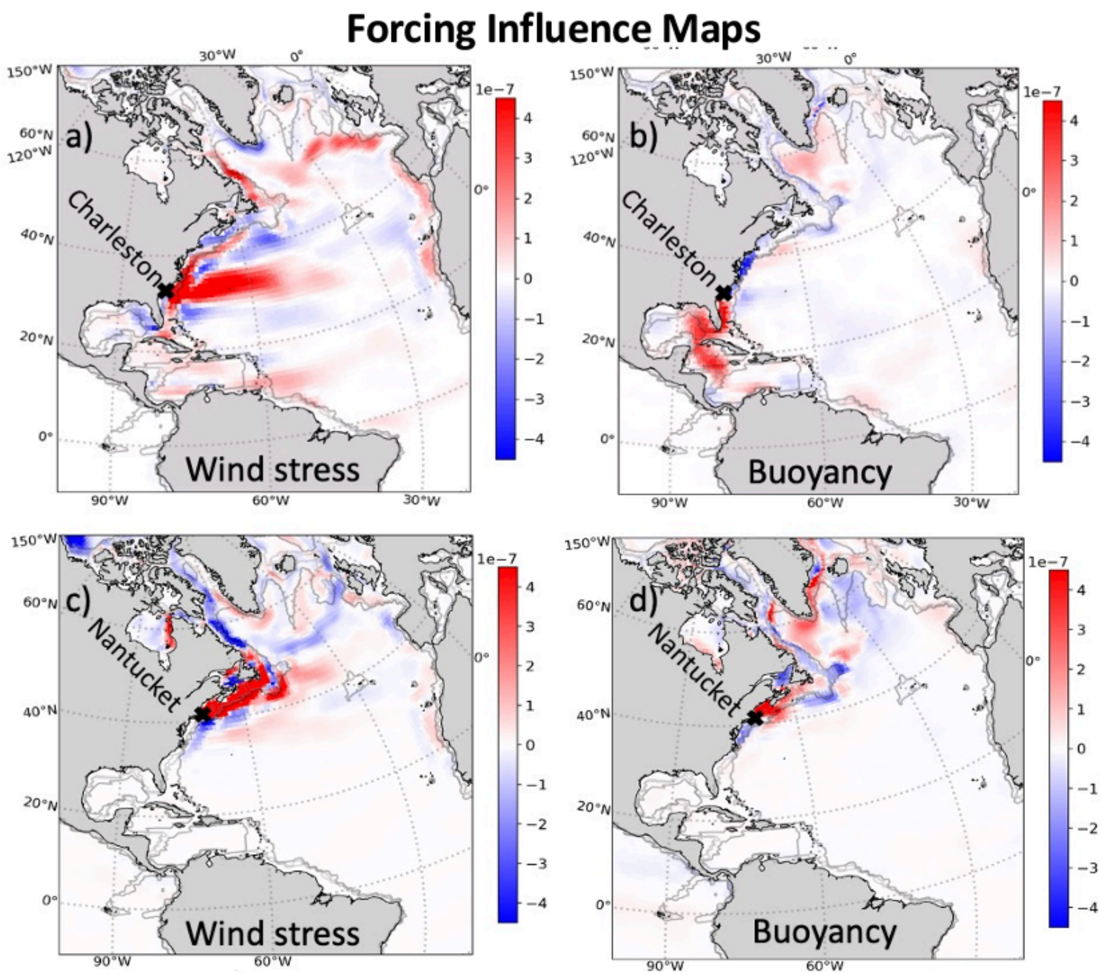


Figure 5.9-3: Forcing influence maps for Charleston SLAs due to a) wind stress and b) buoyancy forcing. Panels c) and d) are the same as a) and b) but for Nantucket. The values represent fractions per unit area (km^{-2}) of variance of total reconstructed interannual SLA variations at Charleston or Nantucket explained by reconstructed SLA using forcing at each location.

5.10 Science II: Large Scale Ocean Circulation Variability and Change

Chairs: Weiqing Han, Nathalie Zilberman

5.10.1 Summary

Han et al. presented “Interannual Sea Level Variability Along the U.S. East Coast During Satellite Altimetry Era: Local versus Remote Forcing” (https://doi.org/10.24400/527896/a03-2023.3759). Using satellite altimeter data, tide gauge observations and analytical models combined with empirical model, it has been shown that interannual sea level anomalies (SLA) along the U.S. northeast coast – in the Mid-Atlantic Bight (MAB) and Gulf of Maine (GOM) - since 1993 are dominated by local forcings through longshore wind and atmospheric pressure over the shelf, with remote forcing from the subpolar ocean also having significant contribution. In contrast, in the U.S. southeast coast (i.e., the South Atlantic Bight (SAB)), remote forcings from the open ocean (via westward propagating Rossby waves and the upstream Gulf Stream variability) have comparable contribution to the local forcings over the shelf.

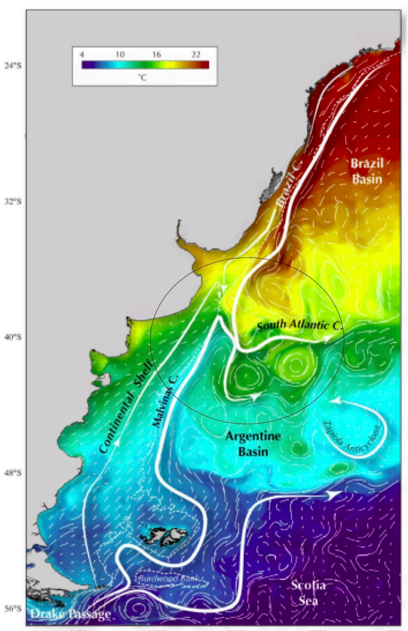


Figure 5.10-1: Schematic of the main features of the upper ocean circulation in the southwestern Atlantic Ocean. The background color is a sea surface temperature snapshot from a high-resolution numerical model.

Bodnariuk et al. presented “Regional impacts of global ocean teleconnections: the influence of Rossby waves in the Southwestern Atlantic” (https://doi.org/10.24400/527896/a03-2023.3682). In the Southwestern Atlantic basin, interannual variability of the cross-shelf transport is suggested to be driven by variability of the Brazil Current (BC). By analyzing the eddy permitting ORAP5.0 ocean reanalysis product from ECMWF which assimilated satellite altimeter data, Bodnariuk and coauthors showed that the leading EOF mode of velocity normal to the coast exhibits a dipole pattern, with onshore (offshore) flow in the north corresponding to offshore (onshore) flow in the south. This dipole pattern is related to the latitude of separation of the Brazil Current (LSBC), which shows 2-year, 4-year and 10-year pseudo periodicities. The westward propagating 1st baroclinic mode Rossby waves across the Atlantic impinge onto the Brazil Current, modulating the BC and cross-shelf transport. The 2-year cycle of the Rossby waves is thought to be linked to the Indian Ocean Dipole (Figure 5.10-1).

Strub et al. presented “Anomalous Poleward Transports in the California Current” (https://doi.org/10.24400/527896/a03-2023.3732). In the northeastern Pacific, the absolute geostrophic velocities derived from satellite altimeter (both two-sat and all-sat), together with the OSCAR Ekman transport in the top 30m, are used to calculate the daily Lagrangian trajectories using the

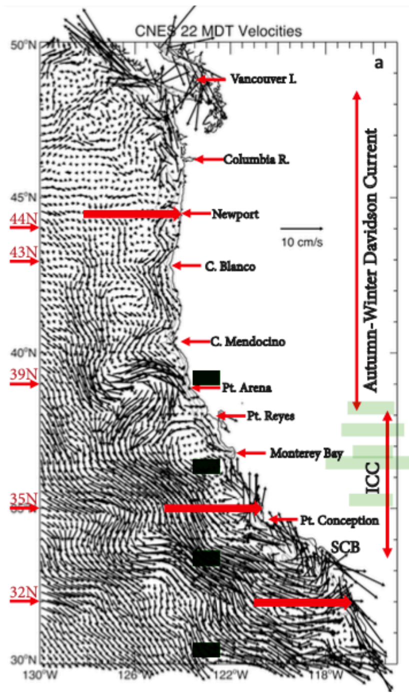


Figure 5.10-2: Absolute geostrophic velocities from SLA and CLS CNES MDT22.

"Parcels" software, to track the poleward transport and zooplankton distributions in the California Current System. It is shown that after one year, passive water parcels can reach the Oregon coast from the Southern California Bight (30°N), and in multiple years, from further south (~26°-27°N) and from the west. During years with greater numbers of parcels reaching 43°N and 45°N, there appear to be more southern "warm water" species and greater "species richness" off Oregon which are often associated with El Niño warm events or Marine Heat Waves. The water parcels travel in the semi-permanent poleward Inshore California Current in the south during summer-fall and in the poleward Davidson Current during fall-winter, and horizontal eddy-diffusion makes them more likely to reach higher latitudes (Figure 5.10-2).

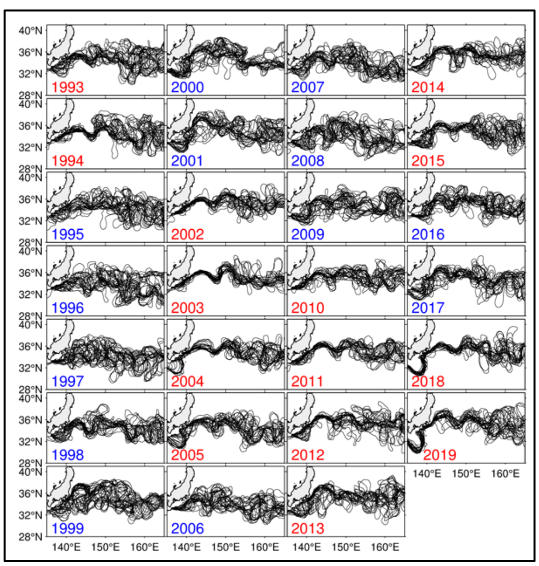


Figure 5.10-3: Annual maps of bi-weekly paths of the Kuroshio extension jet.

Qiu et al. presented "On 'Super' Stability of the Kuroshio Extension System after 2018" (https://doi.org/10.24400/527896/a03-2023.3706). In the northwestern Pacific, the Kuroshio extension (KE) system alternates between unstable and stable states, and SLAs in the southern recirculation gyre region (31°N-36°N, 140°E-165°E) can well represent the synthesized KE index. After 2018, the KE system entered a super stable state, which reduced eddy perturbations east of Izu Ridge and facilitated large-meander (LM) paths. The persistent LM contributed to a poleward migration of the KE jet, and the northerly KE path further strengthened the stable KE system. The question is: What caused the super stable KE and prolonged Kuroshio LM after 2018? The dipolar interior wind stress curl anomalies across ~32°N weakened the southern part of the subtropical gyre and the upstream Kuroshio, which is inducive to the LM path; but they strengthened the northern part of the subtropical gyre, KE, and northerly KE path, which is inducive to KE's poleward migration, less KE eddies east of Izu Ridge and stronger recirculation gyre, stabilizing the upstream LM, and reinforcing the stability of the KE state (Figure 5.10-3).

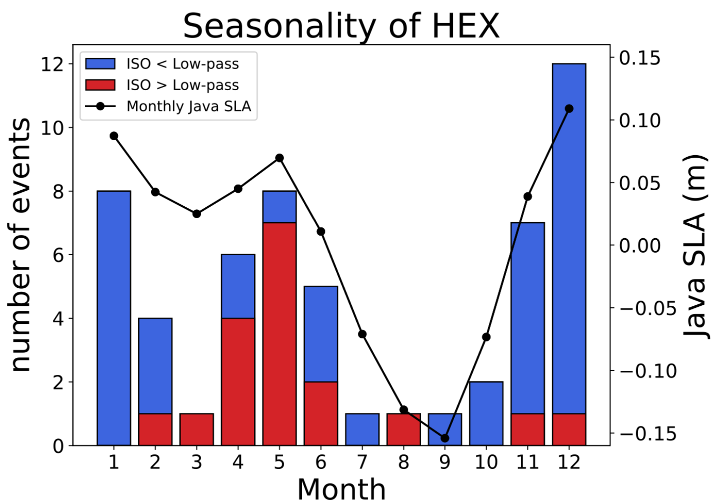


Figure 5.10-4: Seasonal cycle of sea surface High Extreme (HEX) events along the coasts of Indonesia.

Kamp et al. presented "Atmospheric Intraseasonal Oscillations Leading to Sea Level Extremes in Coastal Indonesia during Recent Decades" (https://doi.org/10.24400/527896/a03-2023.3712). In the Indian Ocean, daily satellite altimeter data together with tide gauge observations since 1993 were used to detect sea surface High EXtreme (HEX) events along the Indonesian coasts that border the eastern tropical Indian Ocean. The role of atmospheric intraseasonal oscillations (ISOs), which are dominated by the Madden-Julian Oscillation (MJO), in causing the HEXs are examined. It has been shown that intraseasonal SLAs induced by atmospheric ISOs are significant contributors to HEXs in coastal Indonesia. In 32% of the 56 HEX events detected, the amplitude of ISO-induced SLAs exceeds that of seasonal-to-decadal SLAs. Both the remote zonal wind stress from the equatorial Indian Ocean and alongshore wind stress at the Indonesian coasts play important roles in driving the HEXs. The ISOs caused more HEX events during boreal spring than winter, because during spring the MJOs are associated with stronger convective anomalies over the eastern equatorial Indian Ocean compared to winter, which drive stronger zonal winds across the equatorial basin that lead to more HEXs in spring (Figure 5.10-4).

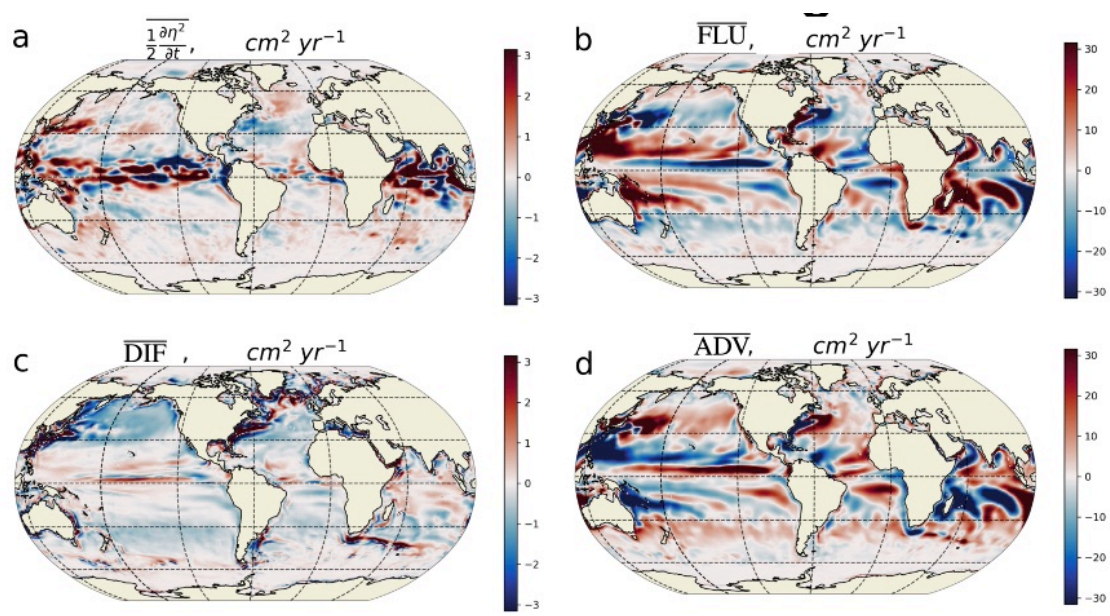


Figure 5.10-5: Seasonal steric sea level variance budget from the ECCO v4r3 model.

Hochet et al. presented “Ocean Dynamics control of the Steric Sea Level Seasonal Cycle” (https://doi.org/10.24400/527896/a03-2023.3708). In the Northern Hemisphere winter, sea level can reach 20 cm below its summer values. It is customary to associate these variations to the seasonal cycle of sea surface net heat flux. The prevailing hypothesis is that the excess of heat received by the ocean leads to a thermal expansion of the surface water that in turns creates a positive steric sea level anomaly. Using a novel framework based on steric sea level variance budget applied to observations and to the ECCO v4r3 model, A. Hochet et al. demonstrate that the seasonal cycle of steric sea level results from a balance between the seasonal sea surface net heat flux and oceanic advection (see Figure 5.10-5). At midlatitude and in the eastern parts of low-latitude regions, surface heat fluxes act to damp the seasonal steric sea level cycle generated by oceanic advection processes. Eddies also play an important role in damping the steric sea level seasonal cycle (Figure 5.10-5).

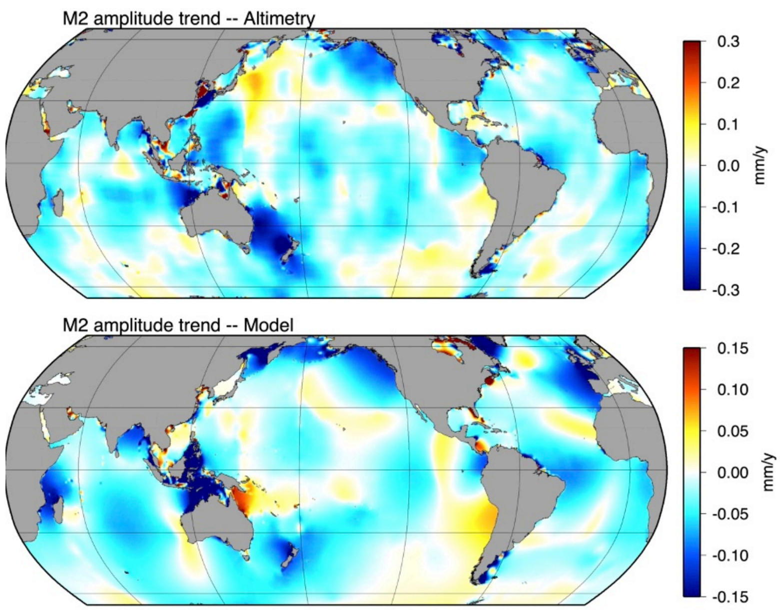


Figure 5.10-6: M2 barotropic trends between 1993-2019.

Ray et al. presented “Changing ocean stratification is changing barotropic-to-baroclinic tidal conversion: evidence from altimetry and 3-D modeling” (https://doi.org/10.24400/527896/a03-2023.3810). A number of investigations have reported ocean stratification increasing over the past half-century. Increasing stratification induces an increase in barotropic-to-baroclinic tidal conversion, with a tendency for amplified internal tides at the expense of the surface tide. Such changes in both barotropic and baroclinic tides are revealed by three decades of satellite altimetry and 3-D numerical ocean simulations. The latter delineate how the tides change in response to stratification. Analyses are based strictly on Topex-Poseidon, Jason, and Sentinel-6 MF data on the primary ground-track. Altimetric trends in the barotropic tide are prone to potentially large systematic errors, especially from tidal leakage in the DAC correction, which is partly caused by errors in ECMWF atmospheric tides. For the 30-y trend in the M2 barotropic tide, altimetry and model simulations both show open-ocean amplitude trends predominantly negative, roughly 0.1-0.2 mm/y (see Figure 5.10-6). Mapped baroclinic tides usually display positive trends, at least near large generation sites, with some exceptions (Figure 5.10-6).

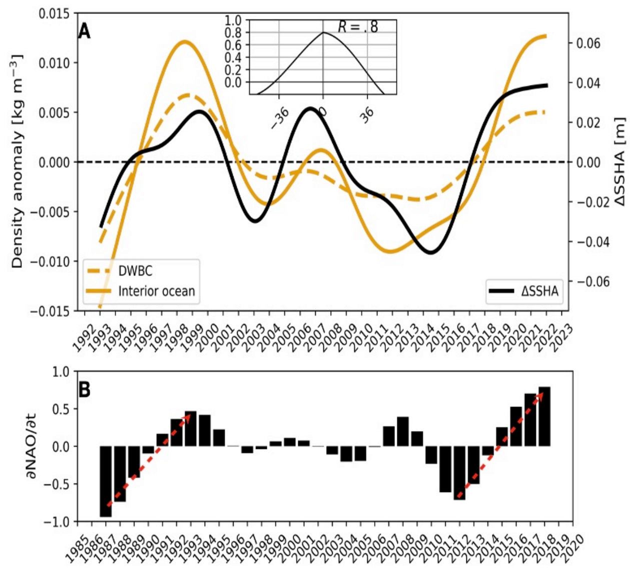


Figure 5.10-7: Deep western boundary current density and relationship to North Atlantic Circulation strength.

Léon et al. presented "Observed mechanisms triggering the recent warming in the eastern subpolar North Atlantic since 2016" (https://doi.org/10.24400/527896/a03-2023.3830). The overturning circulation of the subpolar North Atlantic (SPNA) plays a fundamental role in Earth's climate variability. Increased density anomalies are seen at the intergyre boundary in the eastern SPNA since 2016, due to enhanced subpolar overturning driven by the NAO in the preceding years (see Figure 5.10-7). As deep positive density anomalies spread southward along the western boundary, they enhance the North Atlantic Current and associated meridional heat transport, leading to an increased influx of subtropical heat into the eastern SPNA. This result is confirmed by a Lagrangian analysis based on altimetry-derived geostrophic velocities. The increased heat transport can mainly be explained by the gyre circulation, as shown in a range of ocean reanalyses, and has a specific large-scale sea-surface height imprint in the North Atlantic Ocean (Figure 5.10-7).

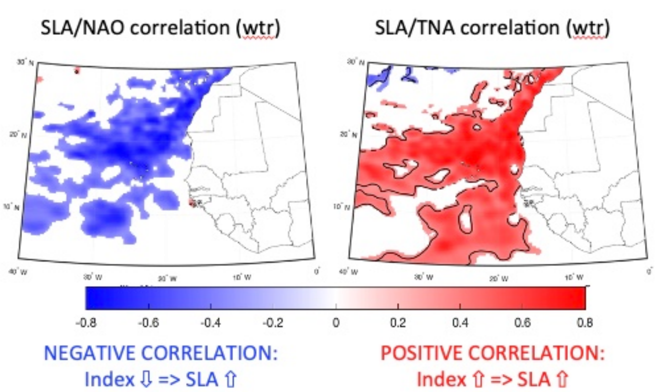


Figure 5.10-8: Correlation between sea level anomaly and climate indices.

Cardoso et al. presented "Understanding Eastern Tropical Atlantic Ocean Dynamics in Relation to Climate Indices" (https://doi.org/10.24400/527896/a03-2023.3787). This study analyses the mean annual and seasonal ocean circulation and mesoscale ocean dynamics in the Eastern Tropical Atlantic Ocean (ETAO) region (3°-30°N; 40°W-0°) over a 28-year period (1993-2020) and correlation with climate indices. Sea level anomaly (SLA; see figure), eddy kinetic energy (EKE) and surface geostrophic currents show pronounced seasonality. The mean rising rate in the ETAO region is 3.25 mm/year, higher than global average. Highest values (5 mm/year) of the northeastern area at (28°-30°N, 40°-27°W) may be associated with the Azores Current. Moderate values (3.5-4 mm/year) south of 10°N might be influenced by the North Equatorial Counter Current (NECC). Linear trends of EKE and surface geostrophic currents exhibit decreasing rates, in contrast to the positive linear trends observed globally, that may be influenced by the NECC. SST appears to be the primary driver explaining the correlation between SLA and climate indices. Wind forcing also contributes to the correlation between SLA and some CI although its influence is confined to the northernmost area of the study region. Sea level pressure contribution explains part of the correlation only for some indices and during limited seasons. The magnitude of surface geostrophic current anomalies appears influenced by the NECC (Figure 5.10-8).

Figure 5.10-9: Ship route of Tachibana Maru to Hachijo osland via Miyakejima and Mikurashima islands.

SSH measurements collected in the Kuroshio twice a day from the Global Navigation Satellite System (GNSS) are used by K. Ichikawa et al. (https://doi.org/10.24400/527896/a03-2023.3740) to study the impact of the Izu Ridge on changes in the meandering path of the Kuroshio (see Figure 5.10-9). SSH is determined by the antenna height from a reference surface, with correction of the distance between the antenna and the sea surface. Observations capture the signature of the northern branch of the Kuroshio at 35°N downstream of Oshima Island, and the southward meander of the Kuroshio at 139°E. Postprocessed kinematic positioning is necessary to provide accurate SSH variations. Additional calibration and validation are necessary to provide reliable estimates (Figure 5.10-9).

5.11 Science III: Mesoscale and sub-mesoscale oceanography

Chairs: Rosemary Morrow, Heather Roman-Stork, Clément Ubelmann, Jinbo Wang

5.11.1 Summary

This session had seven talks, fifteen posters, and four forum-only contributions. Of the seven talks, the final talk (presented by Jonathan Lilly) was borrowed from a previous session due to its relevance to this session's subject matter.

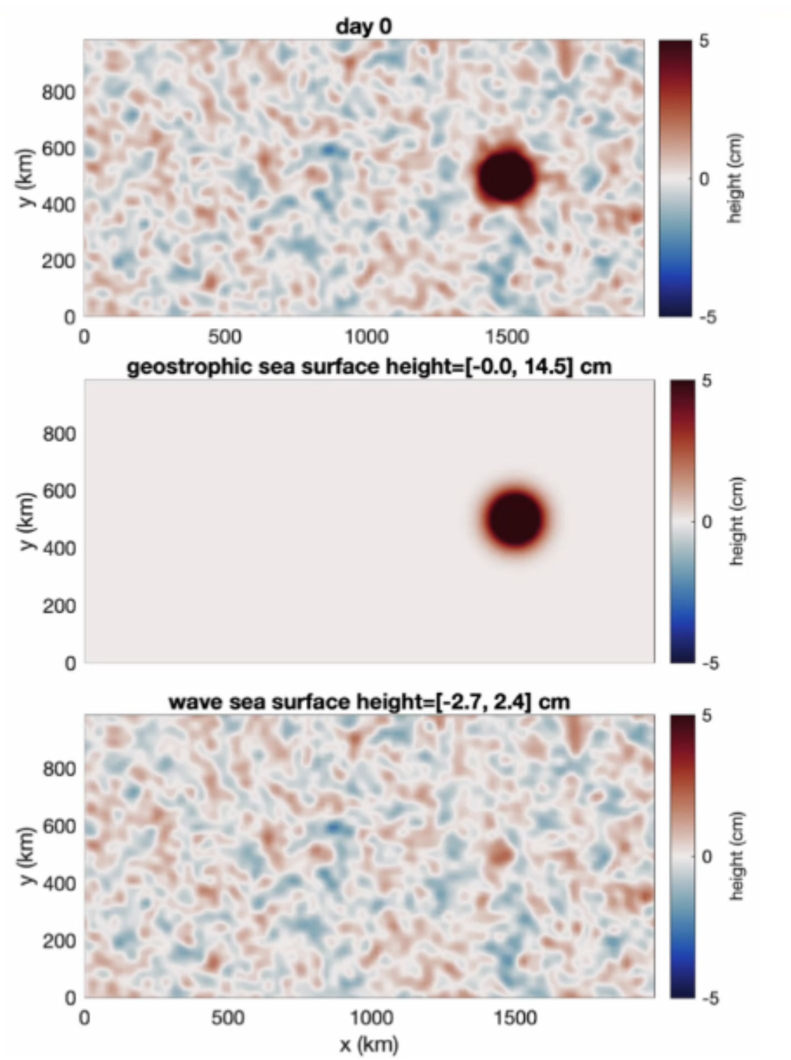


Figure 5.11-1: Results of the wave-vortex model at day 0 of the simulation of wave sea surface height with an eddy (top), just the eddy (middle), and just the sea surface height (bottom).

The first talk, entitled, "Separating waves and eddies from sea surface height: theory, applications, and limitations", was presented by Jeffrey Early (https://doi.org/10.24400/527896/a03-2023.3705). This work used a wave-vortex model to decompose dynamic fields in an instant in time, isolating the energy of waves, inertial oscillations, and geostrophic features, and observing the impact of an eddy on the dynamic field (Figure 5.11-1). The authors further showed how these methods could be applied to SSH mapping with similar applications in along-track eddy detection for instant decomposition into waves and geostrophic motion. They showed that the wave-vortex decomposition method provided a system for inferring interior flow from SSH and SST satellite observations.

The second talk was entitled "The coupling of geostrophic currents to near-surface motions in mesoscale eddies" and was presented by Peter Gaube (https://doi.org/10.24400/527896/a03-2023.3698). The authors described the influence of large wind input on regions where eddies impact chlorophyll-a, recognizing that influence of mesoscale eddies on chlorophyll-a varies regionally and cannot be observed in many areas (Figure 5.11-2). They found that both MLD and N2 modulate SSH, which means that satellite SSH can be used to compare interior ocean energy to surface inputs. Density changes at the base of the mixed layer and MLD were found to be the primary controls on the transfer of geostrophic energy from the ocean's interior to the surface. In regions where wind energy input at the ocean's surface was greater than the geostrophic interior eddy, the significance was not always detectable at the surface. They found that the influence of density changes at the base of the mixed layer and MLD in SSH allows for an estimate of where eddies modulate currents from satellite observations.

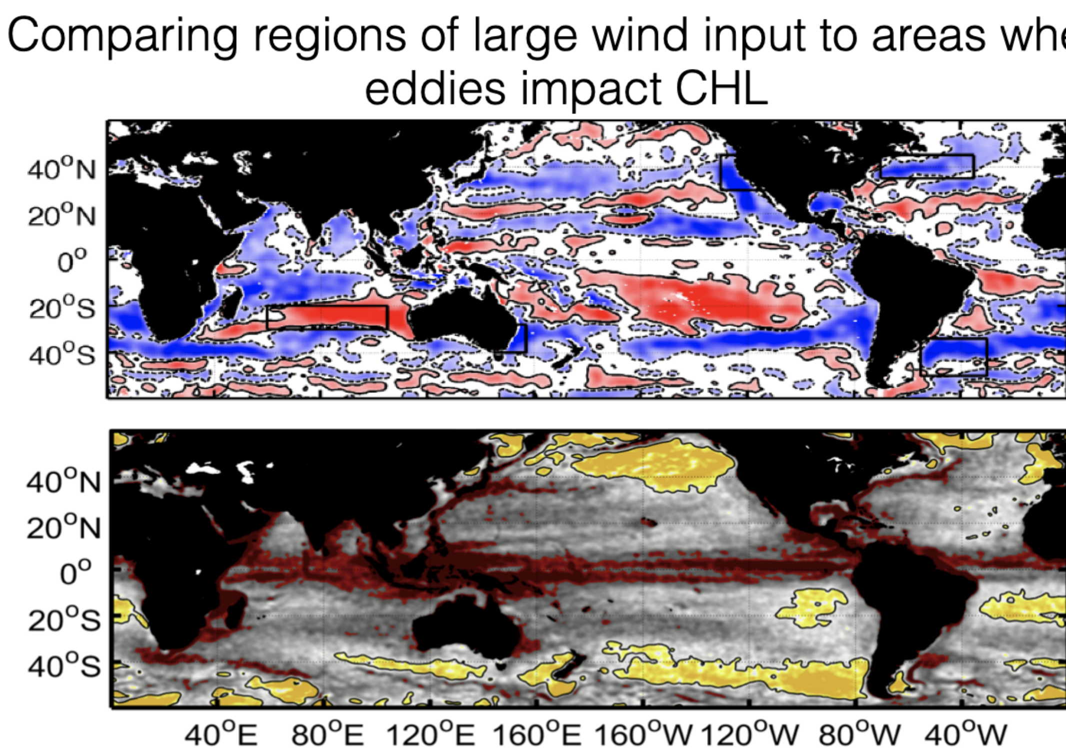


Figure 5.11-2: Comparison of regions where wind input was high with regions where eddies impact chlorophyll-a production.

The third presentation was titled "Evaluating SWOT's Capability in Observing Small-Scale (<100 km) Sea Surface Height," presented by Jinbo Wang (https://doi.org/10.24400/527896/a03-2023.3835). This study focuses on mission calibration and validation, including early, unpublished results from the SWOT KaRIn, compared with the steric height derived from 11 moorings deployed under the cross-over in the California Current in February/March 2023. Wang et al. (2022: On the Development of SWOT In Situ Calibration/Validation for Short-Wavelength Ocean Topography. J Atmos Ocean Tech, 39, 595–617, https://doi.org/10.1175/jtech-d-21-0039.1) provided a detailed feasibility evaluation of such a mooring array. The figure below (Figure 5.11-3) displays the spectrum of the SWOT Nadir altimeter (in red), SWOT KaRIn pass 026 over the region, and the steric height from the 11 moorings, which are separated by a 10 km distance. It also includes the difference between the steric and KaRIn heights (indicated by a green line). Since this difference could potentially include errors from both sources, simply dividing the values by half (shown as a green dashed line) and attributing that to KaRIn indicates that KaRIn meets the science requirement (represented by the gray curve). This analysis marks the first in-situ validation of SWOT KaRIn's performance over short wavelength ranges. The analysis is preliminary, with more rigorous uncertainty quantification in progress. The results are planned for submission to GRL in the spring of 2024: Wang,J. and coauthors from swot oceanography field campaign, 2024: High-Resolution Mapping of Sea Surface Heights: Utilizing the SWOT Ka-Band Radar Interferometer (KaRIn) for Sub-100-Kilometer Wavelengths, GRL, in-prep. Follow https://twitter.com/jinbowang for updates.

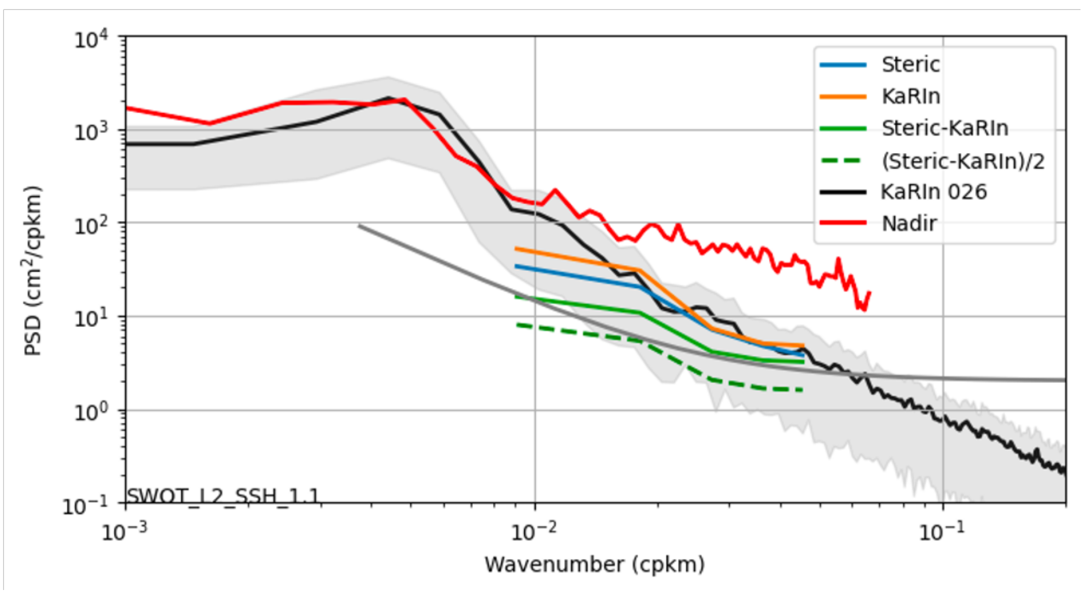


Figure 5.11-3: The wavenumber spectrum of the SWOT science requirement (gray), mooring steric height (blue), KaRIn interpolated on the mooring location (orange), difference between SWOT and mooring (green), half of the difference (green dashed), nadir (red), and KaRIn on the 2 km grid (black).

The fourth talk of the session was entitled, “From low resolution gridded altimetry maps to fine scales in KaRIn images” and was presented by Clément Ubelmann (https://doi.org/10.24400/527896/a03-2023.3860). A summary of the calibration scheme and correction for SWOT KaRIN data were presented, showing exceptional consistency with the

SWOT nadir data in the comparable range (80-10,000 km wavelength). At shorter scales, KaRIn imagery revealed short-to-sub-mesoscale eddies in motion, which may also appear as internal wave signatures, and MSS signatures. Overall, SWOT KaRIn images were shown to be calibrated to be very consistent with respect to SWOT nadir (L2) and the existing nadir constellation (experimental L3 from the science team) (Figure 5.11-4).

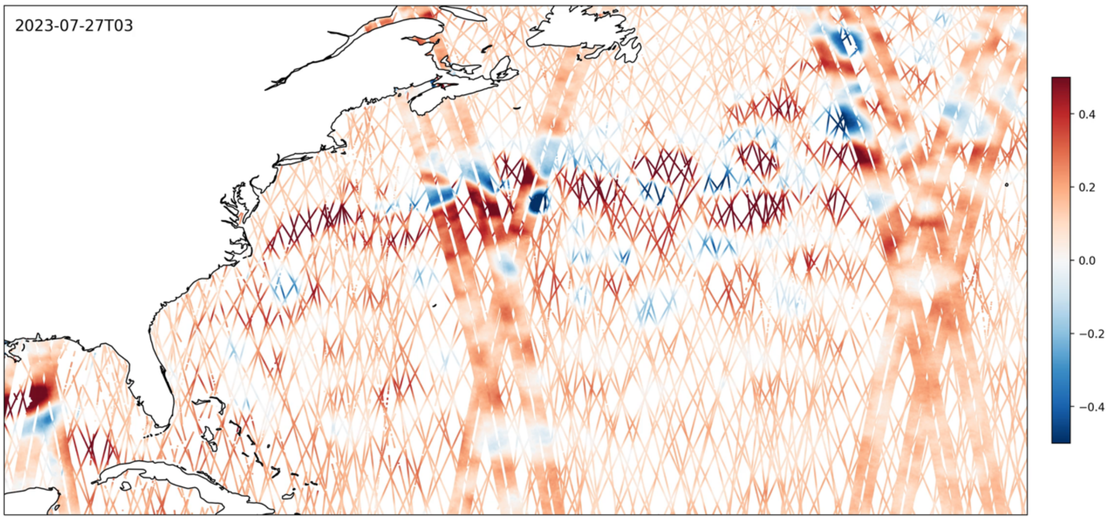


Figure 5.11-4: Illustration of SWOT KaRIn data calibrated with the nadir constellation.

The fifth talk was entitled, "Inserting SWOT/KaRIn images into the multi-mission altimeter constellation products" presented by Yannice Faugeres (https://doi.org/10.24400/527896/a03-2023.3862). In a conclusion of the three talks discussing SWOT processing, this talk highlighted the work on incorporating SWOT data into gridded mapping (MIOST & 4Dvarnet), and how

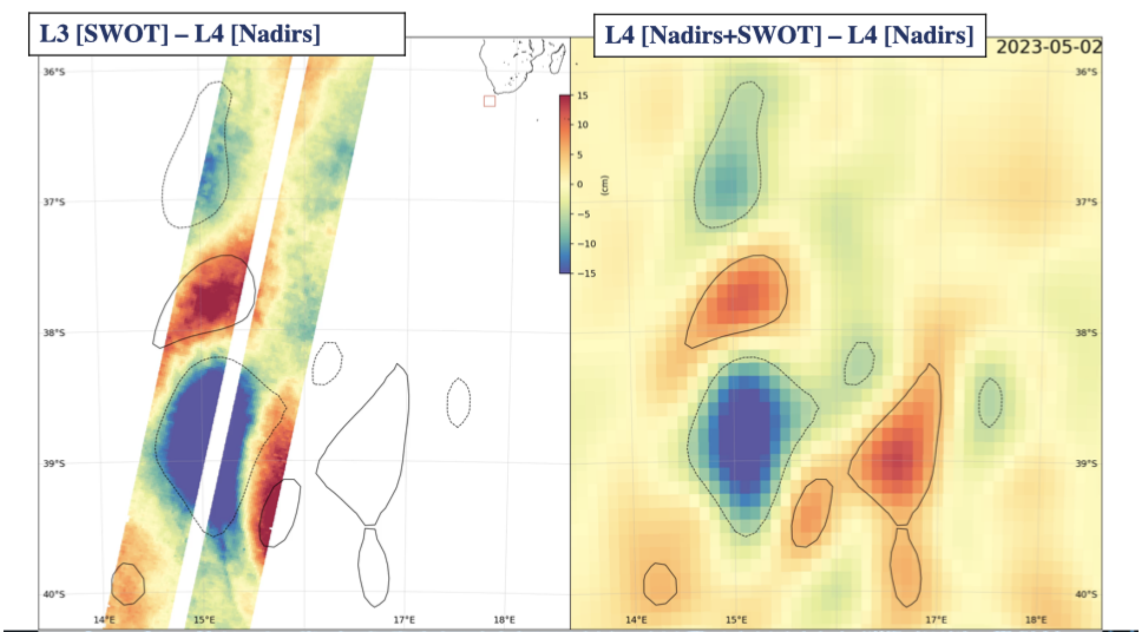


Figure 5.11-5: A comparison of eddy splitting and merging events from SWOT data (left) and SWOT + nadir altimetry (right).

SWOT best captures mesoscale and sub-mesoscale structures. They demonstrated how eddy merging and splitting events that are frequently missed in traditional nadir altimetry blended products were successfully captured in SWOT (Figure 5.11-5). They further noted that the systems behaved well ingesting KaRIn data in addition to nadir data from the constellation. The contribution of KaRIn imagery led to a 15-20% reduction in RMSE in energetic regions, with an 8% reduction in other regions.

The penultimate talk was entitled, "The sea surface height spectrum of internal waves reconstructed from ADCP and altimetry" and was presented by Saulo Soares (https://doi.org/10.24400/527896/a03-2023.3734). They found that it might be possible to use SWOT data to study the internal wave continuum in the southeast tropical Pacific, noting that there are mostly internal waves in the tropics as the sub-meso and mesoscales. Non-stationary internal tides were found to arise as the largest signal when reconstructing SSH using in situ currents compared with altimetry, which overwhelms the continuum (Figure 5.11-6). Methods used in this study could be applied to other global regions with sufficient ADCP transects, data to constrain the frequency spectrum, and a suitable internal wave model.

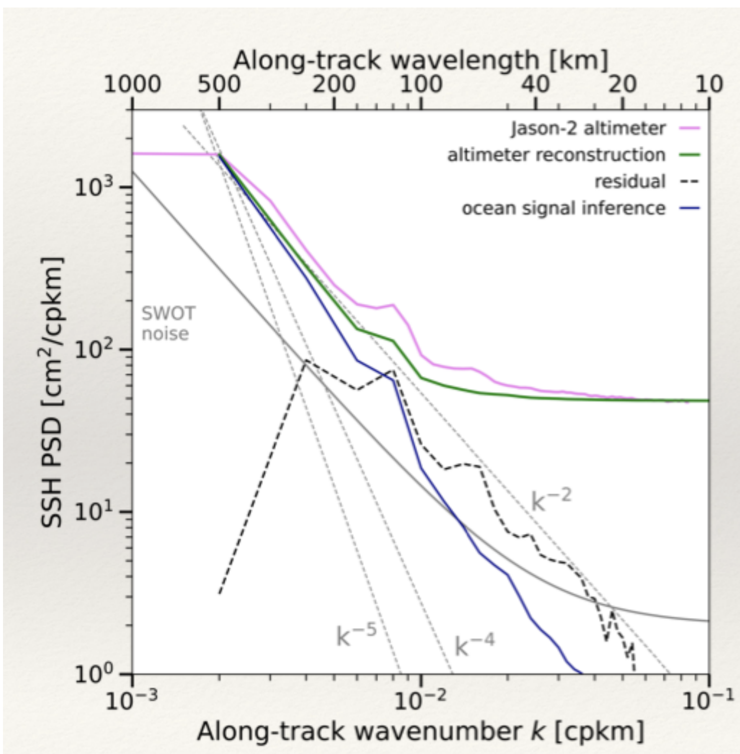


Figure 5.11-6: Along-track wave spectra for the Jason-2 altimeter (pink), altimeter reconstruction (green), the residual (black dashed), and ocean signal interference (blue). The Jason-2 altimery has ~10-40% more energy than the altimeter reconstructions (in situ conversion + stationary internal tide + noise).

The final talk of the session, “Optimal parameters for mapping along-track altimetry” presented by Jonathan Lilly (https://doi.org/10.24400/527896/a03-2023.3757), was not originally scheduled for this session, and was an encore performance from the Instrument Processing: Propagation, Wind Speed and Sea State Bias section. The co-chairs found that his talk was highly applicable to this session, and thus asked him to repeat his talk within the context of mesoscale and sub-mesoscale oceanography. In his presentation, he explained how he had created an open-source gridded SSH product using polynomial fitting on Jason-3 data with added noise. These Jason-only maps rivaled current multimission gridded products, which suggested that current products have considerable room for improvement. Regions with elevated mesoscale activity (i.e. eddies, etc.) were found to be where most of the major inconsistencies were between the Jason-only system and the multimission products, emphasizing the importance of capturing mesoscale dynamics in these products (Figure 5.11-7). He suggested that his method was particularly promising when using highly heterogeneous data, such as the combination of SWOT and along-track altimetry.

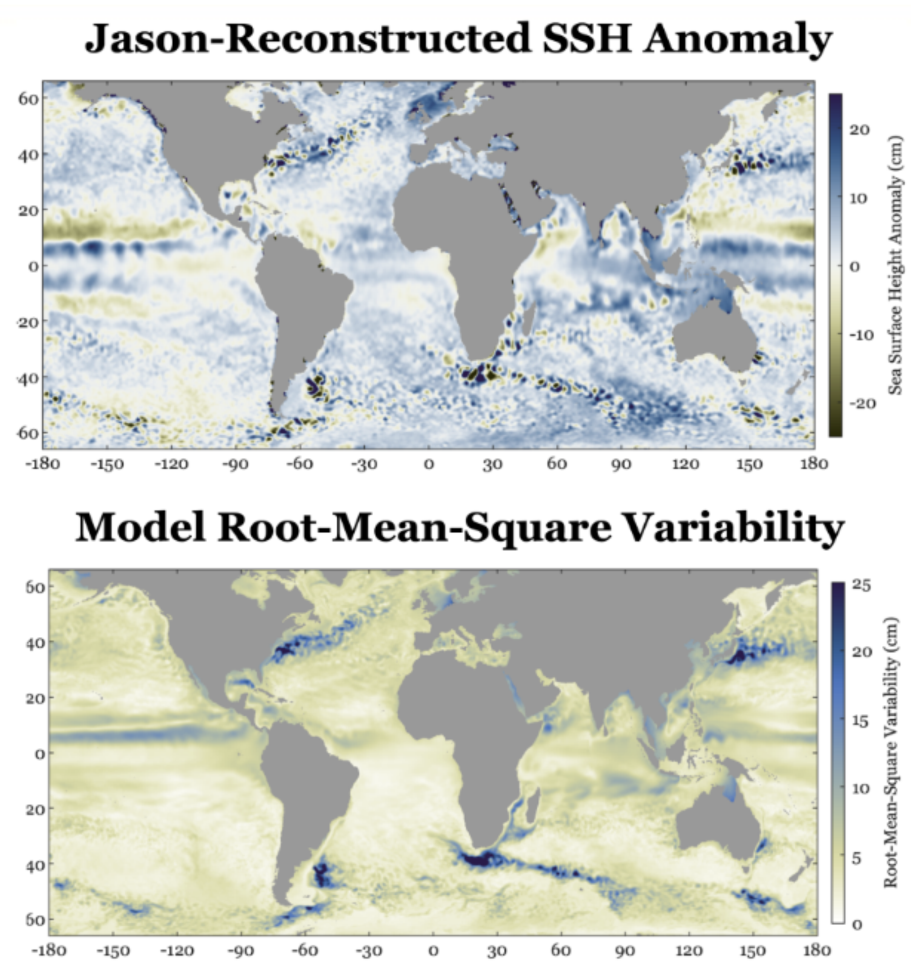


Figure 5.11-7: Reconstructed SSH anomaly from Jason-3 (top) and the associated RMSE (bottom).

5.11.2 Splinter Discussion Points and Recommendations

While seed discussion questions were prepared regarding SWOT, using improved future observation to reinterpret historical mesoscale time series, and the future of wide-swath and nadir altimetry, there was little time for discussion during the session time frame, though suggestions were made for the future formats of OSTST meetings, with most contributors being in favor of in-person meetings and an improved promotion of SWOT applications.

5.12 Science IV: Altimetry for Cryosphere and Hydrology

Chairs: Charon Birkett, Jérôme Bouffard, Jean-Francois Crétaux, Sinead Farrell, Karina Nielsen

5.12.1 Summary

This session had a reduced number of abstract submissions this year but the 6 oral, 6 poster, and 4 forum presentations made for fruitful discussions. The oral and forum sessions were focused on science projects while the posters outlined data product development and status, particularly in relation to the current Sentinel-3 and CryoSat-2 and future CRISTAL missions. The CRISTAL mission presentations highlighted both cryosphere and inland water capabilities, while a proposed Sentinel-3 Next Generation Topography (S3NG-TOPO) mission offered continuity coupled with a much-enhanced performance and hydrology capability.

As a joint session, a diverse range of subjects were discussed including inland waters (rivers, lakes), land ice, sea ice, lake ice, ice bergs, and Arctic sea level. Some highlights from the session included:

"Measuring longitudinal river profiles from Sentinel-6 MF using Fully-Focused SAR mode" (Boy et al., https://doi.org/10.24400/527896/a03-2023.3781**)** discussed a powerful technique which offers a new perspective in the observation and understanding of longitudinal river profile evolution in time and space. While more challenging, extending this approach to Sentinel-3 and possibly to sea ice measurement could be envisaged (Figure 5.12-1).

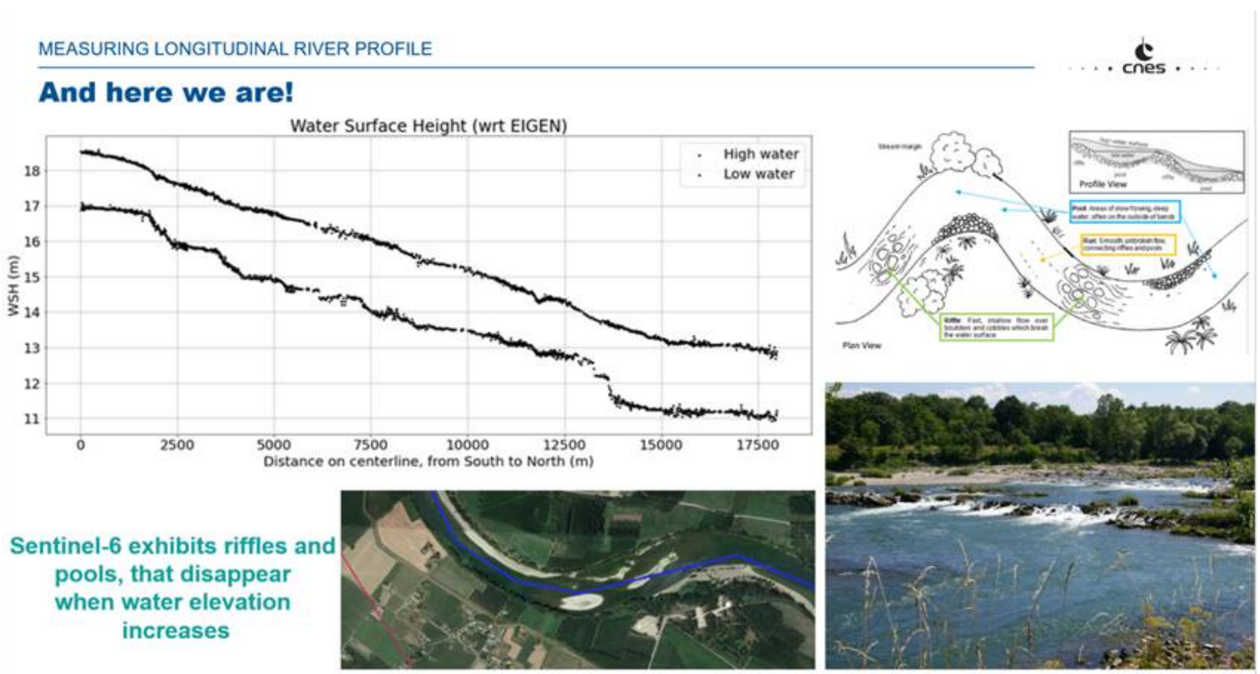


Figure 5.12-1: Garonne River example: With a dedicated processing technique applied on Sentinel-6 MF FF-SAR mode, a longitudinal profile over 18km is computed with a posting rate of 10m. Validation against in-situ measurements (both micro-stations and UAV overflight) shows a total uncertainty better then 10cm.

"The S3NG-TOPO Mission; Enhancing Continuity, Performance and Hydrology Capabilities" was presented by Egido et al. (https://doi.org/10.24400/527896/a03-2023.3823**)**. Hydrology has been recognized as a primary mission objective of S3-NGT and this introduces a new set of stringent mission requirements. The swath instrument would include a specialized HR mode designed for inland water applications. It would allow for the surface height measurement of rivers >100m wide and lakes and reservoirs with surface extents > 250m x 250m.

"Improving the retrieval of lake ice thickness with radar altimetry data" was presented by Mangili et al. (https://doi.org/10.24400/527896/a03-2023.3779). This presentation discussed a novel "double peak" retracking approach for the estimation of lake ice thickness by using LRM and SAR Ku-band radar altimetry data gathered during both unfocused and fully focused mode operation. The proposed method paves the way towards regular and robust ice thickness monitoring with current and future LRM and SAR altimetry missions, including the future CRISTAL mission (Figure 5.12-2).

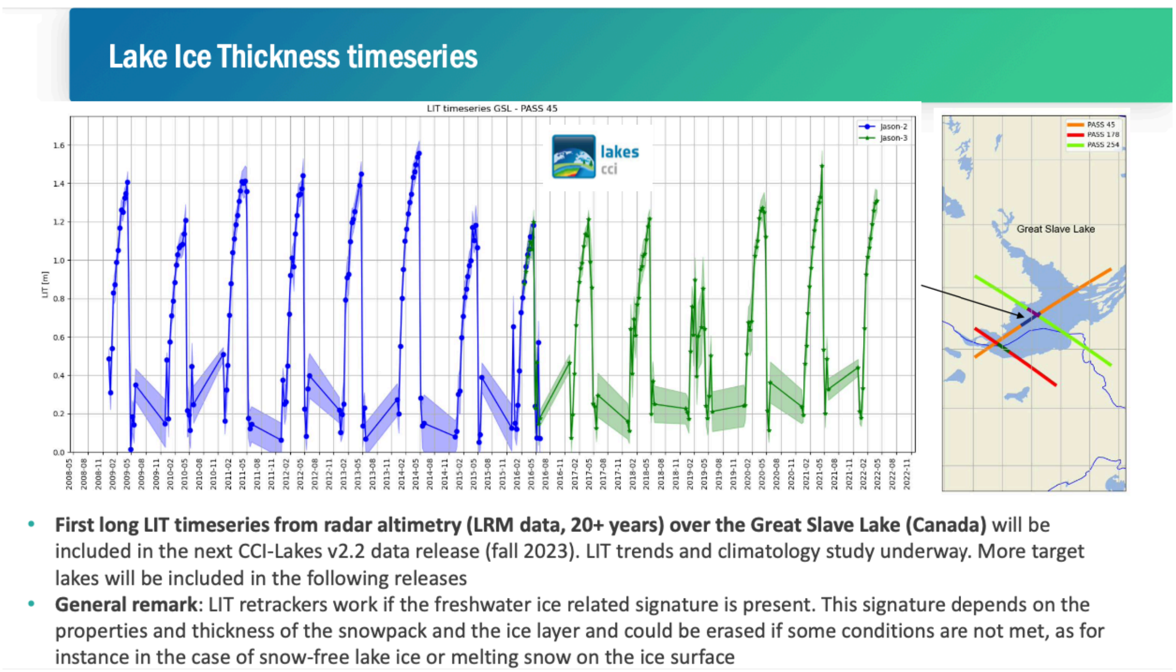


Figure 5.12-2: The first extended Lake Ice Thickness (LIT) timeseries derived from radar altimetry data for the Great Slave Lake (Canada). The full LIT timeseries (2001-2022) is available at the Lakes Climate Change Initiative (Lakes_cci) project portal https://climate.esa.int/en/projects/lakes/.

"CRISTALair, the CRISTAL Airborne Demonstrator" was presented by Garcia-Mondejar et al. (https://doi.org/10.24400/527896/a03-2023.3686). The main advantage of CRISTALair lies in its ability to acquire data simultaneously in Ku- and Ka-band, elevating the Science Readiness Level (SRL) of dual-band algorithms and data processing. Development of CRISTAL though is crucially dependent on dedicated campaigns that will provide the essential data algorithm development and validation.

Sentinel-3 thematic products: Latest results based on full mission reprocessing validation (https://doi.org/10.24400/527896/a03-2023.3683), https://doi.org/10.24400/527896/a03-2023.3684, and https://doi.org/10.24400/527896/a03-2023.3685) were presented by Catapano et al. The ESA Level-2 Sentinel-3 Surface Topography Mission (STM) Altimetry Processor has been updated to generate three thematic products that are optimized for i) inland waters, ii) sea ice, and iii) land ice, with associated full mission reprocessing. Validation results show that the evolution of the original processing algorithms has led to a very significant improvement over all surface type.

“Capitalizing on the experience of iceberg study from classical, SAR, and interferometric altimeter for the CRISTAL mission” was presented by Tournadre et al., https://doi.org/10.24400/527896/a03-2023.3841). Algorithms have been developed to detect and analyze iceberg characteristics utilizing theory connecting backscatter magnitude with iceberg freeboard. Specific SARIn swath processing of Cryosat-2 data show that swath processing can be used to estimate icebergs characteristics within the open sea as well as within sea ice.

5.13 Sentinel-6 Validation Team (S6VT) Meeting

Chairs: Pascal Bonnefond, Alejandro Egido, Eric Leuliette, Remko Scharroo, Josh Willis, and Severine Fournier

5.13.1 Summary

During the 2023 OSTST Meeting, the Sentinel-6 Validation Team conducted its 6th meeting. The meeting was open to all OSTST members with an interest in the on-going mission aspects, product developments, quality analysis, and calibration and validation activities around the Sentinel-6 mission.

Scharroo et al. (https://doi.org/10.24400/527896/a03-2023.3895) introduced the current status of the Sentinel-6 products suite. The current processing Baseline is F08 (as can be recognized from the file names) and is otherwise known as Platform Data Processor (PDP) version 3.7.0. It was deployed in operations on 9 March 2023 and added the much requested low-resolution (LR) numerical retracker (NR) aimed at providing even better long-term consistency in the LR altimeter measurements.

After the first full-mission reprocessing, released in July 2022, that brought all data in line with the operational F06 baseline, full-mission reprocessing has and will continue as long as major additions or improvements to the data products are being made. The second full-mission reprocessing using the F08 baseline was made available in July 2023.

Upcoming events to the Sentinel-6 altimeter production are the move to the EUMETSAT DataStore in December 2023, and further improvements to the high-resolution (HR) data in Baseline F09, including adding range walk in the Level 1 processing, numerical retracking of the HR data in Level 2 as well as correcting the significant wave height (SWH) for vertical wave motion (VWM). In addition, the high-resolution microwave radiometer (HRMR) variables already available in the AMR-C Level 2 products, will also become available in the altimeter Level 2 products.

Martin-Puig et al. (https://doi.org/10.24400/527896/a03-2023.3878) presented the latest work and future plans of the Mission Performance Working Group (MPWG). The working group reported that the Sentinel-6 MF data from Baseline F08 is showing a very high-quality and ensure continuity with Jason-3: LR products are within requirements with only a few marginal exceptions. The group defined a number of evolutions and studies and planned to reassess marginal non-compliant requirements. Among the planned evolutions are the adoption of new multi-mission standards (GDR-G) that the agencies are working towards to implement before the launch of Sentinel-6B.

Results from independent calibration and validation of the Sentinel-6 Michael Freilich mission by Forster *et al.* (https://doi.org/10.24400/527896/a03-2023.3812) demonstrated that the performances of processing Baselines F06 and F08 are similar. The overall performances are within requirements when compared to crossover RMS. The SSHA evolution is almost the same between the two baselines, except a very subtle change due to the antenna aperture update in the retracking. In addition, correction of the radiometer calibrations for AMR removed a notable drift in wet path delay w.r.t. the ECMWF model. A remaining jump in AMR vs. model difference is due to the ECMWF model update on 31 Oct 2021 (Figure 5.13-1).

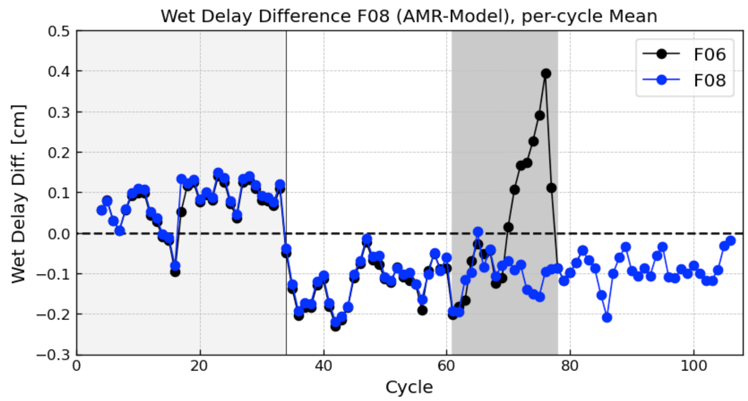


Figure 5.13-1: F08 reprocessing fixes an error in the operational AMR calibrations that was present in F06 (cycles 62 – 77)

Sentinel-6 comparison with Jason-3 highlights improvement of NR over MLE-4. The consistency with Jason-3 (with adaptive retracking) is improved by using the numerical retracker results from Sentinel-6, which is most apparent when comparing MLE-4 versus NR altimeter parameters as a function of SWH and latitude, except for SWH in low SWH conditions due to a known bug in the 1-Hz compression.

Cadier et al. (https://doi.org/10.24400/527896/a03-2023.3802) presented further improvements of Sentinel-6MF performances over ocean thanks to F08 LR numerical retracker, showing that NR makes S6MF mission more robust to any potential future major drift of instrumental behavior. The authors expect much from the HR numerical retracking under development, where a higher impact is expected on the quality of the monitoring of global mean sea level (Figure 5.13-2).

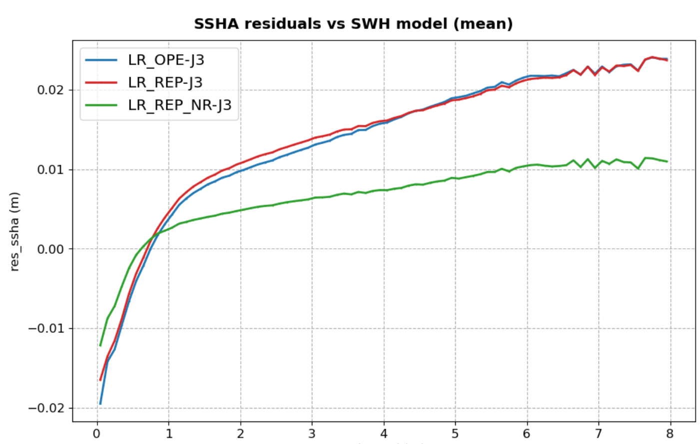


Figure 5.13-2: LR MLE4 SSHA dependence to SWH (coming from range and Iono correction) is significantly improved with numerical retracking.

Buchhaupt et al. (https://doi.org/10.24400/527896/a03-2023.3679) reported on discrepancies in Sentinel-6MF sea surface parameters estimated from HR and LR data. They presented a solution to mitigate the vast majority of HR-LR inconsistencies by introducing new parameters to SAR stack retracking (variation of vertical wave particle velocities and along-track surface velocity) (Figure 5.13-3).

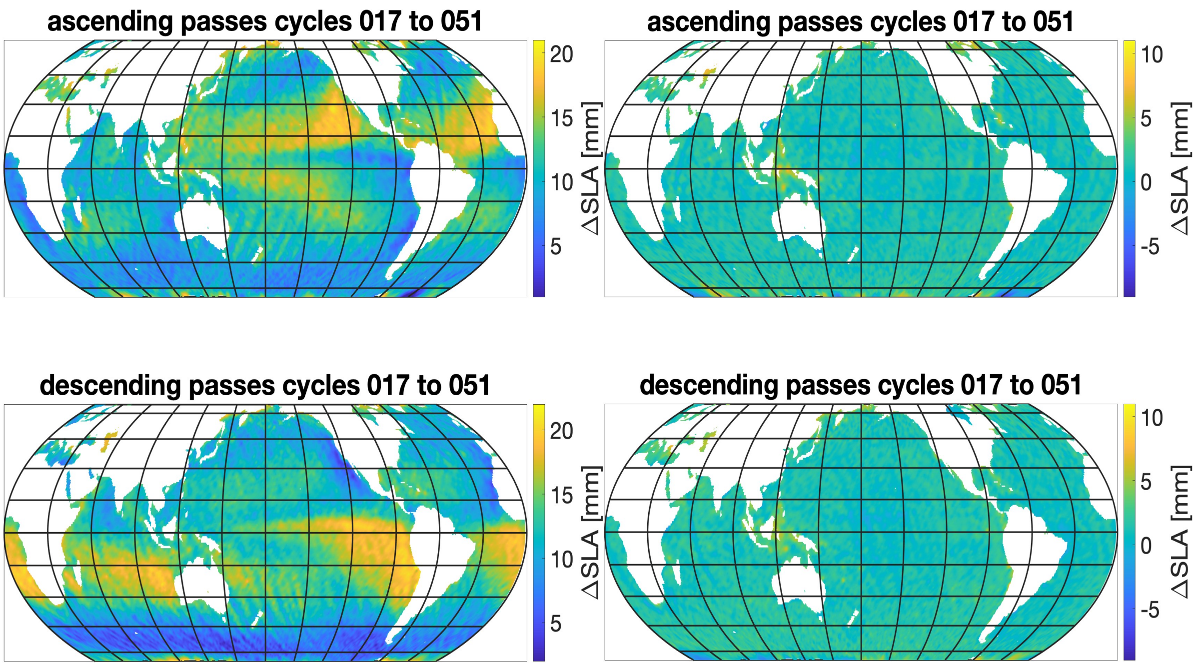


Figure 5.13-3: HR-LR differences can be eliminated by introducing new parameters to SAR stack retracking (variation of vertical wave particle velocities and along-track surface velocity). Left: LR retracker is SINC2 STD. HR retracker is SINCS STD. Right: LR retracker is SINC2 ZSK. HR retracker is SINCS-OV2 ZSK.

The Sentinel-6 Michael Freilich and Jason-3 Tandem Flight Exploitation (S6-JTEX) study was presented by Moreau *et al.* (https://doi.org/10.24400/527896/a03-2023.3829). It encompasses 11 case studies underway to exploit the S6-MF/Jason-3 tandem phase in the areas of

- Ocean cal/val
- Uncertainties in global mean sea level
- Coastal assessment
- Sea state
- Effective number of looks (ENL)
- Fully focused SAR
- Internal wave detection
- Hydrology
- Lake ice thickness

The Transponder Group *(Garcia-Mondejar et al.*, https://doi.org/10.24400/527896/a03-2023.3870) presented their analyses, showing that Sentinel-6 performances over point targets present better precision and stability than other altimetry missions (Figure 5.13-4). The assessment of various sites allowed to understand differences in the results. They showed that corner reflectors, when located at a suitable site, are becoming an excellent alternative to transponders, with publications of their methodologies and results forthcoming.

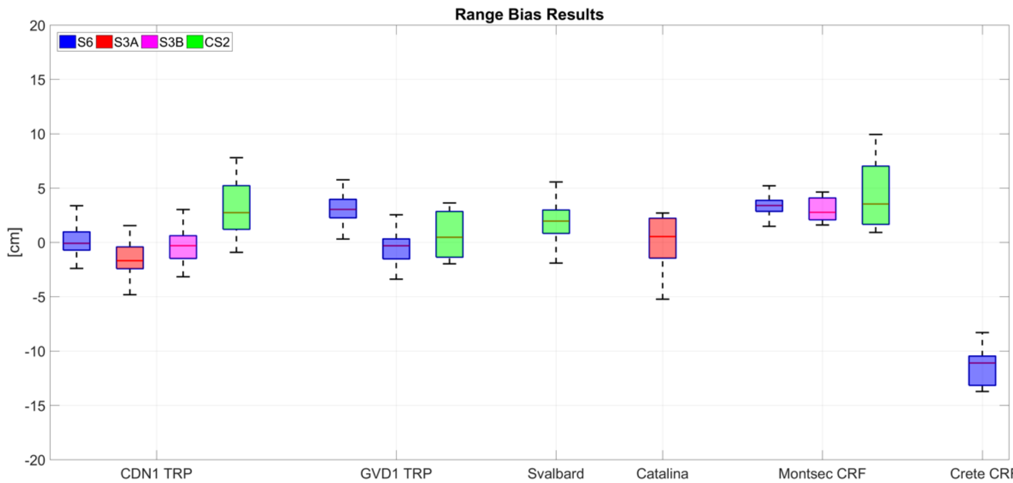


Figure 6.13-4: Sentinel-6, Sentinel-3 and CryoSat-2 range bias results at various calibration sites.

A microwave radiometer stability monitoring system (*Zhang and Leuliette,* https://doi.org/10.24400/527896/a03-2023.3814) has been developed at NOAA/STAR for multiple altimetry missions, for short and long-term time series. Results show that Sentinel-6 MF has achieved stable AMR-C WTC retrievals and brightness temperatures with the latest recalibrated/reprocessed (F08) version. Differences exist between Jason-3/Sentinel-6 MF WTC and brightness temperatures, where Jason-3 on the interleaved orbit is less stable than Sentinel-6 MF. Differences in the Sentinel-6 MF WTC retrieval and ERA-5 show more than 3 mm bias, but the overall difference is relatively stable. When comparing Sentinel-6 MF HRMR brightness temperatures against ATMS, the 90 GHz channel shows relatively stable time series whereas the 166 GHz channel shows a larger bias in 2023 Figure 5.13-5).

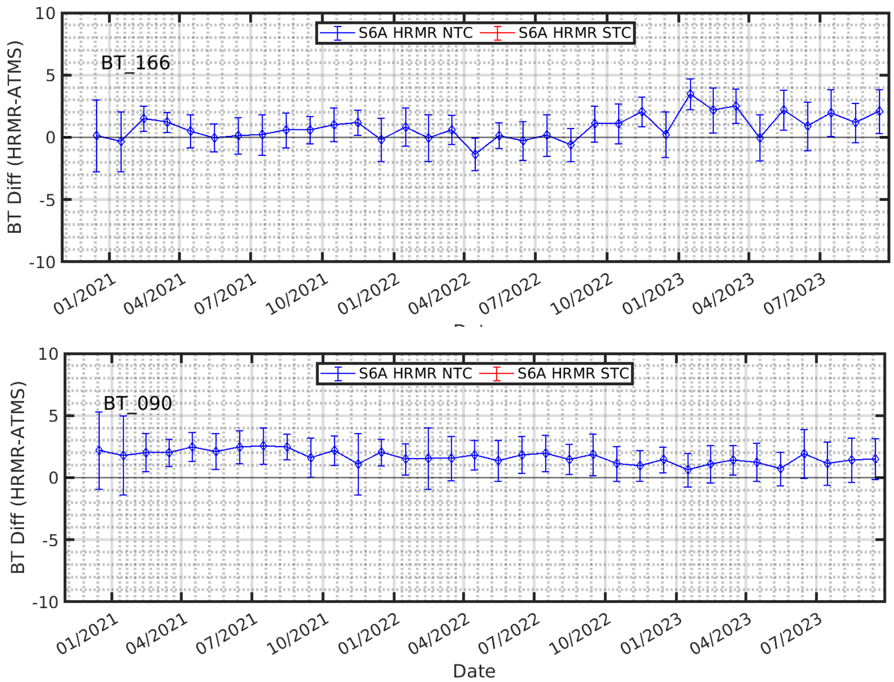


Figure 5.13-5: HRMR brightness temperature stability evaluated with the Simultaneous Nadir Overpass method using SNPP/ATMS observations (upper panel for the 166 GHz channel and lower panel for the 90 GHz channel).

Watson et al. (https://doi.org/10.24400/527896/a03-2023.3760) presented updated Sentinel-6 MF validation results from the Bass Strait validation facility in Australia (Figure 5.13-6). The very low variability in bias estimates at Bass Strait highlights the evolution of altimetry and the high quality in situ data in use at the facility. The Sentinel-6 MF bias estimates are indistinguishable from zero with a variability of HR data now below 2 cm. Short-wavelength contributions (including contribution from the in situ measurement system itself) is now below 1 cm. As far as long-term trends are concerned, they are indistinguishable from zero with negligible differences between the various retracker solutions. Because of persistent non-averaging errors, the limit to the absolute bias uncertainty is likely to be around ±10 mm.

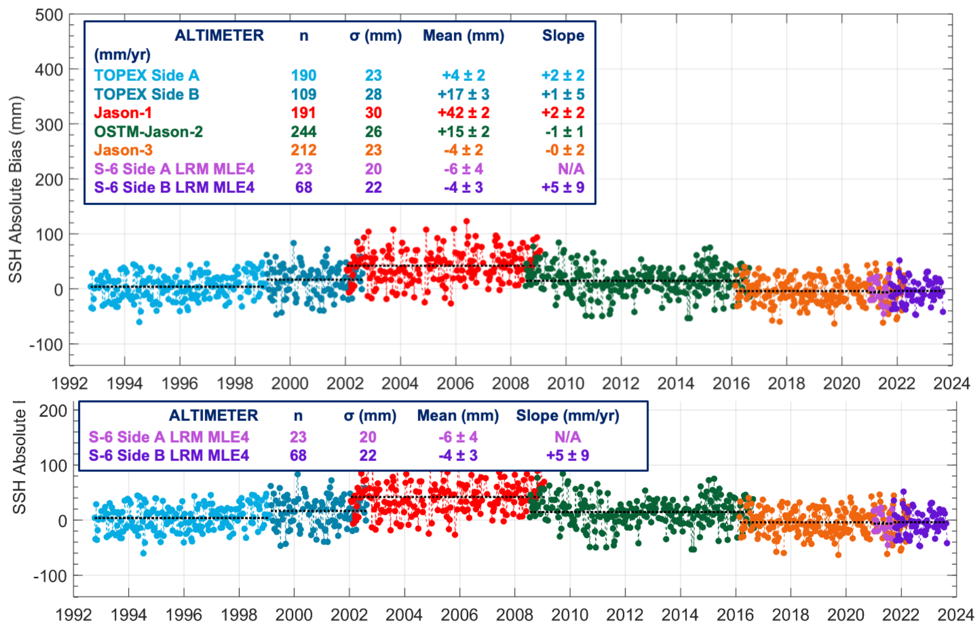


Figure 5.13-6: Calibration of TOPEX, Jason-1, -2, -3, and Sentinel-6 MF at the Bass Strait facility.

Fenoglio et al. (https://doi.org/10.24400/527896/a03-2023.3831) presented their evaluation of Sentinel-6 Fully-Focused SAR altimetry over open ocean and inland water, evaluating the NTC products over rivers, lake and in coastal areas. Over rivers, the accuracy of water surface elevation (WSE) can be improved using FFSAR (e.g., standard deviation of 9 cm near Mainz, where the Rhine has a width of about 100 m. In large lakes the unfocussed SAR (UFSAR) and FFSAR results were similar, with a standard deviation of about 8 cm. In the coastal zone it is preferred to sample at 140-Hz, in which case the UFSAR and FFSAR provide standard deviations of 4 to 6 cm in water level and (at 20 Hz) around 22 cm in SWH.

Two posters were included in this session:

- *Dinardo et al.* (https://doi.org/10.24400/527896/a03-2023.3864) provided the analysis of a complex correction to the end-to-end range impulse response (RIR) of the Sentinel-6 MF altimeter system. This complex correction can better calibrate the instrumental and antenna distortions over the mission lifetime and compensate for the amplitude and phase distortions currently seen in the CAL1 measurements as well as over natural targets (like the Etosha Salt Pan).
- *Escorihuela et al.* (https://doi.org/10.24400/527896/a03-2023.3774) performed calibration and validation of the Sentinel-6 MF altimeter sigma-0 and the radiometer brightness temperature over natural surfaces. Natural targets included Dome C in Antarctica, the Amazon rain forest and the Etosha Salt Pan. Their approach allows for an independent continuous monitoring of the altimeter backscatter and radiometer brightness temperatures.

5.13.2 Splinter Discussion Points and Recommendations

The following recommendations were made by the members:

- Use a higher posting rate in L1 processing, as highlighted in the paper by *Egido et al. (2021)*.
- Increase the sampling frequency in products for hydrology above the 20-Hz in the current operational products.

5.14 Synergies between Argo, GRACE, and Altimetry

Chairs: Felix Landerer, Steve Nerem, Susan Wijffels, and Nathalie Zilberman

5.14.1 Summary

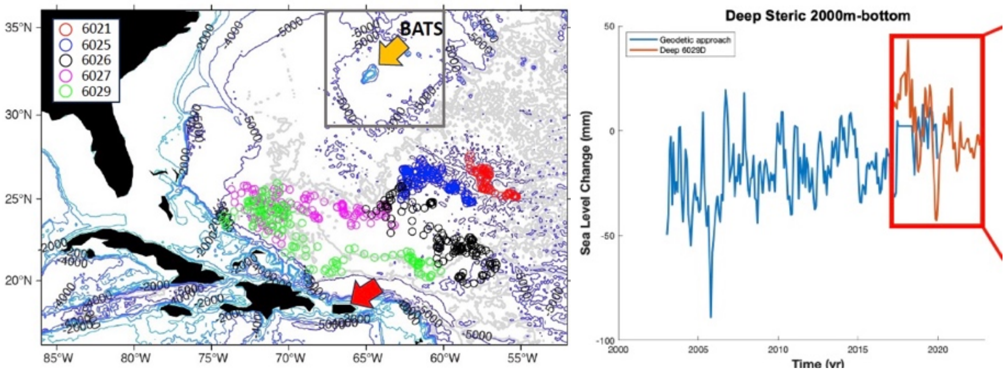


Figure 5.14-1: Figure: (a) Locations of full-depth profiles collected from Deep Argo floats and at the BATS station (Zilberman et al., In Prep). (b) Comparison of deep steric sea level estimates in the DWBC from Deep Argo float 6029 and the geodetic approach using DUACS altimetry, GRACE/GRACE-FO and Roemmich and Gilson's climatology.

Zilberman et al. presented "Deep-ocean steric sea level variations in the Northwest Atlantic Basin revealed using Deep Argo and Bermuda Atlantic Time-series Study full-depth profiles" (https://doi.org/10.24400/527896/a03-2023.3735). Results from Deep Argo temperature and salinity measurements collected between 2017-2022 in the Northwest Atlantic Ocean reveal Deep Argo's ability to resolve changes in deep steric sea level. Deep Argo data show interannual variations of deep-ocean steric sea level stronger along the path of the deep western boundary current (DWBC, floats 6027 and 6029) than over the abyssal plain (floats 6021, 6025, and 6026 and at the Bermuda Atlantic Time-series Study (BATS) station). The deep ocean contributes 30% of the full-depth steric sea level in the DWBC, compared to about 10% over the abyssal plain. Interannual variations of deep-ocean steric sea level from Deep Argo are consistent with the geodetic approach and ocean reanalysis (GLORYS, CGLOR, ORAS, and FOAM) products over the abyssal plain, but strongest variations seen in the DWBC are not well resolved in the geodetic approach and ocean reanalysis (Figure 5.14-1).

Lavin et al. presented "Can Deep Argo Close the Sea Level Budget in the Southwest Pacific Basin?" (https://doi.org/10.24400/527896/a03-2023.3714). Deep Argo profiles collected between 0-6000m in the regional pilot array of the Southwest Pacific Basin show 10-30% deep steric contribution to sea level change at interannual time scale. Results show that some of the non-closure of trends in the sea level budget (SLB) seen in parts of the Southwest Pacific Basin is due to the deep ocean and can be resolved using Deep Argo floats, though there is substantial variability in this term throughout the basin. Future work will consist of assessing the SLB over groups of 2 × 2 mascons (using Core Argo data for shallow steric sea level) both with respect to the trend and seasonal variability of the SLB components (Figure 5.14-2).

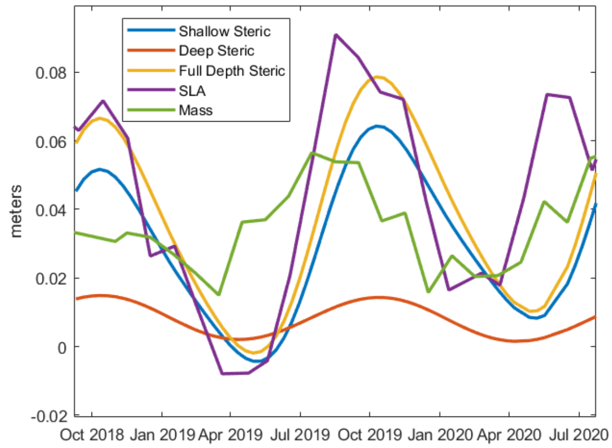


Figure 5.14-2: Sea level budget in a mascon of the Southwest Pacific Basin (Lavin and Johnson, In Prep). The difference between sea level anomaly and the sum of steric and mass components is small (~2.3 mm/year).

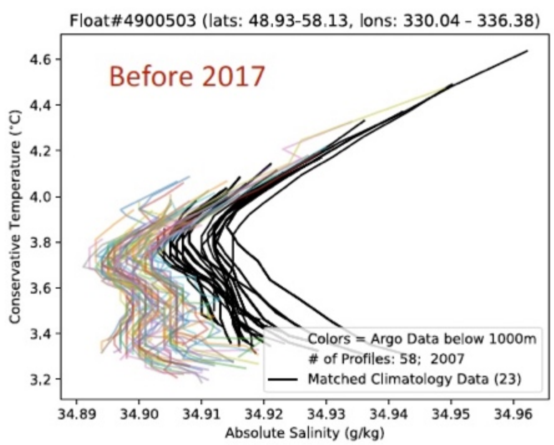


Figure 5.14-3: Example of salinity drift (color) compared to Roemmich and Gilson's climatology values (black) interpolated at Argo profile locations for the case of Core Argo float #4900503.

Reinelt et al. presented "Mapping steric sea level from satellite altimetry, GRACE/GRACE-FO, and Argo" (https://doi.org/10.24400/527896/a03-2023.3792). Comparisons of the difference between total sea level from altimetry, mass addition from GRACE/GRACE-FO and steric sea level from Core Argo floats (measuring only temperature and salinity in the upper 2000m) with Roemmich and Gilson's climatology suggest occurrence of drift in salinity measurements from six Core Argo floats after 2017. The authors will work with Argo delayed-mode operators to investigate further the adjusted fields of Core Argo salinity and study comparisons with raw Argo data (Figure 5.14-3).

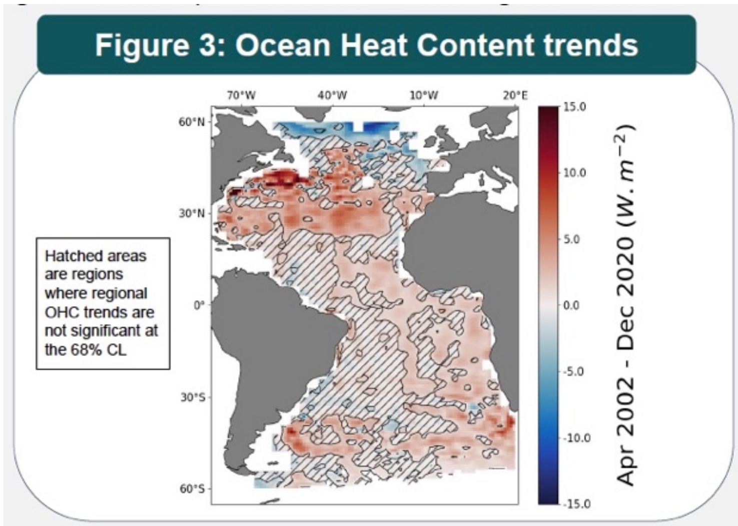


Figure 5.14-4: OHC trends in the Atlantic Ocean inferred by dividing the thermosteric sea level change with the Integrated Expansion Efficiency of Heat (IEEH).

Rousseau et al. presented "Monitoring the regional Ocean Heat Content change over the Atlantic Ocean with the space geodetic approach" (https://doi.org/10.24400/527896/a03-2023.3769). Thermosteric sea level (SL) time series are generated for the case of the Atlantic Ocean between 2002-2020 as the difference between total SL from satellite altimetry and the sum of barystatic SL change from satellite gravity and halosteric SL variations from in situ data. Ocean Heat content (OHC) is then calculated from thermosteric SL using the integrated expansion efficiency of heat (IEEH) coefficient. Results show 0.17 W/m^2 OHC trend in the

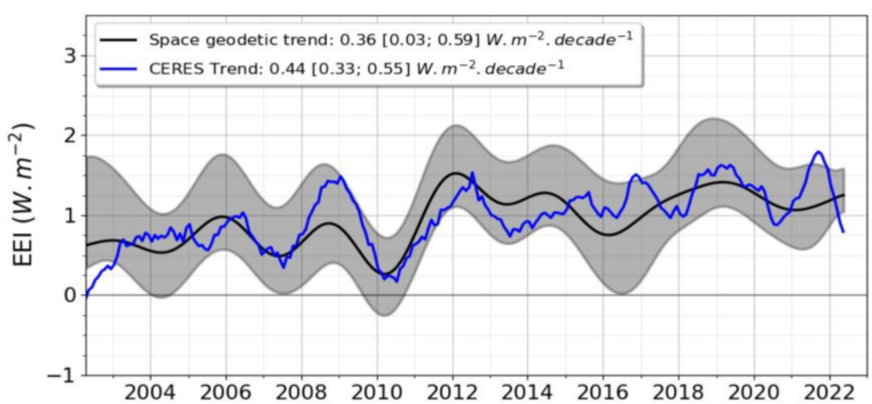


Figure 5.14-5: Decadal variations of the Earth energy imbalance estimated from (black) the space geodetic method and (blue) direct measurements of solar radiation at the top of the atmosphere from CERES. The grey shaded area corresponds to the space geodetic method's uncertainty.

Atlantic Ocean with strongest warming in the southern and northwest Atlantic, and cooling in the northeast Atlantic. Uncertainties in OHC trends stem from manometric uncertainties ranging from 70% to 90% from east to west. OHC trends from the geodetic approach show good agreement with independent datasets from the RAPID and OVIDE sections (Figure 5.14-4).

Ablain et al. presented “Monitoring the global ocean heat content from space geodetic observations” (https://doi.org/10.24400/527896/a03-2023.3722). The ocean absorbs much of the excess energy stored by the Earth system that results from the greenhouse gas emission by human activities in the form of heat (~91%). As the ocean acts as a huge heat reservoir, global ocean heat content (GOHC) is therefore a key component in the Earth's energy budget. An accurate knowledge of the GOHC change allows us to assess the Earth energy imbalance (EEI), which refers to the difference between the amount of energy the Earth receives from the sun and the amount of energy it radiates back into space. Various methodologies exist to estimate EEI from the GOHC, including the use of temperature and salinity profiles, the measurement of the ocean thermal expansion from space geodesy, ocean reanalysis and net flux measurements. Among these approaches, the space geodetic approach, detailed in Marti et al. (2022), leverages the maturity of satellite altimetry and gravimetry measurements, enabling precise, extensive spatial and temporal coverage, and full-depth estimates of ocean thermal expansion. As the EEI magnitude is small (0.5-1.0 W/m2) compared to the amount of energy entering and leaving the climate system (~340 W/m2), a high level of precision and accuracy are required to estimate the EEI mean (< 0.3 W/m2) and its time variations at decadal scale (< 0.1 W/m2). In this regard, the space geodetic approach emerges as a promising candidate capable of meeting the stringent EEI precision and accuracy requirements (Figure 5.14-5).

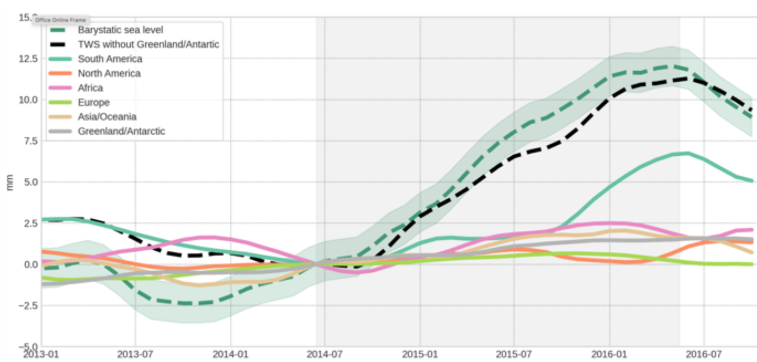


Figure 5.14-6: Different contributions to the global ocean mass budget from 2013 to 2017.

Llovel et al. presented “Cause of substantial global mean sea level rise over 2014-2016” (https://doi.org/10.24400/527896/a03-2023.3691). Global mean sea level rise is one of the direct consequences of the actual global warming. This rise has been monitored for years by satellite altimetry missions which provide high quality data at nearly global coverage. This global rise is caused by global ocean warming (known as thermosteric sea level) and the continental freshwater discharge from land ice melting (i.e., Greenland and Antarctica ice sheets and mountain glaciers; known as barystatic sea level). On top of the background sea level trend, large interannual variability can occur which can be attributed to natural climate mode of variability (such as ENSO, PDO, etc). Since 2005 and at global scale, ocean warming and barystatic sea level can be assessed by complementary observing systems such as Argo profiles and GRACE/GRACE-FO data, respectively. In this study, we investigate the extreme El Nino events occurring in 2014-2016 and their imprints on the global mean sea level change by assessing all the different components of the sea level budget. Over 2014-2016, we find that the global mean sea level experiences a rise of 1.5 cm over 24 months. 20% of this rise can be attributed to global ocean warming and 80% to barystatic sea level rise. Half of the barystatic sea level rise can be attributed to terrestrial water changes in South America with a significant contribution from the Amazon basin (5mm) (Figure 5.14-6).

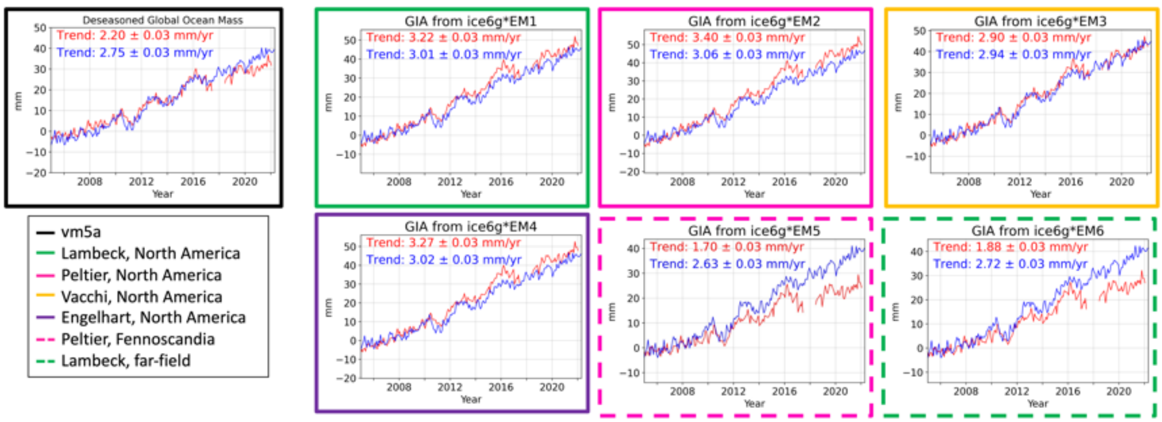


Figure 5.14-7: De-seasoned global mean ocean mass using different GIA models.

Bellas et al. presented "Impacts of GIA Modeling Uncertainties on the Closure of the GMSL Budget" (https://doi.org/10.24400/527896/a03-2023.3824). The closure of the global mean sea level (GMSL) budget can be impacted significantly by errors in modeling Glacial Isostatic Adjustment (GIA). GIA affects both the altimeter estimates of global mean sea level as well as the ocean mass estimates from GRACE/GRACE-FO. We examine the sensitivity of the GMSL closure to choices made in modeling GIA. As an example, relatively small changes in the Earth model used in the GIA modeling can have significant impacts on the GMSL closure between GMSL (altimetry), ocean mass (GRACE), and thermosteric sea level change (Argo). We will summarize these differences and suggest avenues for future research (Figure 5.14-7).

5.14.2 Splinter Discussion Points and Recommendations

Argo plays a critical role in numerous cross-cutting climate-related science topics important to the altimetry, GRACE and broader science communities. In light of Deep Argo's ability to rapidly expand observations of the ocean below 2000 m, resolve variations of temperature and salinity over the full-ocean depth, and close regional and global sea level budgets, the OSTST recommends substantially increased support for the OneArgo Program. Added resources are needed to expand the array to include global implementation of Deep Argo and increased coverage by Core Argo in polar regions and marginal seas.

5.15 The Geoid, Mean Sea Surfaces and Mean Dynamic Topography

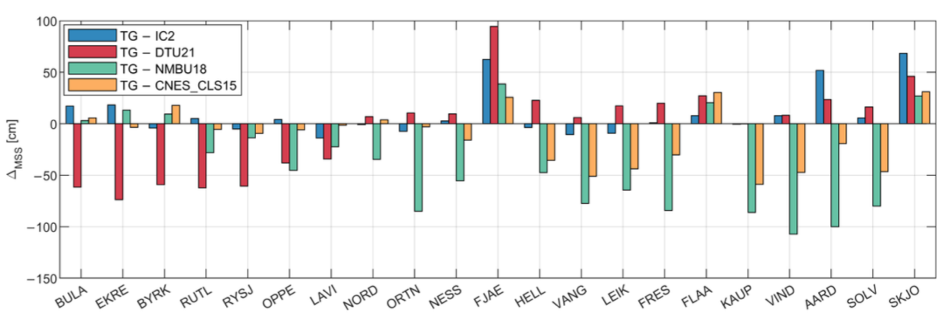
Chairs: Ole B. Andersen and Yannice Faugere

5.15.1 Summary

The session was a poster session with a total of 8 posters:

- ICESat-2 for Coastal MSS Determination—Evaluation in the Norwegian Coastal Zone (Tomić et al.)
- Lake Geoid and gravity from altimetry (Franze et al.)
- Development of Puerto Rico and US Virgin Islands sea surface topography for vertical datum transformation using retracked altimetry and tide gauges (Jeong et al.)
- The mean dynamic topography model DTUUH22MDT from satellite and in-situ observations (Knudsen et al.)
- Accuracy and Resolution of SWOT Altimetry: Foundation Seamounts (Sandwell et al.)
- The 2023 Hybrid Mean Sea Surface (Schaeffer et al.)
- The first validation of NMBU23 – an updated coastal mean sea surface in Norway based on a combination of new-generation laser and radar altimetry (Tomić et al.)
- ICESAT-2 altimetry for coastal MSS improvement (Vrettou et al.)

The presentation by Tomić et al. (https://doi.org/10.24400/527896/a03-2023.3715) presented the use of ICESAT-2 for coastal MSS determination in a comparison with a hydrodynamic model of the tides in Norwegian fjords (Figure 5.15-1).



Δ	MIN [cm]	MAX [cm]	MEAN [cm]	STD [cm]
TG – IC2	-13.8	68.3	9.4	23.2
TG – DTU21	-73.8	94.5	-3.9	42.9
TG – NMBU18	-107.3	38.8	-39.0	45.2
TG – CNES_CLS15	-58.7	31.1	-12.5	21.7

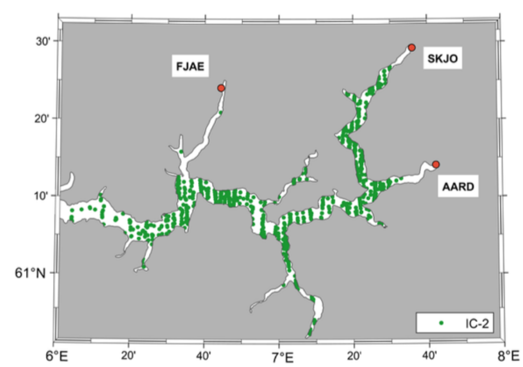


Figure 5.15-1: (Top) the height difference between temporary tide gauges and the IC-2 MSS model inside Sognefjorden. (Bottom left) Statistics of differences between the MSL observed by temporary tide gauges inside Sognefjorden and MSS from altimetry. (Bottom right) Branches of Sognefjorden with available ICESat-2 observations.

Sarah Franze et al. (https://doi.org/10.24400/527896/a03-2023.3837) presented the use of satellite altimetry (particularly ICESAT-2 in lakes for gravity and geoid determination. She intercompared airborne GRAV-D data with gravity derived from Icesat-2, Cryosat-2 and SARAL and demonstrated how Icesat-2 is superior in smaller lakes (Figure 5.15-2).

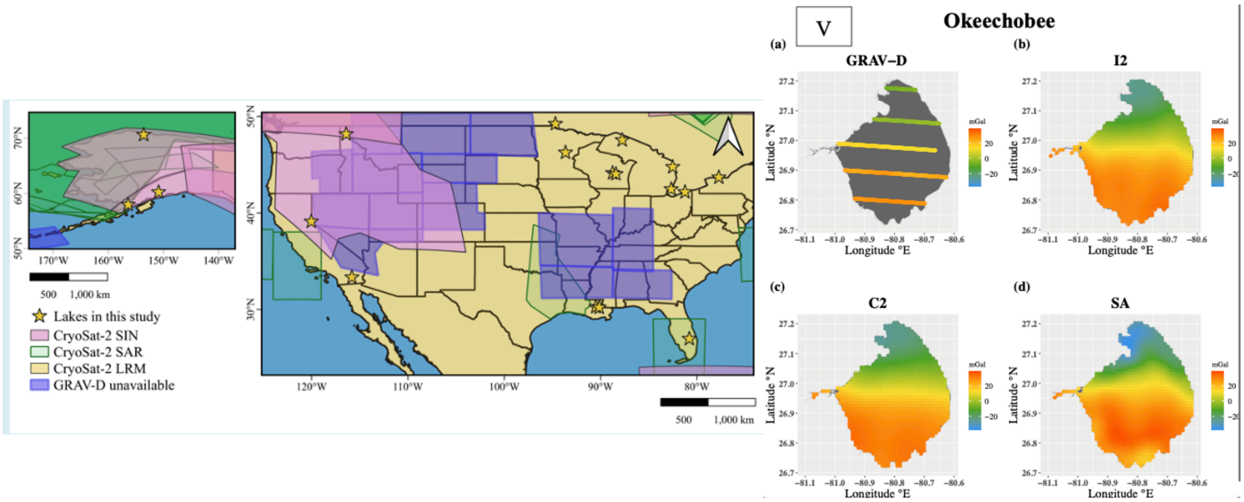


Figure 5.15-2: ICESAT-2 and conventional satellite altimetry for lake gravity and geoid determination.

The Development of Puerto Rico and US Virgin Islands sea surface topography for vertical datum transformation using retracked altimetry and tide gauges was presented by Jeong et al. (https://doi.org/10.24400/527896/a03-2023.3736) (Figures 5.15-3).

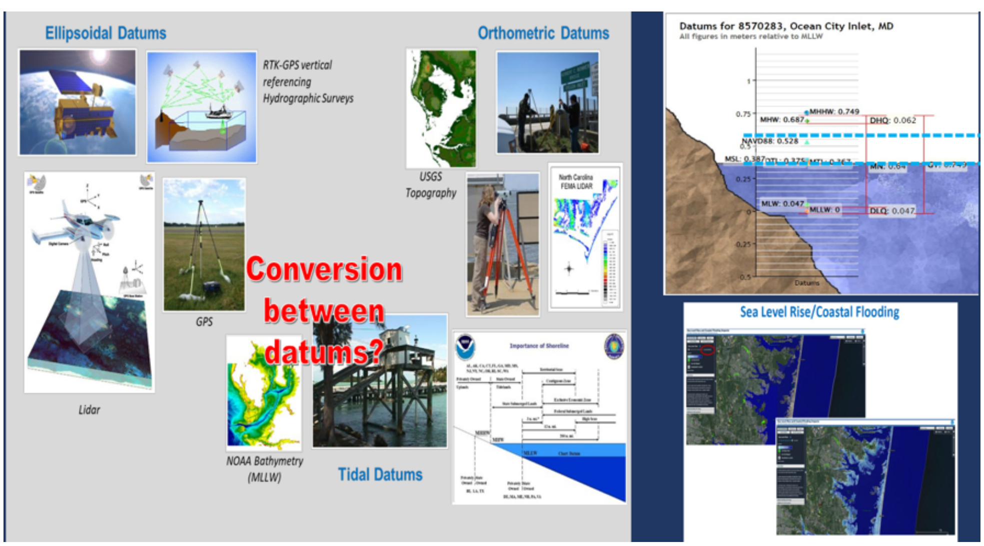


Figure 5.15-3: Puerto Rico sea surface topography and transformation interface.

P. Knudsen (https://doi.org/10.24400/527896/a03-2023.3750) presented a new combined Mean Dynamic Topography called DTUUH22 (Figure 5.15-4).

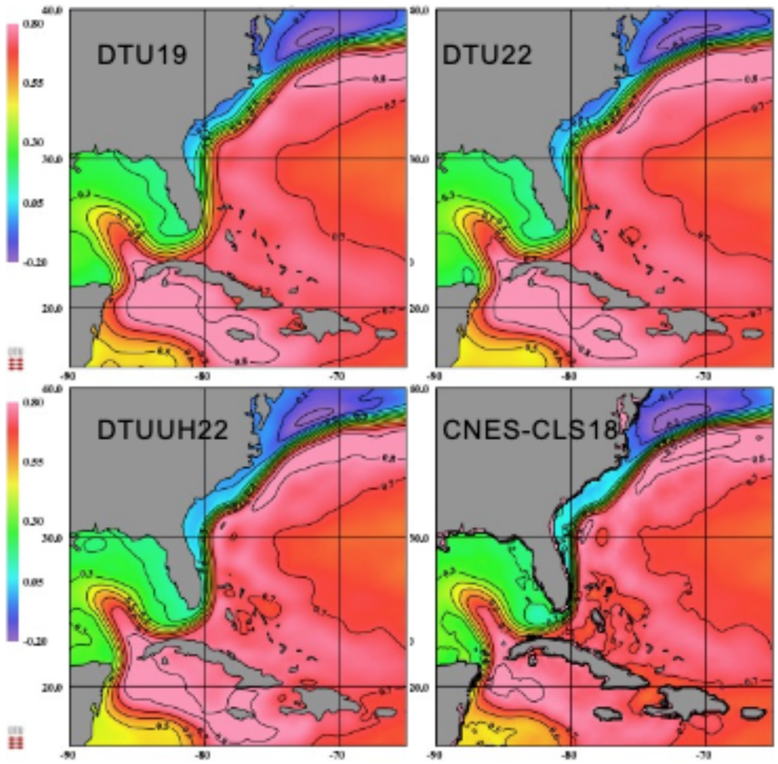


Figure 5.15-4: Mean Dynamic Topography in the Gulf Stream Region from various MDT models: two geodetic and two combination MDTs.

The first accuracy assessment for the Foundation Seamount was presented by D. Sandwell and Y. Yao (https://doi.org/10.24400/527896/a03-2023.3799) (Figure 5.15-5).

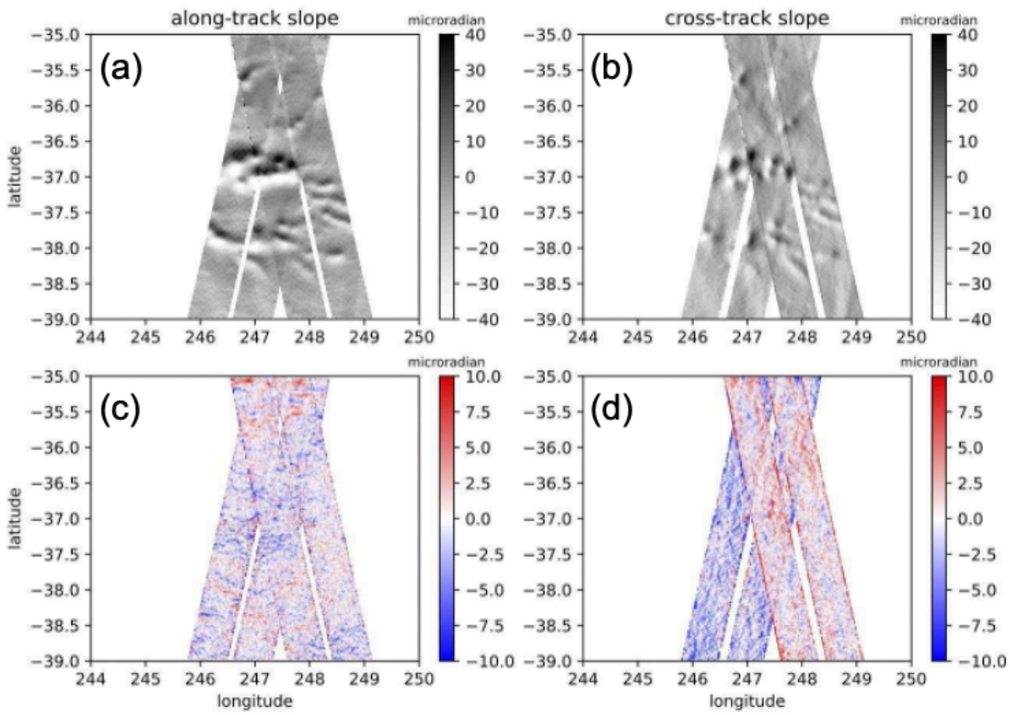


Figure 5.15-5: (a) Along-track and (b) Cross-track slope for one SWOT cycle (541) along ascending (pass 011) and descending (pass 028). (c) Difference between SWOT along-track slope and model slope shows mainly small spatial scale noise with higher noise on the edges of the swaths. (d) Difference between SWOT cross-track slope and model slope shows noise but also a mean slope difference of -2.5 micro rad (pass 011) due to uncorrected spacecraft roll error.

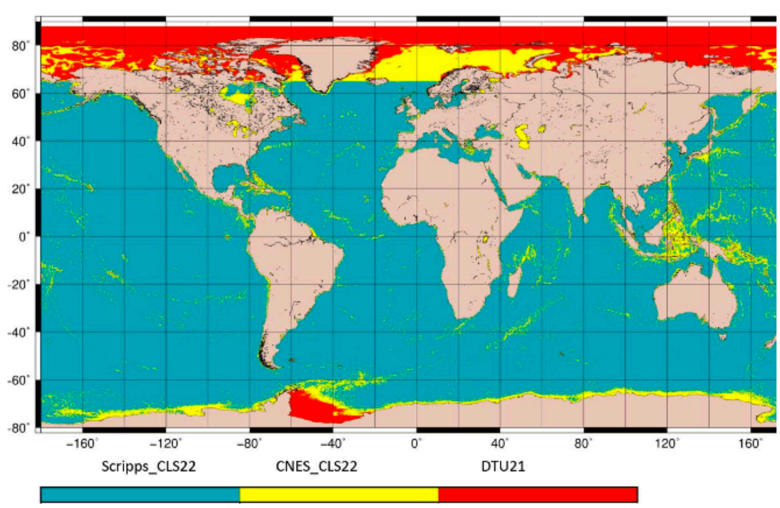


Figure 5.15-6: Data sources in the HYBRID23 MSS model from CLS.

A new 2023 hybrid Mean Sea surface model was presented by Schaeffer et al. (https://doi.org/10.24400/527896/a03-2023.3717). This model is the result of the combination of SCRIPPS_CLS22 in the open ocean supplemented by CNSA_CLS22 in regions of strong ocean currents and near the coast and complimented by DTU21MSS in Polar Region (Figure 5.15-6).

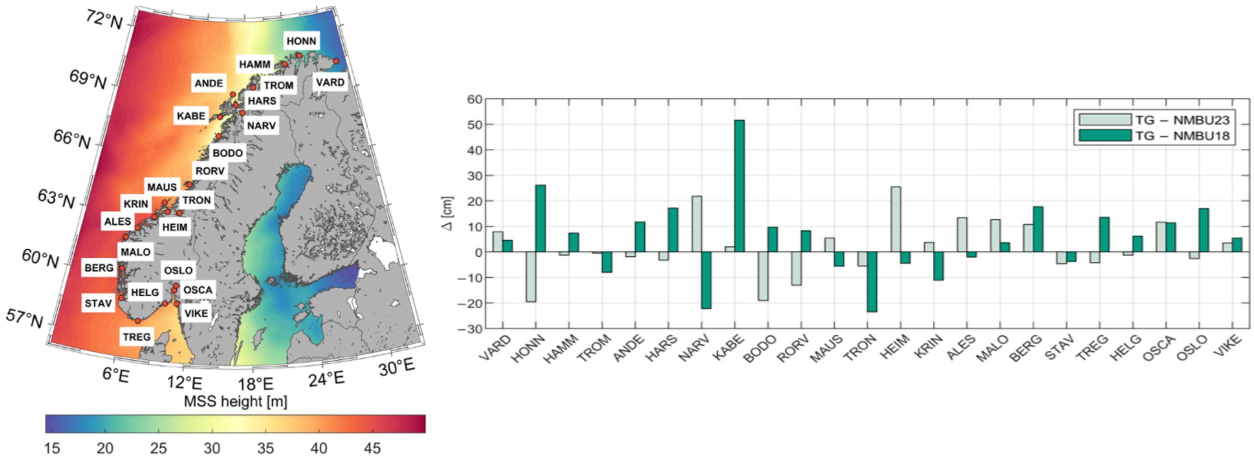


Figure 5.15-7: (Top) Mean Sea Surface for Norway for the period 2010-2023 from combination of radar and laser altimetry observations with marked locations of permanent tide gauges used for validation.

The first validation of NMBU23 – an updated coastal mean sea surface in Norway based on a combination of new-generation laser and radar altimetry was presented by Tomić et al. (https://doi.org/10.24400/527896/a03-2023.3718) (Figure 5.15-7).

Finally a study of the use of ICESAT-2 for coastal MSS determination in Greenland was presented by Vrettou et al. (https://doi.org/10.24400/527896/a03-2023.3838). The problem for the determination of MSS in Fjords around Greenland is the fact that the fjords have tides ranging up to 6 meters, but no tide models is covering the Fjords (Figure 5.15-8).

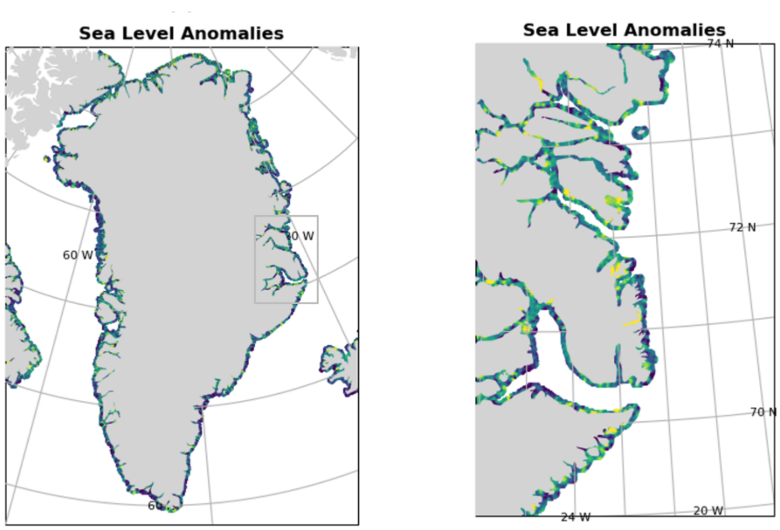


Figure 5.15-8: Averaged MSS from Coastal ICESAT data around Greenland (max 10 km from shore) relative to DTU21MSS.

5.15.2 Splinter Discussion Points and Recommendations

The points raised by the steering committee of OSTST was discussed during the splinter:

Is Long-Repeat Orbit (LRO) still necessary? The Splinter came up with the following recommendations to Jason-3:

- The splinter acknowledges the important work in preparing the Jason-2 LRO and suggests Jason-3 LRO due to its favorable sub-cycles periods and value to oceanography and geodesy and to use this for a potential Jason-3 LRO.
- Jason-3 LRO is paramount in the event of the failure of SWOT in the coming years.
- Jason-3 LRO will compliment altimetry in un-mapped diamonds of SWOT @ 2 km resolution.
- The splinter recommends that the SWOT Science team consider shifting the ground tracks of the mission for a potential SWOT mission extension.
- The Splinter encourages efforts to maximize the operating time of Jason-3 and the importance of completing at least 2 LRO sub-cycles of 369 days.
- The Splinter recommends re-occupying the LRO orbit of Jason-2 with Jason-3.
- The Splinter recommends performing 2 LRO sub-cycles of 369-day sub-cycles shifted by 2 km with respect to Jason-2. This will result in a systematic 2-km global grid combining Jason-2 and Jason-3 LRO data.
- If the health of Jason-3 is high after the 2 LRO sub-cycles, the splinter encourages a further 369 days replacement of the second sub-cycle of Jason-2 due to serious problems with gaps due to safe holds (> 20% of the time).

Recommendations for SWOT:

- The Splinter acknowledges the high quality of SWOT for MSS/geoid after 1-2 years of operation.
- The splinter recommends that the SWOT Science team consider shifting the ground tracks of the mission for a potential SWOT mission extension to avoid measurement gaps, especially at low latitudes, as uniform coverage is paramount to Geoid and MSS determination.

5.16 Tides, internal tides and high-frequency processes

Chairs: Loren Carrere, Florent Lyard and Richard Ray

5.16.1 Summary

This session had 8 poster presentations and 1 forum only presentation:

1. ALBATROSS: Improving the bathymetry and ocean tide knowledge in the Southern Ocean with satellite observations (Berlot et al., https://doi.org/10.24400/527896/a03-2023.3687)
2. Improving the geophysical corrections for altimeters and SWOT: tides and DAC (Carrere et al., https://doi.org/10.24400/527896/a03-2023.3818)
3. Seasonal estimations of baroclinic tides using MIOST model and altimeter data (Carrere et al., https://doi.org/10.24400/527896/a03-2023.3820)
4. Arctic Ocean tidal constituents atlas (Hart-Davis et al., https://doi.org/10.24400/527896/a03-2023.3763)
5. How errors in ECMWF atmospheric tides corrupt the DAC correction (Ray et al., https://doi.org/10.24400/527896/a03-2023.3853)
6. Ocean forcing of tidal winds: evidence from harmonic analysis of altimeter-derived wind speed (Zaron et al., https://doi.org/10.24400/527896/a03-2023.3752)
7. Towards TPXO10, the next version of the Oregon State University ocean tide model (Zaron et al., https://doi.org/10.24400/527896/a03-2023.3753)
8. Internal tide model ZHAO23: A milestone achieved by 30 years of satellite altimetry sea surface height measurements from 1993 to 2022 (Zhao et al., https://doi.org/10.24400/527896/a03-2023.3758)
9. Altimetry-derived ocean tides in the Arctic: a Foxe Basin case study (Hart-Davis et al., https://doi.org/10.24400/527896/a03-2023.3762)

6 Discussion of Recommendations and Closing Plenary

This year discussion of OSTST recommendations took place both on Friday morning along with feedback from the Sentinel-6 Validation Team, and during the closing plenary on Saturday morning. In addition, there was a presentation on the definition of the new Geophysical Data Record (GDR) standards (GDR-G) in a multi mission context.

Cristina Martin-Puig (EUMETSAT) discussed the altimetry mission standards. She noted that currently 11 altimeters are currently operating with data quality still regularly being improved. While agencies have been coordinating to get quite homogenous processing baselines across missions, a full harmonization between missions was never discussed in detail until now. All agencies are working now in full collaboration to define a set of common standards and the best data processing practices to ensure full harmony between missions. She then discussed the different subsequent changes that will impact the new data reprocessings for Jason-3, Sentinel-3 and Sentinel-6 MF in terms of common standards (tides, mean sea surface, geoid, mean dynamic topography, ionospheric, and sea state bias models, standards for precise orbit data products, etc.) and processing practices (harmonizing compression techniques, retrackers, variables, etc.). She noted that some differences will still exist between missions as they have their particularities. Regarding Jason-3 and Sentinel-6, the GDR-G standards will be implemented before summer 2024 as the Sentinel-6B processors will be frozen a year before launch (end of 2025). While similar harmonization efforts will be applied to SARAL/AltiKa, it is still under investigation of the feasibility for Cryosat-2. The SWOT nadir altimeter is already ahead of the curve in terms of standards. Finally, Cristina raised a few questions to the community such as the potential interest in all missions offering geophysical corrections at 20Hz and how this should be implemented.

The closing plenary session also included discussions, notably about the key points that were addressed to the splinters during the opening session. After discussion, the following Recommendations and Appreciations were adopted (other specific recommendations can be found in the splinters summaries):

Recommendations:

- **Sentinel-6 MF Extended Operations Phase Orbit:** In light of that fact that user needs remain very high for altimetry observations complementary to the reference mission, the OSTST recommends extending operations of Sentinel-6 Michael Freilich, assuming it remains in good health, beyond the time when Sentinel-6B has become the reference mission. Specifically, the OSTST recommends:
    1) Moving Sentinel-6 MF to an exact repeat orbit with the same characteristics as the reference orbit, except for a phase difference of 163° along the orbit, either ahead or behind Sentinel-6B, resulting in an interleaved ground-track to the reference orbit. (Jason-3 currently flies 163° behind Sentinel-6 MF).

	Reference	Interleaved
Semi-major axis (km)	7714.4278	
Eccentricity	0.000095	
Nodal period (s)	6745.72	
Repeat cycle (days)	9.9151	
Longitude at Equator for pass 1	99.9242º	98.5069º

2) The project adopt the same data availability requirements as expressed in the EURD (R-U- 00460/490/500/515/520/570/573/576) for the Extended Operations Phase of Sentinel-6 Michael Freilich (See table below), with the understanding that Sentinel-6B operations will be prioritised over Sentinel-6 MF. These requirements are as follows:

	NRT	STC	NTC
ALT L1		95% within 36h (HR: 90%) *R-U-00490*	95% within 60d (HR: 90%) *R-U-00515*
ALT L2	90% within 3h (HR: 85%) *R-U-00460*	95% within 36h (HR: 90%) *R-U-00500*	95% within 60d (HR: 90%) *R-U-00520*
MWR L2	90% within 3h *R-U-00570*	95% within 36h *R-U-00573*	95% within 60d *R-U-00576*

- **Jason-3 Orbit Change:** The OSTST endorses the current plan to move Jason-3 to a Long Repeat Orbit immediately after the conclusion of a second tandem with Sentinel-6 Michael Freilich. This 371-nodal-day long repeat orbit should be the same as the one occupied by Jason-2. The first two LRO cycles should be phased such that Jason-3 will interleave the two Jason-2 LRO cycles, each shifted by 2-km. This will result in a systematic 2-km global grid combining Jason-2 and Jason-3 LRO data. The OSTST also recommends two additional LRO cycles that revisit the Jason-2 LRO ground tracks to fill in gaps and reduce mean sea surface errors.
- **Climate Quality Accuracy in Future Missions:** The OSTST notes that to achieve accuracy in global and regional sea level change as detailed in GCOS requirements, it will be necessary to maintain and continue to improve accuracy of orbital determination systems, such as those achieved using a combination of SLR, DORIS and GNSS. The OSTST has demonstrated that three tracking systems (GNSS, DORIS and SLR) are necessary to achieve maximum accuracy on the determination of regional sea level

trends, and it strongly recommends that such accuracy be maintained in the design of Sentinel-6C. The OSTST also noted that accuracy of the Climate Data Record requires continued maintenance or improvement of the terrestrial reference frame, which also relies on these tracking systems. Finally, requirements on other aspects of the altimetric measurement system must also be maintained or continue to improve.

- **Synergies with Argo and GRACE:** Argo plays a critical role in numerous cross-cutting climate-related science topics important to the altimetry, GRACE and broader science communities. In light of Deep Argo's ability to rapidly expand observations of the ocean below 2000 m, resolve variations of temperature and salinity over the full- ocean depth, and close regional and global sea level budgets, the OSTST recommends substantially increased support for the OneArgo Program. Added resources are needed to expand the array to include global implementation of Deep Argo and increased coverage by Core Argo in polar regions and marginal seas.
- **Altimetry Product Evolution:** The OSTST recommends that agencies study the performance of the three latency products, NRT, STC and NTC with an aim toward understanding if all three still meet user needs, or if their performance and latencies should be redefined or adjusted. This should be considered across all platforms.
- **Potential Gap between CryoSat-2 and CRISTAL:** The OSTST recommends studies to address which satellites, airborne operations, or other assets might help fulfill scientific needs for high-latitude ocean and ice elevation measurements during a potential gap between CryoSat-2 and CRISTAL. The OSTST also recommends minimizing the probability of a gap by extending CryoSat-2 operations through at least 2028 and avoiding delays in the launch of CRISTAL to the extent possible.
- **Integrity of the Altimetry Constellation and Instrument Function:** In light of ongoing efforts to launch a large number of communications satellites in orbits close to the 1336 km altimetry constellation, the OSTST recommends that agencies take steps to determine and establish sufficient margins that will safeguard altimetry missions in both reference and polar orbits from collision, debris and interference with their passive and active instruments.

Appreciations:

- The OSTST expresses its appreciation to NASA and CNES for the successful launch and commissioning of the SWOT mission and its revolutionary new wide swath altimeter for ocean and surface water.