Report of the

Ocean Surface Topography Science Team Meeting

Palazzo del Cinema at Lido di Venezia, Venice (Italy)

Monday, October 31 2022 - Friday, November 4 2022

Edited by
Pascal Bonnefond, Observatoire de Paris - SYRTE, CNES
Josh Willis & Severine Fournier, Jet Propulsion Laboratory
Eric Leuliette, NOAA
Remko Scharroo, EUMETSAT
Craig Donlon, ESA

Organized by CNES, NASA, NOAA, EUMETSAT and ESA

Contents

1 Executive Summary

The Ocean Surface Topography Science Team (OSTST) Meeting was held in Venice, Italy, 31 October to 4 November 2022. Due to COVID-19 pandemic restrictions, this was the first in-person OSTST meeting 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, HY-2, Sentinel-3, CFOSAT), and preparation for SWOT and other future missions.

In addition to the technical and science sessions, the meeting included special splinter sessions "Beyond the history of European–US cooperation on altimetry" and "Feedbacks from the Sentinel-6 Validation Team (S6VT)" (chaired by the Project Scientists) and splinters on Coastal Altimetry and on CFOSAT. Online forums, introduced for the 2020 virtual meeting, were available during and for several weeks after the meeting, and recordings of the plenary sessions were made available. All of the presentations from the plenary, splinter, and poster sessions are available on the AVISO website: https://ostst.aviso.altimetry.fr/programs/2022-ostst-complete-program.html.

Because continued travel restrictions led to postponements of an in-person meeting in 2021, an abbreviated Virtual OSTST meeting was held 21-22 March 2022. The first day included program status updates and mission overviews of Jason-3 and Sentinel-6 Michael Freilich (Sentinel-6 MF) and one keynote on the sea level climate data record. On the second day, four technical splinters provided high-level summaries. After a presentation of a recommendation by the Sentinel-6 Project Scientists, the Committee on Earth Observation Satellites (CEOS) Ocean Surface Topography Virtual Constellation declared Sentinel-6 MF as the new Reference Altimetry Mission for the worldwide altimetry constellation.

Sentinel-6 MF launched on 21 November 2020 from Vandenberg Air Force Base (now Space Force Base, VSFB) 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.

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, 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.

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 land altimetry Level 2 products will be completed in 2023. Sentinel-3C and Sentinel-3D are completing their assembly integration and testing in readiness for launch. A scientific justification for a tandem flight between S3A/B/C/D has been prepared and is being assessed in terms of feasibility.

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 latest CFOSAT Science Team meeting held in Saint-Malo, France (September 12-14 2022). The second full reprocessing of SWIM data in version 6 is now completed, all data from 25 April 2019 to the current date are now available.

After the OSTST meeting, the Surface Water and Ocean Topography (SWOT) mission 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 are expected to be available in mid-2023. Since the OSTST Meeting, the first images from SWOT were released, showing great promise for the instrument capabilities (see NASA and CNES press releases).

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

- **Second Jason-3/Sentinel-6MF Tandem Phase:** Given the societal importance of the sea level record and the need to understand its long-term uncertainty, the OSTST recommends to the Jason-3 Project an additional tandem phase between Jason-3 and Sentinel-6 Michael Freilich (S6MF) that lasts 12 cycles, after at least 2 years in the interleaved mission. The OSTST recognizes that the second tandem mission should have no operational impact on S6MF.

- **Sentinel-6B commissioning:** The OSTST recommends that during commissioning Sentinel-6B should:
    - operate both sides of the altimeter;
    - execute a tandem mission with S6MF of at least 10 cycles on the one side followed by 10 cycles on the most pre-launch performant side, so that no switch back is necessary after tandem;
    - use Mode Mask H on the first side and Mode Mask F on the second side; and
    - should include attitude flip maneuvers as performed for S6MF.

- **OneArgo:** Recognizing the decline in the existing core Argo array and the need to strengthen the complementary observations between altimetry and Argo, including the need for closure of global and regional sea level budgets, quantifying Earth's energy imbalance, and understanding interaction of the biosphere and ocean physics, the OSTST supports the full deployment and sustainment of all three components of OneArgo, an integrated global, full depth, and multidisciplinary ocean observing array.

2 Opening Plenary

The Ocean Surface Topography Science Team (OSTST) held its first in person meeting since the beginning of the COVID pandemic in Venice, Italy, 31 October to 4 November, 2022. On behalf of the Project Scientists (Pascal Bonnefond, CNES; Eric Leuliette, NOAA; Remko Scharroo, EUMETSAT; Craig Donlon, ESA; Josh Willis, NASA), Pascal opened the meeting and presented the agenda and explained the logistics. In particular, he noted the addition of online forums, which accompanied all presentations from this. The forum is available until a new one for the next OSTST will be set-up, it can be access (after login) at: https://ostst.aviso.altimetry.fr

Sophie Coutin-Faye (CNES) also took a moment to express her gratitude to the community and announce her retirement. In addition, Josh Willis announced the addition of a new Deputy Project Scientist at NASA's Jet Propulsion Laboratory, Severine Fournier.

2.1 Program and Mission Status

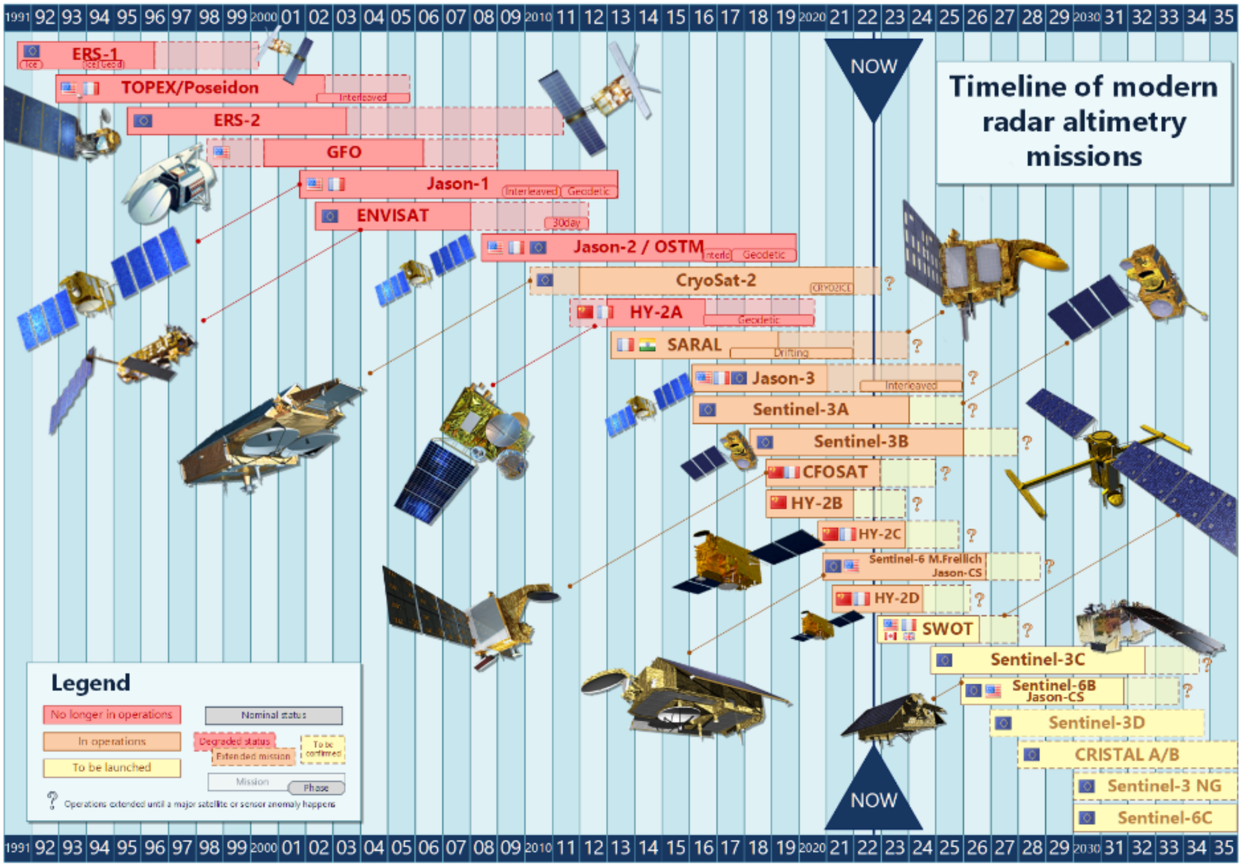

Figure 2.1-1: Altimetry missions' timeline as of November 2022.

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 Benveniste).

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 noted that the OSTST now consists of two parts, one that supports infrastructure, which is not competed, and one that supports research, which is competed. Together, there are 65 members and 19 projects, covered by the $15M budget for the 2021-2025 period.

Annick Sylvestre-Baron (CNES) summarized the CNES Ocean Program, which includes support of Sentinel-6, Sentinel-3, SWOT, and HY-2 as well as Jason-2 and -3. Annick noted that this year, marked the 30th anniversary of the launch of TOPEX/Poseidon, whose reference track is currently occupied by Sentinel-6 Michael Freilich, and the upcoming launch of the first wide swath altimeter, SWOT. She also noted that SARAL/AltiKa received a 2-year mission extension for operation through the end of 2023, as did CFOSAT. The CFOSAT Science Team, which consists of 22 projects from 13 countries was also renewed for the period from 2023 to 2027.

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. Finally, Estelle noted the next Operational Satellite Oceanography Symposium will take place in Busan, South Korea, June 12-15, 2023.

Eric Leuliette (NOAA) provided a status update on the NOAA Jason-mission Program Status. NOAA continues to support PIs as part of the OSTST at a rate of about $800k per year for the current team. Eric also highlighted the new NOAA CoastWatch web site and data portal, designed to provide satellite data products to support research, resource management and decision making.

Finally, Jérôme Benveniste (ESA) provided an updated on the ESA Oceanography Programme. Jérôme noted the FDR4ALT project that is currently reprocessing ERS-1,-2, and ENVISAT altimeter data for consistency across missions. He also noted that CryoSat-2 and SMOS continue to produce sea level and soil moisture/ocean salinity observations, respectively. CIMR is targeted for launch in 2028 and will observe sea ice, sea surface temperature and other variables at high spatial resolution (5-15 km).

On behalf of the Project Managers, Christophe Ferrier (CNES) reviewed the status of the Jason-3 mission. In April of 2022, Jason-3 was moved to the interleaved orbit, with ground tracks spaced halfway between the reference mission tracks, and Sentinel-6 Michael Freilich was recognized as the official reference mission. The satellite is in excellent health with nominal performance of all instruments and systems and with all redundant systems still available. A second tandem mission with Sentinel-6 Michael Freilich has been proposed and the Project team remains ready to support such a move. After a second tandem mission, Jason-3 would then move to a long-repeat orbit (LRO) at an altitude of 1309 km, and will be moved to a graveyard orbit at 1283 km in the event that the satellites were to suffer any serious degradation.

Nadège Quéruel (CNES) gave an update on the status of the SARAL/AltiKa Mission. The SARAL/AltiKa mission continues to perform nominally after almost 10 years on orbit. All altimeter systems are operating nominally and continue to provide high quality data and continues to meet or exceed all requirements. Since July 2016, SARAL has operated in the SARAL Drifting Phase (SARAL-DP), in which the satellite's ground track and altitude have been allowed to drift. Release of the complete GDR-F reprocessed data set occurred at the end of 2020.

Bruno Lucas (EUMETSAT) provided an overview of the Sentinel-3 Marine Mission. The Sentinel-3A & 3B altimeters continue to function well and all marine data is meeting all accuracy, availability and timeliness requirements. Full mission reprocessing is ongoing to provide consistent time series and improvements to polar and coastal data is in preparation. 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 land altimetry Level 2 products will be completed by the second quarter of 2023 and available from ESA on the Open Access Hub. Finally, he noted that Sentinel-3C and 3D are ready to take over from 3A and 3B to extend the time series.

Julia Figa-Saldaña (EUMETSAT) gave an overview of the Sentinel-6 mission on behalf of all of the project and program managers. Julia noted that Sentinel-6 Michael Freilich has now taken over from Jason-3 as the reference ocean altimetry mission. The satellite continues to meet all science and operational requirements and has demonstrated excellent on-orbit performance. Julia also noted that Sentinel-6B successfully completed its Pre-Storage Acceptance Review in July 2022 and will be removed from storage in the fourth quarter of 2024, with launch planned for November 2025. Finally, a third satellite, Sentinel-6C has been proposed to extend the Sentinel-6 reference mission further to 2036.

Jean-Michel Lachiver (CNES) provided an overview of the China-France Oceanography Satellite (CFOSAT), which provides global scale observations of surface wind and wave spectral properties. The satellite continues to perform well after 4 years in orbit, and scientific and operational exploitation is ongoing. The second full reprocessing of the SWIM data will be completed by the end of the year, as will the first full reprocessing of data from the SCAT instrument.

An update on the SWOT mission was provided by Lee Fu (NASA) and Rosemary Morrow (LEGOS). The presentation discussed preparations for the launch of SWOT, including spacecraft readiness as well as the formation of Science Team Working Groups, who will analyze early observations. Since the OSTST meeting concluded, SWOT was successfully launched on December 16, 2022, and first light data looks very promising (see NASA and CNES press releases). The mission science team was renewed for the period from 2020-2024, with 2 virtual meetings held in 2021 and one in person meeting in June 2022. Preparations for forming the next science team will begin in 2023.

Pierrik Vuilleumier (ESA) gave a presentation on the upcoming set of satellites slated to extend the Sentinel-3 record, called Sentinel-3 Next Generation Topography (S3NG-T). Pierrik noted that for S3NG, the optical instruments will be separated onto different spacecraft from the altimeters. The primary objectives for S3NG-T are to guarantee continuity of Sentinel-3 topography measurements from 2030 through 2050, Secondary objectives refer to the development of new products such as directional wave spectra and gradient products. While several variants of S3NG-T implementation have been explored, the Phase A/B1 are envisaged to implement 2 satellites carrying an imaging interferometer and SAR enabled Ku-band nadir altimeter. This was traded against an alternative solution based on a constellation of 10 Ka-band SAR enabled nadir altimeters.

Paolo Cipollini (ESA) and 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. It will include a dual-frequency Ku/Ka SAR altimeter, with the Ku being interferometric. CRISTAL-A is on track for launch in late 2027, with CRISTAL-B launch near the CRISTAL-A end of mission. Because both Ku and Ka band altimeters are primary, the dual frequency will be exploited to provide improved corrections and flagging, resulting in significant product improvements.

2.2 Other reports and issues

In addition to the programmatic and mission talks, three additional talks discussed developments with the Argo array of profiling floats, presentation of discussion topics for consideration by the splinters, and a special talk on the carbon footprint of the OSTST.

Susan Wijffels (WHOI), co-chair of the Argo Steering Team, gave a brief, invited presentation on Argo, its importance for understanding sea level rise, and its relationship to satellite altimetry. Susan 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. Widespread support for OneArgo was voiced during open discussions, and 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) updating the previous OSTST recommendation to perform a second tandem mission between Jason-3 and Sentinel-6 Michael Freilich, aimed at better understanding long-term stability of the missions,
2) finding the optimal duration for the length of the S6MF/S6B tandem calibration phase
3) questions on product evolutions for Sentinel-6 (retrieving RAW mode data in regions of swell, implementing coastal retracking, and GDR-G standards)
4) the form of future OSTST meetings.

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

Finally, François Bignalet-Cazalet (CNES) gave a special presentation on climate change and the carbon footprint of the OSTST meeting itself. The presentation provided an overview of human caused climate change and detailed specific contributions to greenhouse gas emissions from individual actions, and posed the question about what the OSTST can do to reduce its carbon footprint.

2.3 Science keynotes

There were four invited science keynotes on the diverse topics of Earth Energy imbalance, coastally trapped waves, interferometric swath radar altimetry and interpolation methods.

First, Jonathan Chenal (LEGOS, DOI: 10.24400/527896/a03-2022.3371) gave a presentation on the Earth Energy Imbalance. The Earth energy imbalance (N) corresponds to the incoming minus outgoing radiation and 93% of this extra heat is absorbed by the ocean, which is an important contribution to sea level rise. This energy imbalance can be separated into the radiative forcing due to greenhouse gases and aerosols (F) and the radiative response of the Earth. The main hypothesis is that the Earth radiative response is linearly dependent on the global mean surface temperature (T) through a parameter lambda. The equilibrium climate sensitivity (ECS), which represents the equilibrium global surface warming in response to a doubling of atmospheric CO_2 concentration relative to pre-industrial levels, is a fundamental metric for evaluating climate change projections (ECS = $-F_{2x}$/lambda). However, there are large discrepancies between the different methods estimating ECS. While observations tend to give low estimates, climate models tend to give higher estimates. This can be explained by the fact that lambda depends on global mean surface temperature itself, intrinsic internal climate variability, and on forcing agents, which causes in turn a warming pattern on marine low cloud (called pattern effect). Therefore, observational and climate model methods do not actually estimate exactly the same climate sensitivity. The difference between these estimates needs to be modeled. In his work, Jonathan uses estimates for T, F and N (based on different approaches including direct radiative measurements from satellite, in situ ocean heat content estimate, and geodesy ocean heat content estimate that all actually give estimates higher than the IPCC) and then regresses N-F on T. Thus, he gives the first observational time series of lambda as a function of T (Figure 2.3-1). When lambda is highly negative rather than closer to zero, variations of T in response to increase of CO_2 is lower. Furthermore, the variations of lambda are very well correlated with the PDO index (Figure 2.3-1) showing that variations of lambda could possibly be due to the pattern effect from the Pacific Decadal Oscillation (PDO).

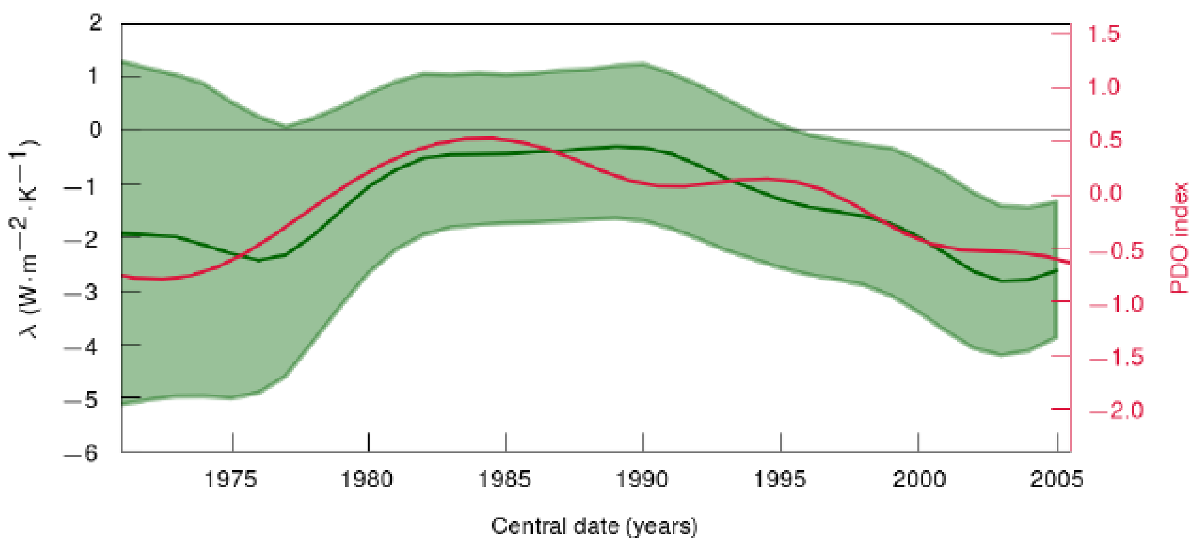

Figure 2.3-1: Variations of the parameter lambda for periods over 25 years (green) and time series of the PDO index (red).

Léa Poli (LOCEAN, DOI: 10.24400/527896/a03-2022.3532) presented her work on the trapped waves around the southern part of South America. These locally trapped waves are important because they contribute to nutrient supply to the Patagonia platform which is a very large fisheries area. The propagation of these waves (southward along the coast in the Pacific Ocean and northward along the coast in the Atlantic Ocean) depends on the continental slope, stratification, and mean flow. While on the Pacific Ocean side, the slopes are steep and the currents are weak; on the Atlantic side, the slopes are smooth and boundary currents are strong along the coast. In her work, Léa shows that altimetry can capture these waves propagating from the Pacific Ocean to the Atlantic Ocean via the Drake Passage (Figure 2.3-2).

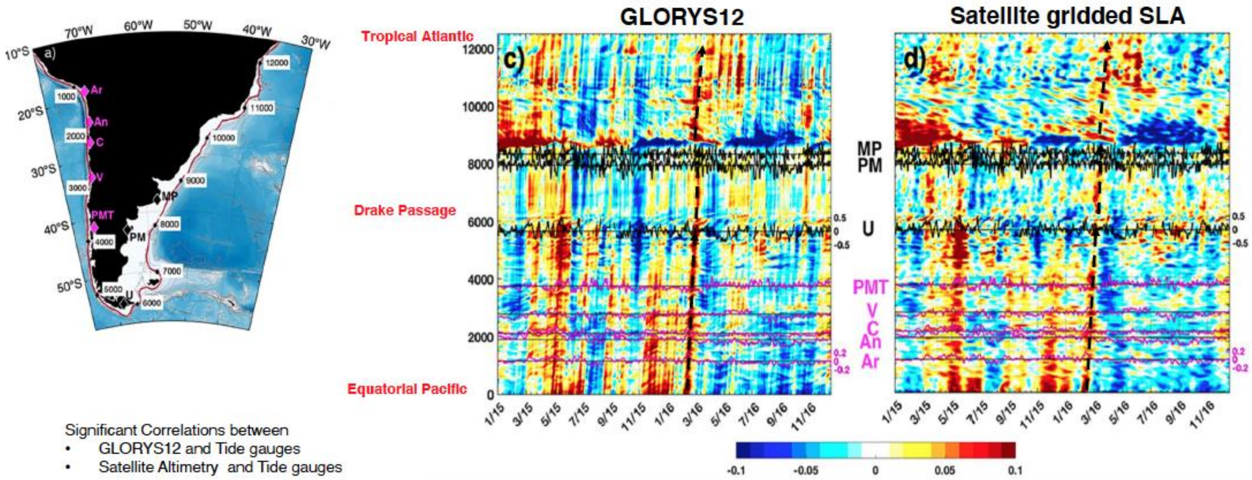

Figure 2.3-2: Hovmueller diagrams of SSH from a model and satellite showing the propagation of waves from the Pacific to the Atlantic Ocean via the Drake Passage.

A spectral analysis of SSH shows that the large-scale signals of 40-130 days are consistent with the propagation of an anomaly. A time-lagged correlation between SSH at a point on the Patagonia platform and SSH in the whole ocean region around the southern part of South America shows a propagation of about 1m/s to 7 m/s on the Patagonia platform (wide shelf) that slows down northward. Léa's work then investigates the forcing mechanisms of these waves. The waves are in part forced by the Madden Julian Oscillation through zonal winds over the Equatorial Pacific Ocean generating waves along the equator towards Peru, that are then trapped along the coast and travel towards the Atlantic Ocean via the Drake Passage. In addition, Léa's work shows that these waves are modulated by the El Niño Southern Oscillation (ENSO).

Noel Gourmelen (University of Edimburgh, DOI: 10.24400/527896/a03-2022.3335) presented his work on the interferometric swath radar altimetry for the study of the cryosphere. Cryosat's primary instrument is the Synthetic Aperture Interferometric Radar Altimeter (SIRAL) that was designed to measure ice-sheet elevation and sea-ice freeboard. Thanks to its Synthetic Aperture Radar Interferometric (SARin) mode, there is an increase in coverage for land ice compared to the Point Of Closest Approach (POCA) mode (Figure 2.3-3).

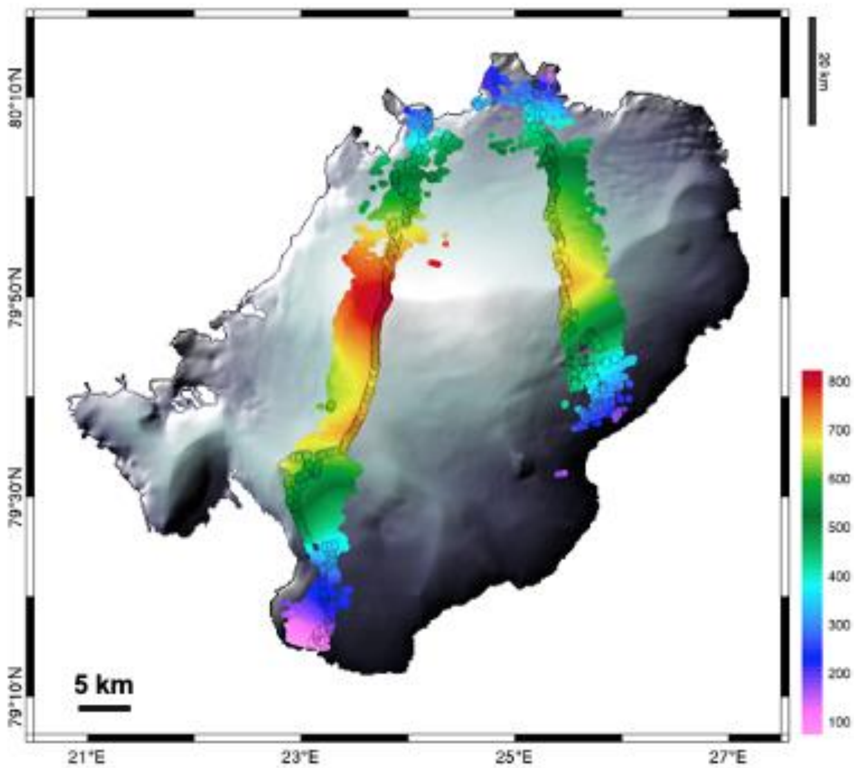

Figure 2.3-3: Scheme showing the spatial coverage of Cryosat swath SARin mode compared to the POCA mode.

This allows Cryosat to be extremely useful for many applications including an estimation of ice shelf thinning and melting, subglacial hydrology, mountain glacier among others. Therefore, Cryosat helps to monitor glacier mass, an important contribution to sea level rise. One of the limitations of Cryosat is its high sensitivity to the satellite attitude, especially rolling, due to its inclination. The recently launched mission SWOT and the upcoming mission CRISTAL will also have a SARin instrument onboard, as Cryosat.

Finally, Maxime Beauchamp (IMT, DOI: [10.24400/527896/a03-2022.3240](10.24400/527896/a03-2022.3240)), gave the last science keynote talk on an interpolation method called 4DVarNet. This method allows to interpolate an observational dataset containing gaps, this can be applied to along-track SSH data in order to obtain gridded SSH maps. Some current methods commonly used for this task are covariance-based methods such as kriging and optimal interpolation, model-based and data-based data assimilation methods. The 4DVarNet method was applied on along track SSH observations (nadir and/or simulated SWOT swath data) in the North Atlantic region and compared with the optimal interpolation method used by AVISO DUACS. The results show that the maps retrieved using the 4DVarNet method compare better with our ground truth (a high-resolution model) than the optimal interpolation maps (Figure 2.3-4). Indeed, features such as fronts and eddies are better captured in the 4DVarNet maps.

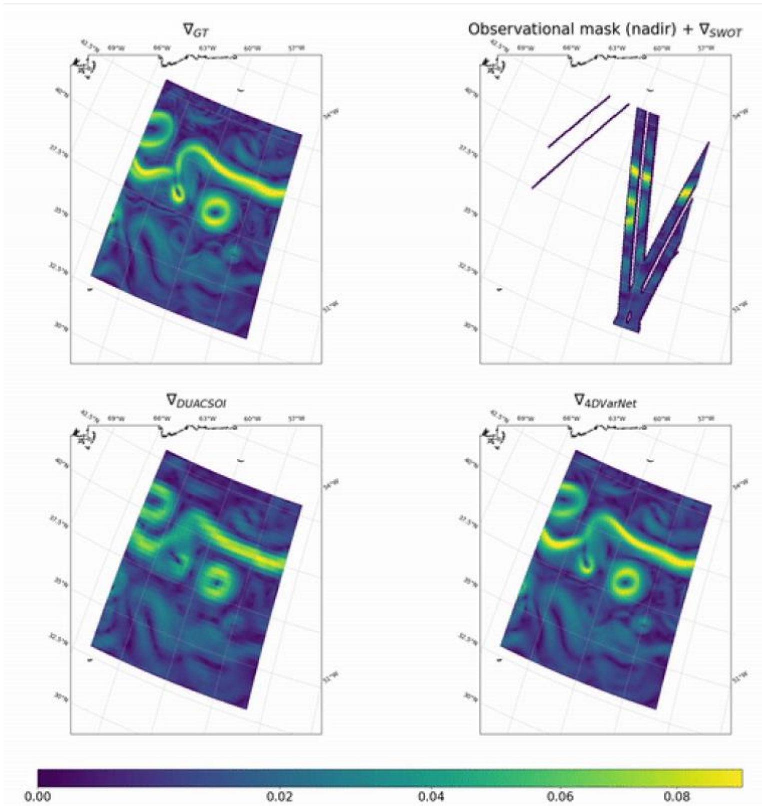

Figure 2.3-4: SSH gradients in the Gulf Stream region from our ground truth (top left), the optimal interpolation DUACS method (bottom left), and the 4DVarNet method (bottom right). The observational nadir and swath along track data used for the interpolation are shown at the top right.

3 Poster Sessions

Two poster sessions were conducted on Tuesday 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/2022-ostst-complete-program.html

The posters were grouped into the following categories:

- Application development for Operations [14 posters]
- CFOSAT [1 poster]
- Coastal Altimetry [15 posters]
- Instrument Processing (Measurement and retracking) [4 posters]
- Instrument Processing (Propagation, Wind Speed and Sea State Bias) [5 posters]
- Outreach, Education & Altimetric Data Services [8 posters]
- Precise Orbit Determination [5 posters]
- Quantifying Errors and Uncertainties in Altimetry Data [5 posters]
- Regional and Global CAL/VAL for Assembling a Climate Data Record [23 posters]

- Science Results I: Climate Data Records for Understanding the Causes of Global and Regional Sea Level Variability and Change [12 posters]
- Science Results II: Large Scale Ocean Circulation, Variability and Change [0 poster]
- Science Results III: Mesoscale and Sub-Mesoscale Oceanography [22 posters]
- Science Results IV: Altimetry for Cryosphere and Hydrology [27 posters]
- Sentinel-6 Validation Team (S6VT) feedbacks [4 posters]
- The Geoid, Mean Sea Surfaces and Mean Dynamic topography [4 posters]
- Tides, internal tides and high-frequency processes [4 posters]

4 Splinter Sessions

The splinter sessions were organized as follows:

Monday, October 31:

- Science Keynotes [4 Oral talks]
- Science Results I: Climate Data Records for Understanding the Causes of Global and Regional Sea Level Variability and Change [7 Oral talks]

Tuesday, November 1:

- Instrument Processing (Measurement and retracking) [11 Oral talks]
- Precise Orbit Determination [12 Oral talks]
- Instrument Processing (Propagation, Wind Speed and Sea State Bias) [7 Oral talks]
- Outreach, Education & Altimetric Data Services [6 Oral talks]
- Special Session: Beyond the history of European–US cooperation on altimetry [1 Oral talk]

Wednesday, November 2:

- Application development for Operations [6 Oral talks]
- Regional and Global CAL/VAL for Assembling a Climate Data Record [11 Oral talks]
- Coastal Altimetry [6 Oral talks]
- Quantifying Errors and Uncertainties in Altimetry Data [6 Oral talks]
- Science Results II: Large Scale Ocean Circulation, Variability and Change [7 Oral talks]
- Science Results III: Mesoscale and Sub-Mesoscale Oceanography [7 Oral talks]

Thursday, November 3:

- The Geoid, Mean Sea Surfaces and Mean Dynamic topography [5 Oral talks]
- Tides, internal tides and high-frequency processes [7 Oral talks]
- CFOSAT [6 Oral talks]
- Sentinel-6 Validation Team (S6VT) feedbacks [3 Oral talks]
- Science Results IV: Altimetry for Cryosphere and Hydrology [8 Oral talks]

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4.1 Application development for Operations

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

4.1.1 Summary

David Trossman et al. (DOI: 10.24400/527896/a03-2022.3325) presented their work on the Next Generation Enterprise Ocean Heat Content which uses machine learning to derive a sophisticated regression between a large historical database of temperature and salinity profiles with ocean topography from altimetry. This observation-based product gives a 3D view of the global ocean with is useful for better Hurricane predictions (Figure 4.1-1). In the latest iterations, the methodology upgrades and in particular the use of machine learning led to a significant improvement when compared to earlier versions with in-situ data.

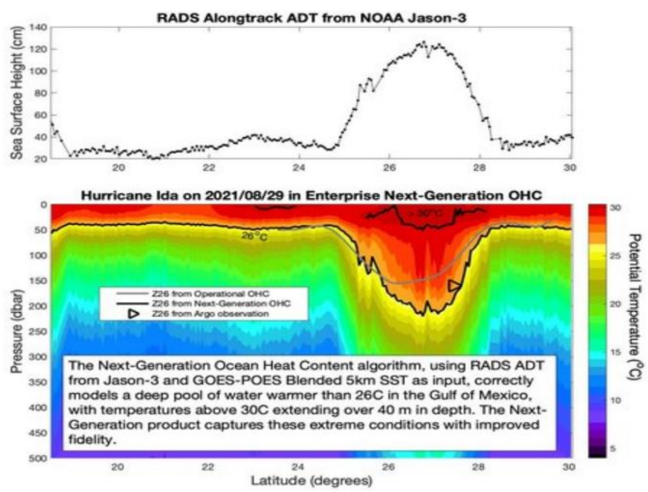


Figure 4.1-1: During Hurricane Ida the NGE OHC algorithm decreased the error in estimating the Argo-observed depth of the 26°C isotherm from 31.5 m (legacy product) to 3.25 m.

Yannice Faugère et al. (DOI: 10.24400/527896/a03-2022.3591) reported their findings on the analysis of altimeter data, and in particular of HY-2B and Sentinel-6, during the Tsunami event of the Tonga islands earlier this year (Figure 4.1-2). In addition to the expected ocean wave that is clearly visible with a sharp gradient of tens of centimeters, the atmospheric wave is also clearly visible in the dual frequency content from altimetry. The tsunami wave propagation was observed at different times by the 9 altimeters that are currently in operations, and the observed signatures and the mismatch with tsunami model prediction are likely to help uncover new findings on the event itself as well as help improve the propagation in the models.

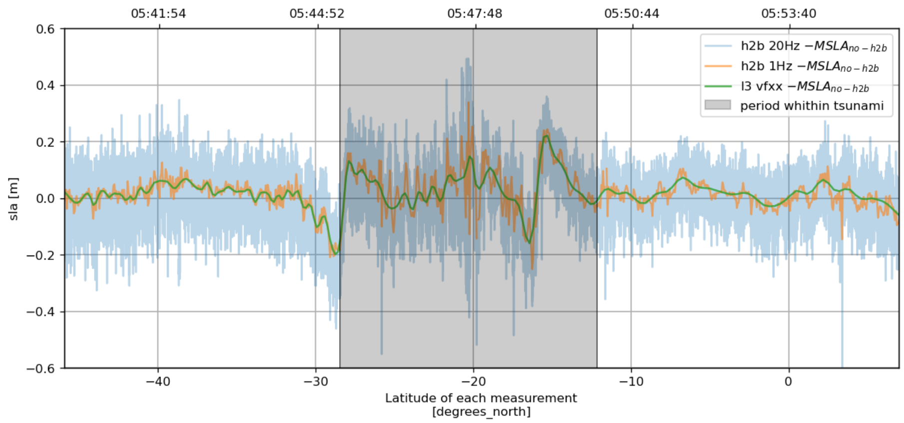


Figure 4.1-2: Analysis of HY-2B altimeter data, during the Tsunami event of the Tonga islands earlier this year. Model prediction for the Southern wave is well phased with HY-2B measurements.

Annabelle Ollivier et al. (DOI: 10.24400/527896/a03-2022.3459) pleaded the case of a 5 Hz wave product for better coverage in coastal regions (Figure 4.1-3), as well as wave&current interactions and extreme events. This user-requested increase of the posting rate is made relevant even for LRM altimeters thanks to noise reduction techniques such as adaptive retracking, high-frequency adjustment and EMD noise removal. Their demonstration product also raises various questions such as the influence of wave groups and how nadir altimetry captures a wide range of signatures ranging from high-frequency instrumental noise to ocean waves and wave groups to small mesoscale.

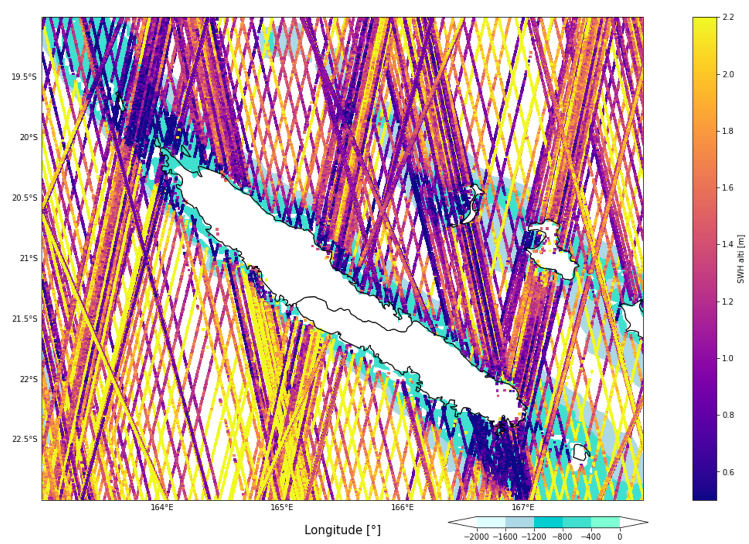


Figure 4.1-3: Demo product 5Hz along track SWH over 2021 shows a better coverage near coasts and inside lagoons (about +20% more valid data below 20km).

Charles Peureux et al. (DOI: 10.24400/527896/a03-2022.3388) presented the first observed Stokes Drift product ever. Using 2D wave spectra from the SWIM instrument of CFOSAT, they retrieve the Stokes Drift which is a missing component in existing surface current products from observations. The comparison between their data with model-based Stokes Drift is already extremely promising when the instrument limitations are accounted for in the retrieval (Figure 4.1-4). Their product is already available upon request as they work on additional algorithm improvements and a formal release.

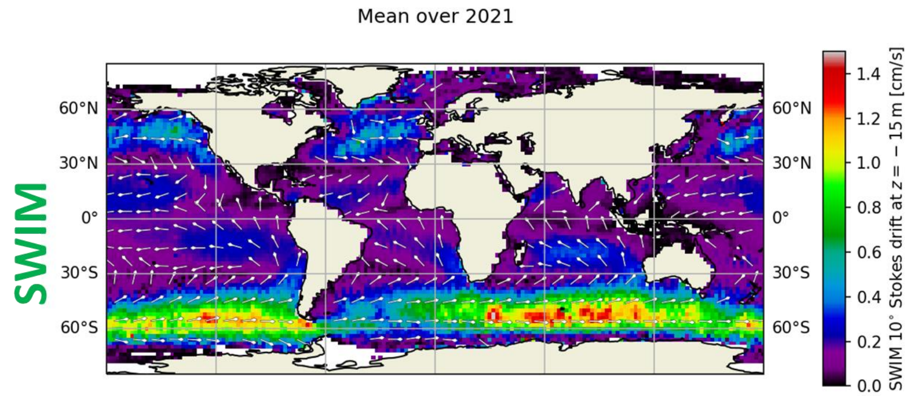


Figure 4.1-4: Mean Stokes drift vector over 2021 (2x2°) on SWIM track.

Jean Tournadre et al. (DOI: [10.24400/527896/a03-2022.3267]()) gave an update of their 30-year Iceberg database named altiberg. They also explained how the database made it possible to infer the fresh water flux (of FWF) from iceberg basal melting as it often happens over hundreds of kilometers in the Southern Ocean (Figure 4.1-5). Accounting for the iceberg drifts from surface currents, the iceberg erosion from waves, and the basal melting induced by SST makes to possible to retrieve better fresh water fluxes statistics at regional and seasonal scale. Their findings are likely to improve the polar fresh water fluxes in ocean circulation models: it is indeed of the same order of magnitude as precipitations in these regions, and the altimetry-derived fluxes are different and more reliable than current iceberg models.

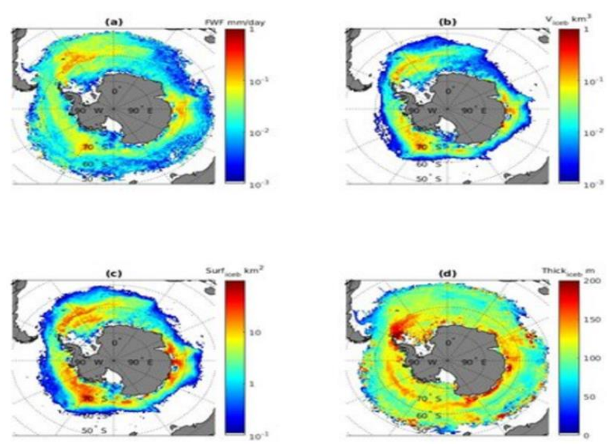


Figure 4.1-5: Mean daily FWF (a), mean daily volume of ice (b), mean icebergs surface (c) and thickness (d): 1992-2021 period, 50x50km grid.

In the poster session 15 abstracts were submitted, which can be separated into three categories.

Firstly, we had updates on operational systems that produce altimeter data. David Donahue et al. (DOI: 10.24400/527896/a03-2022.3256) gave an update on the NOAA Level-2 system and Bruno Lucas et al. (DOI: 10.24400/527896/a03-2022.3485) gave an overview of the Level-2 EUMETSAT system for Sentinel-3, Guillaume Taburet et al. (DOI: 10.24400/527896/a03-2022.3257) described the recent updates of the DUACS/CMEMS multi-mission products, Sabine Philipps et al. (DOI: 10.24400/527896/a03-2022.3420) and Cecile Kocha et al. (DOI: 10.24400/527896/a03-2022.3451) reported the status and upgrades made on the EUMETSAT Level-2P products for Sentinel-3 and Sentinel-6. Lastly Cristina Martin-Puig et al. (DOI: 10.24400/527896/a03-2022.3604) gave an early view of the EUMETSAT involvement and design for the marine part of the future CRISTAL missions.

The second category is an update on operational system which actually use altimetry on a regular basis: Gregg Jacobs et al. (DOI: 10.24400/527896/a03-2022.3340) gave an update on their ALPS system version2, and Jean-Michel Lellouche et al. (DOI: 10.24400/527896/a03-2022.3582) an update on the European operational system from Mercator and the Copernicus Marine Service. Saleh Abdalah et al. (DOI: 10.24400/527896/a03-2022.3599) gave an update of the ECMWF wave model. Lastly Hiroaki Asai et al. (DOI: 10.24400/527896/a03-2022.3555) presented the upgrades the Japan operational system from JMA and the improvements they obtain when assimilating more altimeters in their 2-km nested system.

Finally, we had a description of non-operational systems and applications which also benefit from altimetry: Yang Gao et al. (DOI: 10.24400/527896/a03-2022.3416) described how they use the nadir beam of CFOSAT to look at the integral length scale of surface waves. James Carton et al. (DOI: 10.24400/527896/a03-2022.3500) presented the Blended Ocean Surface Currents with a new daily product. Remy Laxenaire et al. (DOI: 10.24400/527896/a03-2022.3502) reported the upgrades made on their eddy atlas derived from altimetry. Lastly Marion Bocquet et al. (DOI: 10.24400/527896/a03-2022.3284) presented their 30-year record of sea-ice freeboard which leverages new algorithms and products from recent missions as well as the recent reprocessing of ERS and ENVISAT by ESA.

Not all posters were displayed, the ones actually displayed in Venice were: APOP_01 (Donahue), 05 (Philipps), 06 (Kocha), 07 (Lucas), 10 (Asai), 12 (Martin-Puig), and 14 (Bacquet)

4.1.2 Splinter Discussion Points and Recommendations

As far as seed questions are concerned, the splinter did not have time to discuss them during the session itself, but we can recall past recommendations. Regarding the second tandem phase of Jason-3, or the Sentinel-6B tandem, there is no specific recommendation from the splinter. The general opinion is that they should be as short as possible (to reduce sampling loss) and to prioritize the interleaved orbit configurations. But the splinter also acknowledges that the tandems should be as long as needed for other uses and in particular for the Climate record.

As far as recommendations for POE-G and GDR-G standards, most operational systems presented in the splinter would undoubtedly benefit from any improvement brought into NRT /

OGDR or STC / IGDR products. In contrast, offline reprocessing and upgrades might be less critical for most of the application splinter. Lastly, there is no specific recommendation regarding the raw mode of Sentinel-6 or a coastal retracker for Delay-Doppler instruments, although any user-demonstrated benefits would also likely be desirable to the operational systems discussed in the splinter.

The OSTST 2022 continued after the meeting in Venice for a couple of weeks with the Forum. The Application Development for Operations Splinter hosted a few Virtual Coffee Hours to discuss work that was not able to be presented in person during the Venice meeting. Each Coffee Hour lasted one hour, for presentations and discussion. The following presentations were presented:

- The new daily global mesoscale Blended Ocean Surface Current (BOSC) product - Shaun Eisner, University of Maryland, USA
- A new open-source gridded altimetric product - Jonathan Lilly, The Planetary Science Institute, USA
- Development oF Multiparameter Mesoscale Eddy Products for Operational Use - Heather Roman-Stork
- Dynamics of the North Pacific “garbage patch” observed with a suite of Lagrangian instruments for ecological applications - Nikolai Maximenko

4.2 CFOSAT

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

4.2.1 Summary

The CFOSAT session had a good attendance with 6 oral presentations, 5 forum presentations and 1 poster. We had good questions/answers and discussions after each presentation. The CFOSAT session showed the transition from a phase of improvement to the level 2 data retrieval algorithms to a phase of CFOSAT data use and results targeting scientific applications. We observed and noted some new emerging scientific themes such as wave generation in extreme conditions, Stokes drift, wave/ocean coupling and sea ice product development.

The results presented in the CFOSAT session can be classified in two categories:

1) Short-scale variability (5-35 km) of wave height, wave group and sea surface height:

- Small scale Significant Wave Height variability and wave groups analyzed using SWIM data, including spectral information.
- Geostrophic currents from CFOSAT: consistent results with multi-missions’ products and candidate to improve characterization of mesoscale ocean eddies (see Figure 4.2-1 from Faugere et al., DOI: 10.24400/527896/a03-2022.3602).

- Complementarity between wave spectra from SWIM/CFOSAT and SAR of Sentinel-1.

- Implementation of interesting measurements of wave spectra from drone-based LIDAR in coastal area (< 50 km).

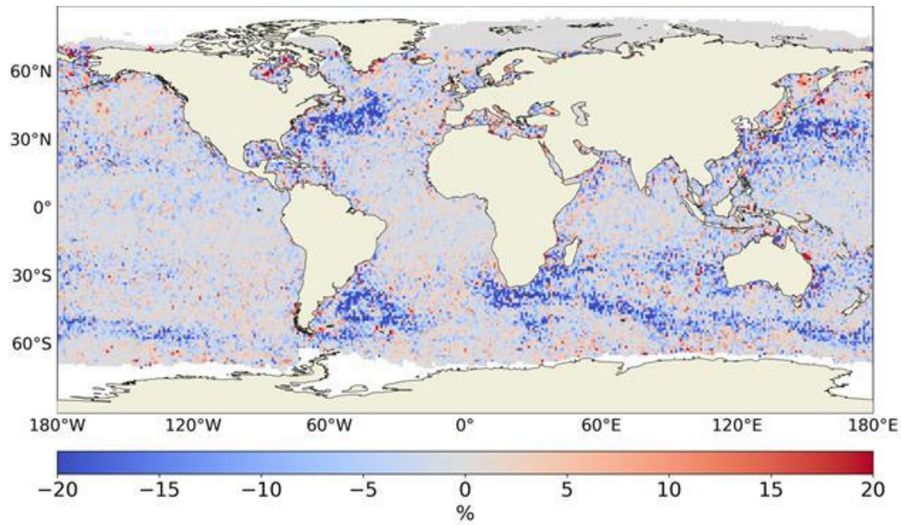


Figure 4.2-1: Error reduction (in %) of SLA from muti-mission products in comparison with independent altimetric mission (Cryosat-2) for the period of 7 months (April 2021 to October 2021). The blue color stand for improved mesoscale when including CFOSAT data (see Faugere et al. 2022, DOI: 10.24400/527896/a03-2022.3602).

2) Applications including Data Assimilation (DA) and Data analysis

- Improved ocean/wave coupling with DA of SWIM wave spectra, particularly in the Tropics, Southern Ocean and Western Boundary Currents (Figure 4.2-2, Aouf et al. 2022, DOI: 10.24400/527896/a03-2022.3346).

- Promising wave spectra analysis with SWIM wave data applied in extreme conditions (Rogue wave detection, wave propagation in hurricane)

- Synergy between SWIM and SCAT to develop a new GMF model to retrieve wind vectors

- Availability of SUMOS field campaign data (February-March 2021) for science applications

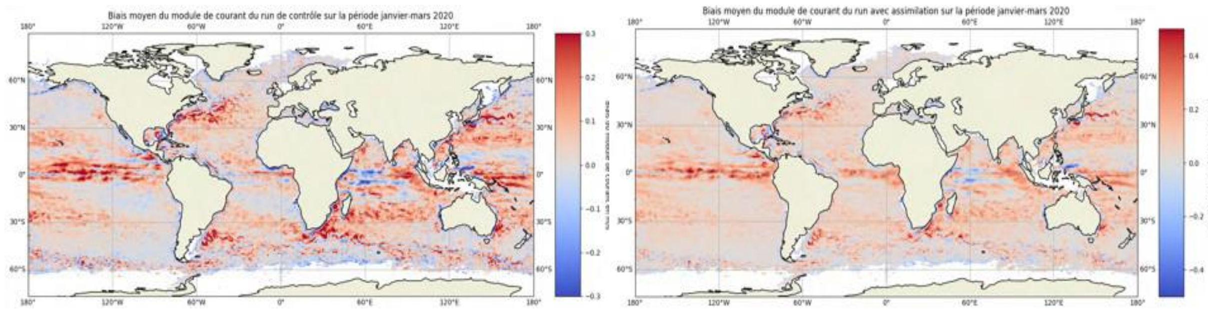


Figure 4.2-2: Bias maps of surface current intensity in comparison with AOML monthly mean current from drifters for the period of January to March 2020. (left) and (right) stand for NEMO simulations without wave forcing, and with wave forcing improved by data assimilation of CFOSAT wave spectra, respectively (see Aouf et al. 2022, DOI: 10.24400/527896/a03-2022.3346).

In summary, the participants of CFOSAT session greatly appreciated the presentations covering waves, currents and wind investigations exploiting CFOSAT data. With the extension of the CFOSAT mission life to 2024, it was highlighted that a new reprocessing of SWIM and SCAT mission data with improved algorithms will become available in early 2023. It was also indicated that several new products are available at the AVISO web portal such as sea ice from SWIM and SCAT instruments, Stokes drift (surface and depth), and geostrophic currents. Work to further improve the level 2 processing of the CFOSAT mission will continue during 2023, and we look forward for new results that can be presented during the next OSTST meeting.

4.2.2 Splinter Discussion Points and Recommendations

No specific recommendation issued from discussions.

4.3 Coastal Altimetry

Chairs: Florence Birol, Mathilde Cancet, Marcello Passaro, Ted Strub

4.3.1 Summary

The Oral, Poster and Forum presentations in the Coastal Session of the OSTST 2022 meeting consisted of a mix of technical methods/algorithm papers and applications to scientific problems, often combining the applications with new approaches.

For the conventional altimeters, *Birol et al.* (DOI: 10.24400/527896/a03-2022.3363) surveyed the various algorithms available to produce SLA products from LRM altimetry. Their respective performance in coastal seas is assessed through metrics for sea level variability, data availability, and impact on SLA as a function of distance to the nearest coast. They finally chose those that will be used in the next production cycle. *Leger et al.* (DOI: 10.24400/527896/a03-2022.3311) described several new data sets from CTOH, including a regional L3 multi-mission product derived from the AVISO+ L2P product and a regional product combining the X-TRACK and ALES methodologies to produce a network of virtual altimetry stations for measuring sea level along the world coastlines. *Cancet et al*. (DOI: 10.24400/527896/a03-2022.3297) focused on the performance of tidal models in coastal regions at the global scale, in order to provide recommendations about tidal corrections for coastal altimetry products.

Applications were mainly based on conventional altimeter data. They included a look at the circulation in the Makassar Strait by *Ichikawa et al*. (DOI 10.24400/527896/a03-2022.3260). Their results suggest that the flow in the strait can be divided into surface and bottom layers, with local winds controlling the surface layer and larger-scale circulation features controlling the bottom layer. *Martinez et al.* (DOI: 10.24400/527896/a03-2022.3250) compared the altimeter heights over the Patagonia shelf to steric height calculation based on CTD data collected by instruments strapped onto Elephant Seals. Although there were good correlations between the altimeter heights and steric heights, the steric heights did not account for much of the total SLA signal seen by the altimeter. *Juhl et al*. (DOI: 10.24400/527896/a03-2022.3581) compared the SLA fields over the Patagonia shelf to wind forcing and found higher coherences over the shelf inshore of the shelf break. Coherences broke down near the mouth of the Rio de la Plata. *Lago et al.* (DOI: 10.24400/527896/a03-2022.3470) looked more closely at circulation in the southern part of the Patagonia shelf (44.7°S) and found that satellite altimetry represents well the SLA and the circulation at seasonal and larger scales. Sampling during the first three months of SWOT will pass over the Patagonia shelf and provide a unique opportunity to look at circulation in this region. *van der Boog and Fenty* (DOI: 10.24400/527896/a03-2022.3496) considered the relationship between alongtrack SLA and deep temperatures around Greenland but found that the SLA is primarily controlled by salinity (fresh water melt) in that system. Thus, SLA may be able to provide a time series showing the history of melt water magnitude during the altimeter record.

Moving to the SAR-based presentations, many documented the improvements in retrievals through the use of Fully Focused (FF) SAR techniques. *Aldarias et al*. (DOI: 10.24400/527896/a03-2022.3337) compared FF SAR to ALES and Unfocused (UF) SAR, finding standard deviations of 10 cm and less within 0.5-1.5 km of the coast for the FF SAR. *Fenoglio et al.* (DOI: 10.24400/527896/a03-2022.3465) compared 5 SAR retrackers against tide gauges and buoys for both SLA and SWH, finding better agreement for the Bonn STARS algorithm and greater noise in the DTU retracker. *Garcia et al*. (DOI: 10.24400/527896/a03-2022.3369) described a retracking method for Cryosat-2 around the Mediterranean coasts that uses retrievals from the open ocean to select the correct nadir gate and then fixes the coastal retrievals on that gate. The method could be applied to conventional altimeter retrievals as well. *Flokos et al*. (DOI: 10.24400/527896/a03-2022.3286) described a retracking method that makes use of two Neural Net procedures: Convolutional Neural Networks and Recurrent Neural Networks (RNN). As with *Garcia et al.* (DOI: 10.24400/527896/a03-2022.3369), the RNN method makes use of knowledge of the nadir gate from the previous retrieval. *Nencioli et al.* (DOI: 10.24400/527896/a03-2022.3435) presented another new product (Cryo-TEMPO) using CryoSAT-2 SAR data for Mediterranean coastal regions. The products include uncertainty estimates and also give cross-track velocities, SLA and SWH. Efforts are continuing to improve the performance in the 0-5 km region. *Cotton et al*. (DOI: 10.24400/527896/a03-2022.3506) evaluate S3 FF SAR alongtrack data in comparison to 4 tide gauge stations in two estuaries. Analysis from the Severn estuary result in RMS differences of slightly more than 1 m. *Vignudelli* *et al*. (DOI: 10.24400/527896/a03-2022.3476) compare S3 SAR alongtrack data to two tide gauges in the Northern Adriatic Sea. They use a new methodology that makes use of the specular or quasi-specular reflections of the high-resolution radar signal. Preliminary results show very good comparisons to in situ data, with errors of 5-8 cm.

Mulero-Martinez et al. (DOI: 10.24400/527896/a03-2022.3250) used the wind speeds derived from the S3 altimeters along ground tracks to evaluate the performance of high-resolution meteorological models, a rare application of altimeter wind products, which can approach closer to land than traditional scatterometers. A separate presentation by *Mulero-Martinez* (DOI: 10.24400/527896/a03-2022.3309) then added a wind-driven surface velocity component to the altimeter geostrophic velocities to look at the total surface circulation in the Gulf of Cadiz.

Considering retrievals of SWH only, *Tourian et al.* (DOI: 10.24400/527896/a03-2022.3552) developed a technique that uses both rise time and the width of the SAR signal to estimate SWH. The RMS error is ~ 1m at distances offshore of 2 km from the coast, rising to 2-3m inshore of 1-2km. *Schlembach et al.* (DOI: 10.24400/527896/a03-2022.3489) used one year of S6 FF SAR to compare SWH retrievals within 5 km of the coast to a high-resolution wave model. They find good results up to ~ 1 km from the coast.

Finally, *Cotton et al.* (DOI: 10.24400/527896/a03-2022.3564) presented results showing the availability of portable tide gauge stations, known as Portagauge. It is designed to be installed and operated for ~ 6 months at any given location, comparing the Portagauge sea level ground truth data to the CMEMS multi-mission SLA product surrounding the station. Sequential deployments at multiple locations will allow the satellite SLA data to provide calibrated long time series of SLA at those locations.

4.3.2 Splinter Discussion Points and Recommendations

In the discussions appearing on the Forum and in email exchanges after the meeting, several broad topics emerged. These relate to the fact that efforts are successfully retrieving high resolution along-track range/SLA and SWH estimates using SAR (and even conventional nadir altimeters). The question remains, however, of how to use these in the regions within 10 km of land where some of the "correction" signals remain problematic (wet troposphere, DAC, tides, SSB, etc.)?

Another more general question in the larger coastal domains (within several hundred kilometers of land) involves the difference in sampling characteristics in time and space. Retrieving the extremely high-resolution along-track data (with for example 300m sampling) every 10 to 27 days leads to the question of what applications can make use of these data. How can this mix of resolutions be used to create time series of high-resolution 2-D fields. Perhaps the answer lies in the synergy between modeling and altimeter sampling, as demonstrated by the atmospheric (wind stress) example of *Mulero-Martinez et al.* (DOI: 10.24400/527896/a03-2022.3250). If the high-resolution along-track data agrees with high-resolution model fields along the tracks, then the model fields can be used with confidence or improved until the agreement is better. This question has direct relevance to the SWOT mission goals, since the SWOT swaths will again have very high spatial resolution separated by long periods without data.

There is also the question of how to relate the sea level variability on short spatial scales to velocity, since geostrophy breaks down at scales below some limit, also a problem for SWOT.

Discussion of these and other topics continued at the Coastal Altimetry meeting in February, 2023.

4.4 Instrument Processing: Measurements and Retracking

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

4.4.1 Summary

- Great advances in understanding the surface motion effects in SAR mode performance
- Fully-focused SAR processing progress
    - Retracking with the SAMOSA model
    - Understanding of "replicas" over non-ocean targets
    - New science for swell characterization
- Possible need higher posting rates (>~40 Hz) to compute unaliased spectra
- Adaptive retracker shows advantages for conventional altimetry and a new formulation may speed it up significantly

Advances in understanding the surface motion effects in SAR performance

The effects of surface wave motion on SAR images have been studied for nearly 40 years. The basic effect is that the surface motion due to waves contributes to the Doppler effect on the signal and thus degrades the image in azimuth (along track). An easily observed consequence is a difference in LRM and SAR significant wave height (SWH) measurements of approximately -0.2 to -0.8 meters, that is a function of SWH. Egido et al. (DOI: 10.24400/527896/a03-2022.3460) proposed a look up table (LUT) correction for the effect. There is also a difference of +/-5 cm in sea surface height anomaly (SSHA) that has the interesting geographic pattern shown in Figure 4.4-1. The effect correlates strongly with the meridional wind velocity. A Doppler shift is caused by the cross-correlation of wave orbital velocity and wave slopes related to the wind that modulates the platform Doppler fore and aft (Egido et al.). As shown in Buchhaupt et al. (DOI: 10.24400/527896/a03-2022.3407), this effect can now be estimated, opening the door to measuring wind/wave direction.

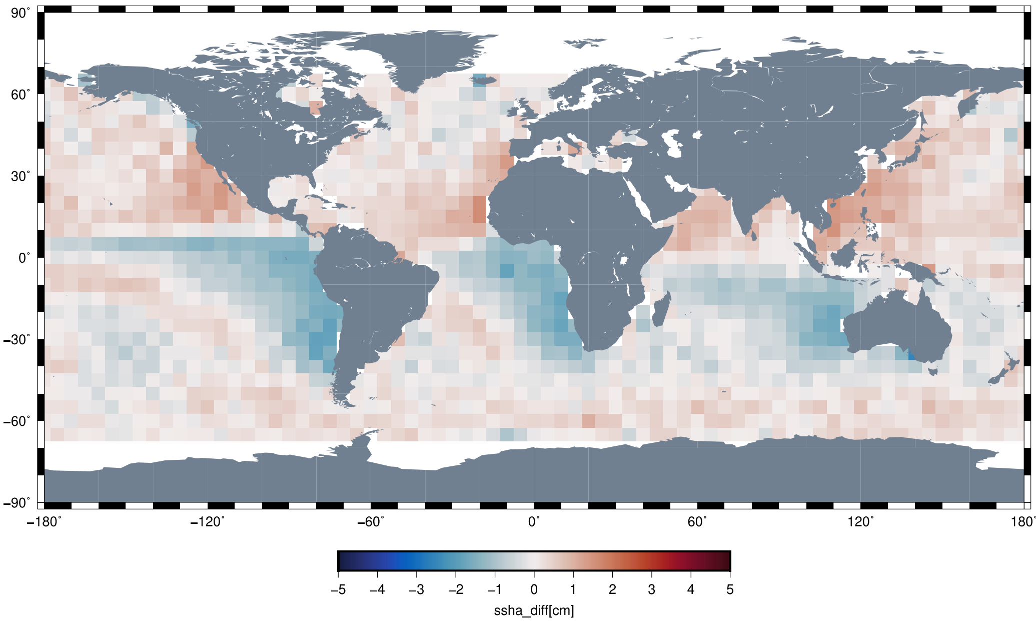


Figure 4.4-1: HR-LR SSHA Difference: Ascending-Descending from (Egido et al., DOI: 10.24400/527896/a03-2022.3460).

Fully-focused SAR processing progress

Retracking with the SAMOSA model

Ehlers et al. (DOI: 10.24400/527896/a03-2022.3401) discussed using existing retrackers (e.g., SAMOSA) with fully focused SAR data. The goals were to provide increased resolution for removing coastal clutter and providing consistent observations of ocean variables. They find noticeable differences between Sentinel-3 and Sentinel-6, which is not too surprising since they have different burst structures (open vs closed). For S-3 unfocused and fully focused SAR waveforms (WF) look similar. For S-6 fully focused WF better resemble the unfocused zero Doppler beam. Thus, existing retrackers can be used in some cases after some adaptation, but some differences remain.

Understanding of "replicas" over non-ocean targets

Fully focused processing on closed burst SAR data over surfaces with multiple point scatterers is severely hampered by "replicas" in the waveforms (Amraoui et al., DOI: 10.24400/527896/a03-2022.3321). Replicas in the Sentinel-6 data over hydrology targets and sea ice arise from gaps in the radargram (CAL + C-band pulses). Figure 4.4-2 shows the characteristic parabolas from point scatters as well as the main surface return. Several methods for removing them are discussed, but it is challenging and further investigation is needed (a simple azimuth windowing may be sufficient in the case of S6). It is suggested that future missions adjust the pulse cycle to reduce the effect.

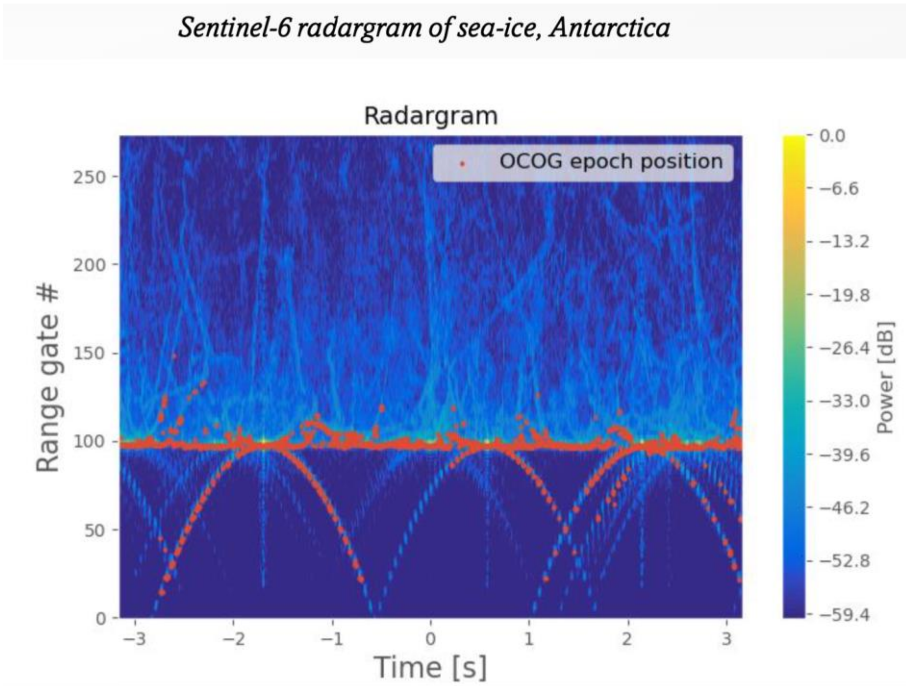


Figure 4.4-2: Sentinel-6 radargram of sea ice, Antarctica (Amraoui et al.)

Two presentations on closely related to inland waters issues and methods were

- Improving inland water altimetry retracking by incorporating spatial dependency of waveforms (Elmi et al.) DOI: 10.24400/527896/a03-2022.3559

- On the Benefits of Stack-Masking in Delay-Doppler Altimetry over Non-Homogeneous Surfaces (Fabri et al.) DOI: 10.24400/527896/a03-2022.3561

2-Dimentional SAR retracker:

For more than ten years, Synthetic Aperture Radar (SAR) altimetry has contributed to a better understanding of sea surface related parameters such as sea surface height (SSH), significant wave height (SWH) and wind speed. However, compared to conventional altimetry data inconsistencies with respect to SWH and SSH estimates are observed. Buchhaupt et al (DOI:10.24400/527896/a03-2022.3407) suggest solving this issue by introducing two additional wind-wave parameters, the vertical wave motion standard deviation σ_v and the along-track surface velocity u_x. This new retracker operates on the stack data (2-dimensional Range/Doppler waveforms); otherwise, it will not be able to distinguish SWH and σ_v. Results are very promising, since a large part of inconsistency between SARM and LRM is removed. Including u_x isessential to mitigate SSH-related biases.

New science for swell characterization

Altiparmaki et al. (DOI: 10.24400/527896/a03-2022.3280) summarized results on detecting swell with fully focused SAR altimetry. Details of the method can be found in Altiparmaki, O., et al., 2022 (“SAR altimetry data as a new source for swell monitoring”, *Geophysical Research Letters*, 49, e2021GL096224, doi.org/10.1029/2021GL096224). The reasons that swell is observable by radar are

- SAR: velocity bunching related to orbital motion affects azimuth processing
- Real aperture: range bunching from slope variations

These effects show in the tail for the fully focused radargram. Figure 4.4-3 shows a wave spectrum from CryoSat-2 for a moderate wave case. Because of the nadir geometry of the altimeter there is a left/right ambiguity that does not occur for side looking SAR. It should be noted that there are four currently operating altimeters that could provide these data.

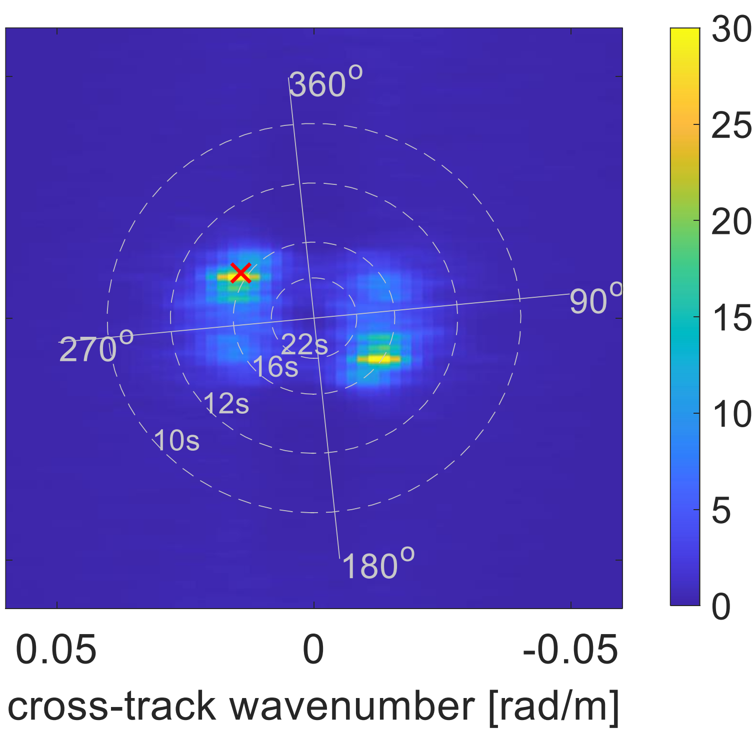


Figure 4.4-3: Wave spectrum from CryoSat-2 for Hs = 2.7 ± 0.2 m, Tp = 15 ± 1 sec, Dir = 309 ± 10 deg. The selected direction is marked with the red x.

Possible need higher posting rates (>~40 Hz) to compute unaliased spectra

It has been observed that higher posting rates for unfocused SAR have advantages. Ehlers et al. (Beyond 20 Hz: Deriving the necessity of increased posting rates from first principles DOI: 10.24400/527896/a03-2022.3580) derive this from the basic geometry of unfocused processing. Higher posting rate could increase performance by taking advantage of still fairly high data decorrelation for posting rates higher than 40 Hz.

Adaptive retracker shows advantages for conventional altimetry

Mangilli et al. (Fast-Adaptive: a new, optimal, unbiased, and computationally efficient retracking solution for the analysis of Conventional Altimetry data DOI: 10.24400/527896/a03-2022.3579) discuss improvements to the standard MLE4 processing involving the "adaptive retracker" and a method to speed it up. Adaptive retracking includes improving the solution in terms of estimator (unbiased, while MLE4 is biased), modeling and inclusion of instrumental related effects (numerical PTR). The speed up (still requires ~2 hours/pass) comes from basically reducing the method to weighted least squares. The results are fairly close to the full adaptive retracker. The main improvements over MLE4 are in SWH variance.

Piras et al. (Towards a homogeneous reprocessing of historical missions: excellent performances of the Adaptive retracker applied to Jason-1 and ENVISAT DOI: 10.24400/527896/a03-2022.3534) reported on progress of an effort to reprocess all altimeter data (except TOPEX) with the fast adaptive retracker as part of the European Long Term Data Preservation Program. Additional information can be found in the poster (Reprocessing of the ERS-1, ERS-2 and ENVISAT missions: performances of the FDR4ALT products. Piras et al., DOI: 10.24400/527896/a03-2022.3332). Adaptive retracking is currently being used on Jason-3 and CFOSAT. Jason-2 is very similar to Jason-3 so reprocessing is in work. Jason-1 needed work on the waveforms as they were compressed for transmission to the ground and also for periods of mispointing that occurred. Jason-1 work is ongoing. ENVISAT needed work on the PTRs to use the adaptive retracker. Retracking is complete and validation is underway. Figure 4.4-4 shows the improvement in the SSHA spectrum obtained with adaptive retracking especially when combined with high-frequency adjustment (HFA). Most notably there is a significant reduction (and flattening) in the SSHA spectrum "hump".

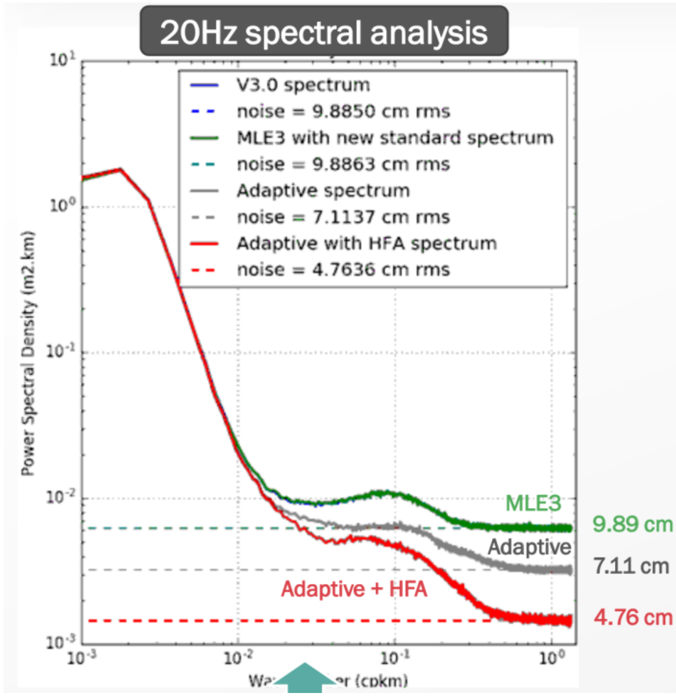


Figure 4.4-4: SSHA spectrum for several retrackers applied to EnviSat.

4.4.2 Splinter Discussion Points and Recommendations

No specific recommendation issued from discussions.

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

Chairs: Shannon Brown, Estelle Obligis

4.5.1 Summary

A total of 12 papers were presented in this splinter 7 oral presentations and 5 posters dealing with 5 different topics:

- Specificities of Sentinel-6 AMRC instrument, processing and products (Brown et al., DOI: 10.24400/527896/a03-2022.3259; Picard et al., DOI: 10.24400/527896/a03-2022.3584)

AMR-C includes innovations from prior generation AMR on Jason series: the use of a supplemental Calibration System (SCS) to maintain the 1 mm/year stability and the High Resolution Microwave Radiometer (HRMR) to provide improved coastal path delay (1 cm accuracy at 10km from land, Figure 4.5-1). Analysis of the first 2 years of data suggest that the SCS system is maintaining the calibration stability to better than ~0.1mm/year. In addition, preliminary analysis shows that the HRMR is meeting its goals of providing the path delay with an uncertainty of less than 1cm up to 5km from land.

Channel	Relative Trend to SSMI TB
18.7 GHz	0.01 ± 0.08 K
23.8 GHz	-0.01 ± 0.1 K
34.0 GHz	0.03 ± 0.04 K

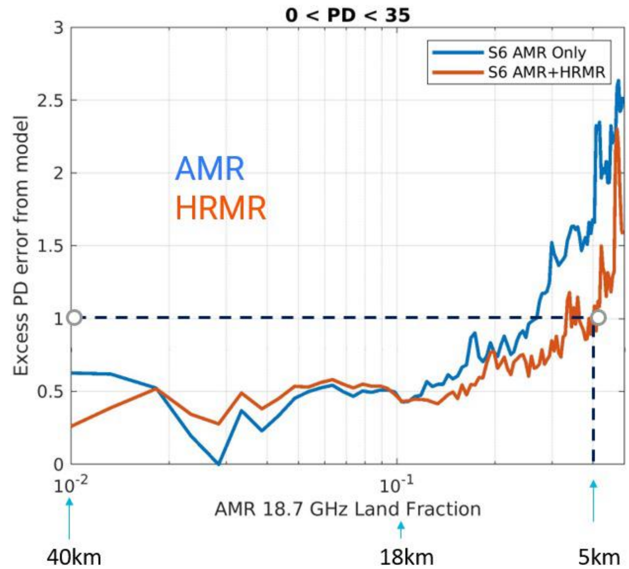


Figure 4.5-1: High Resolution Microwave Radiometer (HRMR) to provide improved coastal path delay.

The HRMR is rich in information and more can be exploited. An initial study investigated the ability of HRMR to detect small scale rain cells and their impact on the measurements (Figure 4.5-2). In general, the HRMR indicated the presence of rain on much smaller spatial scales than resolvable by the AMR. This can be exploited for future algorithm development.

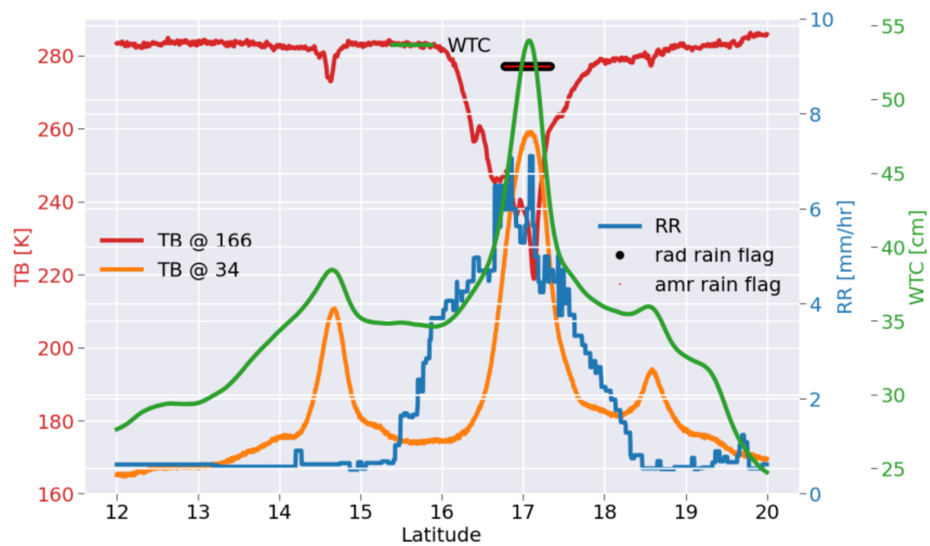


Figure 4.5-2: Ability of HRMR to detect small scale rain cells and their impact on the measurements.

- Assessment and improvement of current wet tropospheric products (Picard et al., DOI: 10.24400/527896/a03-2022.3583)

A 1D-variational approach has been developed and applied to Sentinel-3 A and B topography missions. The performances are similar to the one of the operational algorithm with some regional biases not yet completely understood. But there is clear benefit of this new approach which provides an uncertainty estimation and is suitable to all instruments, all frequencies and all surface type.

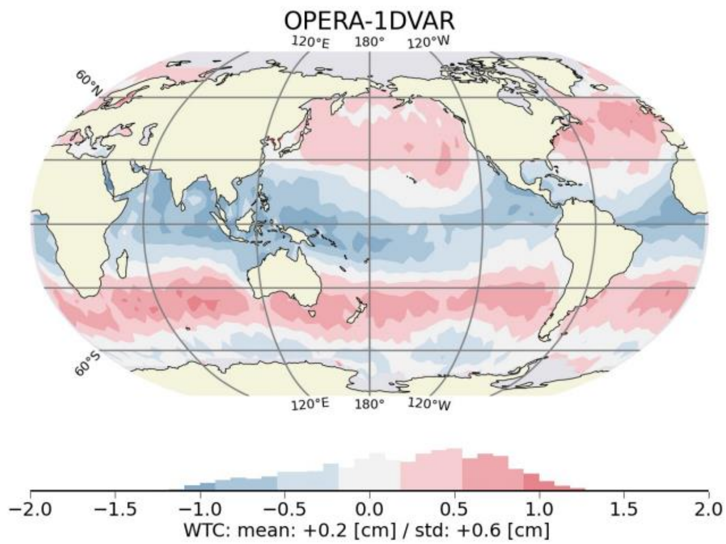


Figure 4.5-3: 1D-variational approach developed and applied to Sentinel-3 A and B.

- Wet tropospheric correction: synergies with other instruments (Aguiar et al., DOI: 10.24400/527896/a03-2022.3379; Fernandes et al., DOI: 10.24400/527896/a03-2022.3486)

The operational retrieval of the Sentinel-3 wet tropospheric correction is based on an a priori knowledge of the SST. I was demonstrated that ERA5 atmospheric model is a good SST input source for the WTC retrieval and that there is no benefit when using SLSTR SST skin observations against ERA5 (Figure 4.5-4).

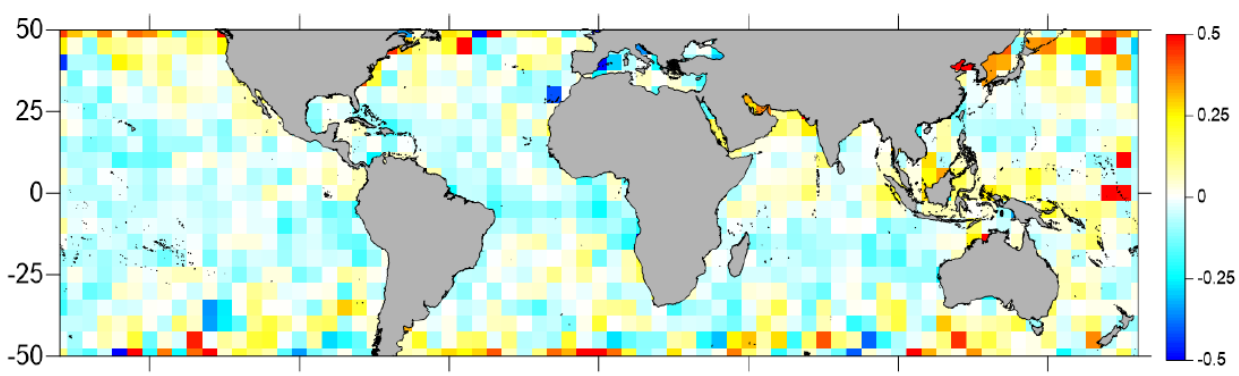


Figure 4.5-4: Differences, in cm, between RMS values for Algorithm 1 – Algorithm 2 (5º by 5º resolution).

A new wet tropospheric correction is provided in the Sentinel-3 NTC products, called GPD+, based on the combination between radiometer information, GNSS products, ECMWF model and estimation from other in-flight radiometers. Excellent results were presented with a significant improvement of coverage especially in coastal and polar areas (Figure 4.5-5).

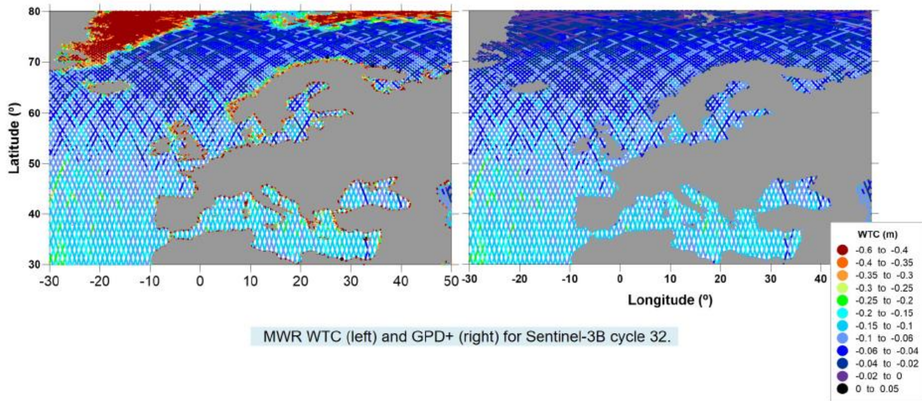


Figure 4.5-5: GPD product assessment – Data completeness. MWR WTC (left) and GPD+ (right) for Sentinel-3B cycle 32.

- Sea state bias (Vandemark et al, DOI: 10.24400/527896/a03-2022.3570)

The wave impact on SSB, especially at different frequencies (Ka, Ku, C) has been analyzed for the first time (Figure 4.5-6) and new Ku-band SSB models for Sentinel-6 are developed, but this does not harmonize Jason-3 and Sentinel-6 low resolution mode range or SSHA.

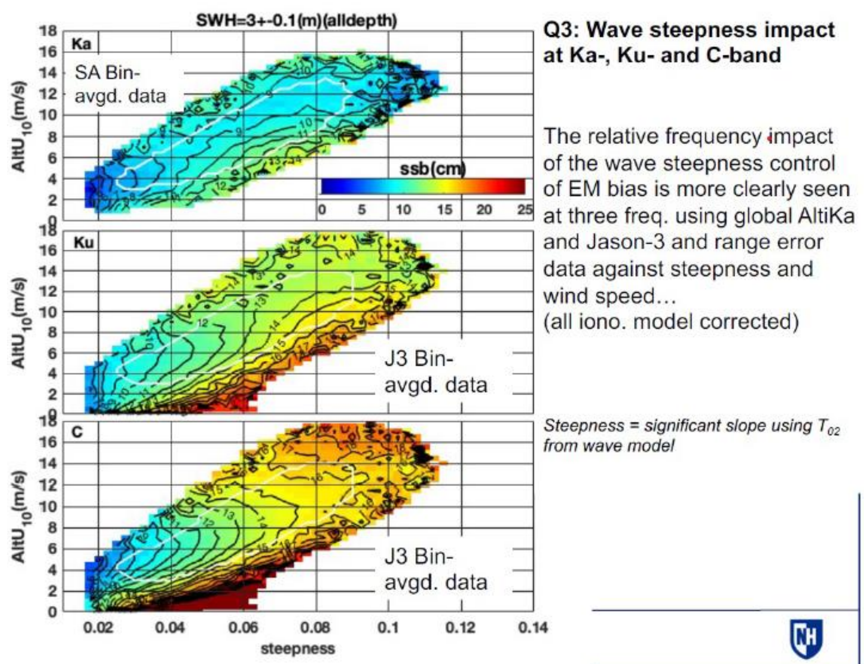


Figure 4.5-6: Wave steepness impact at Ka-, Ku- and C-band.

- Rain characterization (Picard et al., DOI: 10.24400/527896/a03-2022.3329)

Promising results have been shown about the characterization of rain cells using Ka band nadir altimeter information (Figure 4.5-7). The backscattering coefficient in Ka band contains a lot of high resolution information that can be used for a precise estimation of the size of the rain cells and a more accurate retrieval of the atmospheric attenuation. These results are promising in the view of future SWOT down-scaling activities.

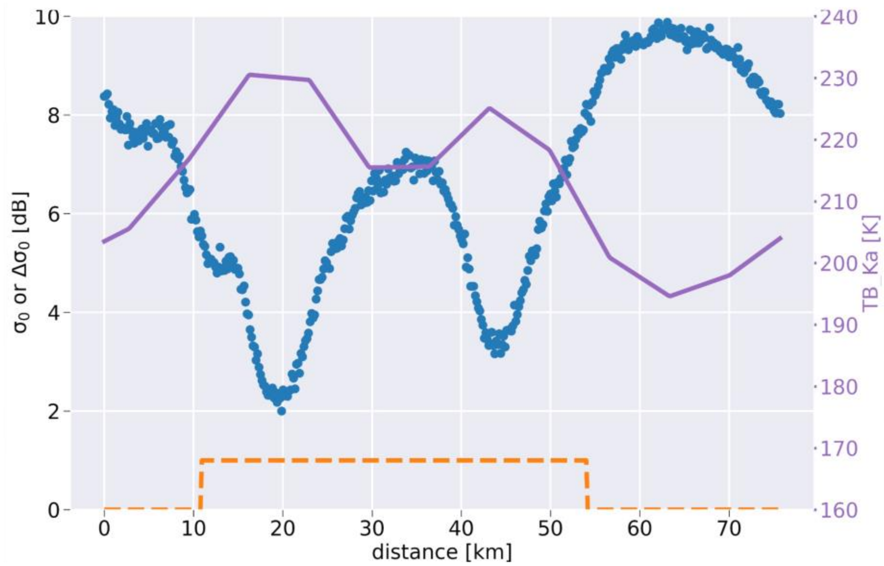


Figure 4.5-7: An illustration of the impact of precipitation on Ka-band sigma0. The rain cell is composed by 2 internal peaks. The atmospheric attenuation is 7 times larger at Ka-band than at Ku-band.

4.5.2 Splinter Discussion Points and Recommendations

In recent years, we have seen significant improvements in the field of wet tropospheric correction for altimetry missions. These improvements are based on new instruments, with better calibration, better stability, higher frequencies for better resolution or new retrieval methods sometimes based on synergy with other products.

SSB remains a major contributor to the altimetry error budget, and the community encourages work to improve our understanding and knowledge of SSB for SAR, Ka and swath missions.

4.6 Outreach, Education & Altimetric Data Services

Chairs: Jack McNelis, Vinca Rosmorduc, Margaret Srinivasan

4.6.1 Summary

Session presentations:

- Argonautica, ocean and satellites from kindergarten to engineering school, Estelle Raynal (CNES, France, DOI: 10.24400/527896/a03-2022.3327),
- Citizen science in FloatEco and GO-SEA projects, Nikolai Maximenko (IPRC/SOEST, University of Hawaii, United States, DOI: 10.24400/527896/a03-2022.3474)

- Altimetry training resources available under EUMETSAT Copernicus Marine Training Service, Vinca Rosmorduc (CLS, France, DOI: 10.24400/527896/a03-2022.3273),

- CEOS Ocean Variable Enabling Research & Applications for GEO (COVERAGE): A Platform to Simplify and Expand the Accessibility and Synergistic Use of Inter-agency Satellite and in-situ Oceanographic Data, Vardis Tsontos (NASA/JPL, United States, DOI: 10.24400/527896/a03-2022.3352),

- Interactive website to visualize and study mesoscale eddies, Jeffrey Early (NorthWest Research Associates, United States, DOI: 10.24400/527896/a03-2022.3399)

- Outreach and data services showcases (DOI: 10.24400/527896/a03-2022.3520):
    - The ESA Altimetry Virtual Lab, Jérôme Benveniste et al.
    - BRAT (Broadview Altimetry Toolbox), Jérôme Benveniste et al.
    - GOCE User Toolbox (GUT), Jérôme Benveniste et al.
    - SWOT Applications, Margaret Srinivasan et al.
    - « Swot Challenges » & "Argonautica serious games", Estelle Raynal et al.
    - Chasing microplastic in eddies with the support of altimetry, Yannice Faugère et al.

Session posters

- Swot and hydrology from space outreach, Vinca Rosmorduc (CLS), Nicolas Picot (Cnes) (DOI: 10.24400/527896/a03-2022.3268),

- Accessing Sentinel-6 and Sentinel-3 altimetry data through EUMETSAT big data services, Ben Loveday (Innoflair UG) (DOI: 10.24400/527896/a03-2022.3274),

- AVISO+ products and service: what's new?, Laurent Soudarin (CLS) (DOI: 10.24400/527896/a03-2022.3278),

- CTOH studies for extending the range of altimetry applications over the ocean and continental surfaces, Fabien Blarel (LEGOS-CNRS) (DOI: 10.24400/527896/a03-2022.3305),

- ODATIS, Ocean Data Information and Services for Easier Access to Data and Analytical Services, Caroline Mercier (ODATIS) (DOI: 10.24400/527896/a03-2022.3370),

- Cryo2Ice Coincident Data Explorer, Alex Horton (Earthwave) (DOI: 10.24400/527896/a03-2022.3381),

- Sentinel-3 Topography mission Assessment through Reference Techniques (St3TART) project – Focus on the FRM Data Hub, Elodie Da Silva (NOVELTIS) (DOI: 10.24400/527896/a03-2022.3539),

- SAR, SARin, RDSAR and FF-SAR Altimetry Processing on Demand for CryoSat-2, Sentinel-3 and Sentinel-6 at ESA's Altimetry Virtual Lab, Jérôme Benveniste (ESA-ESRIN) (DOI: 10.24400/527896/a03-2022.3600),

Demo planned

Figure 4.6-1: Photo taken during the Demo session (COVERAGE Project by V. Tsontos).

- Vardis M. Tsontos - COVERAGE web-based data Viewer tool
- Ben Loveday - EUMETSAT data access & training resources
- Sophie Le Gac - OLTC website
- Vinca Rosmorduc - Swot outreach slides
- Estelle Raynal - ArgoHydro platform
- Elodie Da Silva - SCalSIT, a QGIS plugin to help finding Cal/Val supersites over Inland Water Surfaces

2020-2022 Highlights

The session this year included more presentations focused on data services, with a smaller share of submissions from outreach and education.

The Demonstration format was, once again, implemented this year during the poster sessions. The Demo sessions included a schedule of 15-minute time slots. This format is, in practice, rather difficult to stick to – they are either too long if timing, availability and interest don't coincide with the schedule of talks, or are too short if there are interested people asking questions. A schedule that includes several screens spread around the poster area could be a solution for future meetings. Another improvement would be to make it a "splinter" or dedicated demonstration event with submissions so that it appears in the meeting agenda (and could be extended to topics other than data services and outreach).

Data services

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.

New developments from the Agencies were demonstrated, such as EUMETSAT data access, the AVISO+ new features, ODATIS, OLTC web site (CNES), as well as continuity of existing tools --

ESA's Altimetry Virtual Lab, BRAT, and GUT. NASA's new COVERAGE web-based data viewer tool was shared, including one scheduled and several impromptu demos during poster sessions.

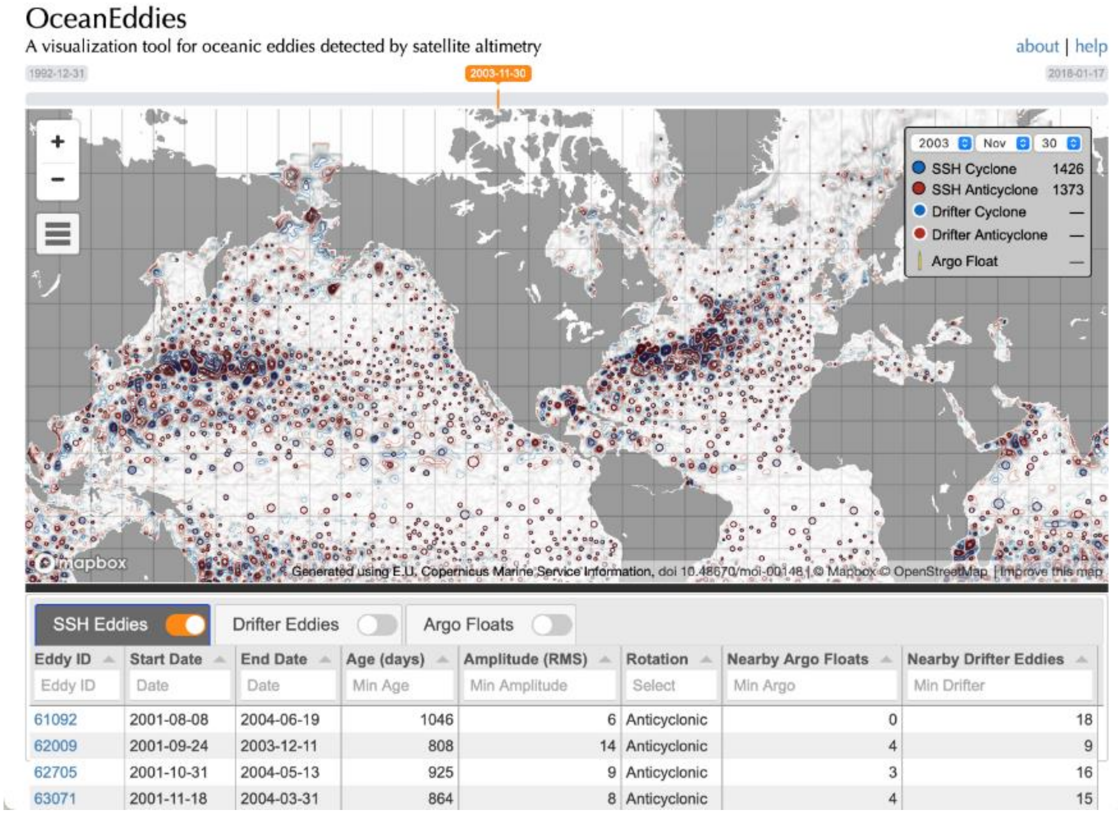


Figure 4.6-2: Interactive website to visualize and study mesoscale eddies.

Other data centers or teams shared data products or tools, such as CTOH, and Interactive website to visualize and study mesoscale eddies from NorthWest Research Associates, the Cryo2Ice Coincident Data Explorer, and St3TART.

Outreach, Education & Training

Figure 4.6-3: Photos of Argonautica annual meetings.

In Argonautica, the "ArgoHydro" data portal is available using for now existing satellite data (water levels from Hydroweb) with the idea of integrating other types of data beginning in 2023, ultimately including, of course, Swot data. Serious games were developed from the existing use cases and quizzes.

Nikolai Maximenko showed the FloatEco and GO-SEA projects, with citizen involved in instrument inspection and in debris sampling. On the plastic debris problematic, Y. Faugère mentioned a "7th continent" project, with altimetry used to corroborate the hypothesis that mesoscale ocean dynamics impact plastic debris distribution.

Preparations for SWOT were also highlighted, with Swot slide sets available on Aviso web site to help anyone wishing to present on this mission. Information about the SWOT Applications program and SWOT Early Adopters were presented.

Figure 4.6-4: Students presenting Argonautica project to the OSTST.

How and where to retrieve data, how to read at the most basic level, and how to process data seem to be important topics that are not always broached in formal curricula. Development of such training events seems interesting both for the users and for the Projects. EUMETSAT is continuing their training sessions online, including altimetry projects and information with a focus on Sentinel-6 Michael Freilich (a short course was given late September 2022).

Figure 4.6-5: Students of an in-person EUMETSAT training.

Most reported trainings are either in Europe, the EU, or in past meetings by U.S. OSTST members working in developing countries. Training events in the USA were not reported in this session.

4.6.2 Splinter Discussion Points and Recommendations

Questions were asked on feedbacks / user statistics, future plans, and in particular for trainings, or possible outputs of some data services.

- Future meeting topics

Feedbacks from past tools / data center / project showed in the session in the past, and which have, or have not continued, could be of interest for lessons learned. This could also be done on launch event communication, social media campaigns, etc.

- Developing exchanges on outreach and training

A workshop format on the training material or on outreach 'good practices' is of interest to propose within the OSTST time frame, but would need to be prepared with very concrete questions, material to exchange, etc. And possibly an output required from attendees – e.g. present their own technical presentation in short (~three minutes) blocks for an audience to be defined, draw lots on OSTST abstracts and try to outreach or explain the one selected to (e.g.) graduate trainees… etc.

We plan to continue inviting personnel from local informal science venues such as museums and science centers to present at the OSTST.

To advance coastal, hydrology, cryosphere, and ocean altimetry, the outreach team propose that tutorials on coastal altimetry, hydrology and cryosphere tools/data products be developed to further use and reported/mentioned/listed somewhere, as well as calls for those.

New Planned Efforts

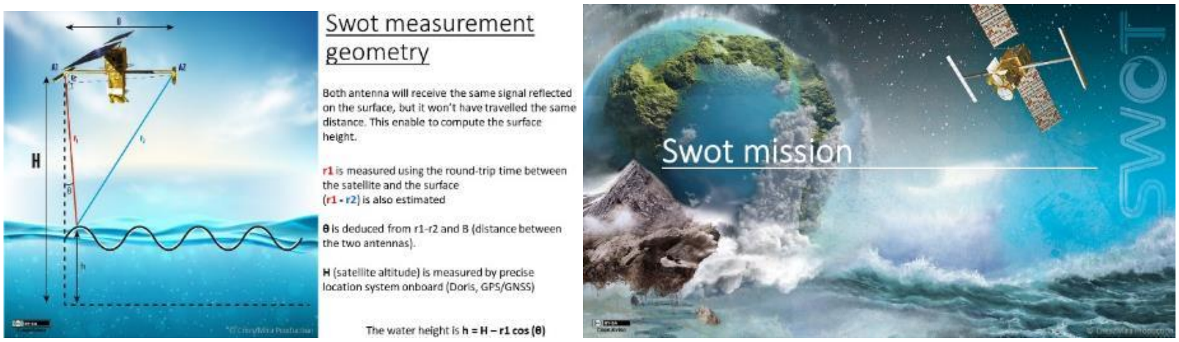


Figure 4.6-6: SWOT outreach slides available on Aviso website.

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 all of the current and especially the upcoming ocean altimetry missions—Jason-CS/Sentinel-6B and SWOT. The anticipated elements of this focus (not withstanding new opportunities) will include:

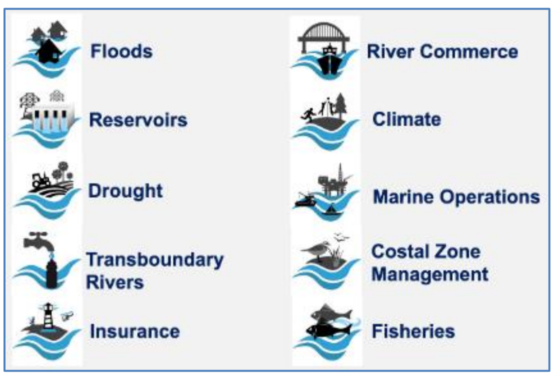


Figure 4.6-7: SWOT application areas.

- SWOT education & public outreach
- SWOT Applications focus on Early Adopters and other applied science users
- Sentinel-6 Michael Freilich
- Training events

4.7 Precise Orbit Determination

Chairs: Sean Bruinsma, Alexandre Couhert and Frank Lemoine

4.7.1 Summary

Contributions

The POD session exhibited this year twelve oral, five poster, and one forum presentations. Seven of them were focused on the reference altimetry missions (T/P, Jason-1/-2/-3, Sentinel-6 MF) with contributions from CNES, CPOD, DLR, ESA, NASA/GSFC, and JPL. Various complementary analyses were also shown on GPS block IIIA antenna calibration (CU Boulder), GPS satellite attitude modeling (CNES/CLS) & attitude-dependent errors in Jason-3 POD (AIUB), DORIS satellites for ITRF2020 (CLS), SLR systematic errors (AIUB) & SLR-based reevaluation of the Earth's GM (CNES/CLS), orbit accuracy of the altimetry constellation (DGFI-TUM), COST-G Time-Variable Gravity field modeling (AIUB), Solar Radiation Pressure modeling (CNES), and Copernicus POD Service (GMV).

POD status

Both the Copernicus missions POD and CNES/JPL/NASA POD analyses are nominal. The current set of reference orbits agrees well with average radial RMS differences of 8-12 mm for Jason-1, 6-8 mm for Jason-2, 5-7 mm for Jason-3 and Sentinel-6 MF (see Figure 4.7-1). The GSFC STD-2006/JPL RLSE-22A/CNES POE-F continue using ITRF2014 for now until the new ITRF2020 is thoroughly evaluated. Now Jason-1 CNES POE-F reprocessed orbits are available, the next set of CNES POE-G Standards is in preparation for 2023.

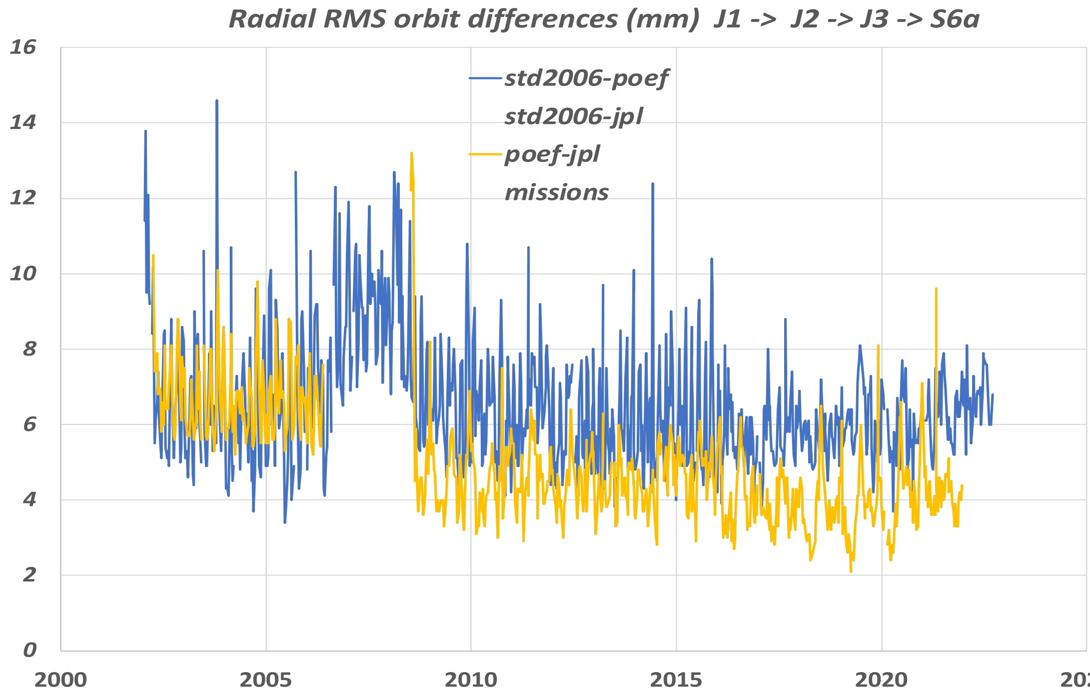


Figure 4.7-1: (Lemoine et al., 2022, DOI: [10.24400/527896/a03-2022.3443](10.24400/527896/a03-2022.3443)) Comparison of Jason-1/Jason-2/Jason-3/Sentinel-6 MF GSFC DORIS+SLR std2006 with CNES POE-F DORIS+GPS and JPL rlse22a GPS-only reduced dynamic orbits.

Sentinel-6 MF a new laboratory for metrology in orbit

Thanks to the co-location of multiple POD instruments (in addition to the shared Ultra Stable Oscillator between DORIS and GNSS), GNSS (GPS+Galileo), DORIS and SLR, with the inclusion of three GNSS receivers and antennas (Figure 4.7-2), one can verify the stability of the platform with an unprecedented accuracy. This means analyzing the relative time-tagging consistency between the different POD instruments, as well as their absolute or at least relative phase center knowledge accuracy.

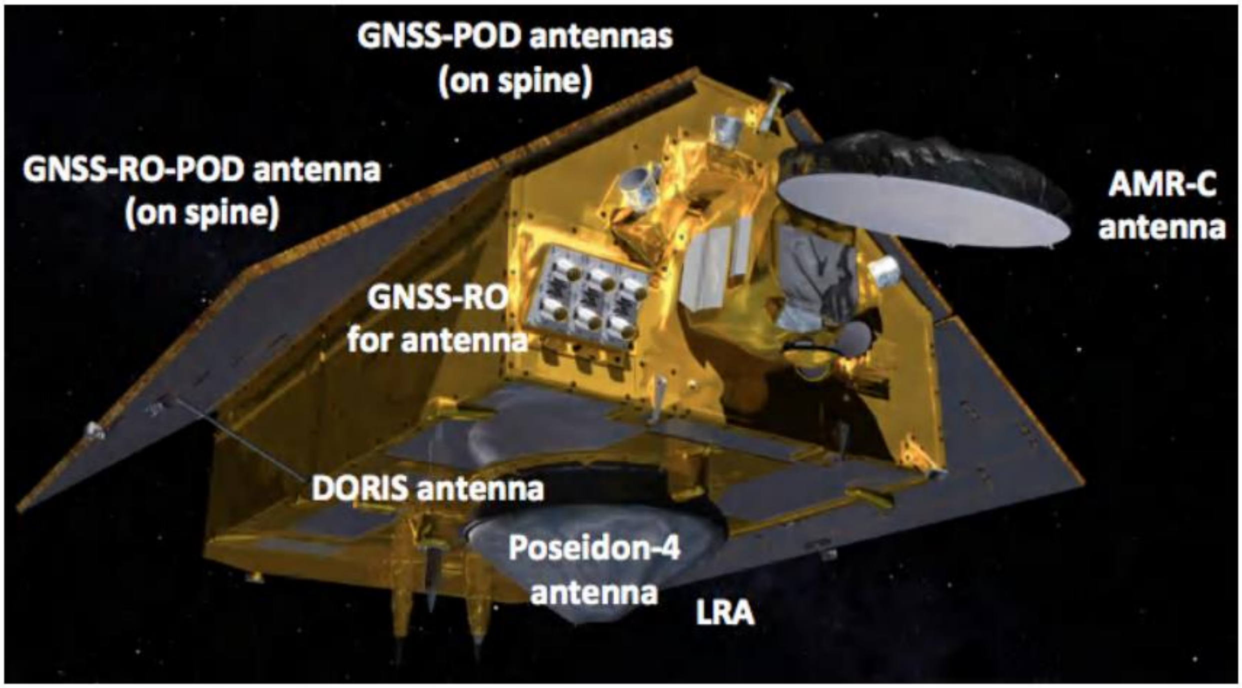


Figure 4.7-2: Sentinel-6 MF satellite and its POD instruments.

4.7.2 Splinter Discussion Points and Recommendations

Double-check star sensor alignment matrix on Sentinel-6 MF

The analysis of the GNSS data from the three receivers and antennas possibly reveals that there is a 0.43° yaw bias (also possibly a small pitch bias) in the attitude of the spacecraft as defined by the quaternions. In the event that this hypothesis is confirmed by ESA, a reprocessing of the quaternions delivered for Sentinel-6 MF with this correction would be necessary. In addition, in that case, it would be necessary to check that the Sentinel-6B ground software avoids a similar problem. The metrological analysis using the GNSS data from the different receivers and antennas just discussed reinforces that Sentinel-6A is a metrological laboratory for precise orbit determination. Future altimetric missions should embrace this design, which helps to ensure the highest accuracy for all of the scientific data products.

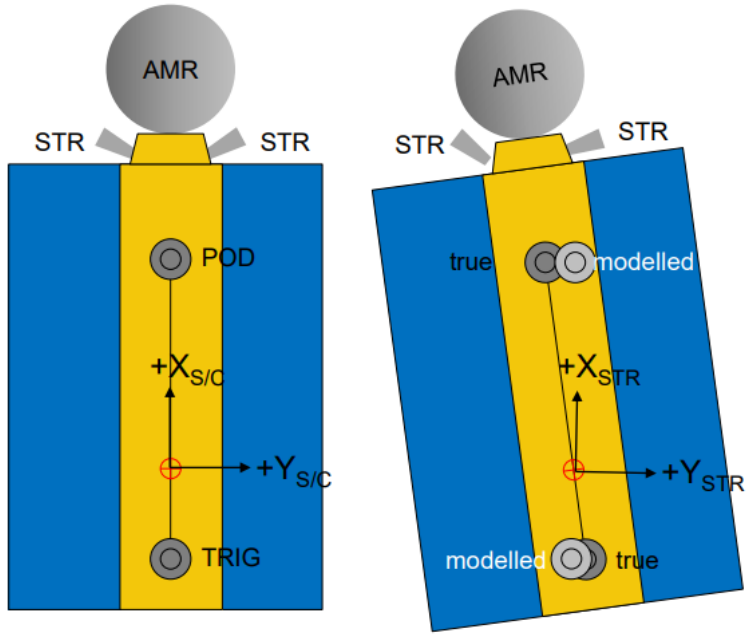


Figure 4.7-3: (Montenbruck et al., 2022, DOI: 10.24400/527896/a03-2022.3307) Schematic representation of star camera misalignment.

Measure on ground Sentinel-6B TRIG-PODRIX timing bias

The POD analyses show that the TRIG (or PODRIX) time tag is too large (or too small) by 1.2 µs, unless it is a shared contribution between the two receivers. Yet, SLR analyses suggest a dominating contribution of TRIG time stamping error. Indeed, there is a 7 mm GPS TriG time-tagging inconsistency as seen by SLR for Sentinel-6A (see **Figure 4**). Thus, it would be useful to verify the TRIG-PODRIX timing bias in a signal simulator for Sentinel-6B.

The attitude flip maneuvers (*thanks to the project team for implementing these maneuvers*) at low beta angles are useful to disentangle center of phase errors from time tagging and dynamic modeling errors. These attitude yaw flips should also be implemented for the commissioning phase of Sentinel-6B.

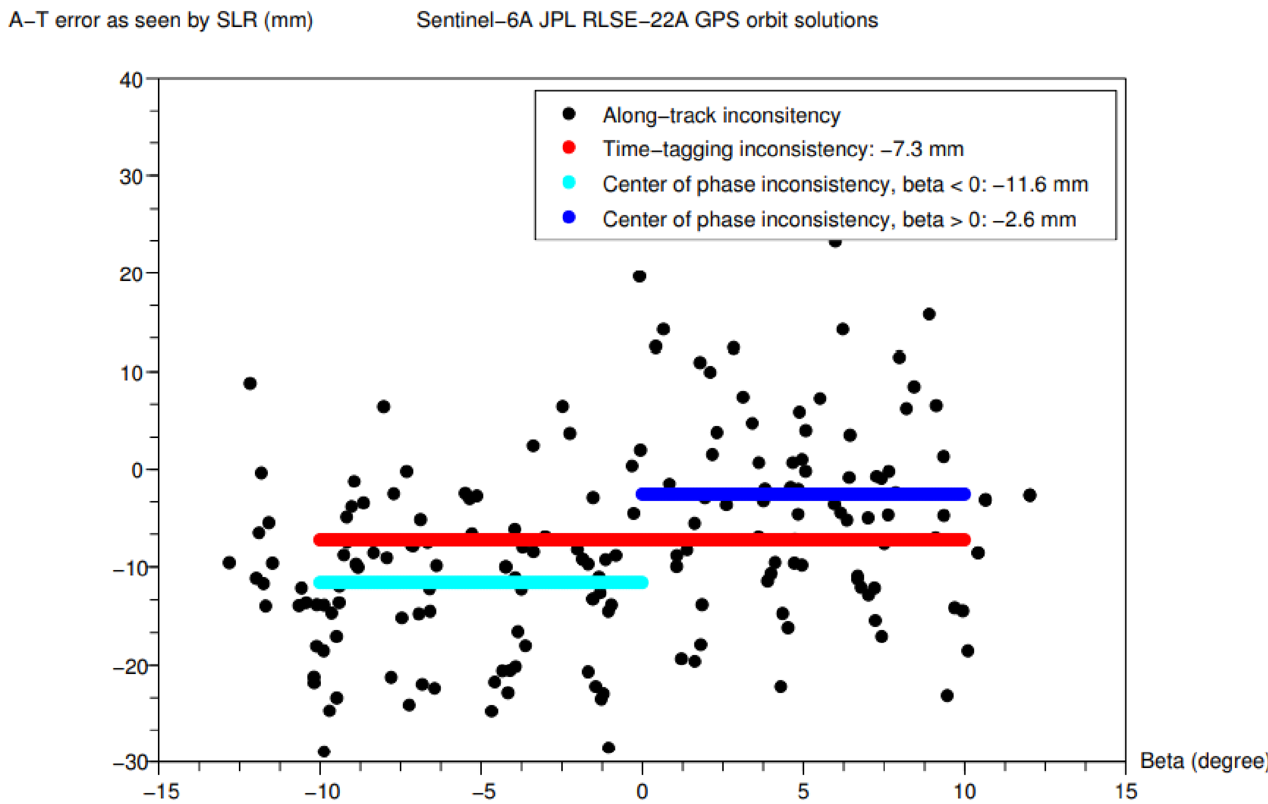


Figure 4.7-4: (Couhert et al., 2022, DOI: [10.24400/527896/a03-2022.3497](10.24400/527896/a03-2022.3497)) SLR-derived along-track Sentinel-6A JPL RLSE-22A GPS (5 mm X-PCO & 7 mm time-tagging) obit error vs. beta angles.

Consider use of products from Time-Variable Gravity COST-G Service

The EIGEN-GRGS-RL04 model (green) has been the standard for LEO-POD of altimeter satellites, but the extrapolation to the GRACE-FO period reveals large prediction errors over the last years, as can be seen from the comparison shown in Figure 4.7-5 with the model fitted to COST-G GRACE-FO gravity fields (red). The reason is that the EIGEN-GRGS-RL04 model relies on GRACE data only through 2017 (J.M. Lemoine et al., 2019, https://doi.org/10.5880/ICGEM.2019.010). Therefore, the availability of such Time-Variable Gravity COST-G models that are frequently updated (based on data from GRACE & GRACE FO) would be beneficial in the future to use in POD for the whole altimetry constellation (Peter et al., 2022, https://doi.org/10.1016/j.asr.2022.04.005).

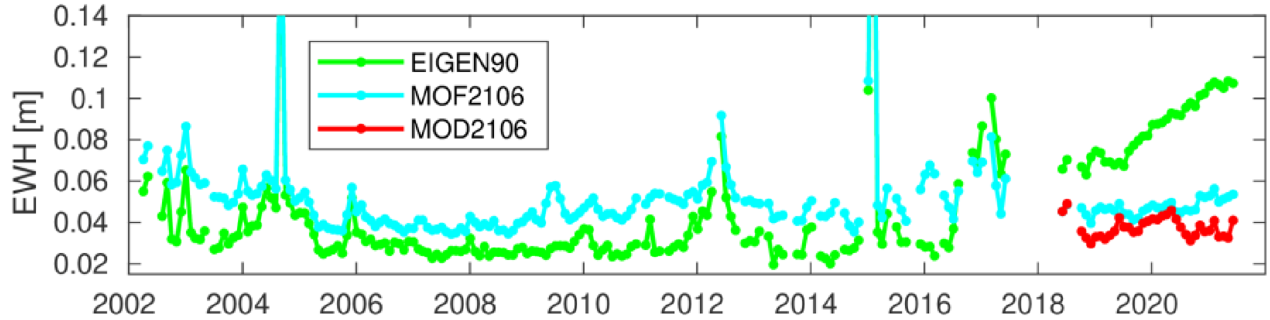


Figure 4.7-5: (Jäggi et al., 2022, DOI: [10.24400/527896/a03-2022.3299](https://doi.org/10.24400/527896/a03-2022.3299)) RMS of differences (over land) with respect to monthly gravity fields.

Challenges for Sentinel-6 MF remain with the Radiation Pressure modeling

The nadir surface of Sentinel-6 MF (up to 5 times larger than the nadir surface for Jason-3) exposes the orbit to solar/Earth/thermal radiation pressure perturbations in the radial direction. Errors in modeling these perturbations could explain the larger radial signatures observed for Sentinel-6 MF in the mean orbit differences with independent solutions exhibited in Figure 4.7-6.

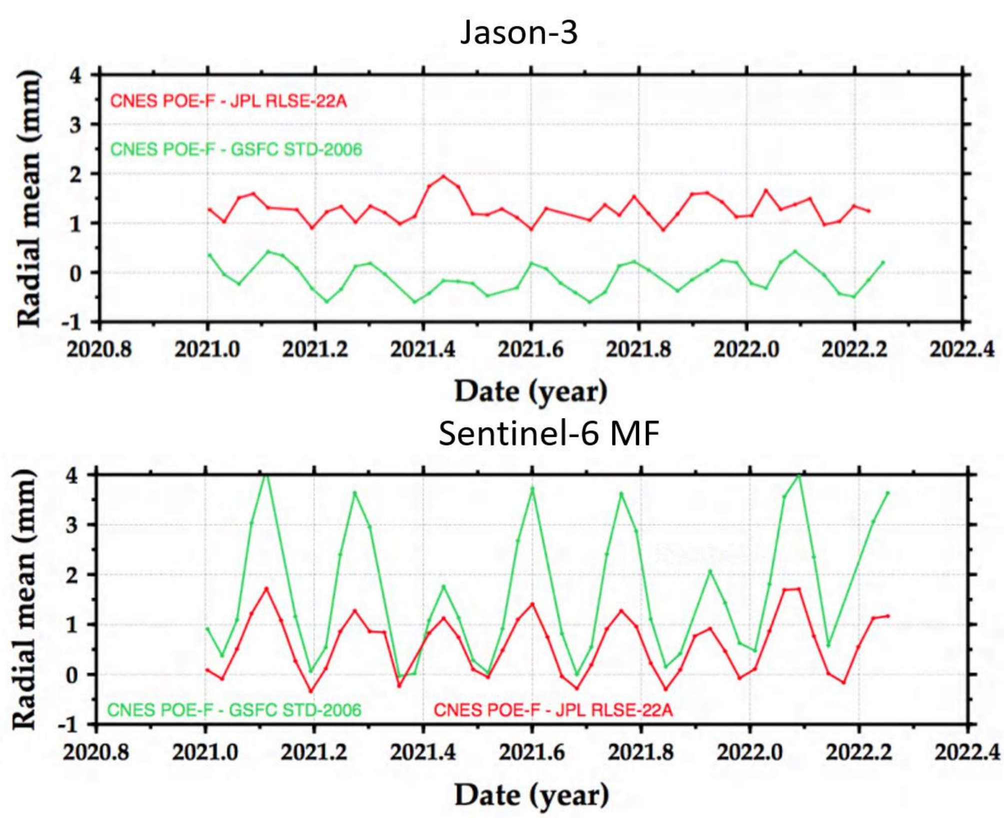


Figure 4.7-6: (Couhert et al., 2022, DOI: [10.24400/527896/a03-2022.3497](https://doi.org/10.24400/527896/a03-2022.3497)) Radial mean orbit differences (mm) between CNES POE-F – GSFC STD-2006 and CNES POE-F – JPL RLSE-22A for Jason-3 (top) and Sentinel-6 MF (bottom).

Multi-constellation GNSS receivers should be the baseline for future altimeter missions

In terms of independent SLR residuals RMS, combined Galileo+GPS orbits seem to perform better than individual GPS-only or Galileo-only solutions (see Table 4.7-1). This is the first time an altimeter mission tracks both the GPS and Galileo constellations. The Sentinel-6 MF is thus a vanguard for the proposed ESA GENESIS mission, which is a multi-technique geodetic mission to improve the ITRF (Delva et al., 2023, https://doi.org/10.1186/s40623-022-01752-w).

Table 4.7-1: (Gini et al., 2022, DOI: 10.24400/527896/a03-2022.3390) External validation using Satellite Laser Ranging residuals over Galileo-only, GPS-only and combined orbit solutions.

	Galileo	GPS	Galileo + GPS
SLR res. Mean (mm)	1.4	1.4	1.5
SLR res. RMS (mm)	8.1	9.3	7.8

4.8 Quantifying Errors and Uncertainties in Altimetry Data

Chairman: Michael Ablain, Joel Dorandeu, Remko Scharroo

4.8.1 Summary

Objectives of this session are to strengthen the link between altimetry experts and applications regarding errors in the altimetry system. This covers information exchange in both directions: the exports informing the end-users about new insights about errors in altimetry, and the end-users providing their needs and requirements in terms of errors but also in terms of error formulation.

The splinter was fruitful given the number and diversity of talks and posters, each of them tackling the error and uncertainty topic with a different approach. This year, the focus has been put on:

- **The detection and reduction of altimeter data errors:** Leveraging Sentinel-6A interleaved mode to characterize High Resolution error budget over ocean (Cadier et al., CLS, DOI: 10.24400/527896/a03-2022.3423), Long-term stability of ionospheric GIM corrections in satellite altimetry data sets (D. Dettmering, DGFI-TUM, DOI: 10.24400/527896/a03-2022.3266)

- **Improvement of the uncertainty characterization:** Uncertainties in SSB modeling and impact on MSL (Figerou et al., CLS, DOI: 10.24400/527896/a03-2022.3456), Limiting factors of the altimetry observing system to the Global Mean Sea Level monitoring accuracy (Guerou et al., CLS, DOI: 10.24400/527896/a03-2022.3408), Improving long term estimates of global mean sea level, global ocean heat content and Earth's energy imbalance using CDR water vapour data (Barnoud et al., Magellium, DOI: 10.24400/527896/a03-2022.3403)

- **New formalism to characterize uncertainties:** Sea level rise uncertainties: insights from a metrological approach (Woolliams et al., NPL, DOI: 10.24400/527896/a03-2022.3592), Propagating uncertainties and error correlation structures through retracking and sea state bias correction (Behnia et al., NPL, DOI: 10.24400/527896/a03-2022.3593)

- **Error and uncertainties assessment:** In-situ measurements for altimetry cal/val: overview of the H2020 CCVS project (Tison et al., CNES, DOI: 10.24400/527896/a03-2022.3283), Validation of altimetry by using in situ observations of pressure and acoustic travel time in the Southern Ocean (Schroeter et al., Alfred-Wegener-Institute, DOI: 10.24400/527896/a03-2022.3331), A Trihedral Corner Reflector to Support Radar Altimeters External Calibration (Garcia-Mondejar et al., isardSAT, DOI: 10.24400/527896/a03-2022.3395)

Improved sea level error budget provided for the S6-MF HR data (Emeline Cadier, CLS) – *DOI: 10.24400/527896/a03-2022.3283*

- A Reduction of uncertainties at different time and spatial scales is described: these improvements will be available in next S6-MF L2 product release.

- A 5 mm SSH signal error detected in equatorial band 20 years ago and attributed to TOPEX data is very likely due to Jason (1/2/3) altimeter measurements (Figure 4.8-1): it highlights the great interest of tandem phase to detect error in previous reference missions

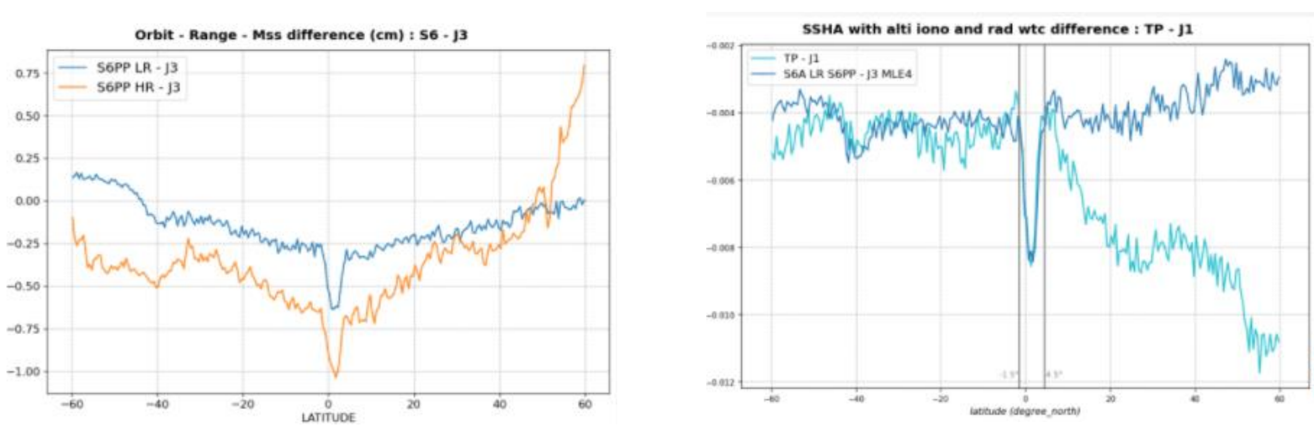


Figure 4.8-1: SSH differences as a function of latitude between S6-MF and Jason-3 on the left, and between TOPEX and Jason-1 on the right: a 5 mm SSH signal error is detected in the equatorial band highlighting most likely the same systematic error in Jason-1 and Jason-3 measurements.

Revisiting the long-term stability of ionospheric GIM corrections in satellite altimetry data sets (Denise Dettmering, DGFI-TUM) – *DOI: 10.24400/527896/a03-2022.3266*

- An updated “scale” coefficient is estimated based on the linear relationship between dual frequency and GIM vertical electron content (using TOPEX, J1, J2, J3) :

$$TEC_{ALTI}(t,\lambda,\phi) = TEC_{GIM}(t,\lambda,\phi) \cdot scale + offset$$

- Recommendation to update the GIM ionospheric correction scaling with constant factor determined over full period (0.881 for reference missions): strong impact on the long-term stability.

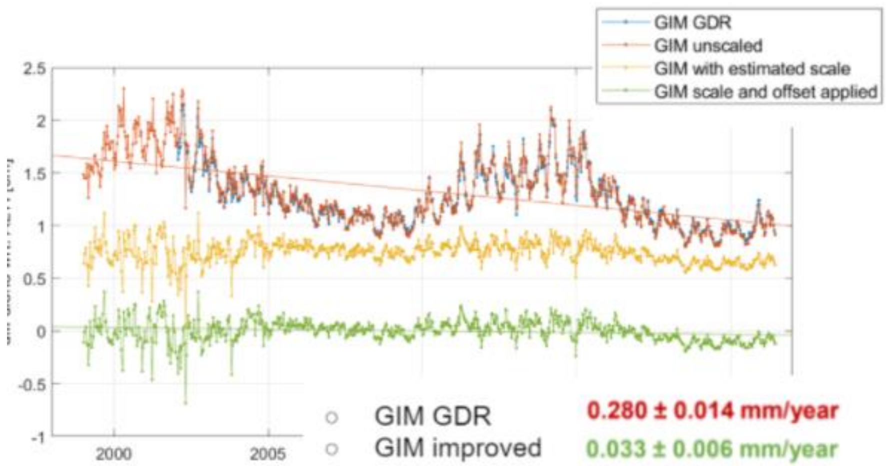


Figure 4.8-2: Evolution of the global mean ionosphere correction derived from GIM compared to the dual ionospheric correction from reference mission over last 20 years for different scaling approaches.

Improvement of the SSB uncertainties characterization (François Bignalet-Cazalet, CNES) – DOI: [10.24400/527896/a03-2022.3456](https://doi.org/10.24400/527896/a03-2022.3456)

- Better traceability , description and assessment of the SSB correction uncertainties

- SSB must be evaluated over at least a 3-year period to reduce the effect of the inter-annual sea state ocean variability

- A 0.01 dB/yr stability is required on sigma-0 (assuming a perfect stability SWH)

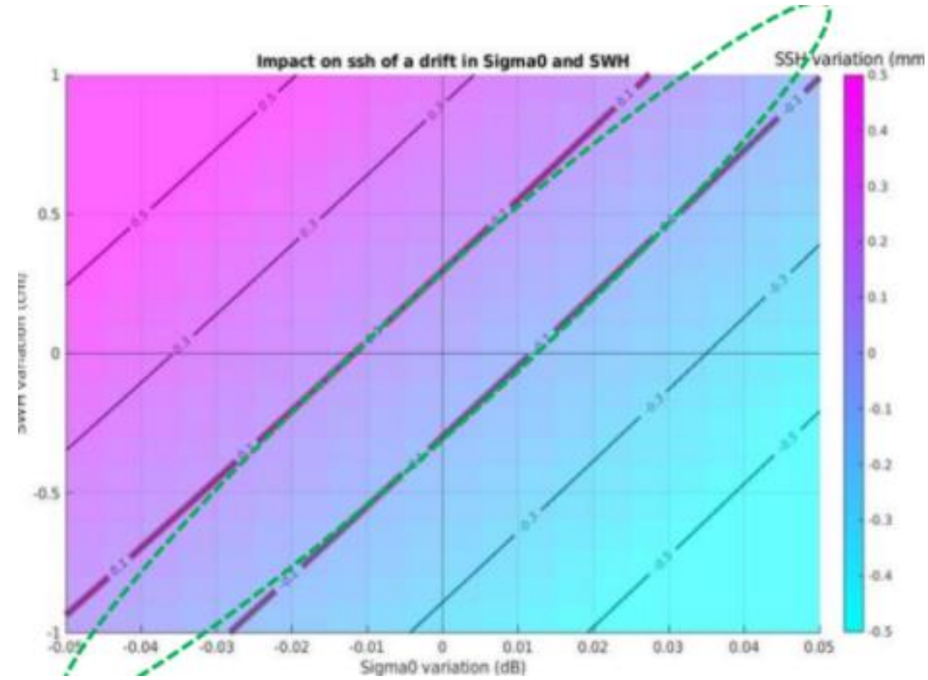


Figure 4.8-3: Impact of Sigma-0 variations (x-axis) and SWH variations (y-axis) on the SSH estimates through the SSB correction

Update of the AVISO GMSL time series and the uncertainty table budget (Pierre Prandi, CLS) - *DOI: [10.24400/527896/a03-2022.3408](https://doi.org/10.24400/527896/a03-2022.3408)*

- The GMSL trend uncertainty meet 0.3 mm/yr [90% C.L.] over the last 20 years of the altimeter record
- The main limitations identified to reach the more stringent GMSL stability requirements are coming from the POD (ITRF), WTC and short time-correlated uncertainties (See Guerou et al., 2022 for more details)

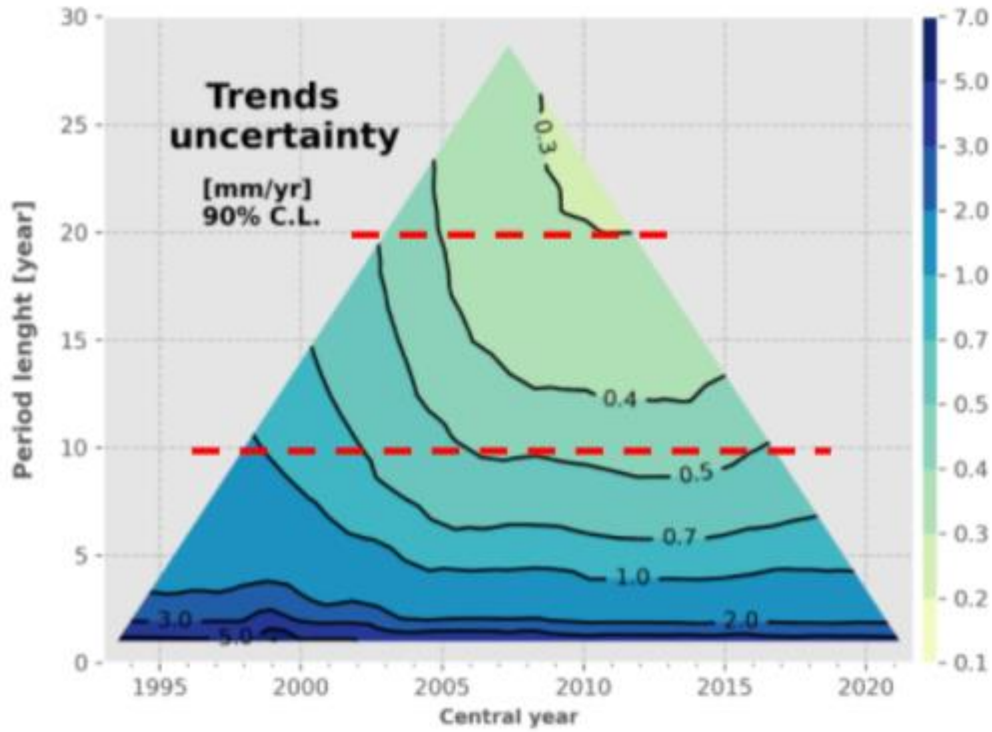


Figure 4.8-4: Diagram of the GMSL trend uncertainties within a 90% confidence for different period lengths (y-axis) and centered over different year (x-axis)

Improvement of the long term estimates of global mean sea level thanks to an alternative WTC correction based on the very stable water vapor CDRs (Anne Barnoud, Magellium) –DOI: 10.24400/527896/a03-2022.3592

- reduction the GMSL trend uncertainty until 30 %
- detection of a drift on the Jason-3 radiometer WTC correction of the order of -0.5 mm/yr
- An empirical Jason-3 global mean WTC based on water vapour CDR is available on AVISO+/ODATIS for an independent assessment

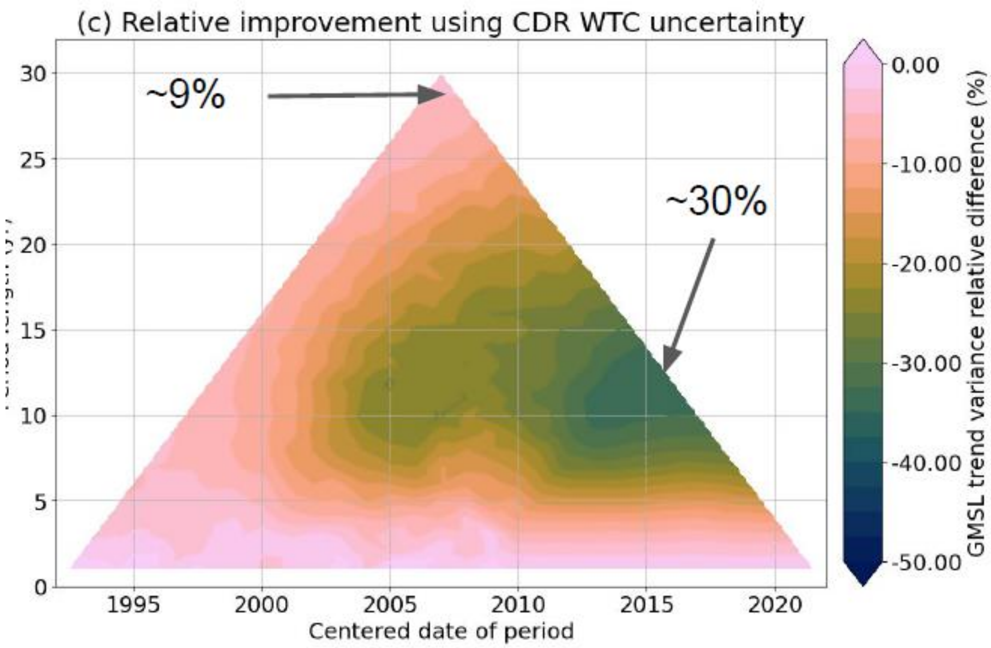


Figure 4.8-5: Diagram of the GMSL trend variance reduction using a CDR-derived for different period lengths (y-axis) and centered over different year (x-axis)

Development of a new framework to estimate the Sea Level Rise Stability Uncertainty Budget from a metrological approach developed in the FIDUCEO project (Emma Williams, and Sajedeh Behnia, NPL) – *DOI: 10.24400/527896/a03-2022.3592*

- Produced systematic review of current processing assumptions and sources of uncertainty to give comprehensive end-to-end uncertainty analysis for altimeter on the framework of the ASeLSU project (supported by ESA)

- To extend this work to POD and WTC

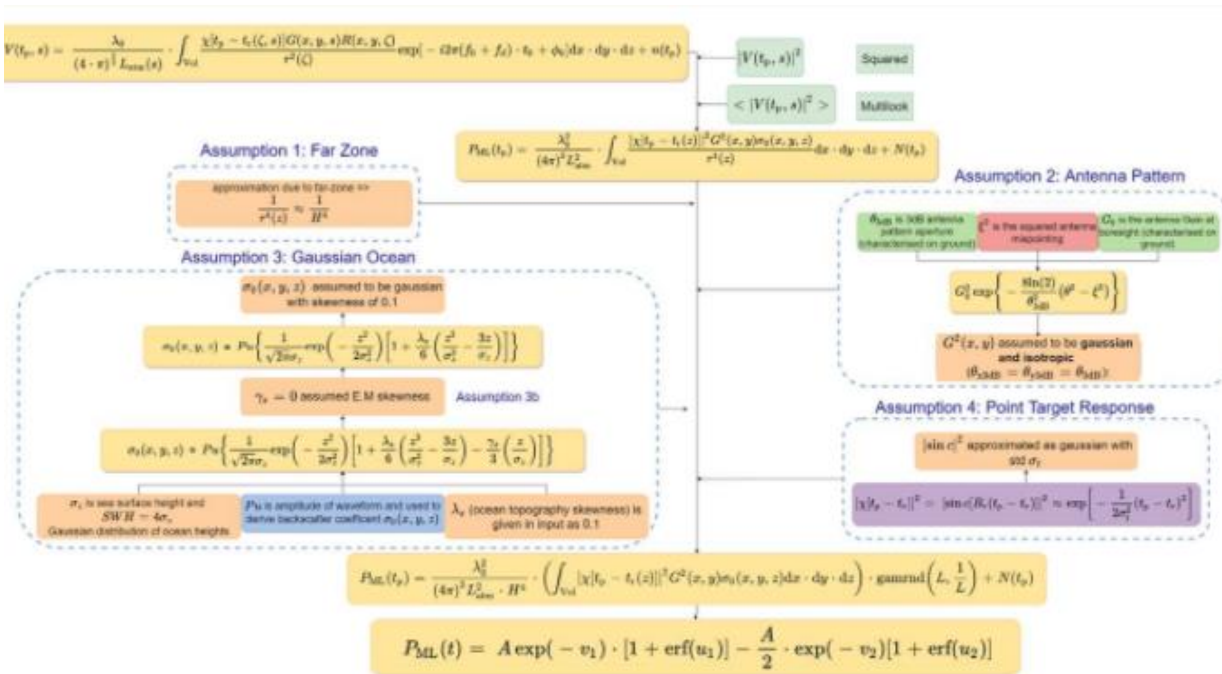


Figure 4.8-6: Diagram of the current derivation of the Brown model to fit the waveforms in retracking from, at the top, the complete radar equation, for LRM mode. This diagram emphasises the approximations that go into this derivation. Splinter Discussion Points and Recommendations

4.8.2 Splinter Discussion Points and Recommendations

No specific recommendation issued from discussions.

4.9 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 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).

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 6 months of each new mission (12 months for Sentinel-6/Jason-CS), 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 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 in particular 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 11 oral presentations (6 in-situ, and 5 global), and 24 poster presentations. 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, and CryoSat-2.

4.9.1 Summary of Results from in-situ calibration sites

Table 4.9-1. 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**
TOPEX-B MGDR†	+17	+5	+24		**+15**
Jason-1 GDR-E	+41	+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 GDR-F (LRM, side A)	−9	+26	+4	−3*	**+5**
Sentinel-6 MF GDR-F (LRM, side B)	−6	+33	+13	−3*	**+9**
Sentinel 3A (SAR)	+19		+20	−1	**+13**
Sentinel-3B (SAR)	+24		+14	−3	**+12**

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

†TOPEX MGDR + orbit from GSFC + radiometer correction

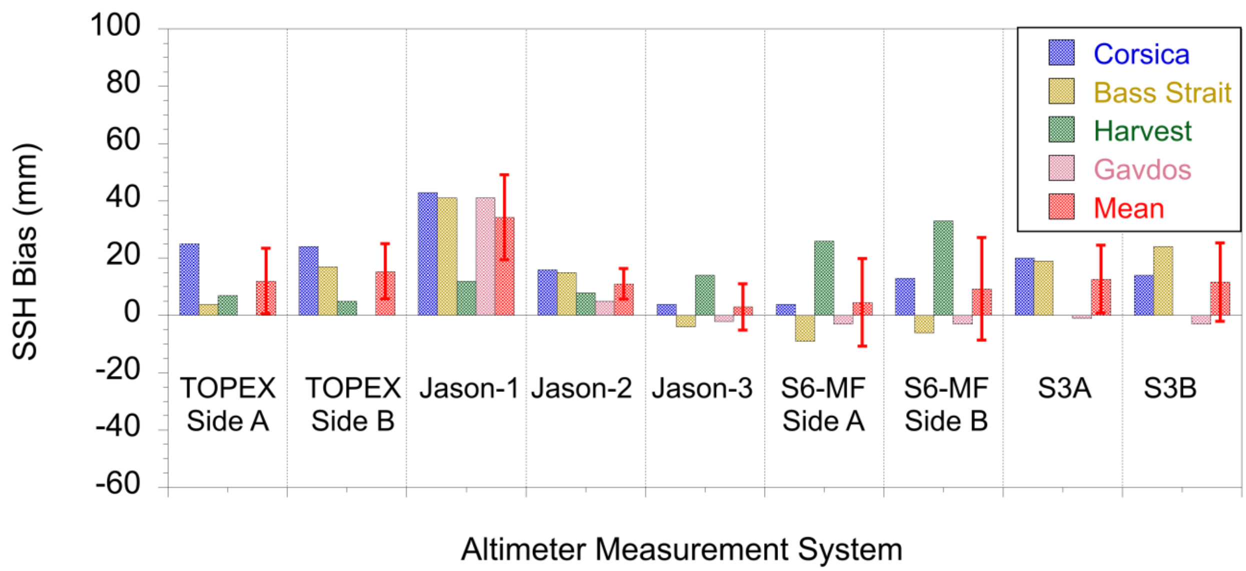


Figure 4.9-1. Absolute SSH bias values (in mm) for different missions and from the different calibration sites (using in situ SSH measurements) (values from Table 4.9-1).

The permanent transponder installed in Crete at a crossover point of the Jason (and Sentinel-6) and Sentinel-3 ground tracks continues to provide absolute calibration results focused on the altimeter range component of the measurement systems. Mertikas et al. (DOI: 10.24400/527896/a03-2022.3492) reported range biases of +14, -7 and +1 mm for Jason-3, Sentinel-6 MF and Sentinel-3A respectively: we must note that the range bias is by definition opposite in sign to the SSH bias). The transponder technique is showing increasing promise in contributing to the understanding of the overall measurement system, and offers a unique perspective on the fundamental behavior of the altimeter in isolation from sea-state effects. In the frame of the Harvest platform decommissioning Haines et al. (DOI: 10.24400/527896/a03-2022.3449) reported on the transition plan to a regional infrastructure in the Southern California bight that includes a transponder on Catalina island (Desjonqueres et al., DOI: 10.24400/527896/a03-2022.3428). See also Flores de la Cruz et al. (DOI: 10.24400/527896/a03-2022.3293) for transponder results for Cryosat-2.

Highlighted in this year's session was the maturing role of new technologies, especially GNSS (GPS) buoy systems to support altimeter calibration initiatives in the frame of SWOT (Zhou et al., DOI: 10.24400/527896/a03-2022.3362, Hay et al., DOI: 10.24400/527896/a03-2022.3303) but also measuring mean sea level with surface drifting buoys (Elipot et al., DOI: 10.24400/527896/a03-2022.3455). Watson et al. (DOI: 10.24400/527896/a03-2022.3623) and Legresy et al. (DOI: 10.24400/527896/a03-2022.3358) updated results from repeated buoy leveling sessions in the Bass Strait, but also described developments with the Current, Waves Pressure Inverted Echo Sounder (CWPIES). In shallow (Bass Strait) water, CWPIES is yielding results comparable to those from surface GPS, while providing additional variables of interest (Legresy et al., Forum only, DOI: 10.24400/527896/a03-2022.3359). A common presentation from Corsica, Bass Strait and Harvest (DOI: 10.24400/527896/a03-2022.3623) highlighted coherent results for the tandem phase of Jason-3 and Sentinel-6 MF.

Newer cal/val sites and approaches demonstrating value of increasing diversity of locations and techniques, including for benefit of historical missions (e.g., Noumea by Chupin et al., DOI: 10.24400/527896/a03-2022.3425, but also Esselborn et al., DOI: 10.24400/527896/a03-2022.3434, Fenoglio et al., DOI: 10.24400/527896/a03-2022.3515, Schöne et al., DOI: 10.24400/527896/a03-2022.3512 and Cancet et al., DOI: 10.24400/527896/a03-2022.3294).

Providing a bridge to the session on global validation studies, Leuliette et al. (DOI: 10.24400/527896/a03-2022.3430) reported on the loss of tide gauges from the global network that impacts altimeter drift estimates. From this study, Leuliette et al. also reported no significant drifts detectable in the short time series of Sentinel-6 MF data. Ray et al. (DOI: 10.24400/527896/a03-2022.3567) showed that altimetry can also be used as a method to detect datum errors in tide gauges.

4.9.2 Summary of Global validation studies

A ~1 cm inter-mission bias between Sentinel-6 LRM and Jason-3 was reported by Bignalet-Cazalet et al. (DOI: 10.24400/527896/a03-2022.3572) and Nilsson et al. (DOI: 10.24400/527896/a03-2022.3354). Hemispheric geographically correlated errors have been reduced when using the POE-F orbit standards (Figure 4.9-2). Beckley et al. (DOI: 10.24400/527896/a03-2022.3574) also reported on the efficacy of the new orbit solutions via tide gauge analyses. They also assessed agreement between Jason-3 and Sentinel-6 MF during the verification phase and evaluated the subsequent impact on current global and regional mean sea level estimates (Figure 4.9-3). However, discrepancy between Jason-3 and Sentinel-6 measurements near the equator is clear and initial investigations suggest that this behavior is most likely coming from Jason-3. A SWH dependency of the bias (~1cm) was also reported that will be improved with Sentinel-6 MF LRM numerical retracking.

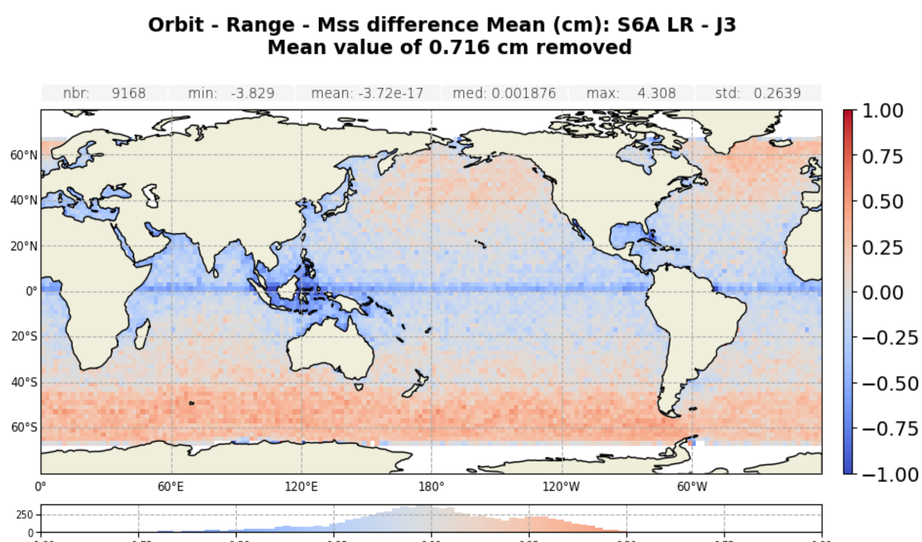


Figure 4.9-2. Orbit – range – MSS map (Sentinel-6 MF minus Jason-3).

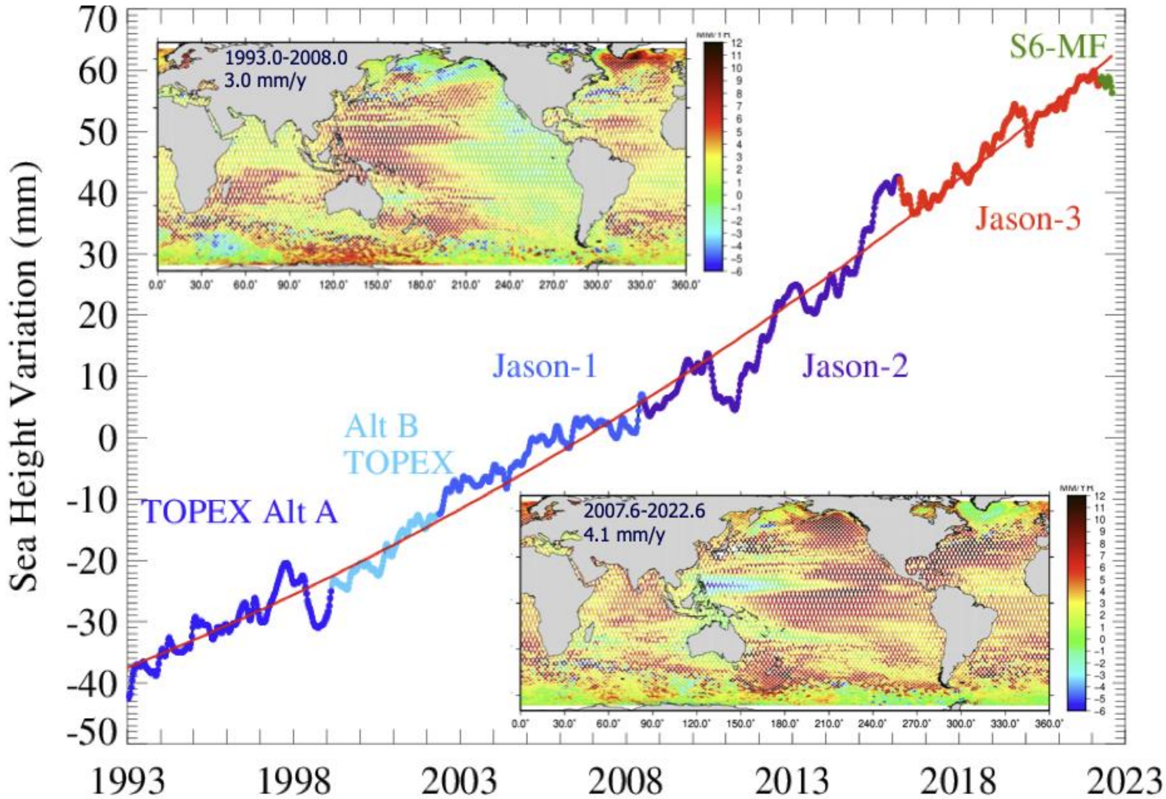


Figure 4.9-3. Global mean sea level variations from 1993 to mid 2022 are estimated from TOPEX, Jason, and S6-MF altimetry referenced to ITRF2020. The red line is the quadratic fit to the SSH variations after removal of annual and semi-annual signal and application of GIA. The linear sea level rate is estimated at 3.4 mm/yr ± 0.04 mm/yr with an acceleration of 0.080 mm/yr^2 ± 0.025 mm/yr^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. Two signatures of note are the reversal of the Pacific Decadal Oscillation (PDO) bringing significantly higher sea level rates to the U.S. West coast, and the rate reversal along southern Greenland coast as a result of ice mass loss post gravitational attraction effects with accelerated rates along U.S. East coast.

Jason-3 data continue to demonstrate good performance, including after transition to the interleaved orbit. Jason-3 data from adaptive retracking shows better performance (Figure 4.9-4) except very close to coasts (Roinard et al., DOI: 10.24400/527896/a03-2022.3385, Forster et al., DOI: 10.24400/527896/a03-2022.3575).

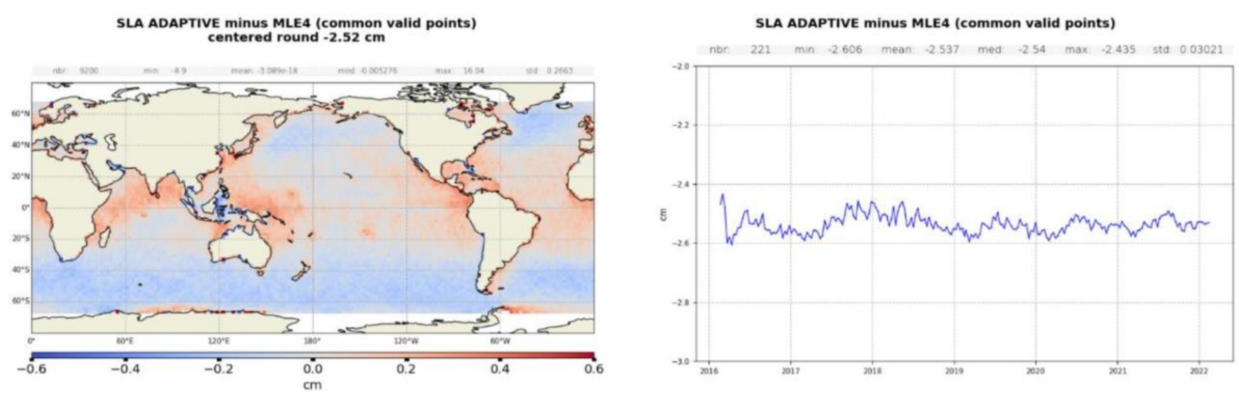


Figure 4.9-4. Jason-3 SLA differences between Adaptive and MLE4 retracking: regional patterns at left and time series at right.

Sentinel-3 A and B data are demonstrating good performance and consistency with other missions. Sources of errors for Sentinel-3A and Sentinel-3B trends have been identified (and corrections will be implemented) (Nencioli et al., DOI: 10.24400/527896/a03-2022.3441).

HaiYang-2B and 2C data are demonstrating good performance, with some planned processing updates (Philip et al., DOI: 10.24400/527896/a03-2022.3446; Mertikas et al., DOI: 10.24400/527896/a03-2022.3499).

CryoSat-2 data is also demonstrating excellent performances (despite the single frequency altimeter and the lack of radiometer data) (Banks et al., DOI: 10.24400/527896/a03-2022.3316; Flores de la Cruz et al., DOI: 10.24400/527896/a03-2022.3293, Naeije et al., DOI: 10.24400/527896/a03-2022.3504; Vignudelli et al, DOI: 10.24400/527896/a03-2022.3476).

SARAL/AltiKa data continues to demonstrating excellent performances, nearly 10 years after launch date (Ghita et al., DOI: 10.24400/527896/a03-2022.3409; Prandi & al., DOI: 10.24400/527896/a03-2022.3405).

TOPEX and Poseidon reprocessing to GDR-F is complete and shows significant improvements (Figure 4.9-5) with products planned for release in 2023. (Desjonqueres et al., DOI: 10.24400/527896/a03-2022.3498; Roinard et al., DOI: 10.24400/527896/a03-2022.3424 ; Guerou et al., DOI: 10.24400/527896/a03-2022.3411).

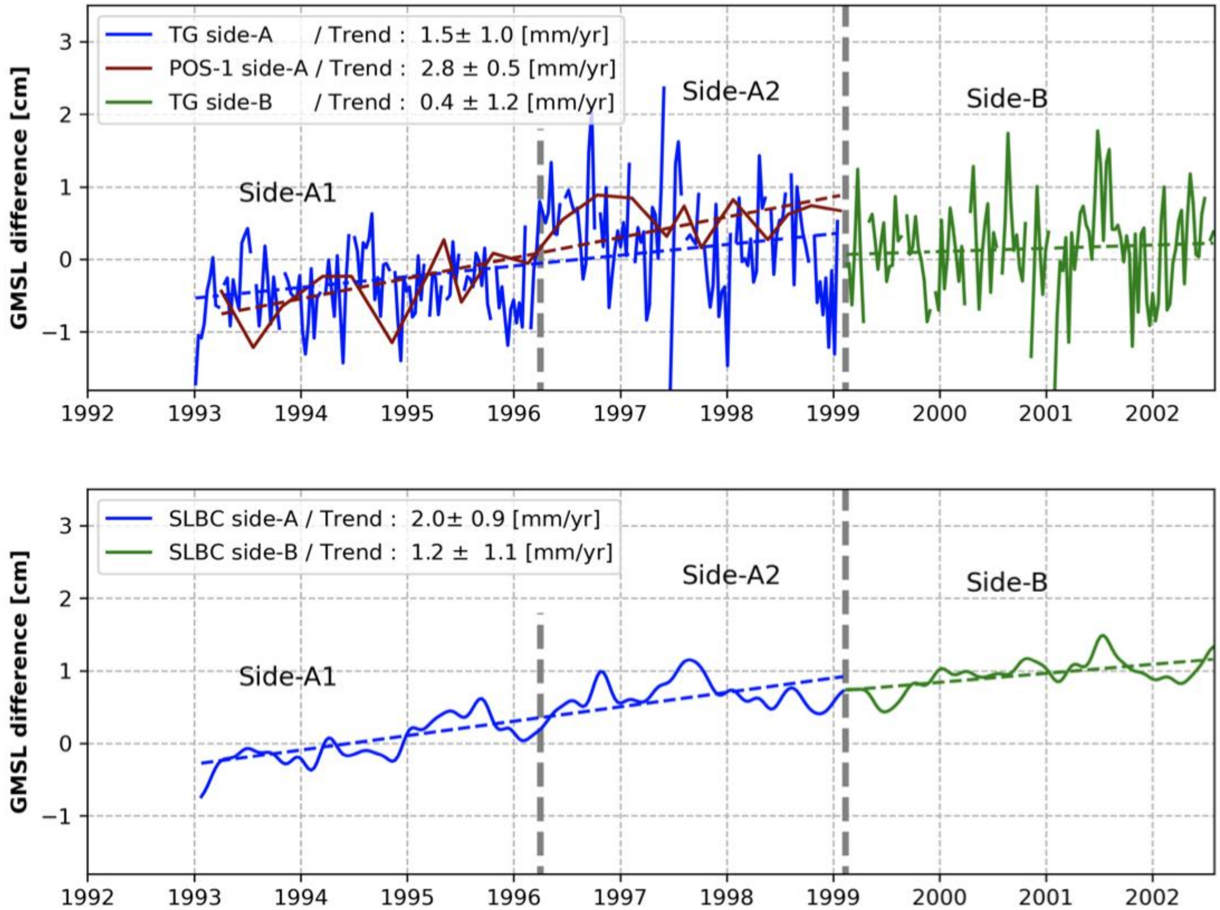


Figure 4.9-5. Stability assessment of TOPEX GDR-F using of three independent methods: (i) GLOSS-CLIVAR tide-gauge network, (ii) sea level budget closure (sum of the thermosteric and ocean mass contributions derived from independent observations) and (iii) Poseidon-1 data.

4.9.3 Splinter Discussion Points and Recommendations

No specific recommendation issued from discussions.

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

Chairs: Ben Hamlington and Benoit Meyssignac

4.10.1 Summary

Argo on one side and Satellite altimetry sea level combined with space gravimetry data on the other side enable an independent estimate of the mean and time varying Earth energy imbalance that is responsible of current climate change. With these consistent estimates, it is possible to derive the global climate feedback parameter and its time variations over past decades, which further provides an observational constraint on the climate sensitivity (see Figure 4.10-1). This recent research in sea level science shows that geodesy measurements from satellite altimetry and space gravimetry can provide independent observational constraints on the climate sensitivity. It also shows how current sea level rise is linked with past and present Earth energy imbalance.

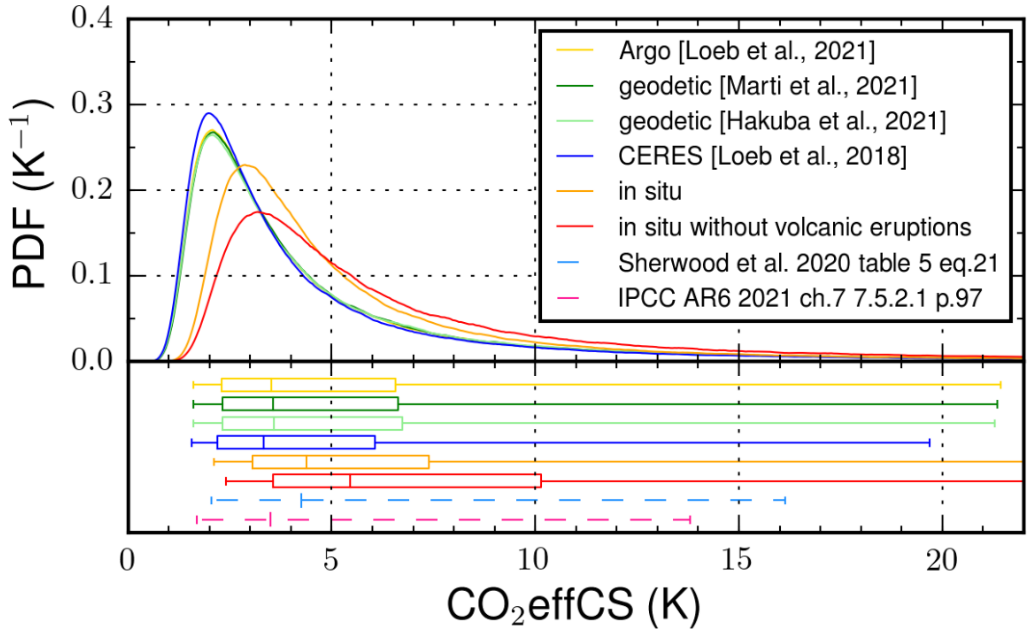


Figure 4.10-1: Equilibrium climate sensitivity estimated from Argo data, from in situ ocean temperature data since 1971, from geodetic data (i.e. satellite altimetry and space gravimetry) and from multiple lines of evidence.

In recent years, however, Argo data is not consistent with satellite altimetry and space gravimetry. The sea level budget evaluated with satellite altimetry, space gravimetry and Argo does not close since 2015, with an estimated departure of 2.0±1 mm/yr (trend computed over 2015-2021). A salinity drift in Argo floats and a drift in Jason 3 WTC explain respectively ~40% and ~20% of this non-closure. ~40% of the non-closure, which corresponds to a significant signal of 1.0±05mm/yr (trend computed over 2015-2021) remains unexplained (see Figure 4.10-2). At the same time, a monthly reconstruction in a 0.5-degree grid of every individual contribution to sea level change from 1992 on, does close the sea level budget after 2015. The reconstructed mass-driven sea level shows large discrepancies in ocean mass signal compared with GRACE after 2015 suggesting the GRACE estimate of the ocean mass could be biased after 2015. This subject needs further research to identify the exact causes in the observing system of the non-closure of the sea level budget after 2015.

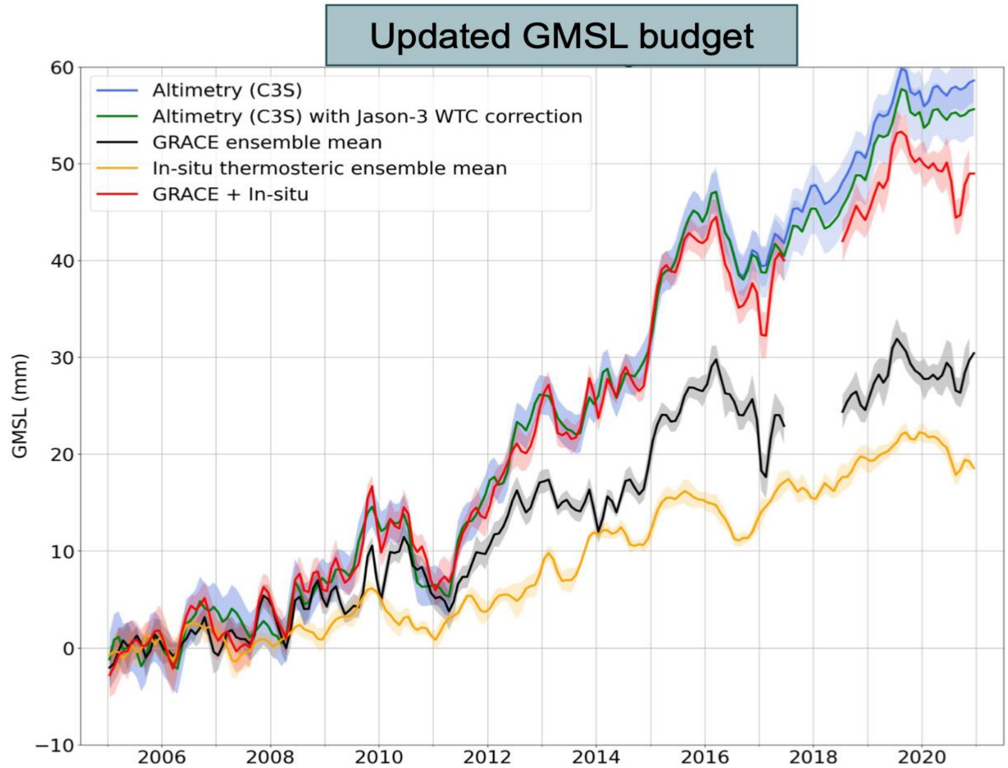


Figure 4.10-2: Sea level budget since 2005 (Barnoud et al., DOI: [10.24400/527896/a03-2022.3322](https://doi.org/10.24400/527896/a03-2022.3322)).

It was also noted that part of the non-closure could be due to the deep ocean contribution that has been only been partially accounted for thus far. The Deep-Argo network is growing and is already measuring significant changes in bottom water properties. The deep Argo network shows an acceleration of previously reported long-term abyssal warming trends in the south west Pacific Ocean.

On global scales, sea level rise is dominated by the forced response to greenhouse gases emissions. On regional scale the situation is different. Large parts of the global pattern of sea level rise since 1993 are explained by changes in the wind-driven ocean circulation and their influence on sea surface height via ocean heat transport (see Figure 4.10-3). These patterns are largely thermosteric in origin – they will fundamentally change in the future as the ice sheets (and their sea level fingerprints) start to dominate regional sea level change.

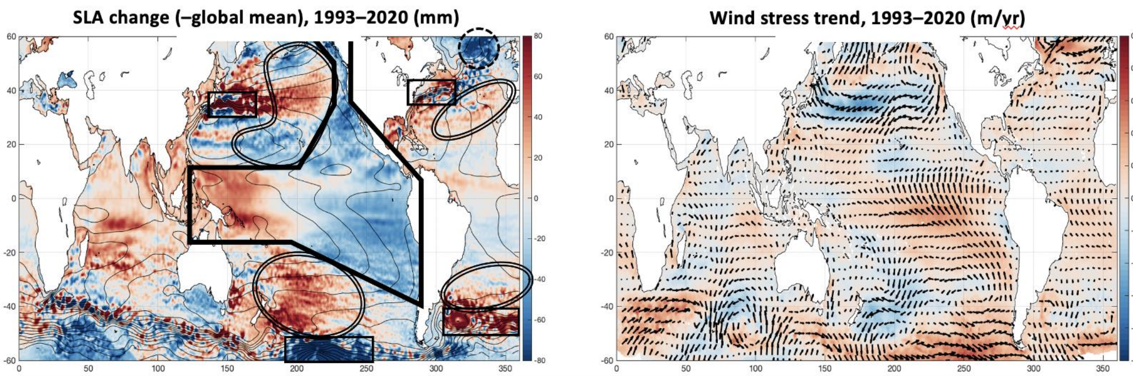


Figure 4.10-3: Large parts of the global pattern of sea level rise since 1993 are explained by changes in the wind-driven ocean circulation and their influence on sea surface height via ocean heat transport (Nerem et al., DOI: [10.24400/527896/a03-2022.3480](10.24400/527896/a03-2022.3480)).

Recent research shows that in the Gulf of Mexico, decadal trends in coastal sea level can largely be explained by import of mass to the Gulf of Mexico (due to land ice melt & terrestrial water storage loss) and subsurface warming driven mass redistribution onto the continental shelf.

Recent new measurement of sea level from ICESat-2 brings exciting new opportunities to cross validate satellite altimetry measurements and also to observe sea level variations in regions that are inaccessible for radar altimetry. Interestingly in the open ocean ICESat-2 shows consistent sea level estimates with satellite radar altimeters in terms of trends and variability. ICESat-2 is filling data gaps in the radar altimetry record especially close to the coast where the altimetry data is of lesser quality see Figure 4.10-4.

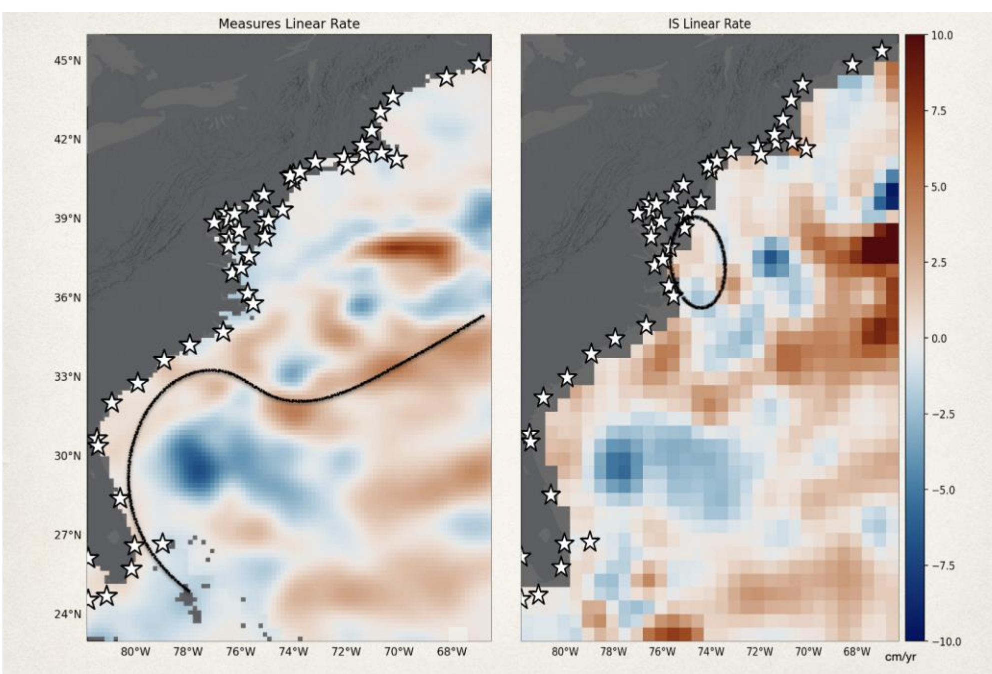


Figure 4.10-4: Trends over 2019-2021 from satellite altimetry (left) and ICESat-2 (right) (Buzzanga et al., DOI: [10.24400/527896/a03-2022.3597](10.24400/527896/a03-2022.3597)).

4.10.2 Splinter Discussion Points and Recommendations

Sentinel-3A shows a drift in SAR mode derived global mean sea level estimate of 1.8mm/yr. 1.4 mm/yr is coming from a difference between the SAR mode and pseudo LR mode data which is still not well understood. An additional 0.4mm/yr is likely due to the point target response deformation. This later can be corrected for by applying a numerical retracking to the data which accounts for the moving point target response provided by the calibration 1 mode of sentinel 3a. Both sources of drift in GMSL should be corrected for when using the data to develop climate studies. In climate studies, in general, there is a need for accurate data that is identified for a long time now.

There is now another need that is emerging: it is a need for comprehensive and robust estimate of the uncertainties in sea level from satellite altimetry at all time scales and temporal scales. A way forward is to characterize the errors with the error covariance matrix which can be estimated from the error budget. For this objective, each subsystem in the altimetry measurement system (POD, WTC,…) should provide an error covariance matrix along with their best estimate of their product. Then, all this information should be integrated in a global error budget of the altimetry system to provide a comprehensive error covariance matrix of the sea level measurements.

Finally, the recent research in sea level science shows a better understanding of the internal variability in sea level, in particular of climate modes' impact on sea level in the Pacific and the Arctic. New promising methods emerge to evaluate and potentially remove natural, internal and even intrinsic variability in the sea level record. These methods should allow to improve estimates of the forced sea level response and help in constraining projections of future sea level.

4.11 Science II: Large Scale Ocean Circulation Variability and Change: summary of session

Chairs: Weiqing Han, Thierry Penduff, LuAnne Thompson, Nathalie Zilberman

4.11.1 Summary

The 2022 OSTST Science II session had 6 oral presentations. These presentations focused on ocean variability in all oceanic basins and at global scale, taking advantage of the whole altimetry record, other in-situ and satellite datasets.

Qiu et al (DOI: 10.24400/527896/a03-2022.3276) highlighted the eddy kinetic energy (EKE) increase observed in most of the global ocean over the last 3 decades (Figure 4.11-1). In the subtropical eastern Pacific, the authors explain this increase by enhanced instability of the circulation due to ocean warming (enhanced upper-ocean stratification) and the phase of the PDO (enhanced Ekman pumping); ongoing work focuses on other regions of increasing EKE.

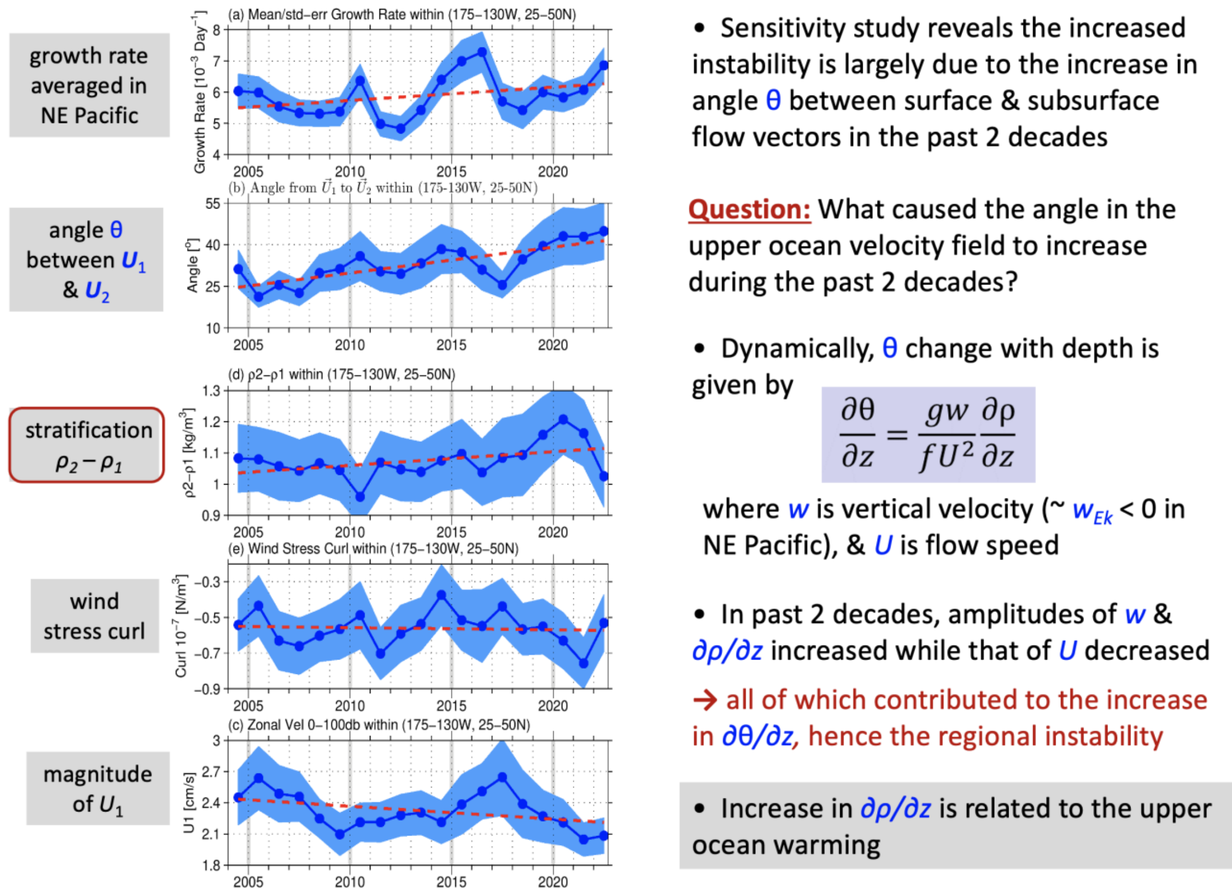


Figure 4.11-1: Sensitivity study reveals the increased instability is largely due to the increase in angle θ between surface & subsurface flow vectors in the past 2 decades.

Prandi et al ([10.24400/527896/a03-2022.3405](https://doi.org/10.24400/527896/a03-2022.3405)) presented new sea level products poleward of 50°N/S based on CryoSat-2, Sentinel-3A and SARAL/AltiKa altimeter data at unprecedented spatiotemporal resolution (25 km, 3 days) and with improved agreement with in situ data (Figure 4.11-2). These products also ensure sea level continuity between ice-free and ice-covered regions.

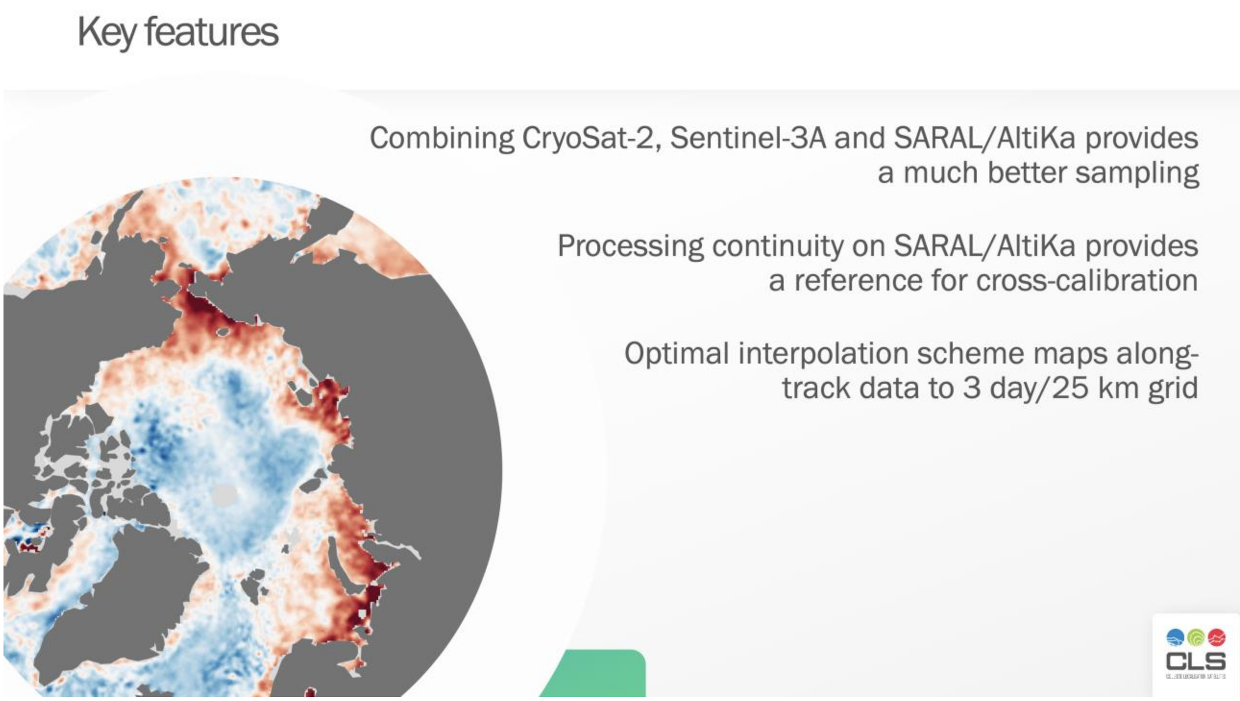


Figure 4.11-2: Key features of the new sea level products poleward of 50°N/S based on CryoSat-2, Sentinel-3A and SARAL/AltiKa altimeter data.

Two studies proposed lagrangian analyses.

Strub et al (10.24400/527896/a03-2022.3282) computed water parcel trajectories from altimeter/wind-derived geostrophic/Ekman velocities in the California Current System (Figure 4.11-3) to show that large capes on the US west coast act as a seasonal barrier to poleward zooplankton transport (that influences salmon population). The authors also highlight a long-term increase in this poleward transport, which is currently under investigation.

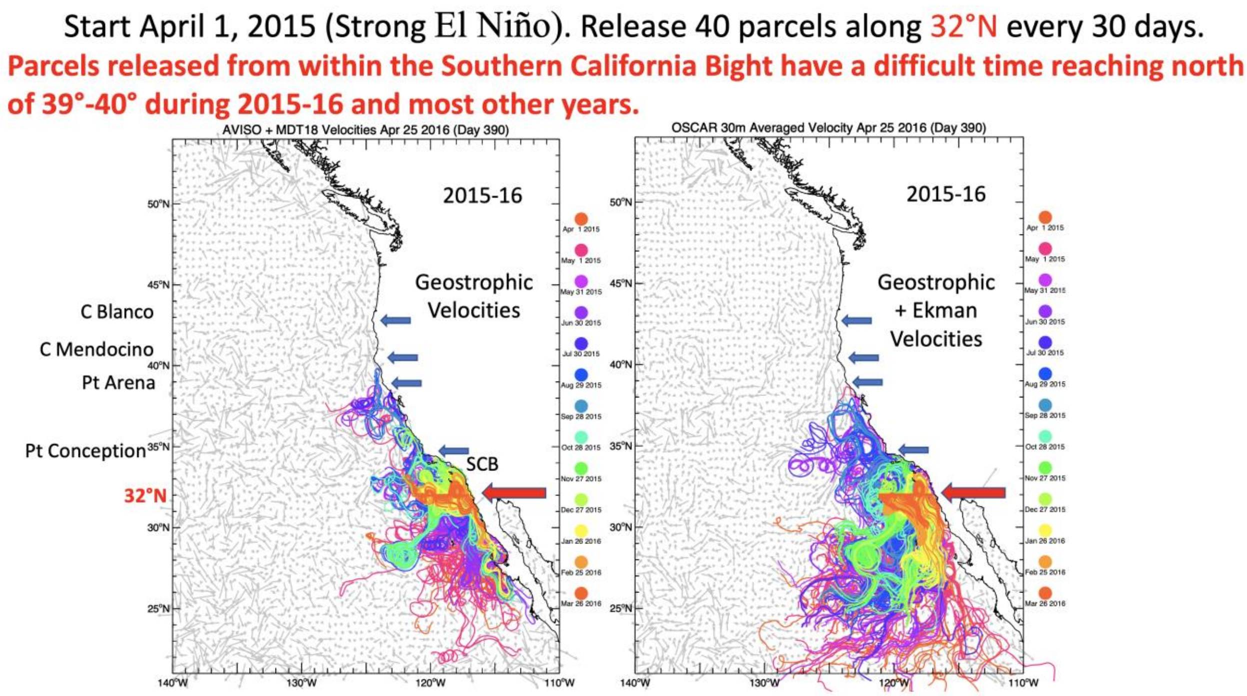


Figure 4.11-3: Water parcel trajectories from altimeter/wind-derived geostrophic/Ekman velocities in the California Current System.

Eisbrenner et al ([10.24400/527896/a03-2022.3334](10.24400/527896/a03-2022.3334)) identified two preferred oceanic pathways from the North Atlantic to the North Sea (along the northern and southern flanks of the Rockall Plateau) using geostrophic velocities from satellite altimetry (Figure 4.11-4). The relative contributions of both lagrangian routes appears to be influenced by the large-scale interannual fluctuations of the subpolar gyre.

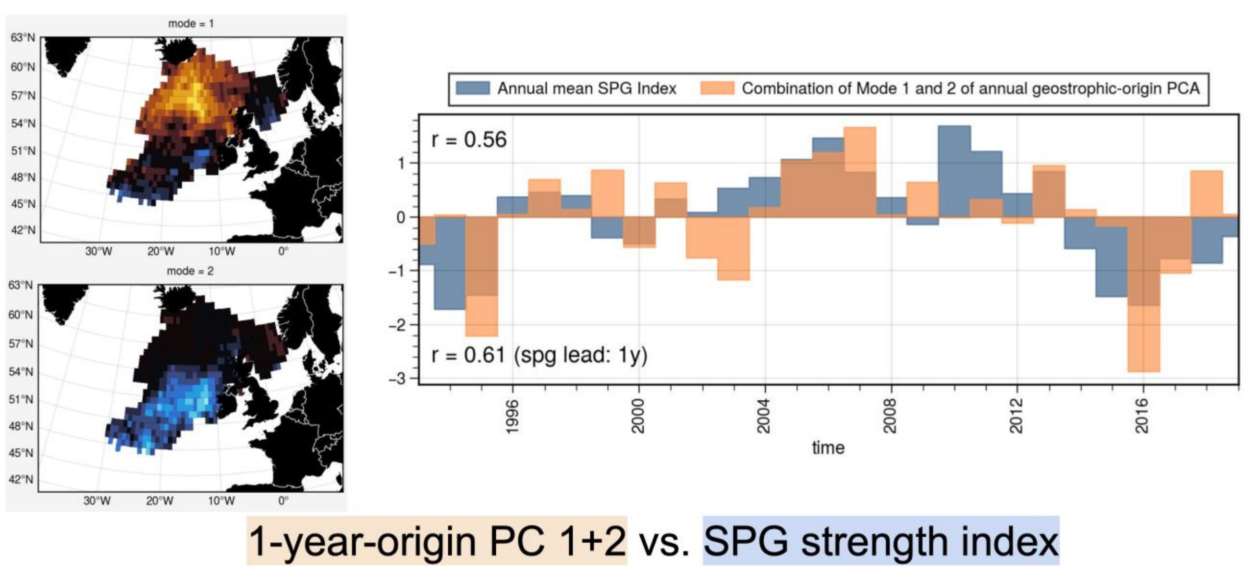


Figure 4.11-4: Combination of mode 1 and 2 of annual geostrophic-origin PC vs annual SPG index.

Two studies also took advantage of model simulations.

Saraceno et al (10.24400/527896/a03-2022.3450) use high resolution CROCO simulations to estimate the heat/salt exchanges between the San Matias Gulf (Figure 4.11-5) and the open ocean off Argentina. Further model calibration using coastal altimetry and moored observations and coupling to a biogeochemical model will help investigate interannual fluctuations of heat/salt budget and monitor biological tracers inside the gulf.

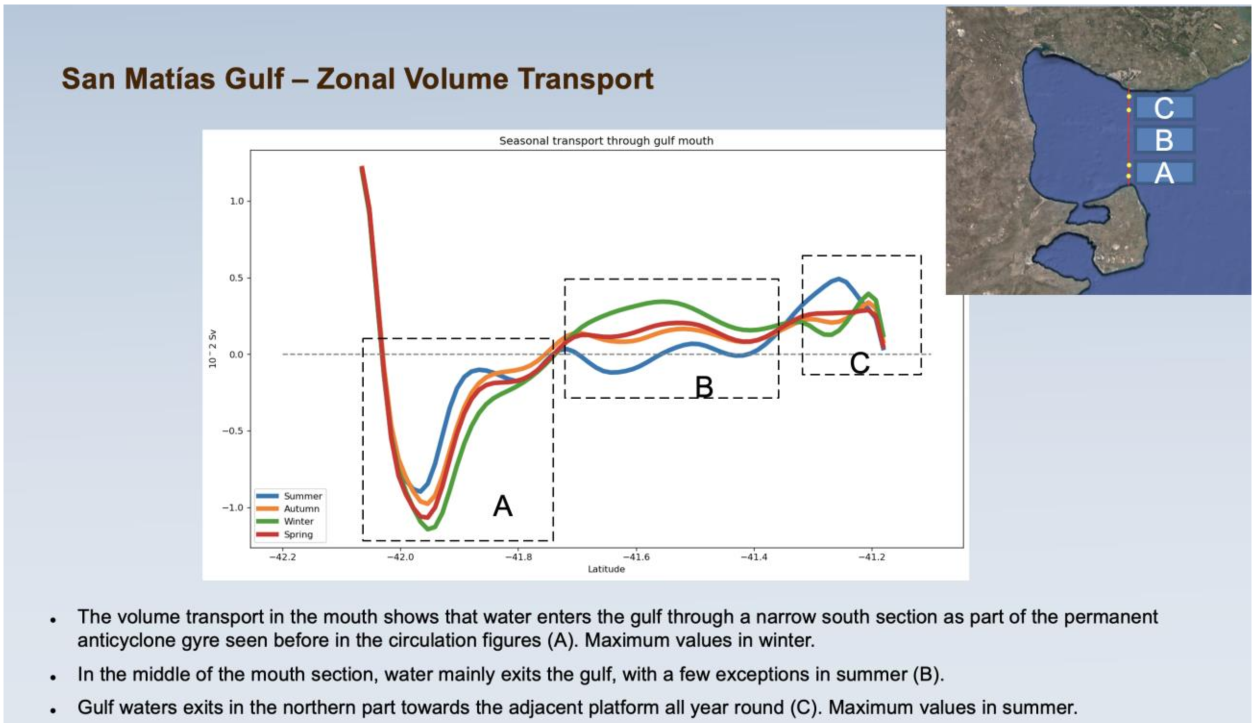


Figure 4.11-5: Zonal volume transport in the San Matias gulf.

Penduff et al (10.24400/527896/a03-2022.3553) study the global ocean response to fully-varying freshwater discharges from rivers and the Greenland ice sheet (derived from recent datasets) using 40-year ocean/sea-ice/iceberg NEMO simulations, with a focus on SSS for this presentation (Figure 4.11-6). Ensemble simulations are now being performed to attenuate the strong imprints of chaotic intrinsic variability and assess the deterministic response of other oceanic indices.

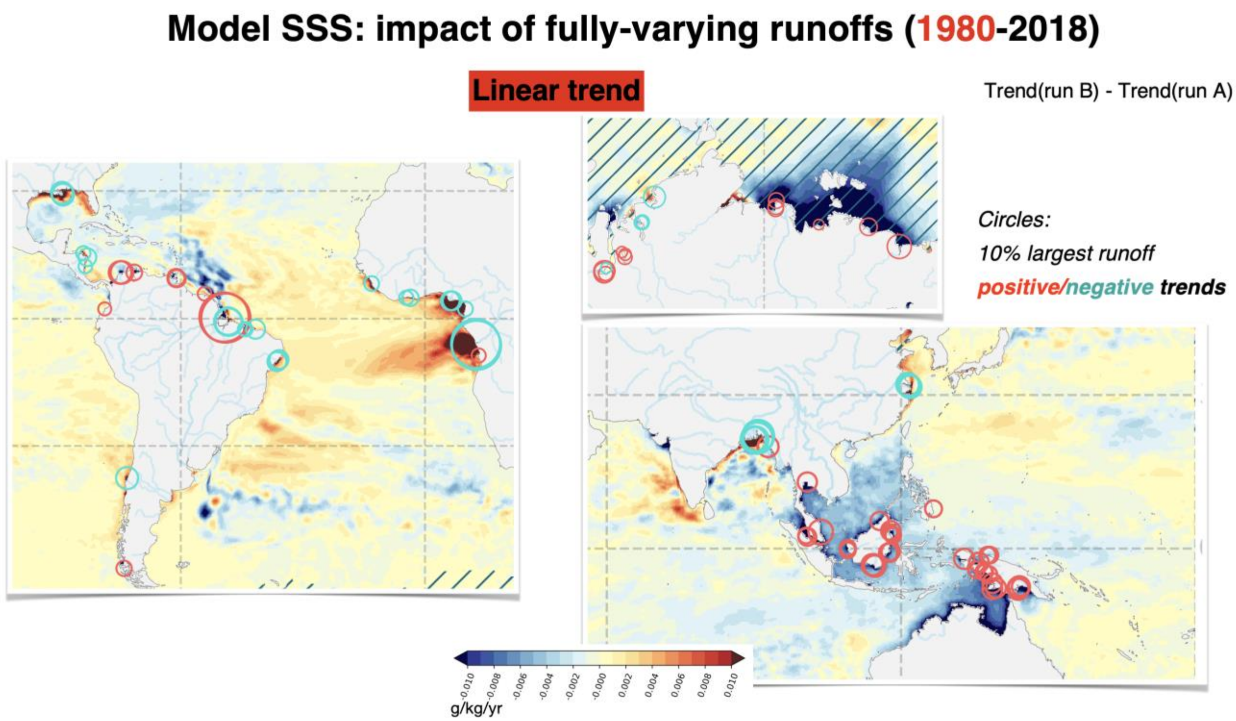


Figure 4.11-6: Model SSS: impact of fully-varying runoffs (1980-2018).

4.11.2 Splinter Discussion Points and Recommendations

No specific recommendation issued from discussions.

4.12 Science III: Mesoscale and sub-mesoscale oceanography

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

4.12.1 Summary

Science III addressed a variety of topics within the mesoscale/submesoscale oceanographic umbrella, with a special focus on preparation for SWOT, which at the time of the meeting was scheduled to be launched in just under a month. The session addressed data assimilation of altimetric observations and SWOT simulated data, and how the assimilated data and simulations impacted energy and heat transport, lagrangian structures, internal tides, and balanced motions. Analysis of SWOT field campaign data provided insight into spectral energy cascades that may improve SWOT data processing after launch. Progress is being made in tracking mesoscale and submesoscale features from both models and satellite observations, with applications of neural networks and multiparameter analysis providing different ways of analyzing the eddy field, tracking merging and splitting events, and shaping contours.

This splinter had 7 talks and 22 posters addressing three major categories: 1) global mesoscale eddy tracking products, 2) Multi-satellite and in-situ analyses, and 3) SWOT preparation. Posters and presentations were also uploaded to an online forum. We present here a summary of the talks as organized by the three general topics they addressed.

Global Mesoscale Eddy Tracking Products

Pegliaso et al. (DOI: 10.24400/527896/a03-2022.3393) introduced a new version of the AVISO+ eddy tracking trajectory atlas for mesoscale applications: META3.2, which uses ADT and is based on the Mason et al. (2014) methodology with overlapping eddy contours used for tracking. META3.2 is an improvement on META3.1, which provided a major shift from META2.0 in pre-processing and to the detection and tracking schemes. META3.2 is based on the DT2021 maps, which include MDT resolving shorter scales, new internal tide corrections, improvements of the ice-sea transition, and changes in energy near the equator. These improvements in the base ADT are reflected in the increased fidelity of the tracked eddy field in META3.2 (Figure 4.12-1**Error! Reference source not found.**). The team are also developing META4.0 which will have improved eddy splitting and merging using networks of contours.

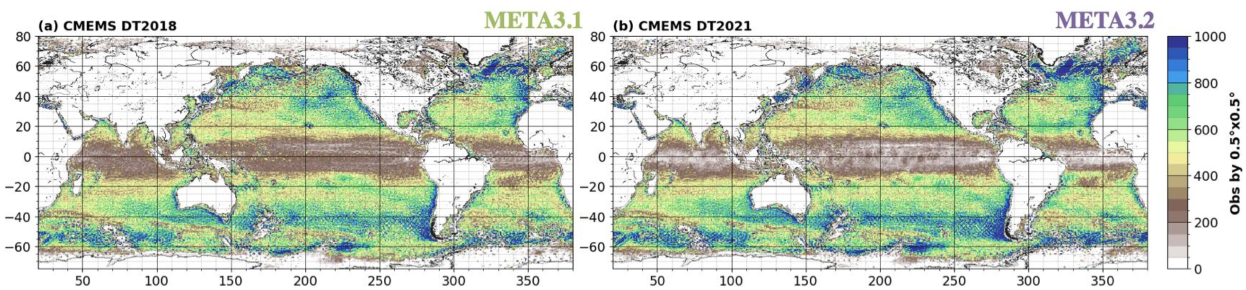


Figure 4.12-1: Number of eddy observations centers part of trajectories lasting more than 10 days in 0.5°x05° boxes, detected from (a) DT2018 and (b) DT2021 Absolute Dynamic Topography daily maps from January 1993 to March 2020.

Roman-Stork et al. (DOI: 10.24400/527896/a03-2022.3347) presented the NOAA multiparameter mesoscale eddy tracking product which is based on NOAA RADS SLA grids and incorporates satellite observations of Geo-polar SST, JPL SMAP CAP V5.0 SSS, and NOAA MSL12 VIIRS multi-sensor DINEOF gap-filled analysis ocean color chlorophyll-a. The system uses a closed-contour eddy tracking method adapted from Chaigneau et al., (2008, 2009) and Pegliasco et al., (2015). The product will also introduce the Multiparameter Eddy Significance Index (MESI), which serves as a first look indicator of an eddy's impact on the upper ocean and biogeochemical dynamics (Figure 4.12-2**Error! Reference source not found.**). The system is threshold free, and thus does not filter out low amplitude or transient eddies, as those may be of interest to some users and have important impacts on air-sea interactions, local weather, and feedback into ocean systems, even if some false eddies and filaments are detected as a result. By incorporating multiple satellite observations into the eddy tracking system, they hope to create a self-contained, user-friendly system that will allow for end-users to perform complex analyses of mesoscale systems without downloading multiple products.

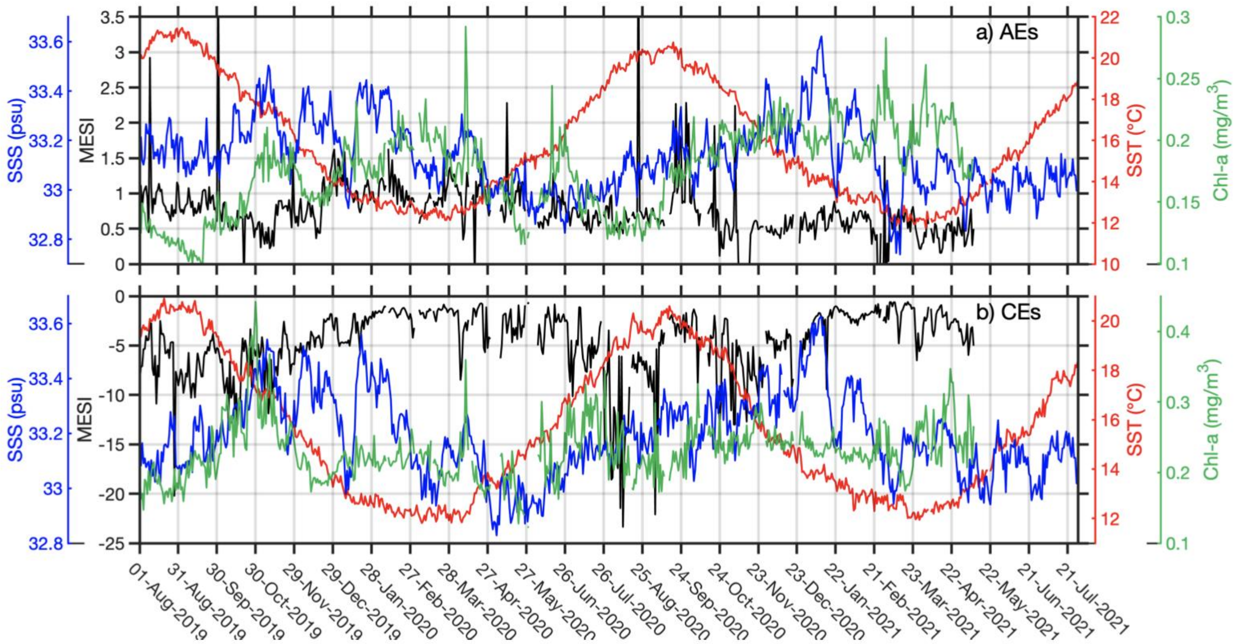


Figure 4.12-2: Time series of mean MESI, mean SSS (psu), mean SST (°C), and mean Chl-a (mg/m^3) averaged across the research area (210-260°W, 10-55°N) for (a) Anticyclonic Eddies (AEs) and b) Cyclonic Eddies (CEs) from August 1, 2019 -August 1, 2021.

Multi-satellite and In-situ Analyses

le Goff et al. (DOI: 10.24400/527896/a03-2022.3387) presented their work on blending ship AIS surface current data and altimetry in the Agulhas and Gulf of Mexico. The work separated rotational and divergent AIS currents, which improved current estimates in shipping lanes. For the blending of AIS surface current data, a Helmholtz-Hodege Decomposition was used, which helped to reveal the physical content of the AIS derived current. Noise was still present and the divergent part remained over-estimated, and there were difficulties in separating physical content from noise and complications from the inhomogeneity in maritime traffic. In their merging experiments, they found that the merging of AIS current data with altimetry was successful and that they could reconstruct SSH and geostrophic current fields in the Gulf of Mexico, which provided improvements over altimetry alone in the region (Figure 4.12-3). Errors were associated with AIS inflated currents, which will need to be improved to better account for the AIS data signal.

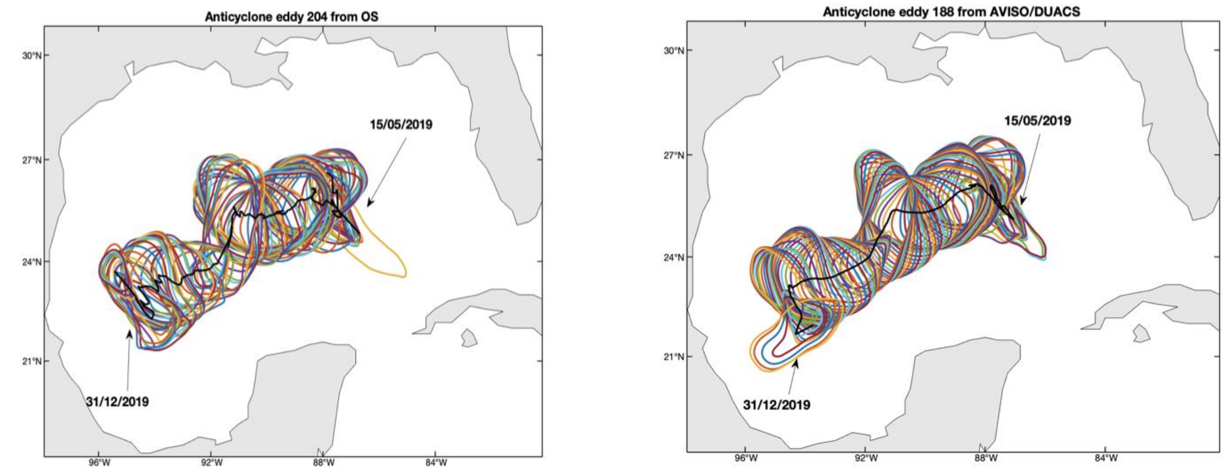


Figure 4.12-3: Tracking of the Loop Current eddy from (left) the AIS derived field, divergent free part (OSr), and (right) Smoother trajectory of the eddy obtained with the DUACS field, from May 15, 2019 – December 31, 2019 in the Gulf of Mexico. Tracking was done through the use of AMEDA (Le Vu et al., 2018).

Antionio Bonaduce (DOI: 10.24400/527896/a03-2022.3238) presented analyses of high datasets for sea-level budgets in the Nordic Seas and Arctic. The study built upon previous work by Prandi et al., (2021) to characterize the mesoscale contributions to ocean dynamics and thermodynamics in the Nordic Seas and Arctic, which in turn affects the sea level budget. They employed eddy detection algorithms on gridded altimetry data and numerical simulation fields and then performed assimilative experiments to assess the potential of enhanced altimetry retrievals. The study employed NEMO as the OGCM with 3DVAR as the assimilation scheme with multivariate EOFs forced by ERA5 reanalysis for the period of 2016-2019, with three experimental schemes: A01, which assimilated in-situ data from Argo, A02, which also included altimetry at 5 Hz, and A03, which also included altimetry at 1 Hz (Figure 4.12-4). At depth they found that all three experiments were comparable, with eddies penetrating the Arctic, but constraining mesoscale variability with the addition of assimilated altimetry had a strong impact on eddy driven heat fluxes and detected more energetic mesoscale features.

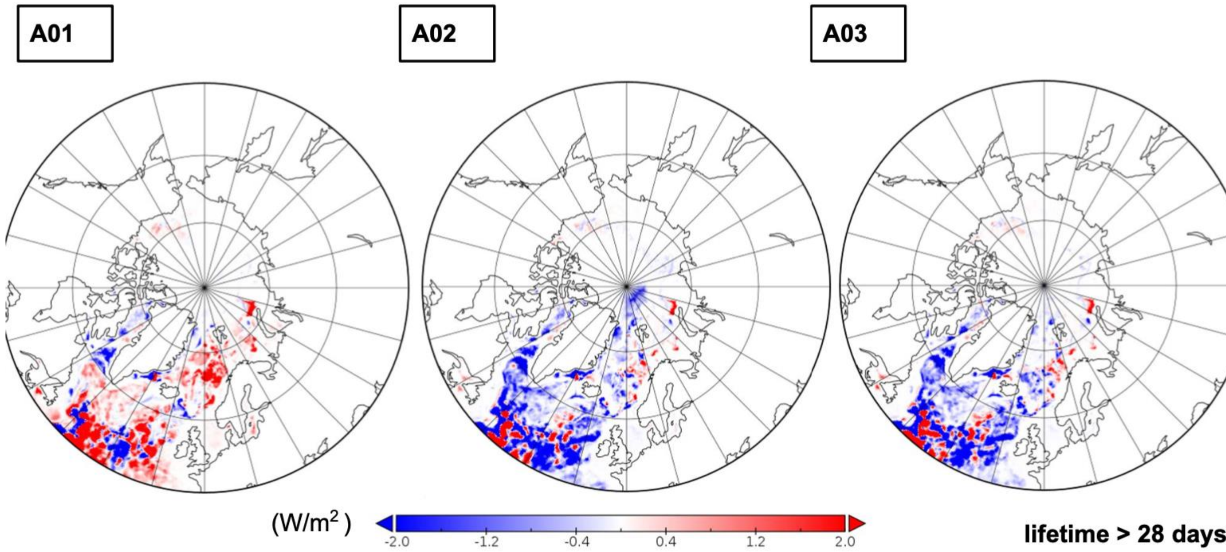


Figure 4.12-4: Eddy influence on the ocean-atmosphere heat fluxes for all three (A01-A03) experiments in the Nordic Seas and Arctic.

SWOT Preparation

Le Guillou et al. (DOI: [10.24400/527896/a03-2022.3320]) presented a joint estimation of mesoscale balanced motions (BM) and internal tides (IT) in 2D maps using simple dynamic models (QG & linear shallow water). Their experiment was performed in the Californian crossover SWOT cal/val site and they used the MITgcm and SWOT simulator. They simulated two observations per day and removed barotropic tides in order to isolate the BM and ITs with the goal of jointly mapping BM and It just from SWOT and nadir data. Their experiment used open boundary conditions to allow waves in, with the control equivalent to control depth and amplitude. Their work showed a successful separation of BM and ITs, both coherent and incoherent with no noise included in the analysis. Future work hopes to improve the handling of wave generation in the study domain, improved handling of SWOT error, and testing with real cal/val data after the launch of SWOT. Their first results do suggest the successful separation of BM and IT, but they did not include any noise, which will be included in real SWOT data.

Rolland et al. (DOI: [10.24400/527896/a03-2022.3488]) presented a reconstruction using nadir sampling and future SWOT sampling that analyzed Lagrangian structures at 10-100 km from model data, using NEMO with DUACS altimetry assimilated and SWOT simulated data for comparison (Figure 4.12-5). They found that SWOT scales have 2-3x more stirring and higher strain rate than the nadir results and greater retention of particles within eddies. There was an underestimation that was mostly found to be due to the smoothing of the DUACS algorithm in the SSH field, but a clear separation of eddy core and boundary. The SWOT simulated data had a much higher eddy retention, and the higher resolution data could more closely follow the movement of the eddy and did not rely on interpolation of eddy movement as strongly as the nadir results. In particular, they found a strong impact of small-scale dynamics in winter and at higher latitudes on biology. With the assimilation of SWOT data after launch, they expect to see major changes in Lagrangian structure identification, especially in regions of low Rossby radius.

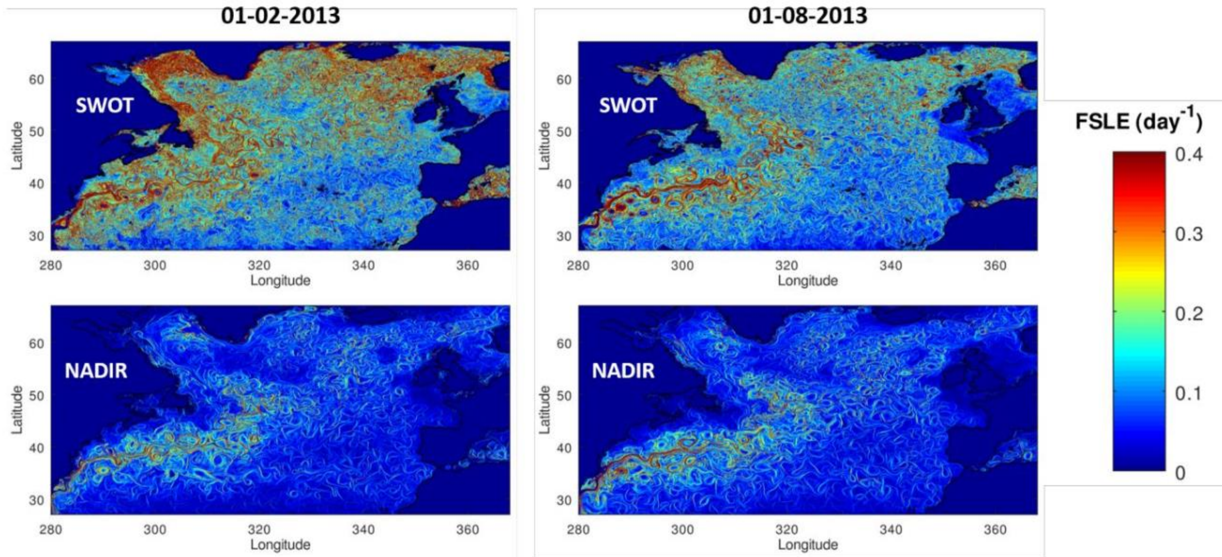


Figure 4.12-5: Finite-Size Lyapunov Exponent (FSLE) in SWOT (top) and nadir (bottom) experiments in February (left) and August (right) 2013.

Villas-Bôas et al. (DOI: 10.24400/527896/a03-2022.3301) presented observations of the SSH spectral energy cascade from mesoscale (red) to waves (blue). They found that the SWOT airborne Modular Aerial Sensing System (MASS) Lidar campaign was able to resolve SSH down to 10s of meters, and that the surface wave band can be very energetic. From this campaign, they were able to compute both the up and downwind spectrum, separate swell and sea within blue spectrum, and see that the up and downwind and crosswind were different (Figure 4.12-6). They found that the SWOT filter was not concerned with aliased wind or wave energy and would not take SWOT data at any scales smaller than the onboard processor gives. The variance in the surface wave band was found to be over 20 times larger than the variance at submesoscales. SWOT onboard filtering at the 500 m wavelength should remove most surface wave energy in the California Current. The potential for aliasing in other regions will depend on dominant wavelength, height, and direction.

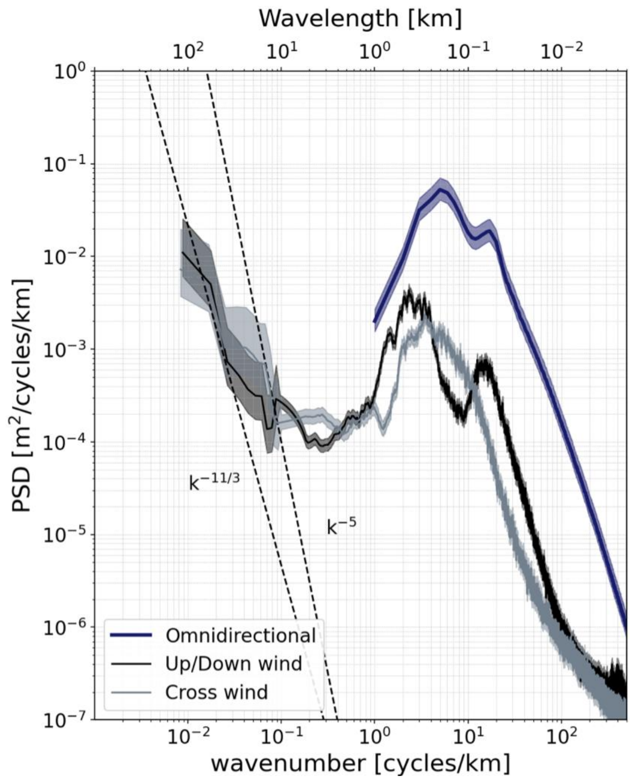


Figure 4.12-6: Across-track average spectrum from MASS experiment, where the blue zone indicates k > 1 cycles/km.

4.12.2 Splinter Discussion Points and Recommendations

The splinter did not address the discussion questions set forth for the meeting, but the launch of SWOT on December 16, 2022 will lead to exciting developments for mesoscale and submesoscale oceanography moving forward.

4.13 Science Results IV: Altimetry for Cryosphere and Hydrology

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

4.13.1 Summary

Over 30 studies were presented at the 2022 OSTST Science IV Session, ranging from technical investigations to overviews of new missions and data programs, to science research over both inland water and polar oceans. Altimetric data from all current missions are being utilized, including Copernicus Sentinel-6A and Sentinel-3, ESA CryoSat-2 and NASA ICESat-2.

Technical studies discussed the fully-focused SAR (FF-SAR) application for iceberg detection and the acquisition of the elevation of small inland water bodies such as lakes and river-reaches. Various innovative retracking algorithms were also presented. In view of the (then) forthcoming SWOT mission, CryoSat-2 based swath data processing from SARIN over inland water was also highlighted.

Copernicus and ESA-lead activities such as St3TART, CryoTempo, S3 MPC, SIN'XS, STREAMRIDE were also discussed at the meeting with emphasis on Cal/Val based on metrology approaches, elevation uncertainties, and the Fiducial Reference Measurements which would need to be further developed and implemented over the cryosphere and hydrology domains. Emphasis was placed on the importance of these in the formation of Climate Data Records.

There was also a new focus at the meeting, the use of altimetric data to derive lake-ice thickness (Anna Mangilli et al, DOI: 10.24400/527896/a03-2022.3394, Jaya Sri Mugunthan et al, DOI: 10.24400/527896/a03-2022.3281). This is an interdisciplinary study crossing the boundary between hydrosphere and cryosphere.

Cryosphere presentation highlights included an overview of a) the dual Ka/Ku-band CRISTAL Copernicus Expansion Mission which has CryoSat-2 SARIN heritage but with increased precision and focused processing, b) the St3TART project which aims to build an in situ network for validation of Sentinel-3 altimetric elevations over all surface types (sea ice, land ice, inland water), c) an investigation looking at the relationship between declining sea ice in the Bering Strait and increasing significant wave height (SWH) observations (Figure 4.13-1, Reint Fischer et al, DOI: 10.24400/527896/a03-2022.3466), and d) the importance of accounting for snow and snow density on sea ice (Sara Fleury et al, DOI: 10.24400/527896/a03-2022.3462).

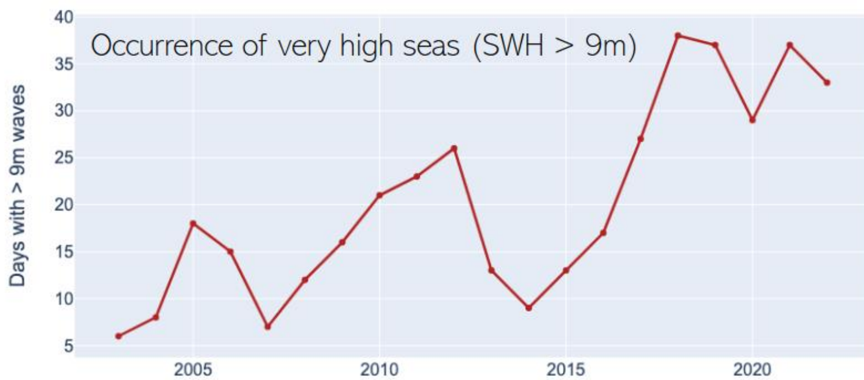


Figure 4.13-1: Altimeter observations of significant wave height (SWH) > 9 m in the Bering Sea in winter (Oct – April) between 2002 and 2022. An increasing number of altimeter missions sample the area, providing better fidelity in ocean observations, resolving more cyclonic events. Although the 20-year time period is too short to verify a long-term climate trend, Bering Sea conditions in the last 5 years have been significantly stormier than in previous winters. Adapted from: Fischer, R. S. L. Farrell, K. Duncan and J. M. Kuhn, Understanding Decadal-scale Trends in Altimeter-derived Significant Wave Height in the Bering Sea, presented at OSTST 2022.

A study assessing the Arctic Ocean sea-surface height using the 30-year record of elevations from ERS, Envisat and CryoSat-2, concluded that although data from the ERS missions was noisy it is a valuable dataset. An Empirical Orthogonal Function (EOF) analysis of the winter months was performed with a case study over the Russian Shelf region (Stine Kildegaard Rose et al, DOI: 10.24400/527896/a03-2022.3367).

Hydrosphere highlights looked at a) Sentinel-6A FF-SAR processing methods for estimating lake levels (accurate to a few cm) and novel surface extents based on reservoir case studies in Spain (Ferran Gibert et al, DOI: 10.24400/527896/a03-2022.3373), and b) correcting Lake Tanganyika geoid signals within CryoSat-2 time series records by examining the spatial (Figure 4.13-2) and temporal variation of ICESat-2 water levels (Karina Nielsen et al, DOI: 10.24400/527896/a03-2022.3317).

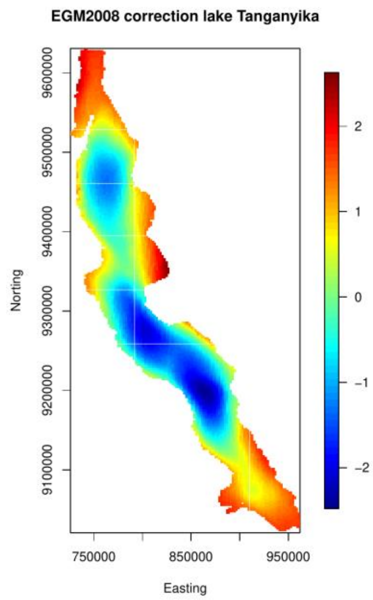


Figure 4.13-2: The spatial distribution of water level anomalies with respect to the EGM2008 geoid model based on ICESat-2 (ATL13) surface elevations (taken from Karina Nielsen, Heidi Ranndal, and Ole B. Andersen, "Reconstructing the spatial and temporal elevation signals on large lakes from ICESat-2", presented at the 2022 OSTST)

4.13.2 Splinter Discussion Points and Recommendations

- Sentinel-6A is performing well but the ice and inland water communities are still focused on fine tuning retracking and FF-SAR algorithms, and there is expectation of improved content within the next generation of Level 2 data products.

- There is a need for a better repository of in situ data for Cal/Val exercises, especially knowledge of inland water levels and snow depth over sea ice. How can the Science Working Team (SWT) community make better connections with ground-based agencies to achieve this? And how to make radar altimetry a more accessible technique to non-experts?

- There is a need to look at how improvements can be made in consideration of synergy with other instruments such as SWOT. How best to merge advantages and reduce limitations?

- More discussion is required on operating mode masks, e.g., the current plan for the CRISTAL mission over inland water is to have a static mask, but what are the real needs of the community? Is there a greater need for SARIn operations over sea ice and continental waters?

- A greater emphasis is needed on the integration of altimetric elevations in modeling exercises i.e., those including the assimilation of sea ice, river reaches and reservoirs. Hydro-dynamic or climate models are currently limited in this respect.

- The hydro-community should consider the potential application of elevations recorded during long repeat cycle (geodetic) missions or mission phases – what are such merits?

- FF-SAR is a very interesting application, but it is still in research phase and computation effort is large. Will there be FF-SAR output in future Level 2 data products? Can it be applied for certain test areas? Will there be an on-demand FF-SAR framework?

4.14 Sentinel-6 Validation Team (S6VT) feedbacks

Chairs: Pascal Bonnefond, Craig Donlon, Eric Leuliette, Remko Scharroo, Josh Willis

4.14.1 Summary

This Session had 3 oral presentations, 3 posters, and 1 forum contribution:

Oral presentations	
Scharroo et al.	Sentinel-6 products status (Scharroo et al.) DOI: 10.24400/527896/a03-2022.3671
Martin-Puig et al.	Cal/Val activities performed by the MPWG (Martin-Puig et al.) DOI: 10.24400/527896/a03-2022.3673
Scharroo et al.	Highlights from the Sentinel-6 Validation Team (Scharroo et al.) DOI: 10.24400/527896/a03-2022.3672
Poster	
Aouf et al.	On the assimilation of LR and HR Sentinel-6MF wave data in wave model : Assessement and perspectives DOI: 10.24400/527896/a03-2022.3366
Dinardo et al.	Sentinel-6-MF Poseidon-4: Main results from the first year and half of mission from the S6PP LRM and HRM Chain DOI: 10.24400/527896/a03-2022.3375
Dinardo et al.	Sentinel-6 MF Poseidon-4 Radar Altimeter In-Flight Calibration and Performances Monitoring DOI: 10.24400/527896/a03-2022.3377

On-line Forum	
Feng et al.	Assessment of Sentinel 6 altimeter data along the Northwest Atlantic shelf (Feng et al.) DOI: 10.24400/527896/a03-2022.3510

Scharroo et al. presented the current status of the Sentinel-6 products and processing. Particular emphasis was made on the upcoming switch to Processing Baseline F08 and the following Full Mission Reprocessing with that Baseline. This new Baseline includes outputs from the low-resolution numerical retracking (LR NR).

Martin-Puig et al. presented the extensive analyses done by the partner agencies in the framework of the MPWG (Mission Performance Working Group). It had established that all the End User Requirements had been met, except a few that will be covered by updates to the processing to be implemented by the end of 2023. The requirement on the drift (< 1 mm/yr) can be assessed next year.

Scharroo et al. thanked all of the S6VT members for their contribution to the success of the commissioning of the Sentinel-6 Michael Freihlich mission with all their calibration and validation work, some of which was highlighted in their presentation to the OSTST.

Dinardo et al., in their posters, showed some of the contributions of CLS and CNES to the Sentinel-6 Performance Monitoring. Particular, the parallel processing with the Sentinel-6 Processing Prototype (S6PP) has been very valuable in independently verifying anomalies and testing out new algorithms.

In their poster, Aouf et al. gave an assessment of the impacts of assimilating Sentinel-6 SWH data into the Météo-France wave model (MFWAM), looking both at 1-Hz, 5-Hz and 20-Hz measurements. The most striking result is how well Sentinel-6 helps observes high waves of over 15 meters.

Feng et al. showed the very good consistency between Jason-3 LR and Sentinel-6 LR and HR data in their analyses in the Northwest Atlantic Shelf region. This shows that the differences between the two missions are small, and generally only reveal biases independent of significant wave height. Only HR sigma0 stands out as being significantly bias. (This is a known issue expected to be fixed by the end of 2023).

4.14.2 Splinter Discussion Points and Recommendations

No specific recommendation issued from discussions.

4.15 The Geoid, Mean Sea Surfaces and Mean Dynamic topography

Chairs: Ole B. Andersen and Yannice Faugere

4.15.1 Summary

This splinter had a total of 5 oral presentations and 4 posters.

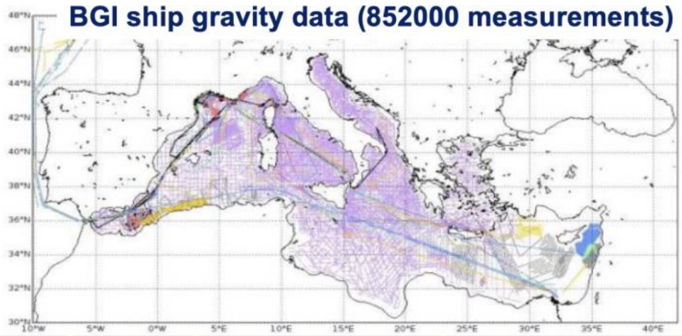
Oral presentations	
Jousset et al.	New global Mean Dynamic Topography CNES-CLS-22 combining drifters, hydrological profiles and High Frequency radar data, DOI: 10.24400/527896/a03-2022.3292
Bruinsma et al.	Assessment of marine gravity models of the Mediterranean, DOI: 10.24400/527896/a03-2022.3255
Schaeffer et al.	New CNES CLS 2022 mean sea surface, DOI: 10.24400/527896/a03-2022.3310
Knudsen et al.	A new combined mean dynamic topography model – DTUUH22MDT, DOI: 10.24400/527896/a03-2022.3482
Andersen and Nerem	Rethinking the Modeling of the Mean Sea Surface in the Era of Climate Change, DOI: 10.24400/527896/a03-2022.3491
Poster	
Knudsen et al.	The DTUUH22MDT combined mean dynamic topography model, DOI: 10.24400/527896/a03-2022.3482
Schaeffer et al.	The new CNES-CLS 2022 marine gravity anomaly model: first validation in the Mediterranean, DOI: 10.24400/527896/a03-2022.3308
Hirose et al.	A new method for estimating steric mean sea surface dynamic height in MOVE system combining in-situ profiles and sea level anomalies, DOI: 10.24400/527896/a03-2022.3576
Jeong et al.	An approach for regional coastal sea surface topography for vertical datum transformation using retracked-altimetry, water

	level gauging and airborne gravity based geoid model, DOI: [10.24400/527896/a03-2022.3573](https://doi.org/10.24400/527896/a03-2022.3573)

Sean Bruinsma initiated the oral session with the presentation on gravity evaluation in the Mediterrenean illustrated in Figure 4.15-1.

Assessment of marine gravity models of the Mediterranean (Sean Bruinsma et al)

New CNES/CLS marine gravity solution, close to the reference solutions DTU & USDC



STD [BGI- Model] (mgal)

	Med	Aegean	Sicily	Alboran
BGI-DTU15	3.78	4.27	3.43	3.85
BGI-DTU21	3.39	3.85	3.29	3.62
BGI-UCSD24	3.85	5.13	3.78	3.87
BGI-USCD31	3.97	5.20	3.71	3.60
BGI-UCSD32	3.78	4.86	3.36	3.64
BGI-CLS	3.78	4.56	3.60	3.83

Figure 4.15-1: Assessment of marine gravity models of the Mediterranean.

Andersen and Nerem recommended the community to rethink the MSS and consider GMSL changes in the development of future MSS models (Figure 4.15-2).

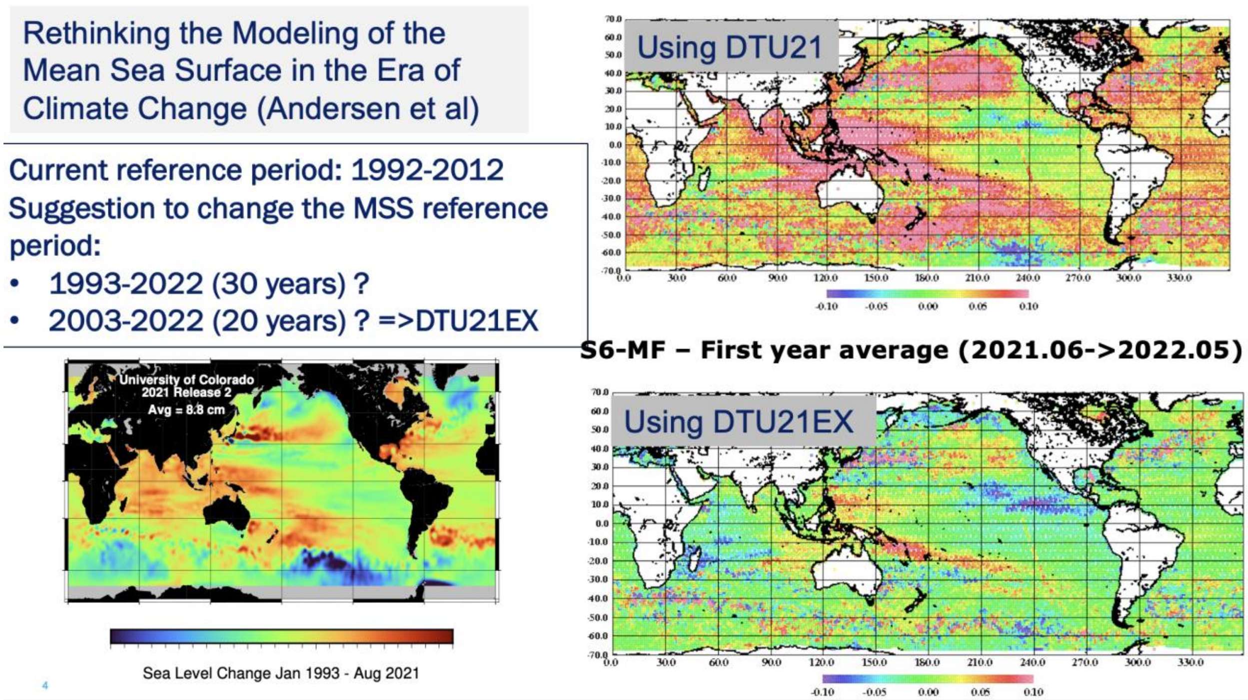


Figure 4.15-2: Rethinking the modeling of the MSS in the era of climate change.

Knudsen, Andersen, Maximenko and Hefner released a new global Mean Dynamic topography (Figure 4.15-3).

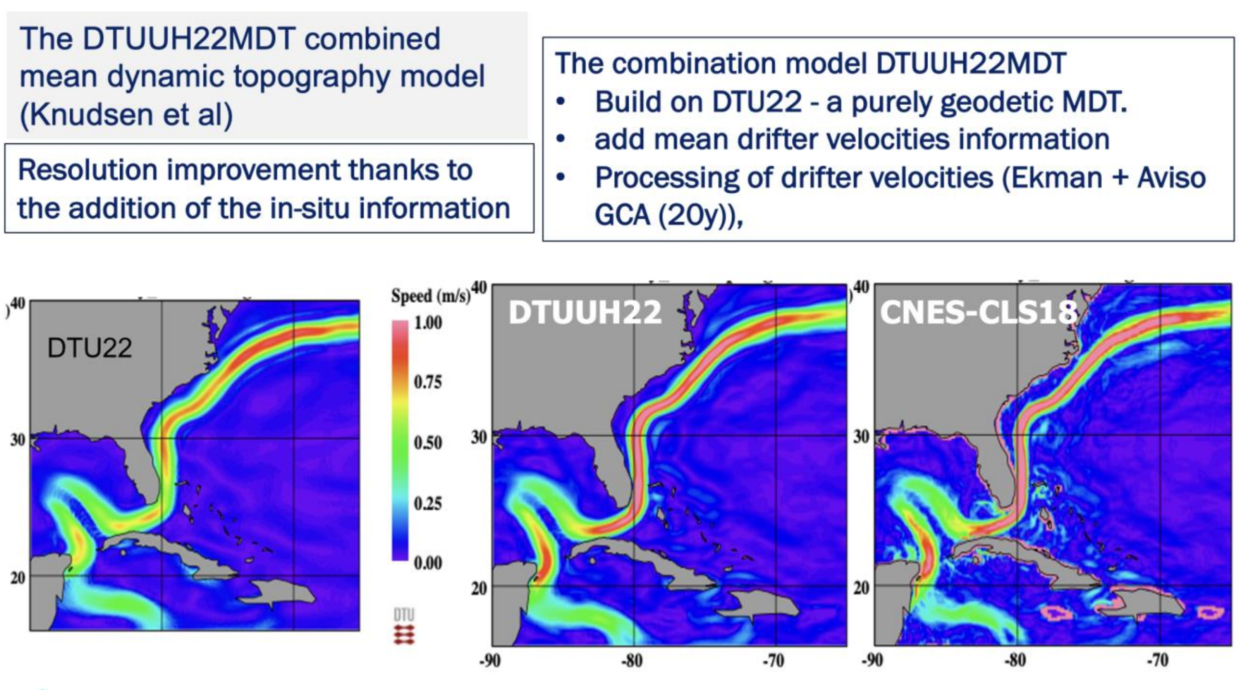


Figure 4.15-3: New combined mean dynamic topography model – DTUUH22MDT.

Jousset and Schaeffer et al. presented new development in MDT using HF radar data and Hydrographic profiles (Figure 4.15-4).

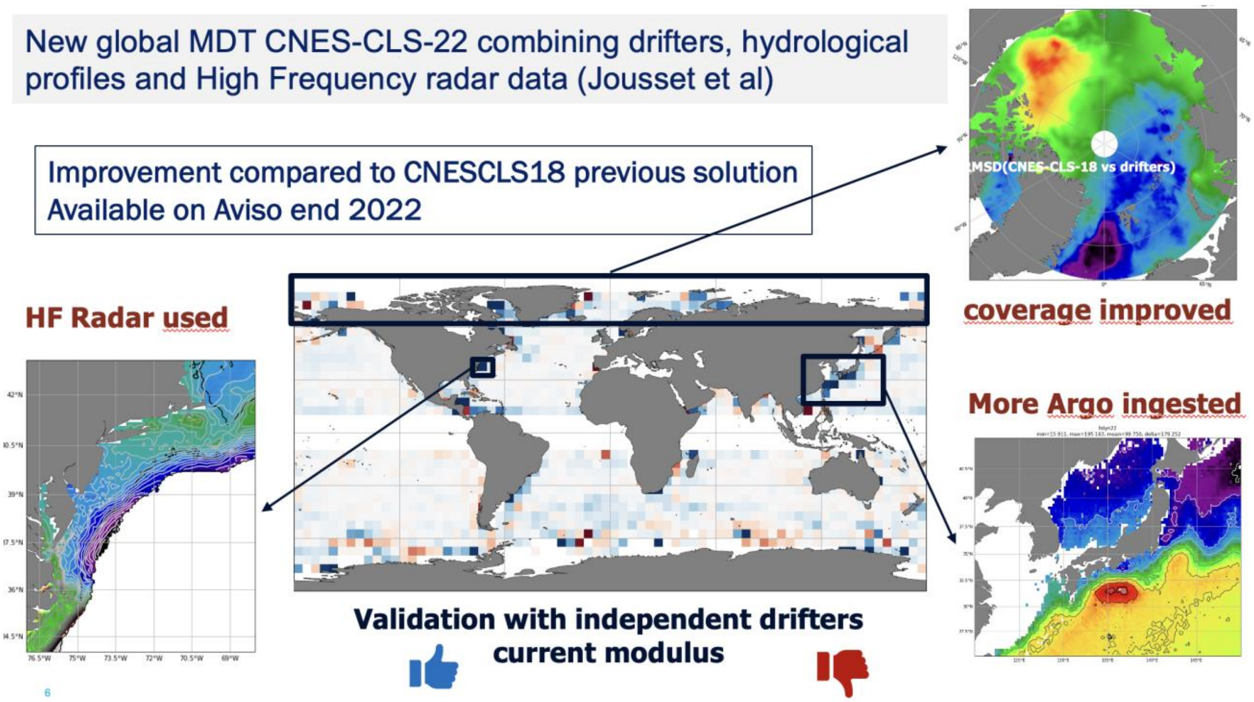


Figure 4.15-4: Improvement of the new global CNES-CLS-22 compared to CNES-CLS-18.

The session is summarized with the following presentations

- 1 Regional Marine gravity model (Mediterranean)
- 3 MSS models
- 2 MDT models

Several groups released new global models for the user community. Performances improved, recommendation to use these new MSS & MDT fields as soon as they are published. Feedback from users are needed!

Regarding MSS: 3 models from 3 teams, each one having its strength

Scripps: improvement of the shortest wavelengths in open ocean

Interest of a Hybrid solution combining all MSS models.

Interest to strengthen the collaboration: We will follow up the work with a MSS workshop early 2023 on various aspects: altimetry processing, reference period, inversion method, and assessment techniques?

4.15.2 Splinter Discussion Points and Recommendations

Following the presentation by Andersen and Nerem there was a discussion on the length of the referencing period (extend from 20 to 30 years).

In order to further improved global MSS models and gravity field in the future it is paramount to increase the availability of non repeat datasets.

The group strongly supports the continuation of the SARAL/AltiKa drifting period for as long as possible. SARAL/AltiKa Ka instrument has a much higher range precision than any Ku altimeters (also due to its 40Hz technology). Consequently, it is the most important altimeter for future improvements in MSS and Gravity.

We also strongly support the continuation of Cryosat-2, particularly in its new orbit following ICESat-2.

Finally we strongly support the transition of Jason-3 into an EOL scenario with long repeat orbits interleaved with the existing EOL scenario of Jason-2 to create a 2 km global grid.

Finally in the future geodetic long-repeat EOL scenarios should also be considered for Sentinel3-A.

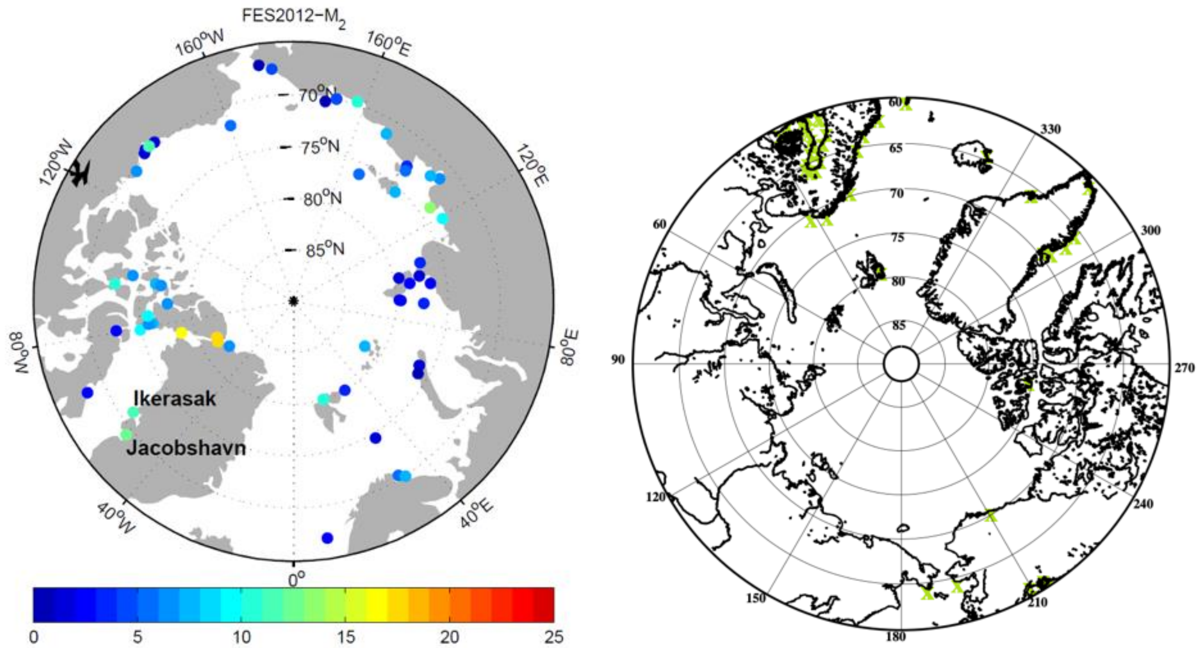
4.16 Tides, internal tides and high-frequency processes

Chairs: Loren Carrere, Florent Lyard and Richard Ray

4.16.1 Summary

The session had 7 oral presentations. Two talks addressed ocean tides in polar seas. Three talks presented new global ocean tide models (EOT20, GOT5, FES2022), and two talks discussed the results of adding tidal forcing into global high-resolution ocean general circulation models.

Ole Andersen and Stine Kildegaard Rose (DOI: 10.24400/527896/a03-2022.3490) presented recent work on using Cryosat-2 altimetry to improve tide solutions in both the Arctic and Antarctic Oceans. The work benefits from the SAMOSA retracking of Cryosat, which includes SAR and SARin data (critical for polar regions), as well as the new DTU21 mean sea surface. New tide solutions highlight interesting regions with large differences relative to the FES2014 model (Figure 4.16-1), including northern Baffin Bay and much of the Weddell Sea.



	Pre 1990 (56 TG)		TICON 2020 (65 TG)	
	FES 2014	“DTU22”	FES2014	“DTU22”
M2	4.74	4.73	2.43	1.88
S2	5.65	4.94	2.40	1.80
K1	2.46	2.47	1.21	1.18
O1	1.60	1.55	0.98	0.80

Figure 4.16-1: Comparison of FES2014 and preliminary DTU22 ocean tide model in the Arctic Oeaan against the historical dataset by Kowalik and Prochutinsky and the new TICON dataset by Hart et al. (2022).

Mathilde Cancet et al. (DOI: 10.24400/527896/a03-2022.3296) showed recent progress in modeling ocean tides in the far southern ocean, including beneath Antarctic ice shelves. Major thrusts include work to improve bathymetry in the region and also the grounding lines of major ice shelves (Figure 4.16-2). Important physical processes are being addressed, such as frictional representation under ice shelves and the dependence on ice roughness. The work also benefits from continued work to improve bathymetry and tidal observations around Antarctica.

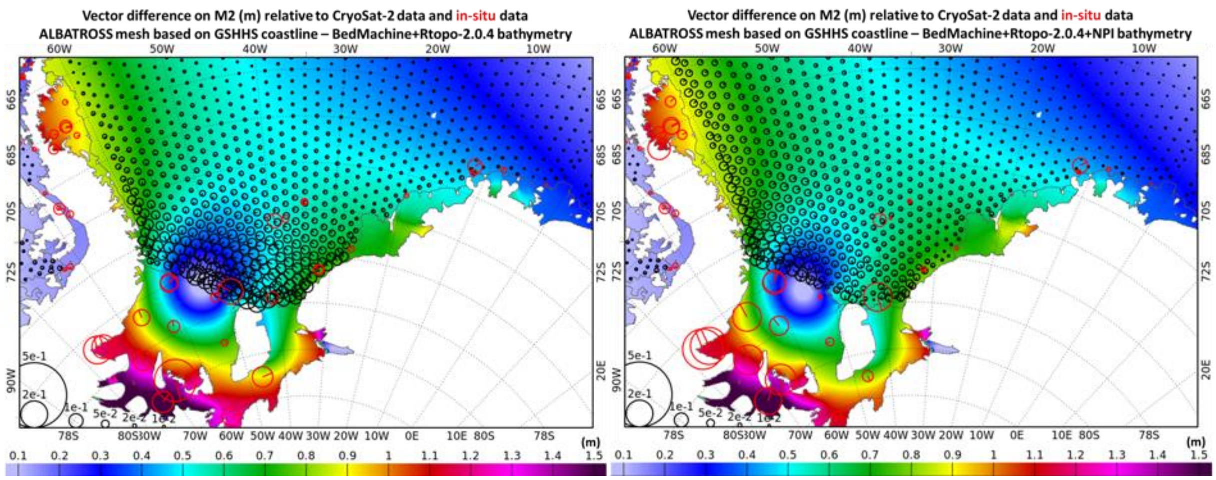


Figure 4.16-2: Improvement in vector differences (M2) against BedMachine 2.0.4 (left) with adding NPI coastal bathymetry (right).

Mike Hart-Davis and colleagues from DGFI (DOI: [10.24400/527896/a03-2022.3290]()) presented an overview of the global EOT20 tide solution. This is a multi-satellite solution based on using FES2014 as prior. Most important improvements are found in near-coastal regions, which has historically been challenging for empirical models (Figure 4.16-3). The polar regions will be the focus of planned future work.

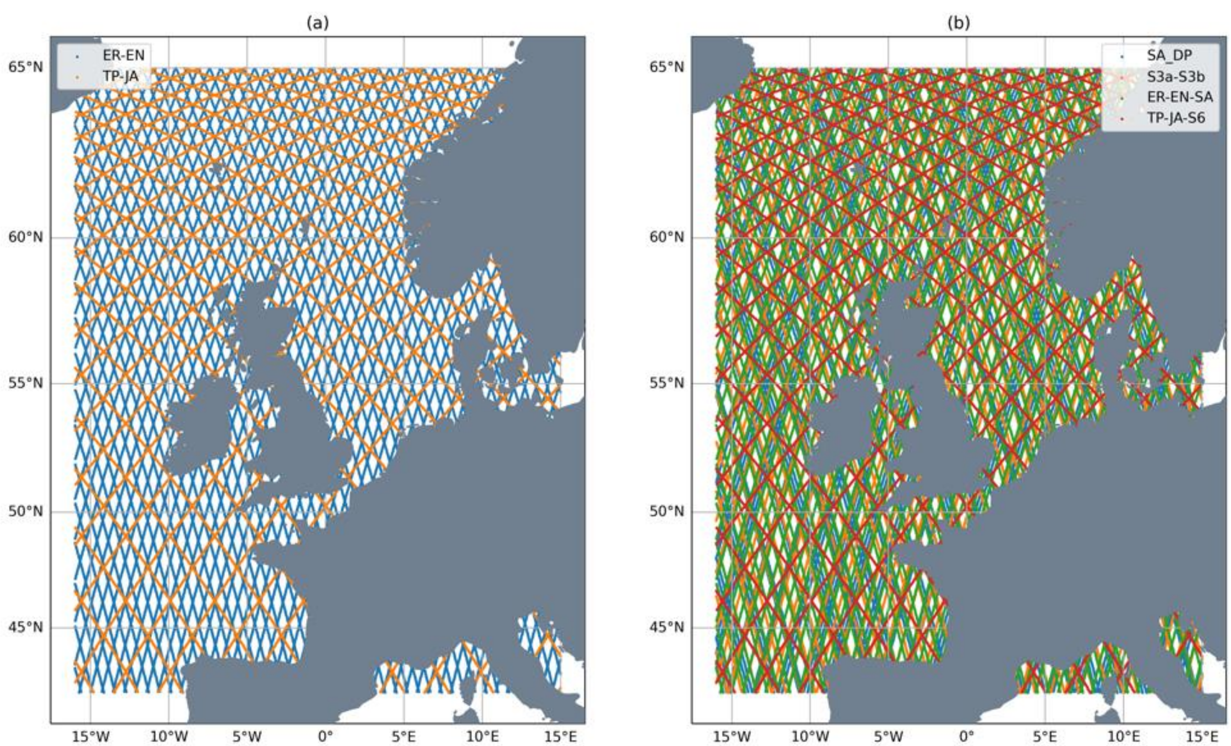


Figure 4.16-3: Altimetry data used in the (a) EOT20 and (b) an updated regional EOT model configuration of the North-West European Shelf.

Richard Ray (DOI: 10.24400/527896/a03-2022.3566) presented an updated empirical solution, GOT5, which, like EOT20, relies heavily on FES2014 as a prior. Polar regions were again a major concern and also pointed to the importance of Cryosat-2 data for much progress (Figure 4.16-4). He has also augmented the coastal "ground truth" dataset previously published in Stammer et al (2014). Finally, he announced the PERTH5 prediction code that flexibly handles all major tide models, including those in netCDF format, GOT4 ascii format, and native OTIS (TPXO) binary format.

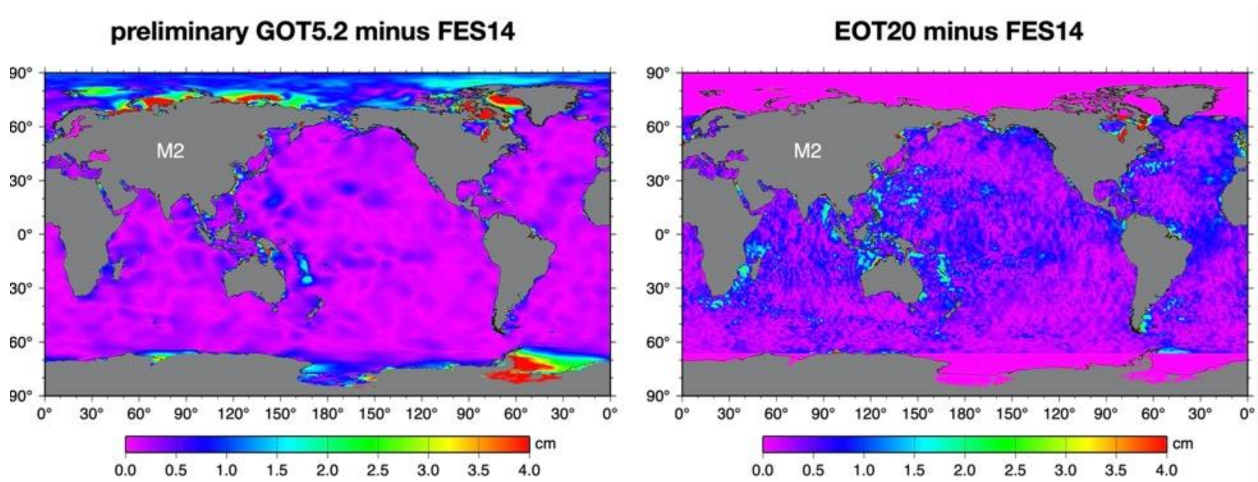


Figure 4.16-4: Comparison of GOT5 and EOT20 against FES14.

Florent Lyard et al. (DOI: 10.24400/527896/a03-2022.3287) presented the new FES2022 atlas, based on their data assimilation methods, now benefitting from a new very high-resolution, global, finite-element mesh. The default coastal resolution is about 4 km, but further refined to 1 km, or even 500 m, in some special regions, while relaxing to about 30 km offshore. Much work has been done on coastline refinements and improved local bathymetry. Tests suggest that the new FES2022 atlas represents an important advance in our ability to model the global tide (Figure 4.16-5), and it is "SWOT ready". Future work will address some known outstanding coastline issues.

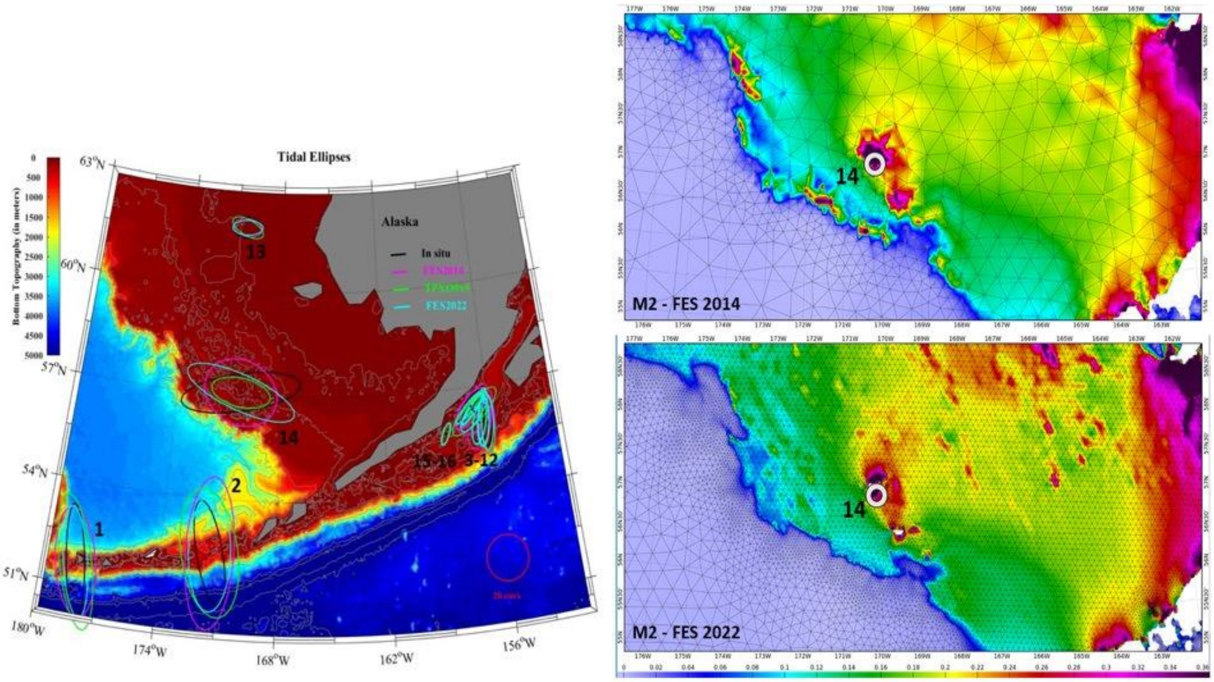


Figure 4.16-5: Validation results of FES2022 currents vs other models. Left: 13 Stations with small Differences ~ 5 cm/s (relative errors<15 %) and 3 stations with differences > 10 cm/s (FES2022 significantly improves). Right: Improvements of the mesh grid resolution for FES2022 in the vicinity of the stations 1, 2 and 14 show better representation of the along bathymetry variability component.

Perrine Abjean et al. (DOI: [10.24400/527896/a03-2022.3562](10.24400/527896/a03-2022.3562)) discussed accomplishments addressing tides in a global 1/36° grid based on the NEMO ocean model. This configuration is expected to be a component of future CMEMS global forecasting system, and also it will address modeling appropriate for future satellite systems, namely SWOT. The presentation compared barotropic and baroclinic tide signals as spatial resolutions improved (Figure 4.16-6).

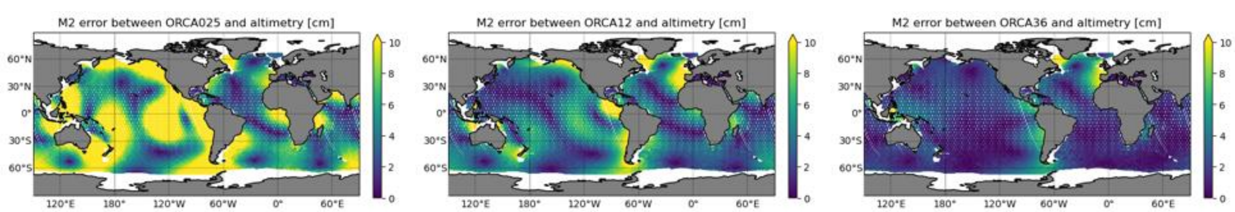


Figure 4.16-6: Comparison to along-track altimetry (TOPEX, Jason 1 & 2) with global 1/4° (left), 1/12° (middle) & 1/36° configurations (right). Resolution improves tidal solution in global configurations.

Miguel Solano et al. (DOI: [10.24400/527896/a03-2022.3342](10.24400/527896/a03-2022.3342)) presented on a similar OGCM with tides, namely the HYCOM system used for some time by his NRL and Michigan colleagues. The focus was on the energetics of internal tides in HYCOM, especially the higher harmonics for which quarter-diurnal and sixth-diurnal waves are pronounced. Some of the energy going into higher harmonics (Figure 4.16-7) appears related to nonlinear internal waves, as seen in observations, although present HYCOM resolution cannot readily resolve internal solitary waves.

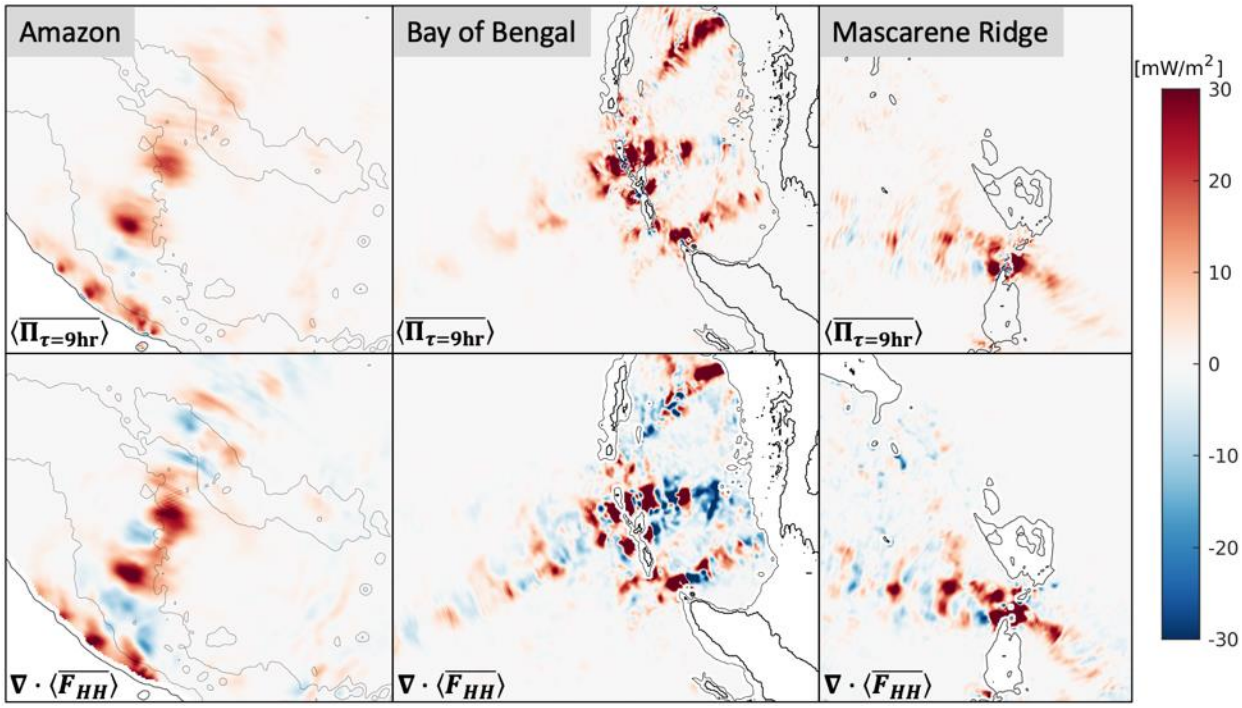


Figure 4.16-7: Top: Nonlinear Energy transfer to higher-harmonics (coarse-grained KE); bottom: Supertidal energy flux divergence.

The OSTST meeting also included 4 tide-related posters: two by Cancet and colleagues (DOI: 10.24400/527896/a03-2022.3304 and DOI: 10.24400/527896/a03-2022.3541) related to on-going and future FES modeling, one by Guarneri and colleagues at TU-Delft (DOI: 10.24400/527896/a03-2022.3605) on shallow-water tides, and one by Santos-Ferreira and colleagues (University of Porto and elsewhere, DOI: 10.24400/527896/a03-2022.3241) on SAR observations of internal solitary waves and their effects on waves. See also "Forum only" contributions in https://ostst.aviso.altimetry.fr/programs/2022-ostst-complete-program.html.

4.16.2 Splinter Discussion Points and Recommendations

1. Empirical models (EOT20, GOT5) continue to advance. Based on existing results, it appears that these could still be further improved, even in this pre-SWOT era. SWOT will open up further opportunities for empirical solutions, addressing inadequate spatial coverage of existing altimeters in near-coastal regions.

2. Initial tests support the superior quality of the new FES2022 assimilation solution.

3. It is now clear that atmospheric tide signals remain in the DAC correction now being applied to nearly all altimeter data. This air-tide leakage is generally regarded as undesirable, since it affects radiational tides in the estimated ocean-tide solutions. Better de-tiding of air tides is thus needed in DAC modeling. On the other hand, tides are required to properly model tide-

surge interactions, which conceivably will be addressed in future DAC-type modeling. How to resolve this tide-DAC tradeoff needs further consideration.

4. Cryosat-2 data are proving critical for improving our knowledge of polar tides. The wider distribution of SAMOSA retracked data will benefit all investigations addressing polar tides.

5 Closing Plenary

The closing plenary took place on Friday morning. Each splinter session provided a summary and comments on the discussion items posed at the beginning of the meeting. In addition, there were presentations on TOPEX/Poseidon reprocessing, Geophysical Data Record (GDR) standards, and Argonautica student projects.

On behalf of the NASA/JPL and CNES/CLS Project Teams, Jean-Damien Desjonquères (JPL/NASA) gave an update on the reprocessing of data from the TOPEX/Poseidon mission. Products for Poseidon and TOPEX are now as close as possible in terms of content and format homogeneity and follow the GDR-F standard. The final TOPEX waveform retracking provides an overall improvement of the data quality, including a reduction of hemispheric bias, synchronization of echo waveforms and altimeter tracker data, and the use of MLE-4 to mitigate errors from platform mis-pointing. The reprocessed products have similar crossover performance as the Jason missions. Reprocessed Poseidon data using MLE-3/4 are included. The products will include new sea state bias solutions (non-parametric 2D and 3D models for TOPEX and parametric model solutions for Poseidon) and two new GDR-F orbit solutions (GSFC and CNES). Updates to the environmental corrections are in line with the GDR-F standard and include a radiometer calibration that is consistent with the end-of-mission calibration. External validation of TOPEX global mean sea level shows improved agreement with tide gauges and Poseidon and significant wave heights are much more stable. Based on validation results, the Cal-1 range correction was not used for the final retracking, consistent with the conclusion of Beckley et al., 2017. Reprocessing and validation have exposed a jump in global mean sea level residuals at cycle 130 (1 April 1996), and the team recommends treating Side-A data as two separate time periods for climate studies. The reprocessed products have been fully generated and a user manual is in progress with a release on PODAAC and Aviso+ targeted for 2023.

On behalf of the Jason Measurement System Engineers, Nicolas Picot (CNES) discussed the status of the Geophysical Data Record (GDR) standards. He noted that currently 10 are operating with a quite homogenous processing baseline thanks to strong coordination among the agencies. The SARAL and Jason-3 missions are using GDR-F standards and Sentinel-3 and Sentinel-6 have been aligned with them. In 2023 SWOT will join them and reprocessed Jason-2 and TOPEX/Poseidon products will be released. He listed a number of changes that could be included in GDR-G standards including retracking evolutions, updated geophysical fields corrections, and further alignment with Sentinel-6 products (e.g. 1Hz compression). The GDR-G orbit standard has not been scheduled but will likely be released by the end of 2023.

Eight students from Lycée Alexis Monteil in Rodez, France, made a presentation of their Argonautica project. In the first part, they presented their studies about how satellites observe phytoplankton blooms. Next, they showed how they compared satellite data to observations from two of the experimental Argos buoys that they built. Finally, they described a design concept for a new scientific buoy, Iris.

The closing plenary session also included discussion, notably about the key points that were addressed to the splinters during the opening session. Given its long history of measuring high-quality climate time series, the OSTST also discussed measures and recommendations it might take to limit its impact on greenhouse gas emissions. This concerns the form and frequency of its meetings, but also the impact of space missions, computer processing, and data storage. After discussion, the following Recommendations and Appreciations were adopted (other specific recommendations can be found in the splinters summaries):

Recommendations

- **Second Jason-3/Sentinel-6MF Tandem Phase:** Given the societal importance of the sea level record and the need to understand its long-term uncertainty, the OSTST recommends to the Jason-3 Project an additional tandem phase between Jason-3 and Sentinel-6 Michael Freilich (S6MF) that lasts 12 cycles, after at least 2 years in the interleaved mission. The OSTST recognizes that the second tandem mission should have no operational impact on S6MF.

- **Sentinel-6B commissioning:** The OSTST recommends that during commissioning Sentinel-6B should:
    - operate both sides of the altimeter;
    - execute a tandem mission with S6MF of at least 10 cycles on the one side followed by 10 cycles on the most pre-launch performant side, so that no switch back is necessary after tandem;
    - use Mode Mask H on the first side and Mode Mask F on the second side; and should include attitude flip maneuvers as performed for S6MF.

- **SARAL/AltiKa:** The OSTST strongly supports the continuation of the SARAL/AltiKa drifting period for as long as possible, its altimeter being the most important for future improvements in MSS and Gravity. See also others recommendations from the “The Geoid, Mean Sea Surfaces and Mean Dynamic topography” splinter (section 4.15.2).
- **OneArgo:** Recognizing the decline in the existing core Argo array and to strengthen the complementary observations between altimetry and Argo, including the need for closure of global and regional sea level budgets, quantifying Earth’s energy imbalance, and understanding interaction of the biosphere and ocean physics, the OSTST supports the full deployment and sustainment of all three components of OneArgo, an integrated global, full depth, and multidisciplinary ocean observing array.

Appreciations:

- **Altimeter Product Research and Development:** Given the importance of advancing Delay-Doppler/SAR-altimetry capabilities and continuing to maintain and evolve the quality of existing altimeter products, the OSTST expresses its appreciation to the funding agencies for their ongoing support of research, technical advancements, and computational resources.