Report of the

Ocean Surface Topography Science Team Meeting

Convene Chicago

Chicago, IL, USA

21-25 October, 2019

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

Organized by CNES, NASA, NOAA, EUMETSAT and ESA

Contents

1 Executive Summary

The 2019 Ocean Surface Topography Science Team (OSTST) Meeting was held in Chicago, IL, 21-25 Octobe. The primary objectives of the OSTST Meeting were to address specific issues on the TOPEX/Poseidon-Jason series of missions, including algorithm and model improvement, Cal/Val activities, merging with other altimetric satellites (CryoSat-2, SARAL/AltiKa, HY-2, Sentinel-3), and preparation for the Sentinel-6/Jason-CS and SWOT missions. Note that since the 2019 OSTST Meeting, the Sentinel-6A satellite was officially renamed Sentinel-6 Mike Freilich (S6MF), in honor of the retired Director of NASA's Science Mission Directorate. While this document attempts to be consistent with this, presentations and other documents referred to herein may still reflect the older nomenclature.

The meeting included special splinter sessions on the Future of Altimetry (chaired by the Project Scientists), a splinter on Coastal Altimetry, and a splinter on the recently launched CFOSAT. All of the presentations from the plenary, splinter and poster sessions are available on the AVISO website: https://meetings.aviso.altimetry.fr/programs/complete-program.html.

Jason-3, which was launched from Vandenberg Air Force Base on 17 January 2016, and took over as the reference mission on 21 June 21 2016, is fully operational with all redundant systems available. In 2020 it will complete the first year of its extended mission beyond the original 3-year prime mission, and will continue the 28-year reference series of measurements of sea level, ocean winds, and waves.

Jason-2, which was launched in June 2008, was finally decommissioned in October 2019 due to age-related degradation of its power system. After more than 11 years in orbit, Jason-2 served as the reference mission prior to the launch of Jason-3 and provided data that improved the resolution of sea surface height observations and improved estimates of the marine geoid as well.

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 precision sea surface height (SSH), significant wave height (SWH) measurements and estimates of sea level change up to 82° latitude (north and south) using advanced Synthetic Aperture Radar (SAR) techniques along high inclination tracks as part of their routine operations. The follow-on Sentinel-3C and Sentinel-3D missions are in the last stage of preparation for a launch in the next few years.

CFOSAT was launched on 29 October 2018 with scatterometers to detect directional wave spectra and wind 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 Copernicus Sentinel-6 (S6) mission is progressing toward launch of the Sentinel-6 Michael Freilich satellite in November 2020, followed by the Sentinel-6B satellite in 2025. The Sentinel-6 satellites will occupy the reference orbit through at least 2030 and will carry a new altimeter capable of simultaneous Synthetic Aperture Radar (SAR) and Low Resolution Mode (LRM) measurements. These data will help improve regional assessment of SWH and SSH correlations observed in other SAR altimeters. The mission also includes a 3-channel radiometer with enhanced capabilities that will improve long-term stability and an additional radiometer for higher spatial resolution. Partner Agencies (EUMETSAT, ESA, NASA and NOAA with CNES providing support) are coordinating selection of a Validation Team (S6VT) and developing plans for the phased release of data products during the commissioning phase to S6VT members.

Finally, presentations on the status of other planned, proposed and existing missions were given, including SWOT, SARAL, the Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL), for example. Several of these were included in a special splinter session on the Future of Altimetry. After discussion of these missions and other issues concerning altimetry, the OSTST adopted (among several others detailed in the full report) the following two **recommendations**:

1. **To minimize likelihood of a gap in polar ocean and ice monitoring, the OSTST encourages Agencies to strive to launch a high-resolution polar altimeter in the early 2020s (such as the proposed High Priority Candidate Mission, CRISTAL) and to maintain operation of CryoSat-2, ICESat-2, and SARAL/AltiKa as long as possible.**
2. **Although the OSTST recognizes the importance of the 5G spectrum for advances in telecommunications, use of this spectral band has the potential to interfere with critical observations used by climate scientists, oceanographers, meteorologists and operational users. In light of this, the OSTST recommends that governments and agencies take steps to mitigate interference from 5G communications by regulation and enforcement as well as improvements to future satellite designs.**

2 Opening Plenary

The 2019 Ocean Surface Topography Science Team (OSTST) Meeting was held in Chicago, Illinois, USA, 21-25 October. On behalf of the Project Scientists (Josh Willis, NASA; Pascal Bonnefond, CNES; Eric Leuliette, NOAA; Remko Scharroo, EUMETSAT; Craig Donlon, ESA), Josh Willis presented the agenda and explained logistics.

2.1 Program and Mission Status

The program managers presented the status of altimetry and oceanographic programs at NASA (Nadya Vinogradova-Shiffer), CNES (Annick Sylvestre-Baron), EUMETSAT (François Parisot), NOAA (Eric Leuliettte) and ESA (Pierre Féménias).

Nadya Vinogradova-Shiffer (NASA HQ) gave a summary of the NASA Ocean Program. She began by thanking Eric Lindstrom (NASA HQ), who announced his retirement from NASA after serving the altimetry community through his science management for more than two decades. Nadya also announced the timeline for selection of the next OSTST, with proposal due in October 2020 and selected team members beginning in April 2021.

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 also noted the successful mission extension of SARAL/AltiKa through 2021 as well as the end of Jason-2 and noted the upcoming deadline for proposals to join SWOT Science Team. The selection process through TOSCA for the next OSTST will follow almost the same time line as for NASA/NOAA. She also presented the recommendations issued from the CNES Science Prospective Seminar held in October 2019.

Francois Parisot (EUMETSAT) presented on the Marine Services and Program status for EUMETSAT. In addition, Francois's own retirement was recognized, as was his multi-decade long support of altimetry and the OSTST at both EUMETSAT and CNES. Both Francois Parisot and Eric Lindstrom were thanked by the OSTST for their contributions to altimetry. Francois gave a brief overview of EUMESATS numerous planned and existing ocean-related satellite activities. He also noted that Sentinel-3A & B missions are operating nominally and providing excellent data availability. Finally, he noted that upgrades to the EUMESTAT Ground Segment for operation of Sentinel-3C (launch mid-2023) and 3D (launch mid-2025) are in progress.

Eric Leuliette (NOAA) provided a status update on the NOAA Jason-mission Program Status. NOAA continues production and distribution of Jason-2 and Jason-3 data and is preparing the Jason Ground System for Sentinel-6A. The NOAA/NESDIS Science Program continues to support and improve the National Weather Service (NWS seasonal and ENSO predictions and HYCOM for hurricane intensity forecasting) as well as OceanWatch, CoastWatch and PolarWatch services. NOAA expects to support the OSTST in the next ROSES (2021-24), funding approximately 4 PI-led studies at a cost of $800K per year. NOAA/NESDIS Office of Projects, Planning, and Analysis (OPPA) is funding two Research & Technology Maturation Projects: (i) Maturing Reflectometry Usefulness to the NOAA Observing System Portfolio for Winds and Altimetry applications ("Phase-Delay" Altimetry Study using Spire GNSS-RO Satellites) and (ii) Dual-band radar satellite altimeter instrument studies for sea ice and sea state (Ku/Ka-band and snow radar studies).

Pierre Féménias (ESA) presented the ESA Programme Status. Pierre noted that ESA currently has 15 Earth observation missions in operation, 25 under development and 15 in preparation. CryoSat remains in excellent condition and mission support has been extended through the end of 2021. The overall quality of data from the Sentinel-3 constellation is excellent and it continues to meet all requirements. A rolling call for membership in the Sentinel-3 Validation Team remains open. The CRISTAL mission, an altimeter for polar ice and snow topography was discussed, as was CIMR, an imaging microwave radiometer for the polar oceans and ice caps.

The FDR4ALT (Fundamental Data Record for Altimetry) project was described. FDR4ALT aims to and exploit the long-standing record of global altimetry measurements from ESA ERS-1, ERS-2 and ENVISAT heritage missions through reprocessing. Finally, G-POD, an online retracking tool for Sentinel-3 and CryoSat data, was announced.

On behalf of the Project Managers, Christophe Marechal (CNES) reviewed the status of the Jason missions. Due to issues with the power supply, the office of the French Space Operations Act requested decommissioning of the Jason-2 satellite and the decision to decommission Jason-2 was adopted by the 4 partners on 26 September 2019. Apart from safe holds related to ongoing issues concerning the satellite gyros, the availability and performance of all instrument data was excellent up to the planned passivation, which took place on 10 October 2019. Through its 11 years in orbit the average availability of data from the mission was 92.8%, and the overall mission was highly successful.

Jason-3, which took over as the reference mission on 14 October 2016, remains fully operational with all redundant systems available. All of the core payload and passengers are operating nominally, as is the ground segment. Satellite pointing, altimeter performance, DORIS, AMR and GPSP are all stable and providing data of excellent quality. Cold sky calibration maneuvers continue to provide mm-level stability for the Jason-3 AMR. The global average path delay computed from the AMR instrument is within ±1mm of the ECMWF model PD over 2 past years. Processing of data to the GDR-F standard is expected by the end of 2020 and a 1-year data set processed to this standard is expected for release by the time of the next OSTST Meeting.

Nadège Quéruel (CNES) gave an update on the status of the SARAL/AltiKa Mission. The SARAL/AltiKa mission continues to perform nominally after more than 6 years on orbit and will continue for two more years. All altimeter systems are operating nominally and continue to provide high quality data and have good agreement with Jason-3, and OGDR, IGDR and GDR data product production 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. Migration to the GDR-F standard is underway and full reprocessing is planned in 2020.

Cédric Tourain (CNES) provided an update on CFOSAT (China France Oceanography Satellite), a wind and wave scatterometer mission to measure spectral properties of these phenomena at global scales. Launched on 29 October 2018, CFOSAT carries a Ku-band wind scatterometer called SCAT and wave scatterometer called SWIM. In July 2019, the first Cal/Val workshop for the mission was held, and in September, the first international science team meeting was convened in Nanjing, China. Data from the mission was found to be of excellent quality and in good agreement with in situ observations as well as other satellite missions. Data was released to all scientific users in February 2020, for SWIM data see https://www.aviso.altimetry.fr/en/missions/current-missions/cfosat.html, and for SCAT data see https://osdds.nsoas.org.cn/.

Pierrik Vuilleumier (ESA) gave an update on the status of the upcoming Sentinel-6 mission. Sentinel-6 will continue the Jason series of research and operational oceanography missions. Two satellites will be commissioned, with the first launching in November 2020 and the second launching in 2025. Responsibility for the mission is shared between EUMETSAT, ESA, NASA and NOAA, with CNES providing expert support. Mission development is progressing toward a planned launch for the first satellite in November 2020. The A satellite is now fully integrated and environmental testing has begun. Shipment to Vandenberg is expected in late September 2020. The B satellite platform integration is ongoing. Production of the Falcon-9 launch vehicle is underway at SpaceX. In addition, the overall ground segment development and testing is underway and on schedule to support the November launch. Finally, phased release of data products throughout the commissioning phase of the mission were explained. The commissioning phase will begin shortly after launch and take most of the first year of the mission. During this time, Near Real Time (NRT), Slow-Time Critical (STC) and Non-Time Critical (NTC) products will have staggered releases, with each being released to the S6VT (Sentinel-6 Validation Team) for validation prior to more general public release.

Lee Fu (NASA) provided an update on the SWOT mission (Surface Water and Ocean Topography mission). The mission will carry a SAR imaging interferometer as well as a traditional nadir-altimeter and operate at a 21-day repeat. Mission science objectives include observation of mesoscale and sub-mesoscale ocean process. It was reported that flight hardware has been completed and integration and testing is ongoing. Plans for evaluating the measurement performance and performing calibration and validation of the data are ongoing. A strawman experiment was presented that included an array of GPS buoys along with an array of hydrographic sensors in a key location along the ground track. In addition, a pre-launch observational campaign began in for September of 2019 (and continued through the end of 2019), and included GPS buoys, CTD moorings and bottom pressure recorders to help interpret the subsurface oceanographic implications for the small-scale height changes that SWOT will ultimately observe.

2.2 Other reports and issues

Before a plenary science session and the remaining splinter sessions, there were two plenary talks of general interest.

Benoit Meyssignac (LEGOS, CNES) gave a presentation entitled “How accurate is accurate enough?” on the scientific and societal need for additional improvements in the accuracy of sea level measurements. This presentation showed that improving the accuracy of the sea level record could help address scientific questions such as projections of future sea level, attribution of present-day rates of rise and constraining the Earth’s energy imbalance.

In addition, Patricia Ward, PhD, the Director of Science Exhibitions at the Museum of Science and Industry, Chicago gave a presentation entitled “Engaging the Public in Addressing Climate Change”. This presentation detailed numerous efforts on the part of the Museum to engage the public on the topic of climate change, focusing especially on an exhibit about the Extreme Ice Survey. Dr. Ward explained how exhibits in the museum were designed to inspire and empower people to explore a sustainable future for life on Earth.

Finally, on behalf of the other Project Scientists, Eric Leuliette (NOAA) presented discussion topics for consideration by the splinter sessions. These included contamination of radiometer data due to the recent commercial sale of 5G frequencies spectrum, long-term stability of Sentinel-3 altimeter observations, Sentinel-6 reprocessing, the Jason-3 mission objectives after Sentinel-6 commissioning, and the future of the OSTST. These key points are detailed below:

<u>Concerns have been raised on radio frequency interference from the 5G spectrum on the 23.8 GHz radiometer channel</u>:

- Splinters are encouraged to comment on the possible impacts of 5G interference.
- Are any additional studies needed to determine the risk to altimetry?

<u>Sentinel-3 altimeter stability</u>:

- A stability issue has been identified in the Sentinel-3A altimeter.
- What cal/val and instrument processing studies should be conducted in advance of Sentinel-6? Sentinel-3A could be a good testbed for these studies.

<u>Sentinel-6 Annual Reprocessing</u>:

- S6 Reprocessing Plan
    - "Annual" reprocessing is planned as part of operations
    - Similar to Sentinel-3 (all instruments)
    - Will be triggered by major evolutions of processing baseline
    - Aimed at keeping the S6 products as near to the state-of-the-art as possible
    - Hence, we expect a reprocessing by end of the commissioning phase
- Consequences
    - Jason-1 through -3 products may be "left behind" if not updated as well, and could break the consistency; should these go through more regular reprocessing as well?
    - Notes:
        - Jason-2/3 products are to be updated to GDR-F standards and format, which is consistent with the Sentinel-6 standards and format at launch
        - From experience, because most evolutions are instrument specific (e.g. sea state bias), many S6 updates would not break the consistency

<u>Jason-3 after Sentinel-6 MF commissioning</u>:

- In late 2021 the tandem phase will be finished.

- Should Jason-3 be placed in an interleaved orbit (like Jason-2)? Or should Jason-3 go directly into a geodetic phase?
- What end-of-life orbits should be considered for after the interleaved phase?

The Future of the OSTST:

- How should we advance coastal, hydrology, cryosphere, and ocean altimetry?
- Should the OSTST try a joint meeting with other teams (Argo, SWOT, etc.)? If so, what other groups?
- Are there suggestions about how lower the carbon footprint of the meeting?

2.3 Science keynotes

After the Opening Plenary session, a special session of science keynote talks. This included 4 invited science talks of general interest to the community.

The session was opened by Denis Volkov (NOAA AOML) with a talk on the relationship between changes in the strength of the Atlantic Meridional Overturning Circulation (AMOC) and coastal sea level in the subtropical North Atlantic. Changes in the AMOC were shown to drive thermosteric sea level changes along southeast coast of the United States, as well as in the Mediterranean Sea and over the northwest European Shelf.

Melanie Fewings (Oregon State University) gave a presentation on marine heat waves in eastern boundary upwelling systems. In coastal upwelling systems like the west coast of the United States, such heat waves can have strong implications for coastal fisheries and regional weather patterns. Associated with strong changes in regional wind stress patterns, these events can generate fast moving coastally trapped waves causing sea level changes of 4-6 centimeters.

Jean Tournadre (IFREMER) presented a new technique for analysis of radar return strength, in traditional altimeter using both Ku and C band radars, for imaging surface films and regions with very low scattering. Furthermore, it was found that further analysis could help distinguish between bright returns that were caused by low wind speed as opposed to surface films, allowing for more robust detection of things like oil slicks using altimeter data.

Finally, Matthis Auger (CLS) presented observations of sea level in the ice-covered region of the Southern Ocean based on data from several satellite altimeters. Care is needed to interpret radar returns over regions partially covered by sea ice. Nevertheless, combination of data from multiple satellites provides increased coverage and improved resolution of sea surface height in the Southern Ocean.

As with other talks and posters from the meeting, the science keynote talks can be downloaded from: https://meetings.aviso.altimetry.fr/programs/complete-program.html

3 Poster Sessions

Two poster sessions were conducted on Thursday and Friday 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://meetings.aviso.altimetry.fr/programs/complete-program.html

The posters were grouped into the following categories:

- Application development for Operations [12 posters]
- CFOSAT [4 posters]
- Coastal Altimetry [7 posters]
- Instrument Processing (Measurement and retracking) [5 posters]
- Instrument Processing (Propagation, Wind Speed and Sea State Bias) [7 posters]
- Outreach, Education & Altimetric Data Services [15 posters]
- Precise Orbit Determination [3 posters]
- Quantifying Errors and Uncertainties in Altimetry Data [2 posters]
- Regional and Global CAL/VAL for Assembling a Climate Data Record [12 posters]
- Science Results I: Climate Data Records for Understanding the Causes of Global and Regional Sea Level Variability and Change [6 posters]
- Science Results II: Large Scale Ocean Circulation, Variability and Change [7 posters]
- Science Results III: Mesoscale and Sub-Mesoscale Oceanography [16 posters]
- Science Results IV: Altimetry for Cryosphere and Hydrology [21 posters]
- The Future of Altimetry [7 posters]
- The Geoid, Mean Sea Surfaces and Mean Dynamic topography [4 posters]
- Tides, internal tides and high-frequency processes [8 posters]
- Others (poster only) [4 posters]

4 Splinter Sessions

The splinter sessions were organized as follows:

Monday, 21 October:

- Science Results I: Climate Data Records for Understanding the Causes of Global and Regional Sea Level Variability and Change [6 Oral talks]

Tuesday, 22 October:

- Instrument Processing (Measurement and retracking) [10 Oral talks]
- Precise Orbit Determination [10 Oral talks]
- Instrument Processing (Propagation, Wind Speed and Sea State Bias) [6 Oral talks]
- Outreach, Education & Altimetric Data Services [6 Oral talks]

Wednesday, 23 October:

- Application development for Operations [5 Oral talks]
- Regional and Global CAL/VAL for Assembling a Climate Data Record [10 Oral talks]
- Coastal Altimetry [5 Oral talks]
- Quantifying Errors and Uncertainties in Altimetry Data [5 Oral talks]
- Science Results II: Large Scale Ocean Circulation, Variability and Change [6 Oral talks]
- Science Results III: Mesoscale and Sub-Mesoscale Oceanography [6 Oral talks]

Thursday, 24 October:

- The Geoid, Mean Sea Surfaces and Mean Dynamic topography [5 Oral talks]
- Tides, internal tides and high-frequency processes [5 Oral talks]
- CFOSAT [4 Oral talks]
- The Future of Altimetry [5 Oral talks]
- Science Results IV: Altimetry for Cryosphere and Hydrology [6 Oral talks]

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

4.1 Application development for Operations

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

This is a summary of the Application Development for Operations splinter session for the 2019 OSTST. It took place on Wednesday, 23 October 2019, from 09:00 - 10:30. There were 5 talks and 12 posters presented. Around 50 participants attended the oral session.

4.1.1 Oral Presentation Summary

First talk: L. Aouf (Météo France) on The Copernicus Marine Service WAVERYS.
L. Aouf presented the results from the validation of the wave parameters provided by the reanalysis WAVERYS and the comparison of significant wave heights of the wave reanalysis with the ones from independent altimeter HY2A, processed and provided by the CNES. Results on the validation with the buoys were also presented. WAVERYS integrated parameters showed very good accuracy: good normalized scatter index of SWH globally ~10% and a better performance of scatter index of SWH from WAVERY by 10 to 15% in comparison with ERA5 wave products. The added value of including wind/waves interactions in the wave reanalysis in particular for years with strong sea surface temperature anomalies such 2010 was also presented and the relevance of using currents forcing in WAVERYS was highlighted as presenting good perspectives for users applications (wave climate, reprocessing of altimeters, etc). WAVERYS wave products will be released in December 2019.

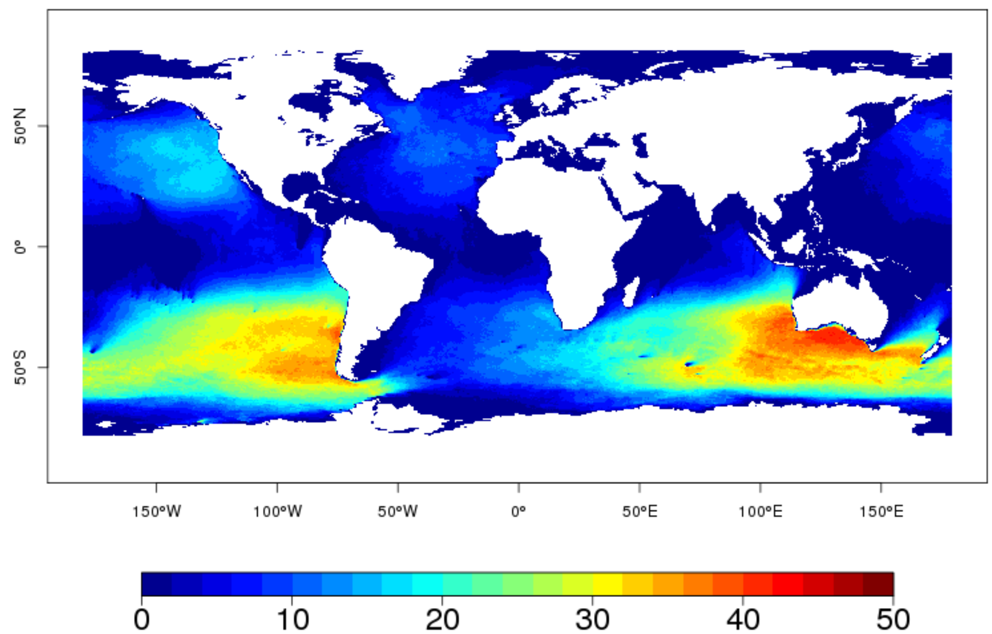


Figure 4.1-1: from L. Aouf. Probability of occurrence of primary swell with height and period greater than 2 m.

Second talk: C. Birkett (NASA/GSFC, USA) on the Water-Watch, a new NASA/USDA funded operational program offering water-related products for lakes, reservoirs, river reaches, and wetland zones.

These products will be derived from the i) NASA/CNES and ESA/ISRO/CNES series of radar altimeters, ii) the Landsat/MODIS series of multispectral imagers, and iii) the SRTM, ASTER, and ICESat-2 DEM's. The products will be a combination of water level, surface extent, water storage, and bathymetry. There is an increasing demand for a global monitoring service that in particular captures the variations in the smallest (1 to 100 km2) reservoirs and water holdings in arid and semi-arid regions, where water resources are critical to both agriculture and regional security. There is also a demand for surface water level products across wetland zones in respect of inland fisheries and assessments of catch potential. Observations of river reaches in gauge-poor regions have also been requested in lieu of spring melts and flood hazards. In addition to meeting operational requirements, recent efforts to create (up to) 25yr timelines has also shown that great care needs to be taken with respect to the merger of results from multiple instrument platforms. This is in regards to the formation of high quality Earth Data Records or for the creation of Long-Term Status Indicators which inform end users of deviations from normal conditions. The additional application of hydrological modeling and the recording and monitoring of hypsometry is also being added to the program. Although not as efficient as (say) direct water level observation, preliminary studies have shown that these alternate methods offer a secondary "inferred" water level product that can be used to highlight seasonal and inter-annual variability to determine trends and inter-decadal changes.

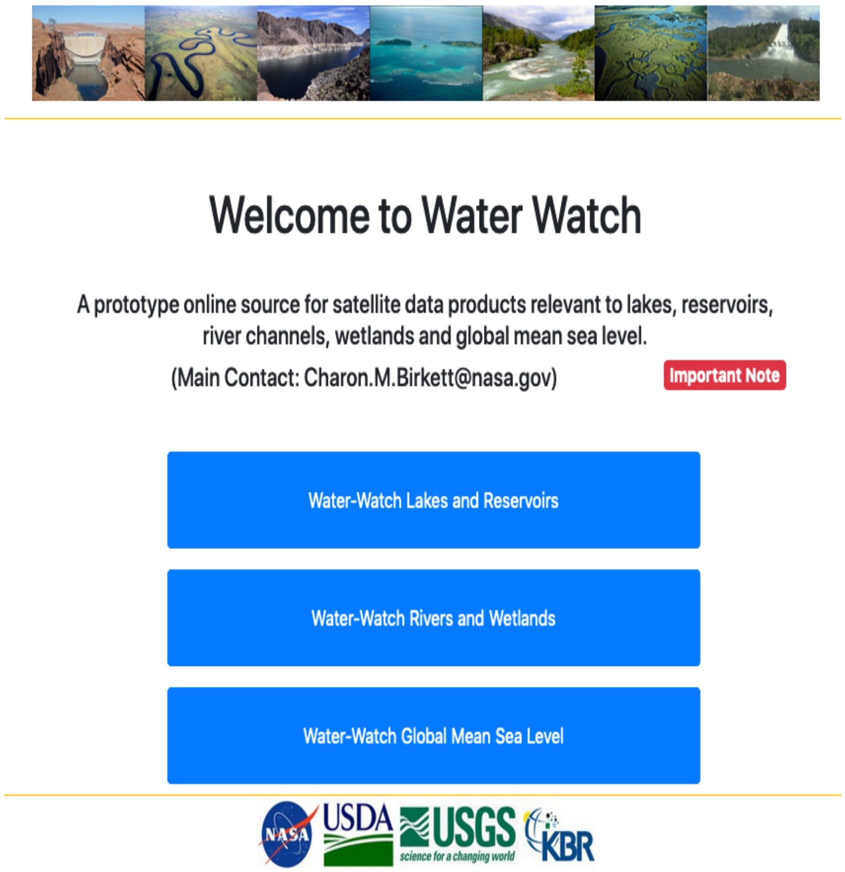
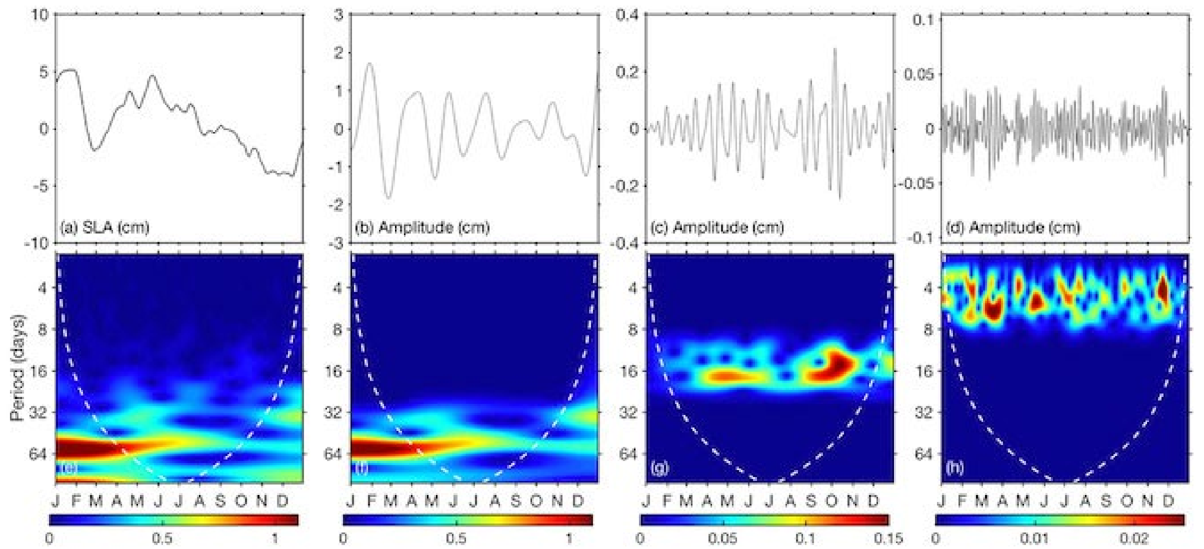


Figure 4.1-2: from C. Birkett. https://water-watch.sgt-inc.com

Third talk: S. Bulusu (University of South Carolina, United States) on the "Utilization of Satellite Altimetry Data in Monitoring Intraseasonal Oscillations in the Indian Ocean".
The presentation addressed the Indian Ocean experiences ISOs on a variety of time scales, including the 30-90 days Madden-Julian Oscillation (MJO) events, the quasi-biweekly 10-20 day signal, and the 3-7 day signal representative of weather/synoptic-scale events as a response to oscillations of the monsoon trough. These ISOs are responsible for variation from mean conditions of monsoonal rainfall and are central in modulating active (wet) and break (dry) monsoon conditions. The MJO is an atmosphere-ocean coupled event that regulates wet and dry conditions in the tropical Indian and Pacific Oceans. Through the analysis of ISOs and SLA, one can develop a clear spatial and temporal understanding of how oceanic conditions respond to atmospheric events. The work presented was focused on local and basin-wide signals, zonal and meridional propagation, and variability of ISOs with respect to the strength of the summer monsoon season over a 25 years period (1993-2018). Bulusu presented the relationship between larger- and shorter-period ISOs in SLA and the usefulness of altimetry data in Indian monsoon studies.



Top panel figures (a-d) represent the time-series of the box averaged [85°E-95°E and 4°N-18°N] SLA (in cm) for (a) unfiltered SLA and filtered SLA in 1994 (strong monsoon) for ISO periods of (b) 30-90 day and (c) 10-20 day and (d) synoptic oscillation of 3-7 day period and the corresponding bottom panel figures (e-h) represent continuous wavelet power spectrum of the box-averaged time-series in (a-d). The white horizontal lines in (e) denote the periods of peak wavelet power, and the white dotted line in each figure signifies the cone of influence (COI) where edge effects might distort the signal.

Figure 4.1-3: from S. Busulu.

Fourth talk: I. Pujol (CLS, France), on the Higher resolution Level3 altimeter products for Assimilation Systems.

The Level3 processing includes a homogenization of the SLA for the different altimeters (i.e. reduction of the global and regional biases), allowing the users to directly use the products without any pre-processing. They are widely used for different applications, including assimilation in numerical models. Since 2008, such products are generated and disseminated by the Copernicus Marine Service (CMEMS; previously MyOcean during its demonstration phase). They allow the user to change the physical content of the altimeter measurement in consistency with the model capabilities and characteristics, thus considerably improving the results of the assimilation of the altimeter measurement into the models. With the future altimeter missions as the large swath SWOT mission, the altimeter processing will face a new challenge: be able to accurately process the signal at finer spatial scales. On the other hand, users and more particularly modelers need to make their system ready for assimilation and propagation of the finer scale structures observed. With that objective, a new generation of along-track products is under development with support from CNES. Experimental datasets, with a nearly 1km (5Hz) sampling, are already available on AVISO+ (https://www.aviso.altimetry.fr/duacs) and can be tested by users. Operational and experimental altimeter products and their impact for numerical models have been presented.

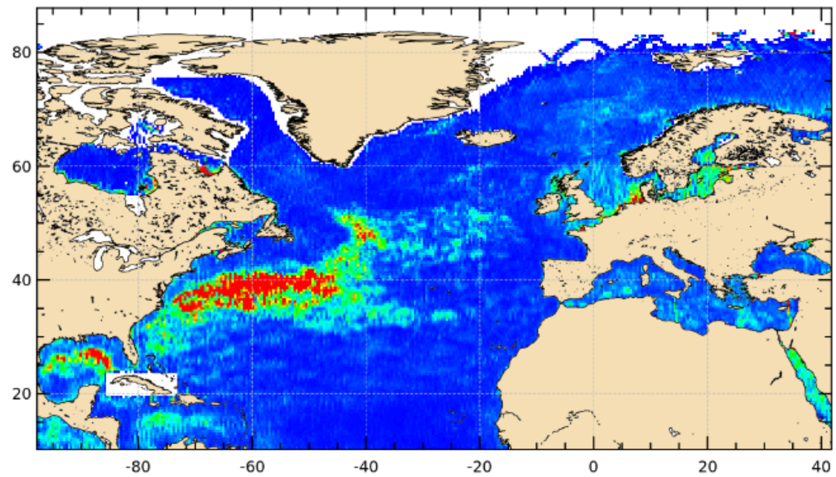


Figure 4.1-4: from I. Pujol. This image shows the SSH RMS variability from the new along-track data sets that retains higher spatial structure. The figure does not show it side-by-side with the RMS variability of the prior data set, but it gives a good picture of the extent of Gulf Stream inertial penetration into the Atlantic, the bifurcation and extension towards Europe, and many of the local circulations in semi-enclosed seas.

Fifth and last talk: T. Strub (Oregon State University, United States), on the Collaborative Design of Real-Time Displays of Forecast Fields for Targeted End-Users.

Strub presented his experience in collaborating with Oregon fishermen to design a web site (NVS Seacast, nvs.nanoos.org/seacast) displaying forecasts from an experimental DA ocean forecast model. The model assimilates altimeter SLA, satellite-SST, and coastal radar surface velocities along the Oregon Washington coast. Those using the marine environment are making decisions that need information regarding the conditions under which they will be working. The more basic problem highlighted was the mutual ignorance: The Information Providers do not understand how the information will be incorporated into the critical decisions made by end-users; while those with the need for the information contained in the products do not understand the range of data that are available from the Data Providers to be converted into the Information Products. Thus, the entire chain needs to be considered as a whole system to provide the best value to all involved. The research also involved a more basic examination of the perceptions of risk and uncertainty for each of the groups. The process led to the identification of the most important information to be communicated to aid in end-user decisions, along with suggestions for visual formats that would be most useful at sea or on land (sometimes different). The data providers also communicated the limitations of the available data (observations and forecasts). The lessons learned have a wide range of possible applications in the development of a range of satellite-derived real-time oceanographic products.

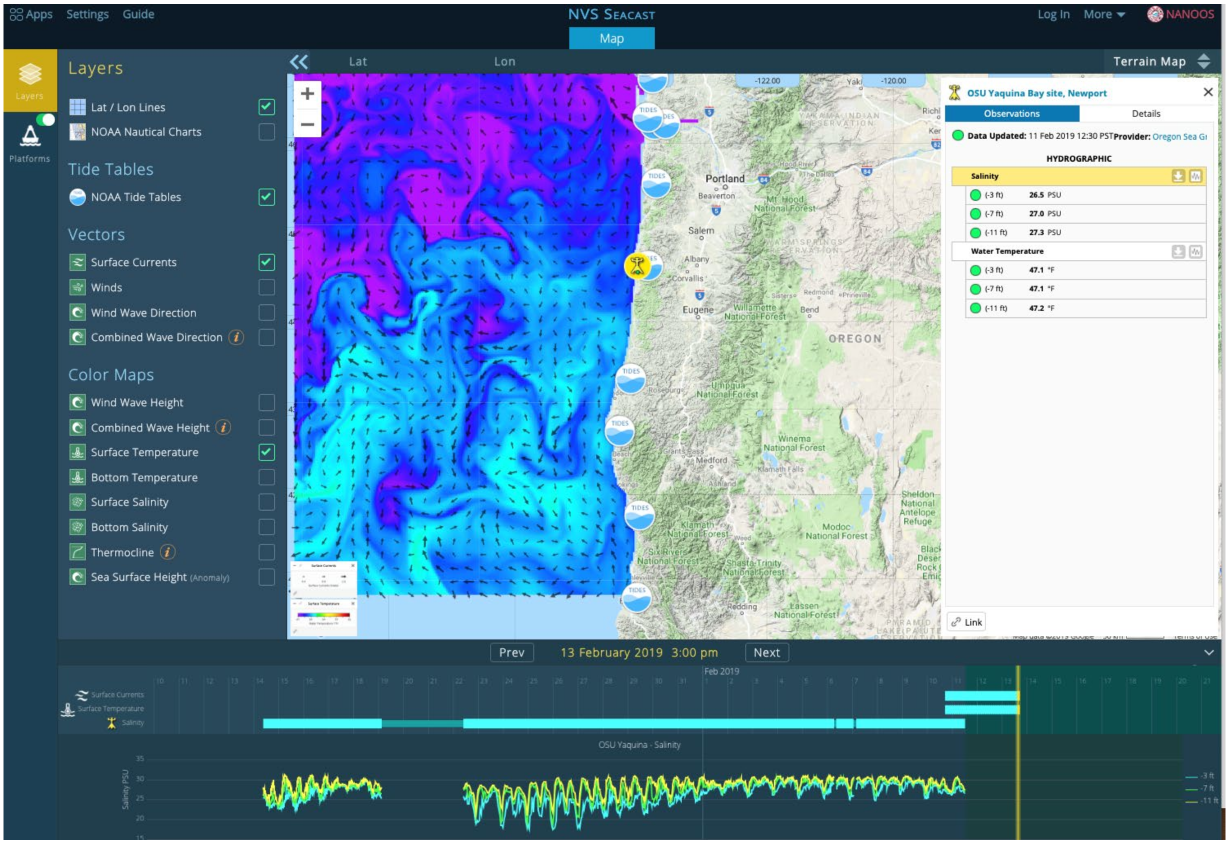


Figure 4.1-5: from T Strub.

4.1.2 Splinter Discussion Points

Current products and systems

- What are the user requirements for accuracy, precision, coverage?
  - MSSH of reference tracks needs to be improved, particularly for coastal altimetry.
  - More reliable products are needed to ensure continuity to get end-user buy-in.
  - We would benefit from establishing an end-user focus group.
- What are the product levels mostly used for operational applications (L2, L2P, L3)?
  - Higher level products for the most part in the open ocean (e.g., RADS, CMEMS);
  - Inland waters definitely using non-gridded (along-track) altimetry.
- What is the preferred access point and protocol for retrieving your data?
  - A single source is preferred, providing consistent formats between missions. One user noted that RADS has had huge impact. **We need a similar, homogeneous interface to the higher frequency data**.
- Are the flags currently provided in the NRT products adequate for your use, or do they flag out too much or too little?
  - OGDR should contain variables that allow flagging of bad SWH.

- About the timeliness of products for Near-Real-Time applications, nominal 3h timeliness for NRT products is considered appropriate.

Future products and systems

- Coastal / regional modeling community would use coastally enhanced 5 Hz data. However, 1 Hz data is sufficient for ocean applications, including assimilation; therefore it is suggested to keep the 1 Hz data available for users.
- Continue to improve the entire time series. Long time series are valuable!
- Other missions/ HY-2A/B/C/D (altimeter) and CFOSAT (nadir beam) data are just as important as any other mission.

Roughly, annual reprocessing planned for S6. J1 – J3 may be "left behind" if not reprocessed. Should these be done regularly as well?

- **Yes**, because the entire time series is important.

What orbit do we recommend for J3 after S6MF tandem phase is over?

- Interleaved! Several presentations highlighted the current global average resolution of 100 km, while many others pointed out the many significant phenomena at smaller scales than this.

How should we best advance ALL of radar altimetry (coastal, hydrology, cryosphere)? Should we try to meet jointly with Argo? SWOT?

- In principle – sure - but the devil is in the details.

How can we lower the carbon footprint of the OSTST?

- Livestream the meeting.
- Perhaps in alternate years, have two meeting venues, one on each side of the Atlantic.
- Insist on local foods.
- Find meeting venues that are sustainably built and run (think, solar-powered straw bale/adobe "ranch" in AZ or NV).

4.1.3 Poster summary

APOP_001 - Multi-Scale Assimilation of Simulated SWOT Observations
Joseph D'Addezio (Naval Research Laboratory) et al. demonstrated the successful assimilation of simulated Surface Water Ocean Topography (SWOT) observations into a high-resolution forecast model using a multi-step 3DVAR analysis procedure.

APOP_002 - Wave Model Confidence Index: A metocean decision support tool.
Chafih Skandrani (NOVELTIS) et al. presented a poster on WMCI, the first service designed and developed by NOVELTIS in the frame of the European NEPTUNE Innovation Support Program providing a unique solution that addresses major needs regularly expressed by maritime Stakeholders.

APOP_003 - CMEMS Level-3 Near-Real-Time Significant Wave Height and Spectral Parameters derived from altimetry and SAR measurements.
Elodie Charles (CLS) et al. presented a poster on a near-real-time wave service started in July 2017 in the frame of the Copernicus Marine Environment Monitoring Service (CMEMS), handled by the WAVE-TAC (Thematic Assembly Center), a partnership between CLS and IFREMER, which provides near-real-time wave products derived from altimetry and SAR measurements.

APOP_004 - Assimilation of high frequency altimeter wave data in regional wave model for the French coastal areas.
Alice Dalphinet (Météo-France) et al. presented a poster on the assimilation of high frequency (20 Hz) altimeters wave data in the operational regional wave model: two datasets of Sentinel 3 were considered: SAMOSA+ reprocessing by GPOD SARvatore Service (Dinardo et al. 2017) and CNES S3PP products obtained with innovative LR-RMC processing (Boy et al, OSTST 2017, Tran et al OSTST 2019).

APOP_005 - Maximizing the impact of altimetry measurements in data assimilation with a high resolution model.
Zhijin Li (JPL) et al. presented a poster on the impact of assimilating multi-satellite altimetry data into a model that resolves submesoscale ocean circulation of order 10 km.

APOP_006 - Impact of altimetry observations in the Mercator Ocean real time monitoring and forecasting systems.
Elisabeth Remy (Mercator Ocean International) et al. presented a poster on the Ocean analysis and forecasts produced in real time by Mercator Ocean, which serves a wide range of applications, from marine safety to seasonal forecasts. It was highlighted the sensitivity of the global ocean analysis and forecasts to changes in the altimetry constellation and to the MDT used as a reference to assimilate SLA.

APOP_007 - Improving DUACS Sea Level products with CFOSAT and HY2B.
Yannice Faugere (CLS Space Oceanography Division) et al. presented a poster on the DUACS system, part of the CNES/SALP project, and the Copernicus Marine Environment and Monitoring Service, which produces high quality multi-mission altimetry Sea Level products for oceanographic applications, climate forecasting centers, geophysics and biology communities. These products consist in directly usable and easy to manipulate Level 3 (along-track cross-calibrated SLA), Level 4 products (multiple sensors merged as maps or time series) and derived value added products such as Eddy Atlas.

APOP_008 - NOAA's Jason Products.
David Donahue (NOAA/NESDIS) et al. presented a poster on the interagency Jason-2 and Jason-3 Ocean Surface Topography Mission products.

APOP_009 - Jason-2 and Jason-3 Near-Real Time Products Latency over the Past Year.
Donald Richardson (Columbus Technology) et al. presented a poster on the latency of Jason-2 and Jason-3 near-real time Operational Geophysical Data Records (OGDR) over the past year, examining timeliness statistics against the requirement that product distribution be less than 3 hours from data collection. Gaps in the ODGR production were addressed, as well as any periods of large latencies experienced.

APOP_010 - Satellite altimeter observations of extreme winds and waves, and special editing required for Jason-2 Geodetic Mission data.
Walter Smith (NOAA Lab for Satellite Altimetry) et al. presented the results of the analysis of the Jason-2 altimeter's data soon after the extreme SWH values estimation during the 2018 North Atlantic hurricane season showing that altimeters seem to be measuring extreme SWH reliably in a variety of storms observed. However occasionally Jason-2 altimeter estimated truly spurious wave heights exceeding 20 m SWH, which seem to be related to extreme rain intensity, which causes the altimeter to loose track of the sea surface.

APOP_011 - New Developments for NOAA's operational upper Ocean Heat Content product suite.
Deirdre Byrne (NOAA) et al. presented a poster on the preliminary results of the NOAA National Environmental Satellite, Data, and Information Service operational satellite-derived Ocean Heat Content product for a testbed region, the Gulf of Mexico, based on an improved algorithm.

APOP_012 - A Real-Time Product to Help Ocean Cleanup Operations.
Nikolai Maximenko (IPRC/SOEST, University of Hawaii) et al. presented a poster on the results obtained by numerical experiments for simulation of debris pattern and the resulting real-time products aimed to help ocean cleanup operations.

4.2 CFOSAT

Chairs: Danièle Hauser, Lotfi Aouf, Doug Vandemark

Session CFOSAT was a 1.5h splitter session dedicated to first results from the recently launched mission called CFOSAT (China French Oceanographic Satellite) which combines a nadir and near-nadir incidence Ku-Band radar instrument (SWIM) and a wind scatterometer.

Four talks were presented during this session and are summarized below. About 35 people attended the session.

As for the associated poster session, although 4 posters were scheduled none of them showed up (2 authors cancelled their participation to OSTST, 1 was not ready to present results, 1 could not print its poster before attending). However, 2 posters in other sessions presented results based on CFOSAT data.

4.2.1 Oral presentation summary

The first talk by **Danièle Hauser** gave a summary of the mission objectives and main characteristics of the SWIM instrument (near-nadir Ku-band radar with a rotating antenna), presented the parameters estimated from the observations (significant wave height and wind speed from the nadir echo, directional spectrum of ocean waves from off-nadir beams), and discussed the overall quality of the retrieved wave spectra as assessed during the verification phase. An emphasis was put on the fact that an accurate radar backscatter speckle correction is essential to reliable directional wave spectra measurements in any SWIM azimuth look direction. In particular, it was shown that the correction of speckle energy spectrum must take into account the reduced number of independent samples when the instrument looks in directions aligned with the satellite track. Comparisons of wave spectra and wave parameters between SWIM and independent data (buoy, wave models) have been presented. It was concluded that gravity wave spectral data from off-nadir are very promising as illustrated by i) the high correlation index between SWIM and model spectra, ii) the consistent shape of 1D height or slope spectra compared to in situ data and model data, iii) case studies of wave growth analyzed under fetch-limited conditions. It was also shown that a proposed approach to better account for the speckle noise is promising and should help overcome the present limitation evidenced in the wave spectra (erroneous spectral signal observed near the along-track direction). The scientific products are already accessible to the CFOSAT science team, and the access will be enlarged through the AVISO+ web data server starting in a few weeks: https://www.aviso.altimetry.fr/fr/missions/missions-en-cours/cfosat.html

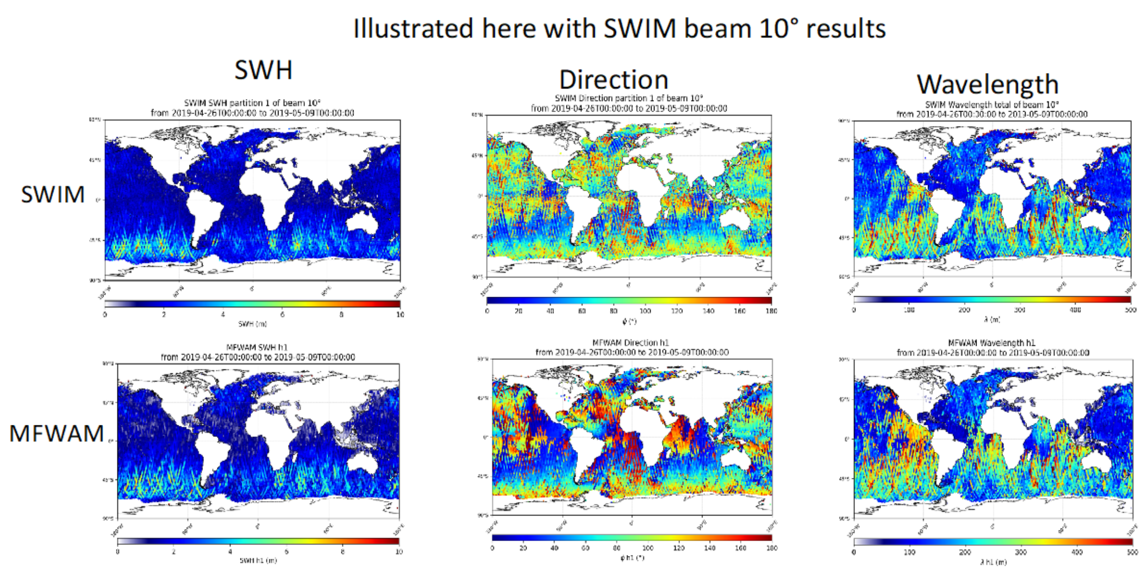


Figure 4.2-1: From D. Hauser. Preliminary assessments: Main parameters of the 1st partition (SWIM and MFWAM partitioned independently)

The second talk by **Annabelle Ollivier**, presented the performance of the SWIM altimeter retracking process based on the "Adaptive retracking algorithm" implemented in the Near-Real time French ground-processor to analyze the nadir wave forms. It was recalled that this method is based on three innovations with respect to the algorithms used in the operational processing of most of the other altimeter missions: i) use of the real Point Target Response of the instrument (as measured from calibration sequences), ii) platform mispointing values used as input to the inversion (estimated from the off-nadir beams in the case of CFOSAT), iii) minimization between the Brown radar return waveform model and the waveform carried out according to a maximum likelihood criterion accounting for speckle noise statistics. It was first shown from simulations that using the real shape of the PTR instead of an analytical Gaussian one decreases significantly the bias on the retrieved significant wave height. This was also confirmed with the real data from CFOSAT. Furthermore, it was shown that the adaptive algorithm reduces the noise level on the significant wave height by 45% compared to the MLE4 algorithm (both applied on a same data set). Thanks to a more accurate fit (Brown model fit to the waveform), the behavior of sigma0 in non-standard scenes (ice, bloom, rain) can be better characterized. Finally, SWH estimated with the adaptive algorithm compared to wave model data or with altimeter observations at cross-over points show a very good consistency with small standard deviation (35 cm) and without any needs for bias correction.

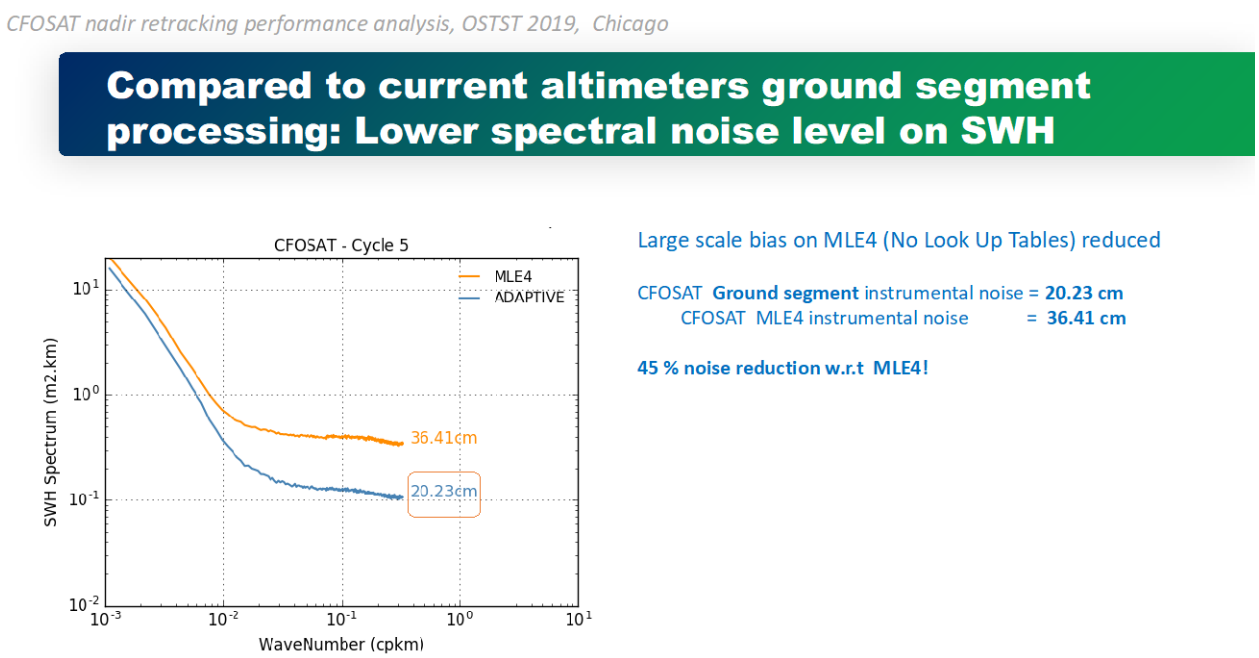


Figure 4.2-2: From A Ollivier.

The third talk by **Bruno Picard** was about methods to flag rain events in the SWIM data from both the nadir and off-nadir beams. For nadir signals, The Rain/Bloom flag for SWIM is based on the Continuous Wavelet Transform approach adapted from the Matching Pursuit Algorithm which is currently applied on SARAL/AltiKa (see Tournadre et al., Marine Geodesy 2015). It was shown that although this method is appropriate in the case of SWIM, its current implementation underestimates the occurrence of rain events (in particular at high latitudes) and overestimates the occurrence of bloom near the coastal regions. Tuning of the matching pursuit algorithm is in progress to correct these shortcomings. As for a rain flag for the off-nadir beams an indicator based on the variability of the signal (filtered at 500 m) at the scale of the swath has been proposed. It was shown that this indicator is a good candidate for detecting variability on the backscatter profiles due to rain.

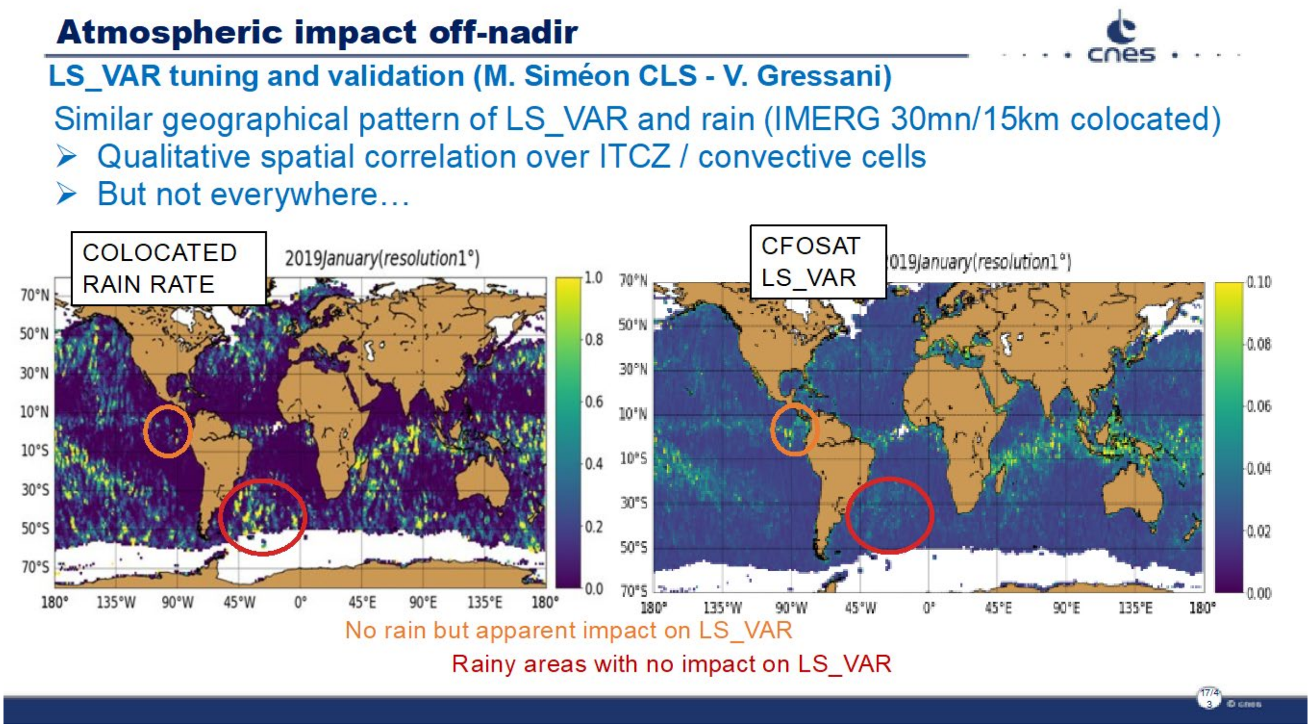


Figure 4.2-3: From B. Picard.

The fourth talk by **Lotfi Aouf** was about assimilation of CFOSAT wave data into the global wave forecast model of Meteo-France (MFWAM). From a routine comparison it was first shown that the scatter index of the difference between nadir and MFWAM SWH is in general of the order of 10% except during periods of cyclonic events. Then, different tests of data assimilation were presented. The assimilation of SWIM L2 Nadir data shows significant impact on SWH in the analysis and in the forecast period and better agreement with altimeter observations in terms of the SWH scatter index metric. The impact of the assimilating SWIM wave period data is also significant. Results clearly suggest the utility of SWIM-nadir data operationally. Furthermore, the CFOSAT data were shown to efficiently adjust model misfits in storms events (cyclones, typical Mediterranean cases). The assimilation of spectral data from SWIM beam 6° and 10° already indicate similar performance as regarding SI of SWH. Retrieval Improvements are still needed to enhance the forecast system impact using directional wave information via assimilation of partitioned spectral wave mode information (work in progress).

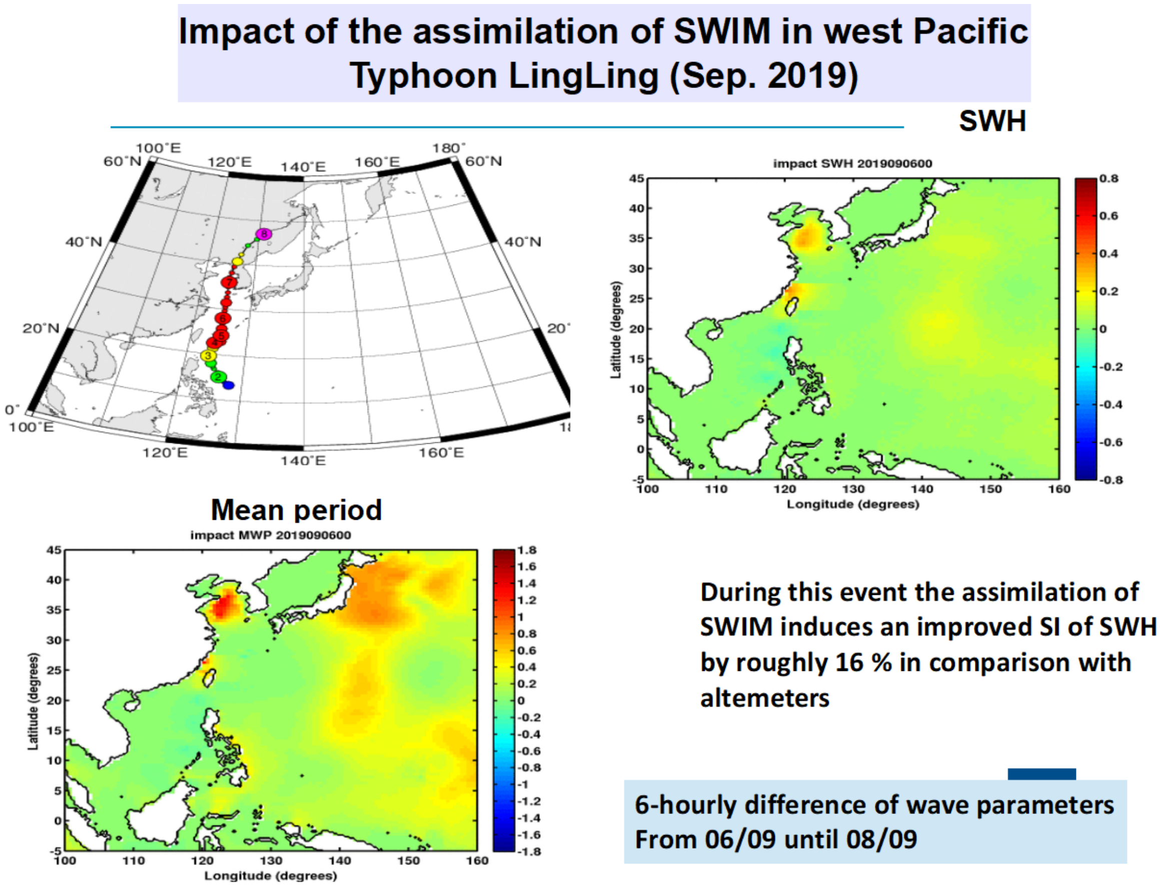


Figure 4.2-4: From L. Aouf.

4.2.2 Splinter discussion points

These were the points proposed based on session discussions:

How can CFOSAT complement other altimeter mission objectives?

- in terms of enhanced spatial coverage for SWH (including 2-D gradients)
- in terms of new products (wave period, directional spectra of waves, altimeter combined to scatterometer wind)
- Could SSH be derived from the CFOSAT altimeter?
- In terms of new/enhanced applications (MIZ, coastal, wave-current)
- New insights for sea state bias correction?
- Interpreting interferometric altimeter data (e.g. SWOT)?
- Understanding swell impacts on Delay Doppler (and/or GNSS, SKIM,..)?

Moreover, details related to these discussion points were raised:

- SSH is not derived from the nadir beam wave form of CFOSAT because strictly speaking CFOSAT is not an altimeter mission (no precise orbit measurement/determination, no collocated measurement for atmospheric corrections), but the wave form is one of the product of the mission
- the Adaptive method instead of the MLE4 method is used for retracking the nadir wave form. If the scientific community is interested, CNES could provide some data sets processed with MLE4 in addition.
- there should be an interest to analyze the wave forms from the 2° beam In a way similar to that used for the nadir echo (after adapting the reference Brown model).

4.3 Coastal Altimetry

Chairs: Mathilde Cancet and Ted Strub

There were five oral presentations and six posters in the Coastal Altimetry session. The presentations covered three main topics: 1) Creation and validation of coastal altimetry products; 2) Applications to regional coastal circulation and sea level rise; and 3) Comparisons between altimetry and tide gauge estimates of sea level variability. The studies were carried out in a wide range of regions, include the North-East Atlantic (North Sea, Baltic Sea), the Mediterranean Sea, the Patagonia shelf, the larger-scale South Atlantic Ocean and the African coasts. Summary statements from each of the presentations are found below.

4.3.1 Creation and Validation of Coastal Altimetry Products:

- Fenoglio et al.: The SAMOSA+ SAR retracking and the STAR RDSAR retracking show the best performance in terms of noise reduction and gain of data close to the coast, in the German Bight and in the Eastern Baltic Sea.
- Dinardo et al.: The SAMOSA+ SAR retracking reduces the noise over the standard PDGS SAR retracking. Including the Range Integrated Power (RIP) in the SAMOSA+ retracking (SAMOSA++) reduces the along-track noise near the coast slightly more.
- Dayoub et al.: Within 8 km of the coast, ALES retracking improves the PLRM data from Sentinel-3 (A&B) altimeters. However, SAR mode retrievals provide significant improvements in comparison to the PLRM mode from both SGDR and ALES processing. Estimating SSB at 20 Hz has a positive effect in reducing range noise of the LRM and PLRM products close to the coast.
- Léger et al.: The X-TRACK editing at 20 Hz improves the ability to retrieve data close to the coast compared to 1 Hz X-TRACK (2-4 km). Adding ALES retracking improves it slightly more.
- Müller et al.: A new altimetry product called SEAL is under development for the Baltic Sea. It is based on unsupervised (AI) classification of altimetry waveforms and ALES+ retracking for peaky waveforms. The method includes regional inter-mission cross-calibration. The SEAL data set fills in the northern part of the Baltic Sea.

4.3.2 Applications to Regional Coastal Circulation and Sea Level Rise

- Bosson et al.: X-TRACK altimeter data along the Guinea coast shows the seasonal variability. During the maximum eastward velocities in summer, they reveal a reverse current very close to the coast, which is not resolved in the standard AVISO fields.
- Casella et al.: An index of intrusion of the Northern Current and transport into the Gulf of Lion was developed using synthetic altimetric data from SYMPHONIE model and winds. It works well except for rapid intrusions and when there are strong wind events.
- Lago et al.: An estimate of the transport over the wide Patagonian shelf has been developed and represents time scales from day to inter-annual. The annual and shorter time scales are associated with the meteorological forcing and the inter-annual variability associated with the Southern Annular Mode (SAM)
- Le Hénaff et al.: The coastal altimetry data are used to fill the gap between the offshore mooring array and the shelf, in order to estimate the transport over the wide Patagonian shelf.

4.3.3 Altimetry/Tide Gauge/Model Comparisons

- Dieng et al.: The comparison of the altimeter to the tide gauges along the African coast (35°S–25°N; 25°W–African coasts) gives mixed results depending on location. Possible causes for poor comparisons include placement of the tide gauges (within small bays or protective features), geophysical corrections, and errors in the tide models used in the comparisons.
- Shaw et al.: Tide gauges located in regions with small sea level coherence will not reflect the performance of altimetry measurements. The NEMO numerical ocean circulation model is used to group the tide gauge locations based on the alongshore decorrelation length-scales for the long sea level trend records (not just the sea level itself).

4.3.4 Discussion

In the Discussion that followed the presentations, several points were made regarding questions posed by the meeting and session organizers:

- Interleaved versus geodetic orbit for Jason-3:
    - If, by placing Jason-3 into another geodetic orbit, we would improve the mean sea surface in coastal regions, this would allow us to compute more accurate SLA values close to the coast in a consistent fashion for multiple missions.
    - On the other hand, placing Jason-3 into an interleaved orbit similar to the previous ones might improve the tide estimates in coastal regions.
    - Before a decision is made, we need to study and quantify the duration of the interleaved phase that would significantly reduce the errors on tide estimates; similarly we need to assess the duration of a new geodetic phase that is needed to improve the mean sea surface in coastal regions.

- MDT: We continue to need improved estimates of the long-term Mean Dynamic Topography and the mean surface geostrophic currents. These are needed at higher resolution in coastal domains. Assimilating a few sparse drifter velocities in coastal regions into these MDT fields can produce unrealistic features in the MDT that then contaminate any field that uses the MDT to produce absolute geostrophic velocities. This is an ongoing problem with the stand-alone MDT fields and also in the numerical model mean SSH and surface geostrophic velocity fields, which also assimilate the available drifter velocities, regardless of their sampling characteristics. We need uncertainty estimates on the MDT fields and their associated velocities.
- The altimetry missions (along-track data) should be carefully and regionally cross-calibrated. People need to combine along-track data from multiple missions to increase the spatial resolution within smaller coastal regions. This is needed for circulation studies and even more so for regional sea level rise studies.
- It is suggested that we need more connections and interactions with coastal physical oceanographers, especially for those who collect in situ data to relate the remotely sensed data to observations and insight into a larger range of coastal circulation phenomena. The Gordon Conference on Coastal Oceanography was mentioned as a possible venue for joint meetings.

4.4 Instrument Processing: Measurements and Retracking

Chairs: Phil Callahan, Jean-Damien Desjonqueres, Alejandro Egido, Cristina Martin-Puig and Walter H.F. Smith [Unable to participate: Francois Boy and Robert Cullen]

The Instrument Processing Measurements and Retracking Splinter (IPM) had ten oral presentations and five posters. Much of the material discussed SAR processing with additional work on improved methods and new applications of the improved accuracy provided by high rate data.

The main conclusions were:

- Features of the TOPEX data including hemispherical signatures, sigma0 calibration, and the Wallops Range Correction are now understood and can be mitigated in the new retracking process.
- The effects of surface motion in high-resolution altimetry leads to bias and noise increase in the geophysical retrievals; explains most of the difference between SAR and PLRM. Methods to account for it in processing need significant additional work.
- Instrument calibration data must be analyzed in depth and used in processing to provide the best products. This was illustrated by applications to TOPEX, AltiKa and Sentinel-3A.

All the work presented is promising and provides candidates for algorithm evolution, but further testing is needed to properly quantify the improvements.

Recommendations:

- The GDR-F format should include important processing and auxiliary information such as Point Target Response, waveform filter weights, environmental data pointers, and information from the platform such as attitude. Most of these data can be added as metadata, but some may need to be on a point-by-point basis.
- The GDR-F format should include additional environmental variables such as wave model parameters (e.g., swell). This is needed for future missions (e.g. Sentinel-6) that also adapt these standards to fully understand sensitivity of High Resolution or SAR altimetry to these effects.
- While consistency among missions is crucial for climate studies, bringing all missions up to the latest standards is also important. Processing and distribution agents should coordinate so that the best data are available for climate studies.
- A common benchmark should be defined to evaluate if an innovation is mature, and justifies its added value in operations. The benchmark needs to contain a significant amount of data spanning many conditions.

4.4.1 Session Summary

4.4.1.1 TOPEX Reprocessing

Desjonqueres et al. gave an update on TOPEX reprocessing. The historical TOPEX data products contain well-documented anomalies that are particularly obvious in the time series of Significant Wave Height (SWH) from the side-A altimeter but also in hemispheric differences (north/south, ascending/descending, see Figure 4.4-1) related to range rate in both the original GDR and retracked products until now. The SWH drift was caused by changes in the Point Target Response (PTR) as has been discussed previously. Use of “Cal Sweep” data to enhance the sparsely sampled Cal-1 data together with numerical retracking improve mitigation of this effect. These improvements also provide a consistent sigma0 without need for an empirical adjustment. Full understanding of the determination of the PTR also reproduces the previously-disputed Wallops range correction. Careful application of the Cal-2 (filter “weights”) data consistent with the altimeter functioning, significantly mitigates the hemispherical effect. In the course of this investigation an error in the alignment of waveforms and telemetry data was found. Correcting this reduces noise and improves the agreement with Jason-1 during the colinear calibration period. The reprocessed data are being evaluated, mainly by comparison with Jason-1. It is also hoped to have the POSEIDON data reprocessed as an external calibration source, especially for the side-A to side-B transition.

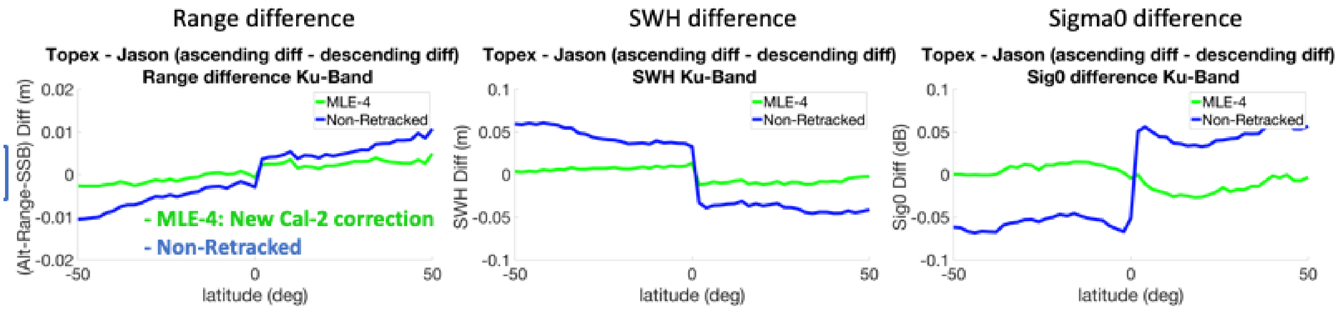


Figure 4.4-1: Mitigation of North/South Ascending/Descending difference in new numerical retracked (MLE4) TOPEX data compared to Jason-1.

4.4.1.2 Point Target Response drifts impact on geophysical parameters

Poisson et al. discussed and compared instrumental drifts for Sentinel-3, Jason and AltiKa missions. Sentinel-3 Point Target Response drift impacts on geophysical estimates are evaluated. Four features of the PTR have been here considered for this evaluation, taken as independent parameters:

- Total power
- Internal path delay (energy median location)
- Main lobe width
- Sidelobe asymmetry

The effects of the first two are accounted for using calibration data in the regular ground processing while the latter two are not. The effect of the last one is likely to be more significant as it affects both range and SWH estimates.

The Sentinel-3A/SRAL SAR PTR is drifting in each of these ways. The first three are similar to other altimeters, but the asymmetry change is much stronger compared to other altimeters. This impact must be accounted in the Level-2 products and progress is in progress to compensate for this drift. As noted above, asymmetry can strongly affect SWH estimates (~3.4 mm/yr), so the effect on Sea State Bias (SSB) is nearly as large (~ -0.10 mm/yr) as the direct effect on range (~0.175 mm/yr; total ~ -0.277 mm/yr). Both drifts are SWH dependent, but the SWH drift is particularly sharp for SWH < 2 m. The impact on PLRM data is similar; the net range drift is estimated also to be ~ -0.32 mm/yr.

The method used here allows generation of Look Up Table corrections which is compatible with the current regular ground processing. However, the authors mention that the most rigorous approach to correct for the drifts involves numerical retracking and directly introducing the measured PTR.

4.4.1.3 Effect of surface motion in SAR altimetry

The effect of surface motion in SAR altimeter observations was discussed by three groups: Egido et al., Buchhaupt et al, and Amarouche et al.

For SAR systems with a moderate resolution, as is the case of delay/Doppler altimetry, [Raney, 1998], Egido et al. assumed that waves of intermediate wavelengths are the ones that play a more significant role, and in this case, it is the finite surface coherence that induces the degradation of azimuth resolution. Egido et al. developed a SAR-Altimetry numerical simulator to evaluate that effect:

- The simulations do not include thermal or speckle noise, just to concentrate on the effect of along-track resolution degradation on the retrieval of geophysical parameters.
- They assume an along-track resolution degradation due to vertical wave motion based on a classical SAR paper [Alpers and Bruening, 1986].
    - They observed that the ENL ratio between 80 Hz and 20 Hz delay/Doppler waveforms presents a similar degradation with wave height as the along-track resolution variation.
- The numerically simulated echoes were then retracked with a model that doesn't include vertical wave motion present significant sea state dependent errors, whose trends are comparable to the SAR vs PLRM trends observed in Sentinel-3A data.
- Those trends are highly dependent on the DDM processing options.
- The vertical wave motion effect will soon be implemented in the NOAA/LSA SAR Altimetry Processor.
    - This will be used to retrack S3A data to verify if sea-state dependent biases can be mitigated.

Along the same lines, Buchhaupt et al. argued in their presentation that the "frozen surface" assumption leads to SWH-dependent errors in SAR processing. They also showed that the resolution degradation in FF-SAR could be severe. The authors implemented a 2D-retracking method to account for vertical velocity. They observed that:

- With LRMC-F the SWH consistency with respect to RDSAR improves.
- The estimate standard deviations of vertical wave particle velocities have a good consistency with ECMWF.
- The estimated wave steepnesses have a reasonable range.
- However, it is still necessary to thoroughly validate all geophysical parameters with in-situ data.
- An additional examination of fully focused SAR shall be considered in future works.

Amarouche et al. analyzed the effect of wave motion with realistic numerical simulations of sea surfaces by estimating the statistics of the Doppler shift induced by the surface motion, using El-Fouhaily spectrum for different sea states conditions, angles of incidence and frequencies.

They determined that the effect of vertical wave motion is stronger for higher significant slopes, i.e. shorter wavelengths and higher amplitudes, and is not dependent on the wave propagation direction.

The numerical simulation results showed that the high positive biases observed on the SAR mode significant wave height (SWH) estimations of real Sentinel-3 data, in comparison to the low-resolution mode, are explained by the waves orbital velocities that affect the Doppler signal. At the same time, SWH is underestimated in the case of swell with high wavelengths propagating in the same direction as the satellite. In this case very high noise is observed on SWH and range estimates.

It was also determined, that, at a first order, the waves vertical velocity has no significant impact on the range estimates, as no biases are observed.

4.4.1.4 Reducing noise on SWH high-frequency estimations

Tran et al. discussed a method for reducing the high-frequency noise in Jason-3 and Sentinel-3A SWH data. They focused on SWH data precision to improve the signal-to-noise ratio to increase the consistency between different missions and processing algorithms at intermediate scales and to identify short wavelength features (< 100 km). The method proposed an additional post-processing step that is not low-pass filtering where one gets loss of small-scale geophysical information depending on the cut-off choice, but rather an empirical correction that reduces the high-frequency variability in the SWH estimations using the correlation between range and SWH that occurs in retracking. The approach is basically the inverse of previously proposed methods for reducing range (SSH anomaly) noise using this correlation. The corrected 20-Hz SWH values are

SWH_corr = SWH – High_Frequency_Adjustment

where the HFA depends on mission, processing mode, and retracking algorithm through terms based on the cross-correlation of SWH and SSHA residuals smoothed empirically determined scales (perhaps different). The spectra of SWH_corr extend down to about 50 km and show noise floors about 50% lower than the original MLE4 results. The improvements are less dramatic for SAR data.

4.4.1.5 Evaluation of Sentinel-3A & B sea-state data from tandem phase

Banks et al. reported on using the Sentinel-3A and Sentinel-3B tandem phase to evaluate the quality of wind speed and SWH from the two missions. Sentinel-3A (S3A) has been in orbit since February 2016 and routinely provides data on ocean wind and waves (significant wave height/SWH, Sigma0 and wind speed). S3A was joined in orbit by Sentinel-3B (S3B) in April 2018 with a requirement to establish the consistency of the instruments on the two satellites, through inter-comparisons with each other and also comparisons with independent data. The operation of S3B in tandem with S3A during the early phase for approximately four months provides a unique opportunity to obtain data close in space and time to quantify instrument-related sources of discrepancies. During the tandem phase, S3B flies as little as 30 seconds ahead of S3A. Direct comparisons of SWH and wind speed generally show excellent agreement with data clustered around the 1-to-1 slope line, although with "wings" of outliers for SWH <~3 m. Agreement with wave models is not quite as good, especially at low SWH. A collection of results for SWH at shown in Figure 4.4-2. Similar results are obtained for wind speed with a standard deviation of <~1.5 m/s. The main observations are

- Sentinel-3 Tandem phase reveals excellent agreement between altimeters on S3A and S3B for SWH and wind speed
- Very good agreement between SAR and P-LRM for both S3A and S3B
    - SAR SWH still occasionally biased high in low sea states
- Special S3A SAR/S3B LRM dataset especially useful and encouraging
    - Further work to study SAR/LRM in different sea states
- Comparisons with models (Hi-WW3, ERA5) reveal various issues with wave model data

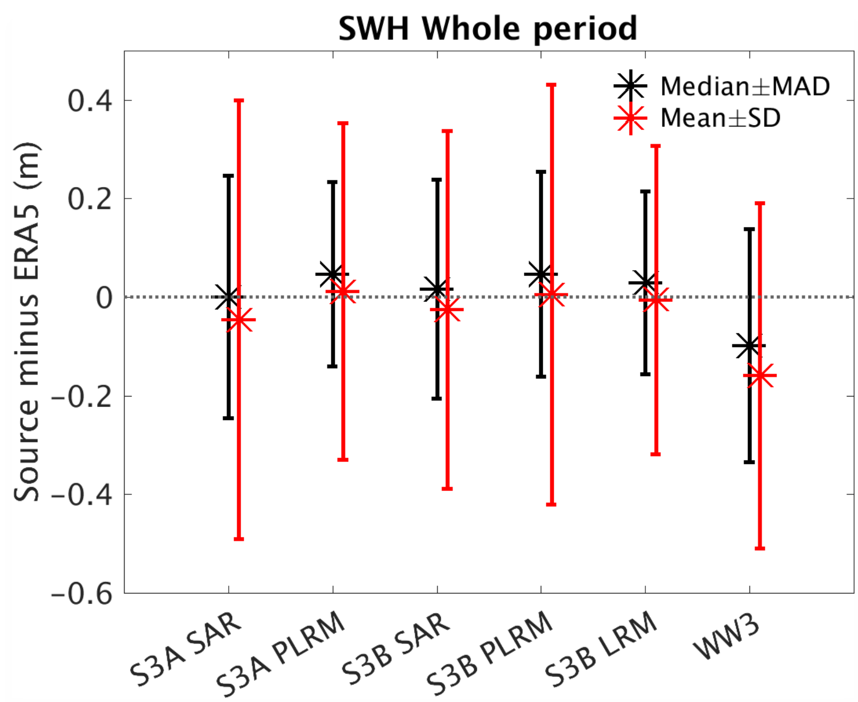


Figure 4.4-2: ERA5 SWH Difference for various data sets during 8 June 2018 – 15 October 2018 (14 June – 11 July 2018: S3B in LRM, S3A in SAR mode).

4.4.1.6 Using Sentinel-3A & B tandem phase to better characterize SAR altimetry signals

Rieu et al. used the four-month-long close formation of S3A and S3B, during which the two satellites were observing the same scene a mere 30 seconds apart, to better characterize open ocean SAR signals with unfocused and focused processing. By exploiting the reduced time lag between the datasets, the signals related to rapidly evolving phenomena, like propagating swells, surface heterogeneities and surface motion, can be identified in a more efficient way than with a single satellite data. Only fully focused SAR (FF-SAR) processing (not standard unfocused SAR, UF-SAR) sampling frequency satisfies Nyquist for sampling swell. FF-SAR data are multi-looked to ~50 m which is adequate for swell >150 m. FF-SAR spectra of SSH anomalies shows a peak at the wavelength given by wave models (~500 m for the cases studied). UF-SAR aliases this peak due to larger sampling resolution. Furthermore, phase shift analysis between S3A and S3B spectra are consistent with the wave phase velocity given the relative direction of swell and footprint displacement. In fact, the phase shift in the cross-spectral density also provides the orientation (correlated or anticorrelated) of the swell propagation with respect to the satellite flight direction.

It confirms the UF_SAR is impacted by swell, in particular, it explains its colored noise spectrum at high frequency. It also demonstrates that higher resolution processing like FF-SAR could be useful to recover the swell signal period.

4.4.1.7 Ice thickness estimation

Fleury et al. discussed ice thickness estimation and the uncertainties in determining freeboard (height of ice above water surface) using altimetry. One major source of errors is the misinterpretation of complex multi-return echoes by the retracker. Even for SAR returns can be confused by bright off-nadir returns in the sidelobes.

The method presented allows identifying the peak of the waveform that corresponds to the nadir, even in very complex configurations. It relies on the flatness characteristic of the sea-ice (+/-50cm) and the use of a good mean sea surface (DTU15) to align and extract the key part of the waveform which is then used for detection along the whole echogram one satellite track. The results show relatively good agreement with measurements from Operation Ice Bridge (airborne) and Beaufort Gyre moorings. There remain possible uncertainties in the ice thickness because of the effects of snow and surface penetration.

4.4.1.8 SCOOP project

Cotton et al. presented SCOOP (SAR Altimetry Coastal & Open Ocean Performance), which is a project funded under the ESA SEOM (Scientific Exploitation of Operational Missions) Programme Element, to characterize the expected performance of Sentinel-3 SRAL SAR mode altimeter products, and then to develop and evaluate enhancements to the baseline processing scheme in terms of improvements to ocean measurements.

They reported the development and testing of new processing approaches designed to improve performance, including:

- Application of zero-padding
- Application of intra-burst Hamming windowing
- Exact beam forming in the azimuthal direction
- Restriction of stack processing to within a specified range of look angles.
- Along-track antenna compensation
- Data used in the tests were from ten fairly small regions selected to cover a wide range of oceanographic conditions over 2012-13 (except the Harvest area which includes additional data). Two test data sets were generated: TDS1: CryoSat FBR baseline C data – reprocessed with Sentinel-3 SRAL baseline configuration
- TDS2: Modifications to TDS1: SAR processing includes zero padding in range, and intra-burst Hamming windowing

The data also included an enhanced wet troposphere correction from University Porto (GPD+).

The main results were a significant improvement in SWH performance and fairly small improvements in SSH and sigma0. The SSH anomaly spectrum was unchanged for wavelengths longer than 50 km, with the expected improvement for SAR processing for wavelengths down to about 30 km.

The main **recommendations** from the work are:

SAR Mode Processing

- The use of the innovative SARM processing (Zero-padding and Hamming window) for Sentinel-3 mission is recommended to improve ocean altimetry products
- In situ measurements are needed to fine tune and calibrate the PTR settings.
- SSB correction dedicated to the SAR SSH is needed to compute accurate SSH.
- Further studies should be carried out into the development of coastal re-trackers for SAR mode echoes.

RDSAR Processing

- Coastal re-trackers should be applied for coastal data sets.
- Further tests on MLE4 re-tracker on the RDSAR product should be carried out.

Wet Troposphere Correction

- The GPD+ correction clearly outperforms the ECMWF operational model-derived correction.
- The composite correction present in Sentinel-3 products is not suitable for use. The GPD+ WTC would be an added value for Sentinel-3A products

4.4.1.9 POSTERS

IPM_001: Applying the pulse-pair processing to high PRF nadir altimeter data: sensitivities to geophysical parameters and possible applications: Pierre Rieu et al.

IPM_002: Exploring the potential of Sentinel-3 fully-focused SAR altimeter range data for enhanced detection of coastal currents along the Northwestern Atlantic Shelf: Hui Feng et al.

IPM_003: Evaluation of FF-SAR Altimetry Observations over the Open Ocean: Alejandro Egido et al.

IPM_004: Impact of the Sentinel-3A SRAL PTR Evolution on the L2 Marine Measurements: Salvatore Dinardo et al.

IPM_005: ICESat-2 Altimetry of the Open Ocean: James Morison et al.

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

Chairs: Shannon Brown, Estelle Obligis, Marie-Laure Fréry

The instrument processing corrections splinter focused heavily on the wet tropospheric path delay correction on various altimeter missions, including Sentinel 3 and Jason 2/3. The IPC splinter had the following recommendations discussed further below:

Recommendations:

- Future altimetry missions should consider radiometer designs that are more adaptable/tolerant to an increasingly contaminated RF environment
- Existing missions should plan for RFI detection/filtering algorithms to developed and implemented in the ground software
- The IPC splinter unanimously agreed that any algorithm/calibration updates related to corrections (e.g. WPD, SSB) should be back-applied to prior missions routinely.

4.5.1 Wet Path Delay – Calibration

Jason-3 AMR

Several independent analyzes showed that the Jason-3 AMR path delay is stabilized to the mm-level over the mission to date. This level of stability was verified against multiple independent sources including the ground based GPS path delay product (GPD+), SSMI and NWP models.

Sentinel-3 MWR

The Sentinel-3 MWR brightness temperatures are monitored relative to vicarious sources including the Amazon rainforest and cold ocean points. In both cases, the S3 TBs are found to be stable within the uncertainty of the comparison. The WPD is also shown to be stable over mission relative to external sources, including GPD and NWP models.

Coldest ocean points		Amazon forest	
3 years	S3A	3 years	S3A
23.8 (K/yr)	-0.02 (-0.07 / 0.04)	23.8 (K/yr)	0.02 (-0.12 / 0.17)
Liq. wat/. (K/yr)	-0.05 (-0.11/0.00)	Liq. wat. (K/yr)	0.02 (-0.11/0.16)

Figure 4.5-1: Comparison of Sentinel 3 MWR to vicarious TB references.

4.5.2 Wet Path Delay – Algorithms

The current wet path delay algorithm for S3 MWR uses a neural network with 3 input parameters. An updated version with 5-input parameters is currently under test, but not yet showing improved performance. This will be updated at the next OSTST.

Work is also progressing on 1-D variational approaches. Comparisons with climatologies show that a 1DVAR retrieval provides results for water vapor and wet tropospheric correction with a level of quality similar or higher than the heritage algorithm. On top of geophysical products, 1DVAR retrieval provides a traceable and physical uncertainty estimates alongside each retrieved parameter. Additionally, it was shown that active/passive 1DVAR simultaneously improves wet tropospheric correction, atmospheric attenuation and altimeter wind speed products in physically consistent way.

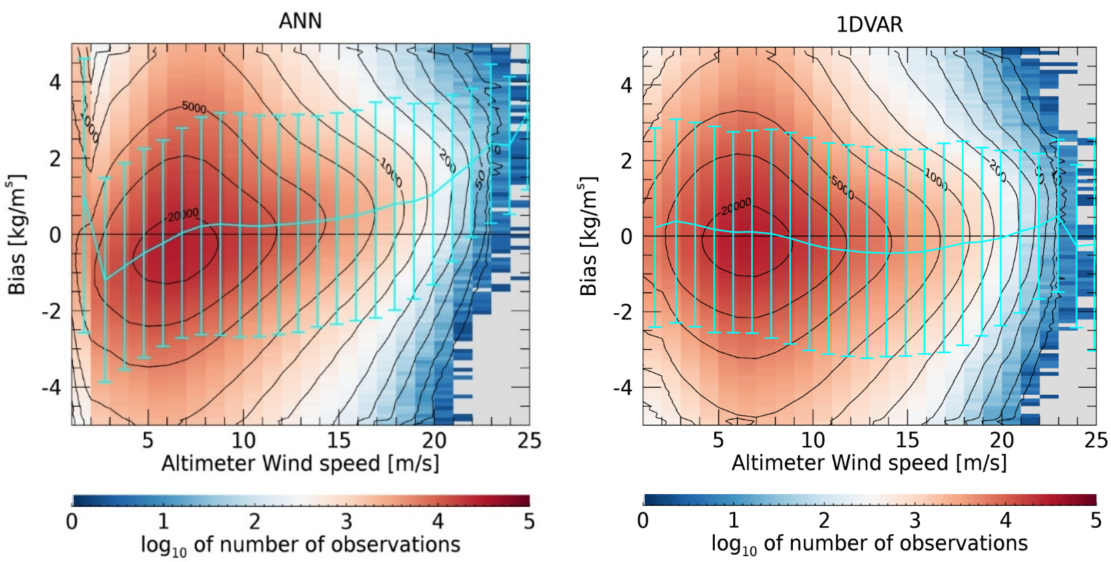


Figure 4.5-2: Comparison between a 1DVAR algorithm and the heritage PD algorithm showing slightly better performance.

4.5.3 Issues from Project Scientists

The IPC splinter considered the following issues raised by the project scientists:

5G Contamination: Concerns have been raised on radio frequency interference from the 5G spectrum on the 23.8 GHz radiometer channel

<u>*Response*</u>:

This is a serious concern that could impact the ability of future altimeter missions to provide accurate wet tropospheric path delay corrections. The issue is that spectrum for 5G communications has been allocated in a band adjacent to the passive 23.8 GHz band used by most water vapor radiometers. The allowable power levels in the adjacent band are high enough that it could leak into the passive. International agencies have provided inputs on this 5G issue, raising concerns about impacts on passive microwave water vapor measurements. The expectation is that RF spectrum contamination issue will only get worse with time.

<u>Recommendations</u>:

- Future altimetry missions should consider radiometer designs that are more adaptable/tolerant to an increasingly contaminated RF environment
- Existing missions should plan for RFI detection/filtering algorithms to developed and implemented in the ground software

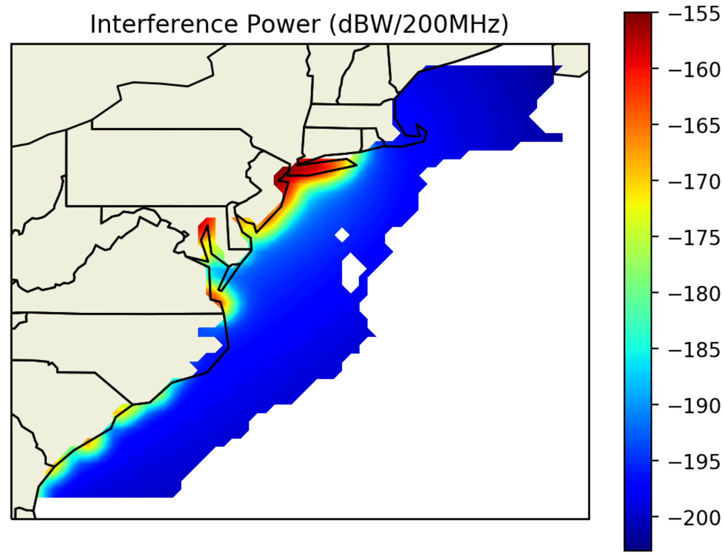


Figure 4.5-3: Interference power from 5G ground sources.

Sentinel-6 Annual Reprocessing

- "Annual" reprocessing is planned as part of operations (similar to Sentinel-3 all instruments) triggered by major evolution of processing baseline. Aimed at keeping the S6 products as near to the state-of-the-art as possible.
- Jason-1 through -3 products may be "left behind" if not updated as well (Jason-2, -3 will be updated to GDR-F), and could break the consistency. Should these go through more regular reprocessing as well?

Response:

The IPC splinter unanimously agreed that any algorithm/calibration updates related to corrections (e.g. WPD, SSB) should be back-applied to prior missions routinely.

4.6 Outreach, Education & Altimetric Data Services

Chairs: Jessica Hausman, Vinca Rosmorduc and Margaret Srinivasan

4.6.1 Session presentations

- The Latest Updates at PO.DAAC, Jessica Hausman
- Some cool things we do with ERDDAP, John Wilkin
- Ocean and Climate Change Education Using Fiction, LuAnne Thompson et al.
- Citizen science and volunteers in floateco project, Nikolai Maximenko et al.
- Argonautica, altimetry from kindergarten to engineering school, Danielle De Staerke et al.
- Showcase of altimetry outreach & data services

- RUS: Research and User Support for Sentinel Products, Simon Boitard et al.
- JPL altimetry ruler, Annie Richardson
- Use of satellite oceanography data in The Coastal Ocean Environment Summer School in Ghana, Brian Arbic et al.
- TUDaBo: The SAR-RDSAR Processing Service on G-POD, Luciana Fenoglio et al.
- Argonautica complete reprocessing, Vinca Rosmorduc et al.
- ROMS Doppio* regional model of northeast U.S. coastal waters, John Wilkin
- SWOT Applications, Margaret Srinivasan

4.6.2 Posters

- Outreaching hydrology from space & SWOT (updates), Vinca Rosmorduc et al.
- RUS: Research and User Support for Sentinel Products, Simon Boitard et al.
- Exploring ocean eddy characteristics through the DynEd atlas, Yannice Faugere et al.
- TUDaBo: a G-POD service for SAR and RDSAR Products, Luciana Fenoglio et al.
- PO.DAAC's Redesigned Web Portal, Jessica Hausman et al.
- PO.DAAC in the Cloud: Data Services and Access, Jessica Hausman et al.
- The ESA CCI Knowledge Exchange: explaining climate from space with altimetry and other EO data, Stephen Plummer et al.
- Aviso+ products & services: what's new?, Laurent Soudarin et al.
- Feedback loops in product development for Sentinel-3 and Sentinel-6 altimeter missions, Remko Scharroo et al.
- Altimetry Applications Program Status, Margaret Srinivasan et al.
- SAR and SARin Altimetry Processing on Demand for Cryosat-2 and Sentinel-3 at ESA G-POD, Jérôme Benveniste et al.
- The BRAT and GUT Couple: Broadview Radar Altimetry and GOCE User Toolboxes, Jérôme Benveniste et al.
- NOAA CoastWatch/OceanWatch Altimetry Products, Jessica Burns et al.
- Homogeneous along-track sea level anomalies (Level-2+) data set for all altimetry missions, Sabine Philipps et al.

4.6.3 Demos this year:

- PO.DAAC new services
- An unlikely insurgency web series
- ESA RUS
- Argonautica web site

4.6.4 2018-2019 Highlights

The session had a full share of submissions from outreach and education as well as from data services; in fact, we received substantially more requests for oral presentations than there were time slots available. This year there were more posters on data services, and more Showcases on outreach and education topics.

Updates of data services were shared from NASA PO.DAAC, NOAA STAR, EUMETSAT, AVISO, and ESA.

Outreach and education projects from partner agencies continue to provide insight and illumination on altimetry science and technology, educational opportunities, and societal benefits. New activities may arise as we approach the launch of SWOT. This will follow from the addition of new people joining the community, and from new topical areas such as hydrology and coastal studies.

There were fewer training topics presented this year, but discussion afterwards showed that some more people might have presented on this. We will emphasize this aspect of relevant presentation topics for future OSTST abstract calls for the ODS splinter.

The demo format recommended during the last two OSTST meetings was realized this year with several candidates providing demonstration opportunities throughout the meeting space, and at several scheduled times. Logistical and technical challenges, as well as improved communication of the demo times and locations will make this a more substantive part of the ODS splinter in future meetings. We will solicit more candidates to demo activities and tools, and hope to attract more attendees. One method would be to provide a schedule for demos in the general meeting agenda.

4.6.5 Data services

Data Services provide a way of exchanging information and linking projects and users for greater benefit from the wide variety of altimetry-derived data available.

PO.DAAC and Aviso showed their latest tools and new datasets, and outlined plans for new mission data systems in development (i.e., Cloud for SWOT). EUMETSAT described Sentinel-6 data product distribution plans. Toolboxes and cloud services were also presented by ESA, with the now classical GOCE User Toolbox (GUT) and the renamed Broadview (formerly, “Basic”) Radar Altimetry Toolbox (BRAT), and also the ESA Grid Processing On Demand (GPOD) service.

4.6.6 Outreach

Brief summaries of Outreach and Education presentations include;

- LuAnne Thompson showed the first episode of former OSTST member Kathy Kelly’s “cli-fi” (climate fiction) web series, “An Unlikely Insurgency”. More information and video is available online.
- Nikolai Maximenko is working with a group that collects trash from the “garbage patch” around Hawaii, and analyses the biological material it carries. The project began with the tsunami debris but is more widespread now.
- Ted Strub is working with fishermen with a dedicated interface (showed in Applications session).

- John Wilkin demonstrated ERDAP capabilities.
- Patricia Ward, Director of Science Exhibitions and Partnerships at the Museum of Science and Industry, Chicago, gave a well-received keynote talk, “Engaging the Public in Addressing Climate Change,” during the 21 October plenary session. Dr. Ward introduced the OSTST to the Museum and highlighted their “Extreme Ice” exhibition. This was in keeping with our goal of providing local outreach opportunities in the city hosting the OSTST. In Miami, Florida, it was outreach from a local laboratory; In La Rochelle, France, free admission to the Aquarium was provided as part of the outreach session (in Miami it was outreach from a local lab, in La Rochelle the Aquarium in outreach session, and a free entry for it)

4.6.7 Education

NASA/JPL, in partnership with CNES, and now also NOAA and EUMETSAT, have developed various engagement materials over the years. Some new activities and products were shared.

Argonautica updated its processing system with new maps and reprocessed the entire time series from 2000; the latter enabling demonstration of long-term use cases. To prepare for SWOT, an “ArgoHydro” module is now available, with local measurements (in particular through GLOBE), but it also uses existing satellite data (e.g. water levels from Hydroweb).

4.6.8 Training

There are several ongoing training initiatives, by different agencies, programs, projects, Universities and even individuals, in different places and continents, with different focuses (data retrieval, ocean data uses, wind/waves operational applications, Sentinel-3 data uses, etc.). Brian Arbic showed one such example in Ghana. Eumetsat is continuing its series – (Copernicus Marine Data Stream training on Sentinel-3 data, mostly on ocean color and SST, but a little altimetry too), and ESA is organizing Synergy Ocean Training Courses (this year in November in Chania, Crete, with the collaboration of S. Mertikas).

How and where to retrieve data, how to read at the most basic level, and how to process data seem to be an important topics, that are, not always broached in formal curricula. Development of such trainings seems interesting both for the users and for the project.

4.6.9 Discussion

Discussion topics covered a broad range of formal and informal education potential, expanding the topical reach of ODS activities, and planning for future meetings. Some outcomes and specific questions included:

- How can we better reach out to museums and science centers to provide satellite data for input to climate change exhibits?
- The TOPEX/Poseidon data should be reprocessed, along with the proposed plan to reprocess the Jason-1 to 3 data, so that they will be more comparable to Sentinel-6.

- How should we advance coastal, hydrology, cryosphere, and ocean altimetry information to a broad audience of students, general public and data user communities?
- Should the OSTST try a joint meeting with other teams (Argo, SWOT, etc.)? If so, what other groups?
  - Yes, pair up meetings, including meetings that focus on modeling and/or in situ
- Are there suggestions about how to lower the carbon footprint of the meeting?
  - Less frequent meetings (e.g. every 1.5 to 2 years)
  - Expand reach via virtual meetings (i.e., WebEx, Zoom)
    - Local concentrations of members can host physical space (Pasadena, Toulouse, etc.)
    - Record meetings for viewing later
    - Upload your poster so people who are not here can still see them (a service already available!... but less and less posters are uploaded…)
  - And/or intermediate WebEx-only working groups?

4.6.10 Recommendations

A lot of abstracts were submitted this year on both aspects of the session. Keep it going!

We recommend that the demo format continue to be part of the program, with announced hours/topics for improved access and attendance. Optimally, we would like to have the demo screen situated in the very middle of the poster area, and/or close to the coffee to make it more accessible to the ST community.

We plan to continue inviting personnel from informal science venues such as museums and science centers to present at the OSTST. In the U.S., the NASA Museum Alliance – over 400 informal education organizations (museums, aquaria, etc.) exists, which can link the OSTST with such centers. The U.S. contingent of OSTST Outreach could engage this group. Science museum organization exists in Europe, and/or in each country.

To advance coastal, hydrology, cryosphere, and ocean altimetry, the outreach team propose that tutorials on coastal altimetry, hydrology and cryosphere tools/data products are developed to further use. The idea of coordinating/combining OSTST & SWOT ST after the next call (in 3 years) seems logical on the outreach & data services point of view.

We fully approve the idea of reprocessing the “old” data to stay in line with Sentinel-6 ones.

4.6.11 New Planned Efforts

The focus of the outreach team for the coming year will be on climate and hydrology education, public outreach, as well as on applications outreach for all of the current and especially the upcoming ocean altimetry missions—Sentinel-6 and SWOT. The anticipated elements of this focus (not withstanding new opportunities) will include:

- SWOT and Sentinel-6 education & public outreach and applications outreach
- Development of a SWOT GLOBE program (NASA, CNES, U. North Carolina, GLOBE Program collaboration)

4.7 Precise Orbit Determination

Chairs: Sean Bruinsma, Alexandre Couhert and Frank Lemoine

4.7.1 Status of OSTST satellite POD

The reference Ocean Surface Topography Mission (OTSM)/Jason-2 satellite was in orbit for more than eleven years (since June 2008) when its scientific mission successfully ended on 1 October 2019. It extended the climate record of highly accurate sea surface height measurements established by TOPEX/Poseidon in 1992 and continued by Jason-1 in 2001. Its successor Jason-3 (launched in January 2016) continues the sea-level monitoring work of the previous reference missions.

The Centre National d'Etudes Spatiales (CNES), Goddard Space Flight Center (GSFC), and Jet Propulsion Laboratory (JPL) project centers gave a status of the performances of their recently updated orbits for the Jason-3 satellite: CNES POE-F (DORIS+GPS reduced-dynamic), GSFC tvg0012 (DORIS+SLR dynamic), and JPL Rlse19a (GPS-based reduced-dynamic). **Error! Reference source not found.** shows the level of agreement reached between the three POD analysis centers in term of radial RMS differences for Jason-3, which compare at the sub-centimeter level (below 7 mm RMS, and below 5 mm RMS for JPL-CNES).

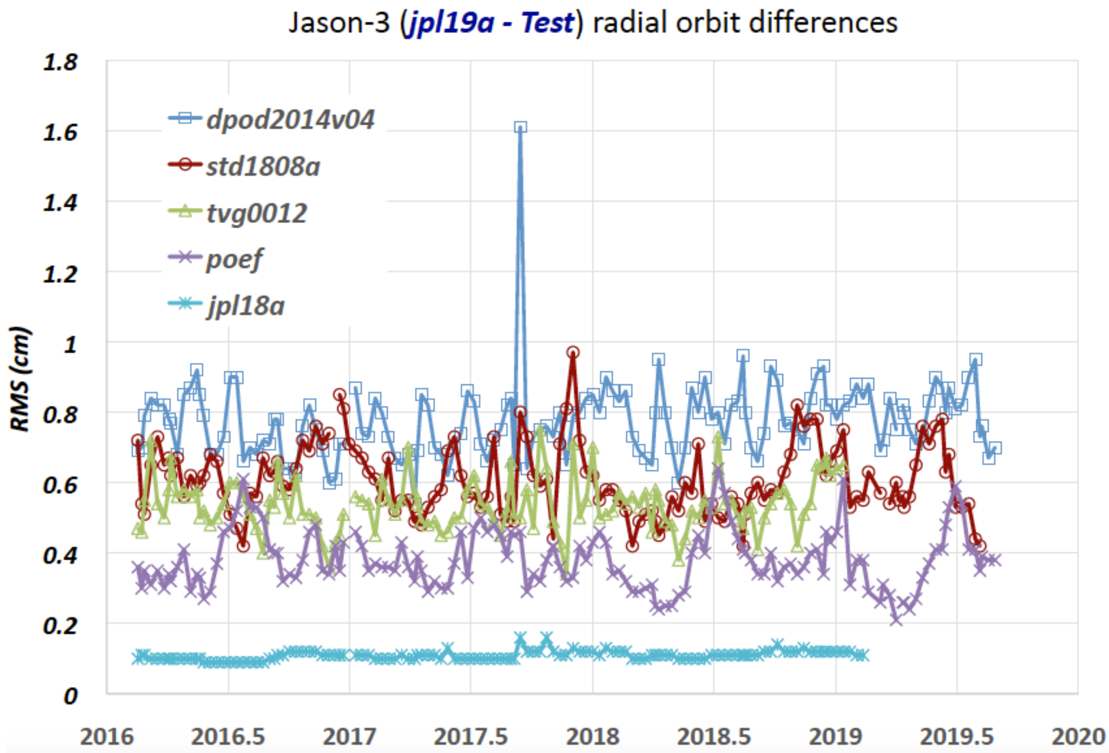


Figure 4.7-1: RMS radial orbit differences for Jason-3 between the CNES POE-F DORIS+GPS reduced-dynamic orbits, GSFC dpod2014v04/std1808a/tvg0012 SLR+DORIS dynamic orbits, and JPL Rlse18a GPS reduced-dynamic orbits compared with JPL Rlse19a.

Radial differences rates between the three sets of orbits still display considerable regional signals, shown in Figure 4.7-2, possibly due to systematic or unaccounted-for errors in the satellite tracking measurements, incomplete modeling of Time-Variable Gravity (TVG), and mismodeling of non-conservative forces. Typical effects are in the order of 0.5 mm/yr for JPL-CNES, while they can be as high as 2 mm/yr for JPL-GSFC.

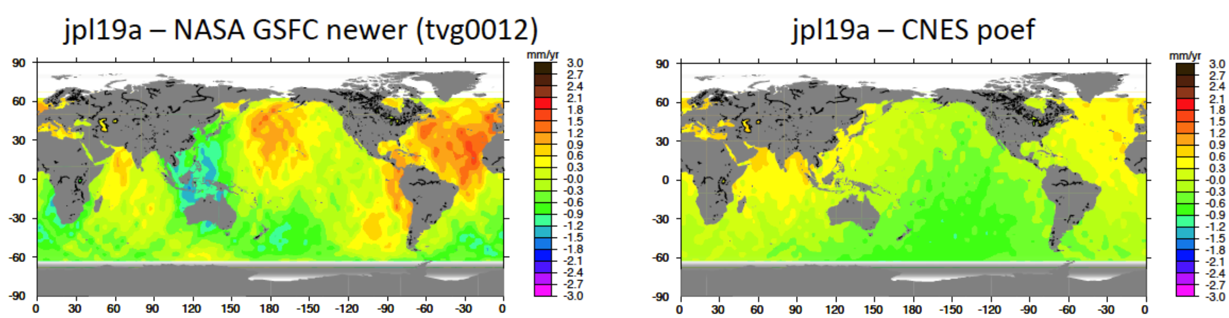


Figure 4.7-2: Radial orbit difference rates for the current JPL Rlse19a/GSFC tvg0012 (left) and JPL Rlse19a/CNES POE-F (right) Jason-3 orbits (mm/yr; 17/02/2016 – 23/01/2019; cycles 1-108

In particular, the Deutsches Geodätisches Forschungsinstitut Technische Universität München (DGFI-TUM) showed the impact of different thermosphere density models (CIRA86, NRLMSISE00, JB2008) in conjunction with the Horizontal Wind Model 2014 (HWM2014) on the Jason-1, Jason-2, and Jason-3 satellite orbits using SLR and DORIS data.

4.7.2 Status of complementary mission POD

The non-reference missions, with lower altitudes and higher inclinations than the OSTST satellites, also contribute to the altimeter constellation and enhance the global coverage. Several altimeter missions switched from CNES GDR-E to CNES POE-F orbit standard along with Jason-3 (in November 2018): The European Union Copernicus twin satellites Sentinel-3A and Sentinel-3B (in December 2018), the Indian Space Research Organization (ISRO)/CNES SARAL/AltiKa (in January 2019), the European Space Agency (ESA) CryoSat-2 (in May 2019), and the Chinese National Satellite Ocean Application Service (NSOAS) HY-2B (since launch in October 2018). The radial accuracy of the POE-F DORIS-only reduced-dynamic orbits for CryoSat-2, SARAL/AltiKa, Jason-3 and Sentinel-3A, displayed in Table 4.7-1: Performance of DORIS-only and GPS-based CNES POE-F reduced-dynamic orbits as seen by SLR (RMS over 2017 in cm)., approaches that of the GPS-based orbit. The orbit accuracy of the POE-F GPS-only reduced-dynamic for HY-2B is already comparable to the Sentinel-3A mission.

SLR Core Network	CRYOSAT-2	SARAL	JASON-3		SENTINEL-3A	
	DORIS	DORIS	DORIS	GPS	DORIS	GPS
3D	1.18	1.14	1.59	1.06	1.25	0.85
High Elevation (radial)	0.68	0.66	0.89	0.70	0.63	0.54

Table 4.7-1: Performance of DORIS-only and GPS-based CNES POE-F reduced-dynamic orbits as seen by SLR (RMS over 2017 in cm).

PosiTim presented results from their validation of planned POD standard updates to stay up-to-date and continuously guarantee the quality of the Sentinel-1/2/3 orbit products. As a complement to this analysis, JPL assessed the in-flight tracking performance of the two GPS receivers onboard the Sentinel-3A and Sentinel-3B mission satellites. Especially, a comparison of these receivers, manufactured by RUAG, with the BlackJack on the higher-altitude Jason-2 and IGOR+ (BlackJack heritage) on Jason-3, was performed.

CLS is currently preparing the processing configuration for their International DORIS Service (IDS) contribution to the next International Terrestrial Reference Frame (ITRF) realization (ITRF2020). The results obtained for the currently flying DORIS satellites (CryoSat-2, HY-2A, SARAL/AltiKa, Jason-2/3, Sentinel-3A/B) were evaluated in the light of comparisons to independent precise orbit determination solutions. In addition, GMV focused on the impact of the GPS ambiguity fixed carrier phases on the resulting Sentinel-3 orbit products. To this end, different bias products were analyzed: the GPS wide-lane biases from the historical CNES/CLS and the CODE biases, which recently became available.

4.7.3 Residual geocenter signals Geocenter motion estimation

As can be gleaned from **Error! Reference source not found.**, regional annual signals between Jason-3 CNES POE-F and JPL Rlse19a solutions are observed at the 4-mm level. These patterns are probably related to differences in the geocenter as realized by the motion model that was introduced to correct for GPS data centering errors in Jason-3 CNES standard F orbits. Thus, the sensitivity and impact of various strategies for handling geocenter motion through GPS orbit/clock products was tested by JPL: ignoring geocenter motion and using JPL's standard IGS14-based orbit and clock products; using of so-called no-net-rotation orbit and clock products for the GPS constellation; using models to account for geocenter motion while generating orbit and clock products for the GPS constellation. The main outcome of this study is that validation criteria to assess how well an orbit is aligned with the Earth's center-of-mass are still sorely lacking.

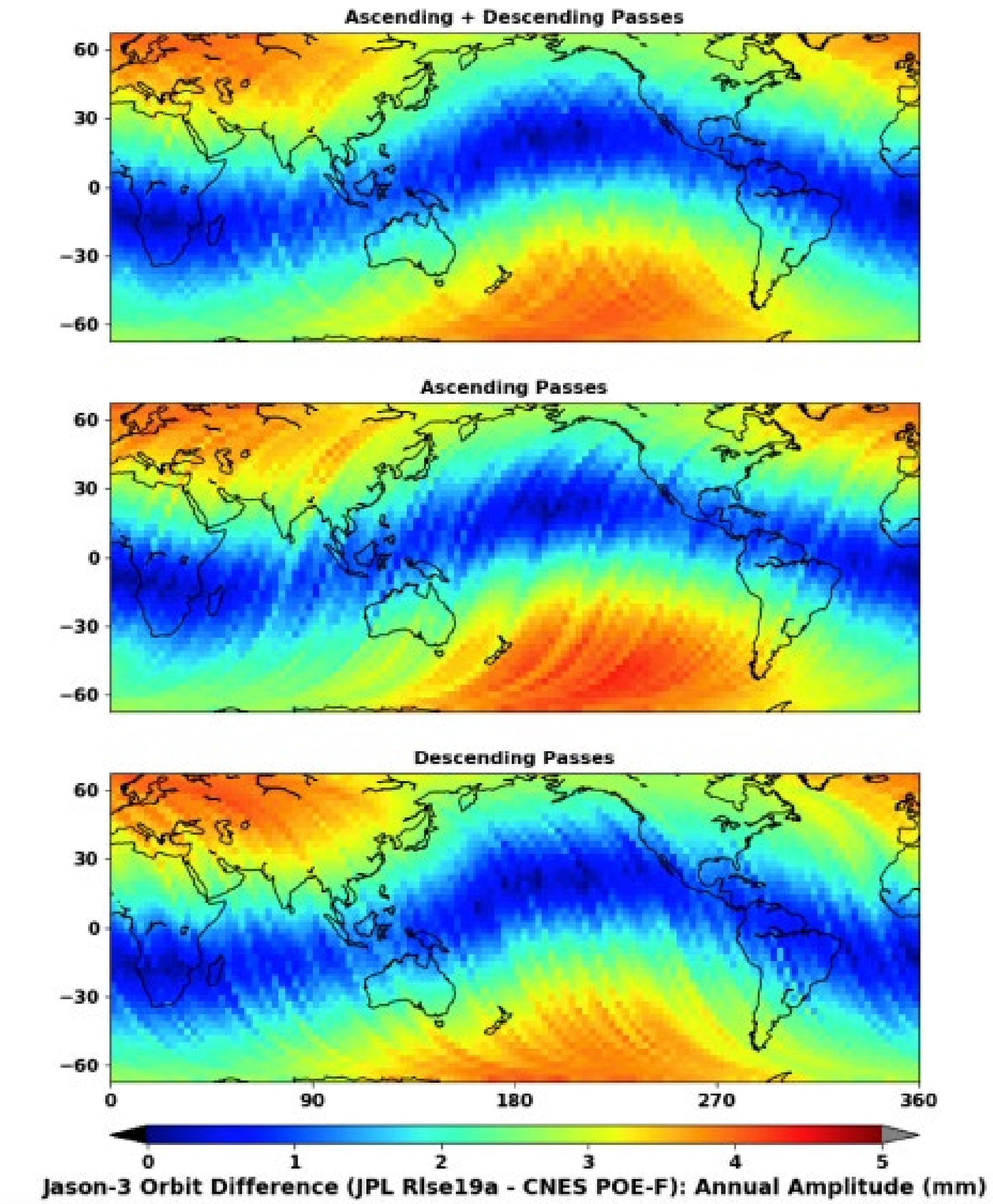


Figure 4.7-3: Jason-3 geographically correlated radial difference 365-day signals between the JPL Rlse19a and CNES POE-F reduced-dynamic orbit series.

4.7.4 SLR station bias issues

The Astronomical Institute University of Bern (AIUB) and CNES analyzed the complete SLR network to improve the laser station ranging data processing for the validation of altimeter satellite precise orbits. Given the high quality presently achieved of these orbits (below 7 mm

RMS in the radial direction), it is now necessary to improve our knowledge of the SLR measurements: the observed measurement noise can be as good as 2 mm RMS, but the limitation is the value of the systematic biases (varying from a few millimeters to several centimeters for some stations).

The current practice is to choose a reduced set of stations ("core network"), which are considered to have negligible biases, and to analyze the radial performance of the orbits relying on the high-elevation SLR residuals. With this approach, the number of stations used can be as low as 5 and very few high-elevation measurements are usually available. The objective of the studies led by AIUB and CNES is to enlarge the SLR core network with the estimation of accurate and reliable station biases, using multiple altimeter and gravity satellites tracked by DORIS and GPS (Jason-3, Sentinel-3A/B, CryoSat-2 or Swarm-A/B/C, Sentinel-3A/B, GRACE-FO-C/D) to suppress the possible effect of geographically correlated orbit errors that could corrupt the estimate of the station bias (like station height modeling errors). **Error! Reference source not found.** shows an example of the biases estimated for a given year.

Station	SOD	E [mm]	N [mm]	U [mm]	B [mm]
Badary	18900901	8.0 ± 0.6	-0.2 ± 0.6	6.0 ± 2.2	8.4 ± 1.4
Yarragadee	70900513	4.8 ± 0.1	-0.3 ± 0.1	-2.5 ± 0.4	0.6 ± 0.2
Greenbelt	71050725	3.4 ± 0.2	6.1 ± 0.2	-12.7 ± 0.6	-6.3 ± 0.3
Monument Peak	71100412	-2.7 ± 0.2	-7.6 ± 0.2	-10.8 ± 0.9	0.3 ± 0.5
Haleakala	71191402	4.5 ± 0.4	-4.5 ± 0.4	1.2 ± 1.3	11.0 ± 0.8
Papeete	71240802	12.1 ± 0.6	4.5 ± 0.6	-5.1 ± 2.1	-12.7 ± 1.2
Arequipa	74031306	0.2 ± 0.4	3.5 ± 0.4	-4.2 ± 1.4	8.1 ± 0.8
Hartebeesthoek	75010602	-2.7 ± 0.3	6.4 ± 0.3	-6.6 ± 1.0	4.2 ± 0.6
Zimmerwald	78106801	0.6 ± 0.2	2.0 ± 0.2	9.4 ± 0.6	7.5 ± 0.3
Mount Stromlo	78259001	5.8 ± 0.3	2.3 ± 0.2	5.5 ± 0.9	1.6 ± 0.5
Wettzell (SOSW)	78272201	-1.3 ± 0.5	-9.6 ± 0.5	-6.7 ± 1.7	5.6 ± 1.0
Graz	78393402	2.7 ± 0.2	3.2 ± 0.2	8.7 ± 0.7	11.9 ± 0.4
Herstmonceux	78403501	3.1 ± 0.3	1.5 ± 0.3	-4.1 ± 1.0	-2.5 ± 0.6
Potsdam	78418701	0.9 ± 0.3	3.7 ± 0.3	17.1 ± 0.9	-0.6 ± 0.6
Matera	79417701	1.7 ± 0.4	4.8 ± 0.4	4.2 ± 2.0	-5.3 ± 1.0

Figure 4.7-4: Estimated corrections w.r.t. SLRF2014 (corrections from 1-year of ambiguity fixed Swarm-A/B/C, Sentinel-3A/B, and GRACE-FO-C/D orbits) over the period 2018.5—2019.5.

Based on the developed approaches to correct for station biases, it was possible to extend the SLR core network from 5 to close to 15 stations. Some larger corrections still ask for further investigations, as this is only a first step. Such a set of common biases could be applied in the future to any other kind of satellites to improve the validation of their orbit accuracy.

4.7.5 PCO estimation dependence on yaw regime

The in-flight calibration of the GPS antenna Phase Center Origin (PCO) onboard the Jason-series has benefited from their specific yaw attitude regime: transitioning between a yaw-steering mode characterized by large (e.g., +/- 120 degrees) sinusoidal yaw angle variations and a yaw-fixed mode, as well as yaw-flips where the satellite transitions from flying ‘forward’ to flying ‘backward’, dictated by the variations of the satellite’s beta-prime angle. The Sun-synchronous Sentinel-3 satellites on the other hand are designed to always fly in yaw-steering mode with variations of very low (e.g., +/- 6 degrees) amplitude. Thus, JPL used the Sentinel-3A/B satellites to evaluate the impact of each attitude mode on the Low Earth Orbiter (LEO) GPS receiver antenna calibration in preparation of the future Sentinel-6 and SWOT missions, as both will be flying in fixed yaw only.

Given the challenges associated with the poor observability of the PCO vector in the satellite’s direction of motion when flying in fixed-yaw (**Error! Reference source not found.**), the recommendation is to use the along-track component of PCO from prelaunch antenna calibration when estimating the coordinates of the PCO.

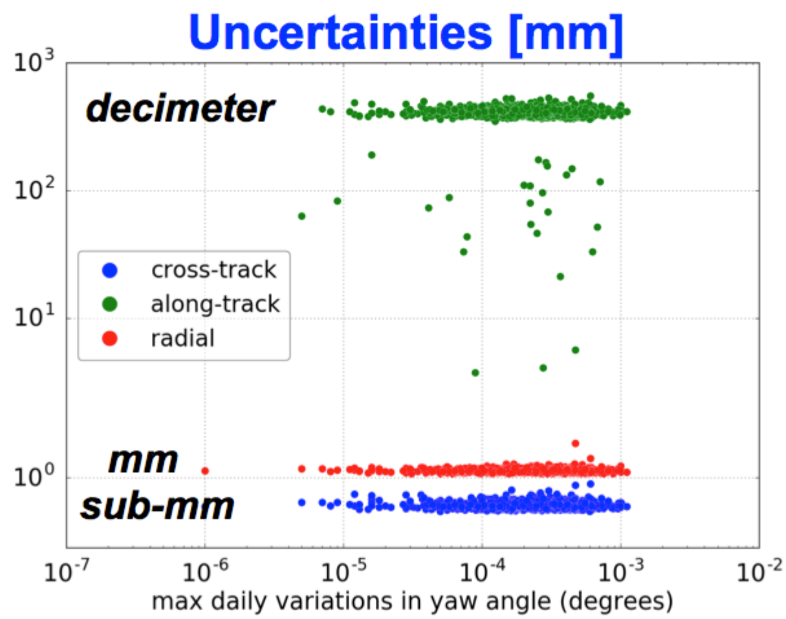


Figure 4.7-5: Uncertainty (based on formal errors) of the GPS PCO estimates for Sentinel-3A in each orbit direction as function of maximum daily yaw angle variations.

The availability of ‘forward’ and ‘backward’ flying phases makes it possible to disentangle relative along-track offsets between POD instruments from time tagging differences. For Jason-3, these properties can be observed in **Error! Reference source not found.** through the along-track bias seen by SLR on GPS-derived orbits during fixed yaw periods (on each side of the flips). The relative positioning error along the satellite X-axis maps into a jump around the flip whose amplitude is twice the error. **Error! Reference source not found.** shows that an error of 7 mm and 4 mm appears in the distance between SLR and GPS in the along-track direction for the Jason-3 CNES POE-F GPS-driven and JPL Rlse19a GPS-only orbits, respectively.

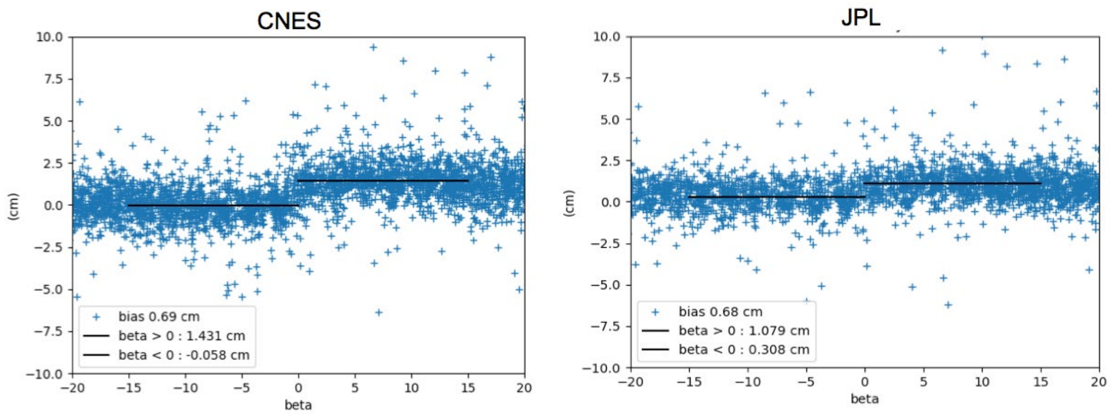


Figure 4.7-6: Along-track Jason-3 CNES POE-F (left) and JPL Rlse19a (right) orbit error as seen by SLR as function of beta-prime angle variations.

Additionally, the two GPS-driven orbits display the same along-track mean bias of 7 mm with respect to SLR measurements. Such a bias, much smaller for DORIS-based orbits (~2-3 mm), reflects a time-tagging inconsistency of about 1 microsecond between the SLR and GPS tracking systems.

4.7.6 Future outlook and issues

We need to continue to investigate the causes of large regional radial orbit rate and annual differences between the different sets of orbits. Strong candidates are differences in TVG parameterization and sensitivity, and how the different tracking techniques respond to the geocenter. By the next OSTST meeting, the POD group needs to reflect on robust criteria to validate the alignment of orbits with the Earth's center-of-mass, as well as on improved SLR and crossover validation procedures.

The propagation of errors in the altimeter system via analytical approaches dedicated to the transfer of errors from the orbit to geodetic products would also be useful to identify the sources of orbit errors (gravity field, ocean tide model, solar radiation pressure) and derive a complete global and regional error budget, on condition of having an all-inclusive analytical model.

4.7.7 **Recommendations** from the POD team proposed to the OSTST

- Based on the lessons learned from the 'forward' and 'backward' flying attitude regimes for the in-flight calibration of some POD instrument offsets, we recommend a specific attitude on Sentinel-6 to observe such parameters: the satellite should fly 'forward' and 'backward' by doing flips around its yaw axis every 60 days when the solar beta-prime angle nullifies, like Jason-3.
- The ability to discern long-term systematic errors in the orbits of altimeter satellites relies on having the three independent tracking techniques (DORIS, GPS, SLR). CRISTAL

(currently planned with GPS and SLR only) ocean products would benefit from a better knowledge of the long-term orbit errors with the addition of a DORIS system.
- GNSS RINEX files for all altimeter satellites should be made publically available.
- Taking into account the importance of TOPEX/Poseidon for precise computation of long-term sea level record and the absence of precise and complete information on the TOPEX/Poseidon Laser Ranging Array correction that is necessary for precise orbit computation using SLR observations, OSTST encourages ILRS to provide this information.
- OSTST also encourages space agencies to make all possible efforts to provide the measured attitude of past altimetry missions, such as TOPEX/Poseidon, ERS-1 and ERS-2, for further improvement of their orbits.

4.8 Quantifying Errors and Uncertainties in Altimetry Data

Chairman: Michael Ablain, Remko Scharroo and Joel Dorandeu

4.8.1 Overview

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 topic with a different approach. This year, the focus has been put on:

- **Error formalism and method**: Ensemble approach to characterize uncertainties in altimeter sea ice thickness products (**Florent Garnier**), 2D spectra to represent the error budget of any altimeter mission (**Pierre Thibaut**), New method to denoise altimeter measurements for high-resolution geophysical signals (**Yves Quilfen**),
- **Error detection and characterization**: Description of the Sentinel-3A error budget description (**Matthias Raynal**), Errors of daily harmonics of ionospheric Total Electron Content for single-frequency altimeters (**Richard Ray**),
- **Error reduction**: Improvement of DAC de-aliasing model by combining GRACE gravity data (**Jennifer Bonin**), Harmonization of the altimeter Rain Flags (**Matthieu Talpe**)

The main topics of the session have been listed hereafter.

4.8.2 High frequency error characterization and reduction on S3-A measurements: New approach to better characterized uncertainties in altimeter sea ice thickness products (Florent Garnier)

- The different sources of errors are not considered to provide Sea Ice Thickness Uncertainties => Freeboard uncertainty is currently very likely too weak: 0.037 mm for CryoSat and 0.093 mm for Envisat.

- Uncertainties can be more realistically described by producing an ensemble of observation by an EnKF stochastic method (Evensen, 2003; Burgers et al, 2018)

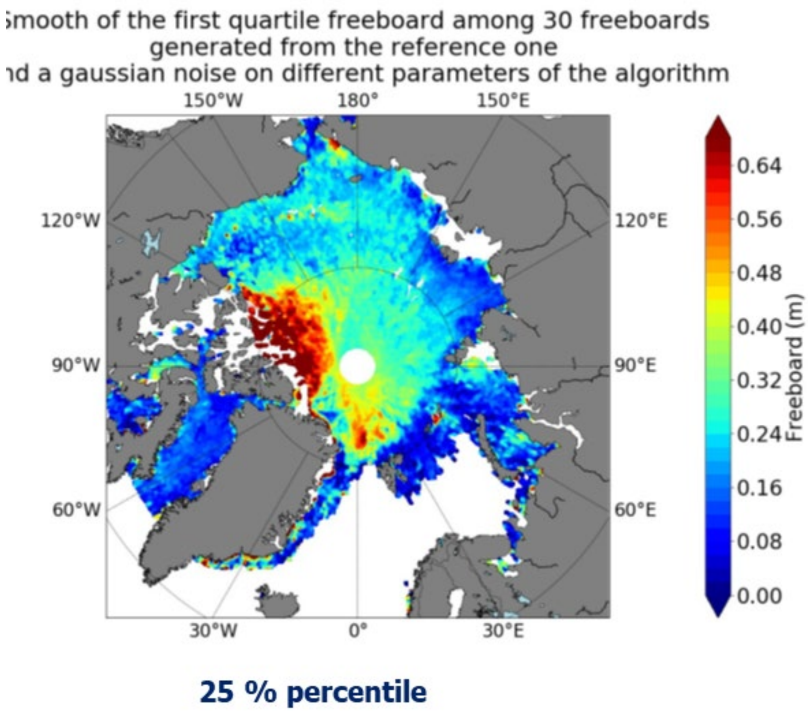


Figure 4.8-1: first quartile freeboard among 30 freeboards generated from the reference

<u>**Recommendation**</u>: These more realistic errors should be provided in ice thickness products

4.8.3 2-D spectra approach to represent and estimate the errors of altimetry data at any spatial and temporal time scale (Pierre Thibaut)

- Based on a simple description of altimetry errors: variance and wavelength of errors
- Applicable to any altimeter missions: past, current and future

Error Source	STD (cm)	Spatial correlation length	Temporal correlation length	References
Altimeter Random error	1,2	0 km	0 day	S3 performance doc (CLS)
SSB Noise	0,3	300 km	Inf.	S3 performance doc (CLS)
SSB correlated	0,1	100 km	1 day	Tran & al, 2019
Ionosphere	0,15	600 km	0 day	S3 performance doc (CLS)
Wet Troposphere	1	50 km	1 hour	Brown & al, 2015; Stum & al, 2011
Dry Troposphere	0,2	600 km	2 days	S3 performance doc (CLS)
Mean Sea Surface	0,5	1 km	Inf.	Pujol & al, 2018
Ocean Tides	1	1000 km	< 1 day	Lyard & al, 2018
Orbit solution	1,5	> 10 000 km	< 1 day	Ollivier & al, 2018; Couhert & al, 2015

Table 4.8-1: Sources of error for altimetry data

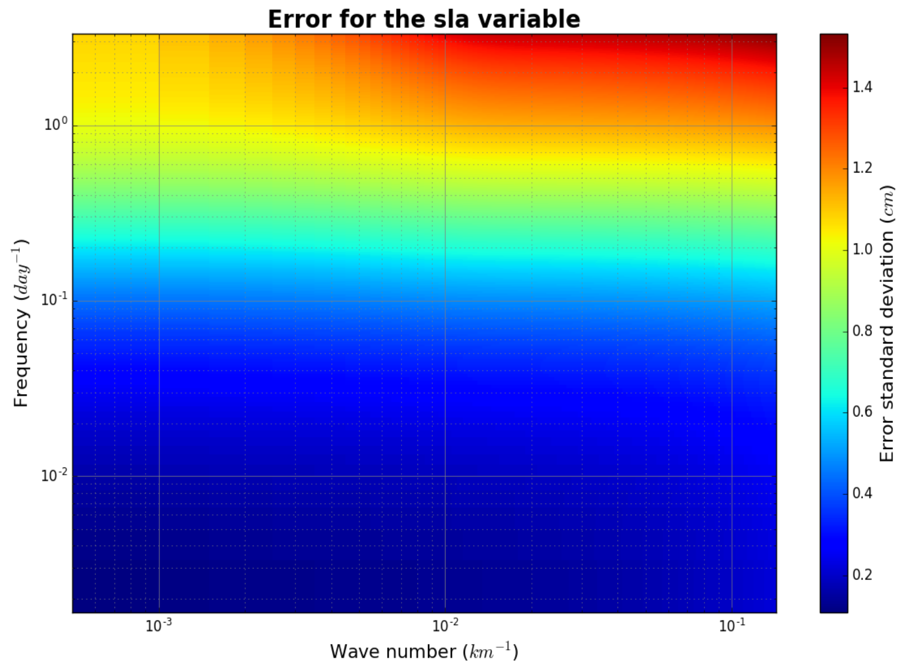


Figure 4.8-2: Error in sea level anomaly

<u>Recommendation</u>: Error budget tables should be improved by independent studies based on uncertainties calculation dedicated to each source of error.

<u>Recommendation</u>: Providing error budget of altimeter missions with this formalism.

4.8.4 Description of the Sentinel-3A error budget (Matthias Raynal)

- Very good performances: availability and quality Submesoscale error: although the SARM noise floor (instrumental + processing) is lower than for conventional altimetry, it is affected by swell waves (depends on swell period and direction
- Climate scale errors: SARM /P-LRM range comparisons highlight variations as function of time linear and close to 1 mm/yr over a 3mm: not yet explained.

Param	Error	Amplitude	Wavelength
Range & SWH	Swell impact (T02, Dir)	~several cm	<= 10 km
Range	Meridional wind speed effect	2 cm	>100 km
SWH	Wave height dependency	10/15 cm	>100 km
SWH	Swell dependency	5/10 cm	>100 km
SWH	waveform centering dependency	10 cm	> 100 km
Sigma0 / WS	Radial velocity dependency	0.1 dB / 30 cm/s	> 100 km
Range	Temporal drift	1 mm/y	> month
?	others	?	?

Table 4.8-2: Sentinel-3A errors

Recommendation: These errors should be investigated to improve our understanding of the SARM sensitivity to geophysical effects.

4.8.5 Harmonizing the Jason-1, Jason-2, Jason-3 Time Series of Rain Flags (Matthieu Talpe)

- Altimeter and radiometer rain flag discrepancies can be harmonized: 1) mitigating altimeter rain flag inconsistencies and 2) setting altimeter LWC threshold to 0.75 kg/m2 ensures consistency in number and geographic coverage.
- "Rain flag" = rain event detection?... or just a measurement quality flag?

Recommendation: Need to revisit the rain flags in L2 altimeter products: calibration and for which use?

4.8.6 Proof of concept to improve the DAC de-aliasing model by combining with sub-monthly GRACE gravity data (Jennifer Bonin)

- Current DAC model dominates at high frequencies and near equator.
- At longer periods and at higher latitudes, GRACE can add value.

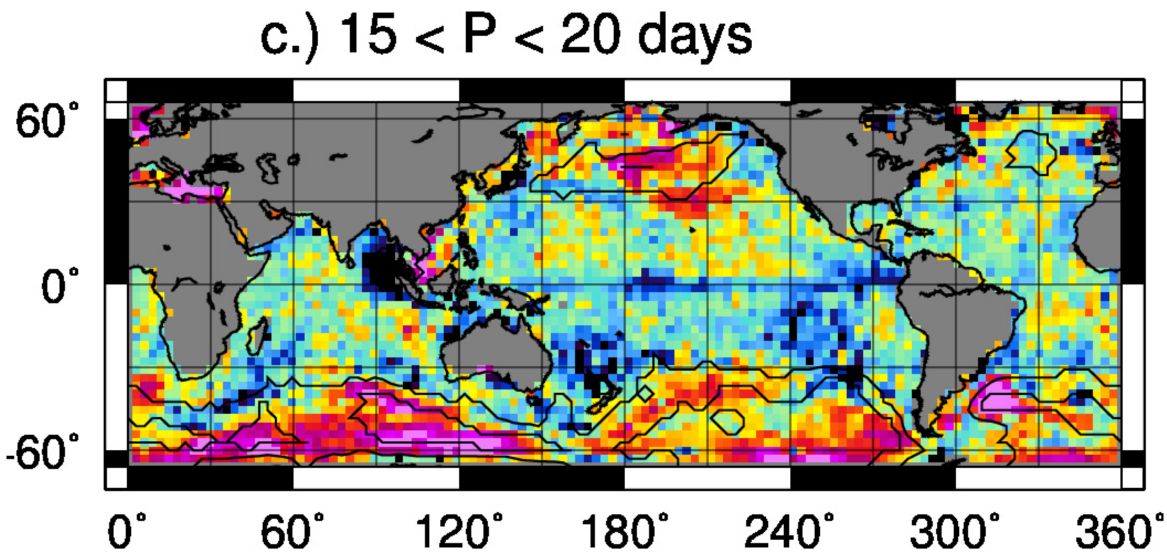


Figure 4.8-3: Improvement in PVE (Percentage)

Recommendation: Need to revisit the DAC

4.8.7 Summary of discussions

In terms of recommendations, the splinter encourages:

- Need for systematic (and rigorous) uncertainty estimations, need for agreed formalism
  - Standard uncertainty formulation: drifts, calibration/Validation results, climate signals
  - Input for applications: a) Assimilation into ocean models, b) Climate studies: MSL close out budget, c) Some gaps to fill: variance/covariance matrix of Orbit Errors and MWR WTC for, e.g. local MSL trend estimates
- From Science Team: Stability of Sentinel-3
  - Need to propose and adopt an error formalism to estimate drift impact and corrections.
  - Each drift impact study or correction should then be presented according to this formalism
- Improving the involvement of user community (e.g. from assimilative systems) in OSTST in order to better understand their needs in terms of data quality and uncertainty requirement
  - Open question: forum should we target? Ocean, Hydro, Climate, etc. communities
  - How to make then contribute, then report (feedback) in OSTST

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

4.9.1 Introduction

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:

- Assess the performance of the measurement system, including the altimeter and orbit-determination subsystems;
- Improve ground and on-board processing;
- Enable a seamless and accurate connection between the current (OSTM/Jason-2 and Jason-3) and legacy (TOPEX/Poseidon and Jason-1) time series, but also prepare the connection between Jason-3 and Sentinel-6
- 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), 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:

- Local CALVAL (focusing on bias estimates from in-situ measurements) and
- 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 10 oral presentation (5 in-situ, and 5 global), and 12 poster presentations. Presentations spanned calibration and/or validation results with in-situ or global methods from numerous missions ranging from TOPEX/Poseidon, Jason-2 and -3, Sentinel-3A and 3B, HY-2B, SARAL/AltiKa, and CryoSat-2.

4.9.2 Results from in-situ calibration sites

The latest (2019) results from the dedicated in-situ calibration sites are provided in Table 4.9-1: Absolute SSH bias values (in mm) for different missions and from the different calibration sites (using in-situ SSH measurements) and Figure 4.9-1. They continue to show good overall consistency among legacy and current missions, but particularly for Jason-2 and -3. Three years into the mission, the Jason-3 SSH bias estimates are stabilizing, and the overall results are in keeping with prior-year (2018) results. There are some minor changes due to the accumulation of additional overflights, and also to the evolution of in-situ models (e.g., land motion) and techniques. The Jason-3 SSH bias estimates from the four primary sites are all slightly negative (SSH too low) and tightly clustered in the range of –2 to –15 mm (σ = 5 mm). Analysis continues to support that all Jason-3 data products (OGDR, IGDR and GDR) are of very good quality, and show small differences with Jason-2 during the verification phase. Jason-3 SSH, however, remains slightly lower (by 2 cm on average) than comparable values from Jason-2. Detailed analysis shows that this relative SSH bias is due mainly to the Ku-band range, but probably also to the C-band range. Together, they lead to smaller (by < 1 cm) ionosphere delays for Jason-3.

As was noted in the 2018 report, the Jason-1 (GDR-E) results depict a puzzling discrepancy: results from three sites (Bass Strait, Corsica and Gavdos) are clustered tightly together, yielding positive SSH bias estimates in the range of 4–5 cm. Observations from Harvest, on the other hand, yield a significantly lower bias (<1 cm), consistent with the comparable Harvest result for Jason-2 (GDR-D). Work is underway to better understand the allocation of errors contributing to this discrepancy.

Absolute SSH bias estimates for all reference (Jason-class) missions, including the original TOPEX/POSEIDON mission, are in the range of –1 to +4 cm. The specific sources of larger (decimeter-level) biases that have plagued historical versions of the data products have been gradually identified and removed, a decades-long process that has been informed by careful and continuous monitoring from the dedicated (absolute) calibration sites, using disparate measuring technologies (tide gauges, moorings and transponders). The focus has now turned to smaller (1–3 cm) discrepancies that are attributable to systematic, site-specific in-situ errors and geographically correlated patterns in the altimeter measurement system errors. We note that a major update to the TOPEX data product is imminent. While preliminary results were shown at this meeting, the evaluation of this retracked GDR (RGDR) will be a significant focus of the coming year.

Regional calibration techniques are routinely employed at the dedicated sites to monitor altimetric missions that are not flying on the reference (10-d repeat) ground track. The latest results for Sentinel-3A indicate that SSH observations remain very stable, and that the overall bias is statistically indistinguishable from zero. Results from the newer Sentinel 3B mission (April 2018 launch) are stabilizing with additional overflights. These results suggest SSH data from this new (3B) mission are well aligned with comparable values from its predecessor (3A) mission (cf. Table 4.9-1).

Mission	Bass Strait	Harvest	Corsica	Gavdos	Average
TOPEX-A	+8	–3	+25		+10
TOPEX-B	+19	–3	+24		+13
Jason-1 GDR-E	+47	+6	+43	+41	+34
Jason-2 GDR-D	+19	+5	+16	+5	+11
Jason-3 GDR	–7	–15	–7	–2	–8
Sentinel 3A	+20		+8	–4	+6
Sentinel-3B	+32		–14	–4	+5

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

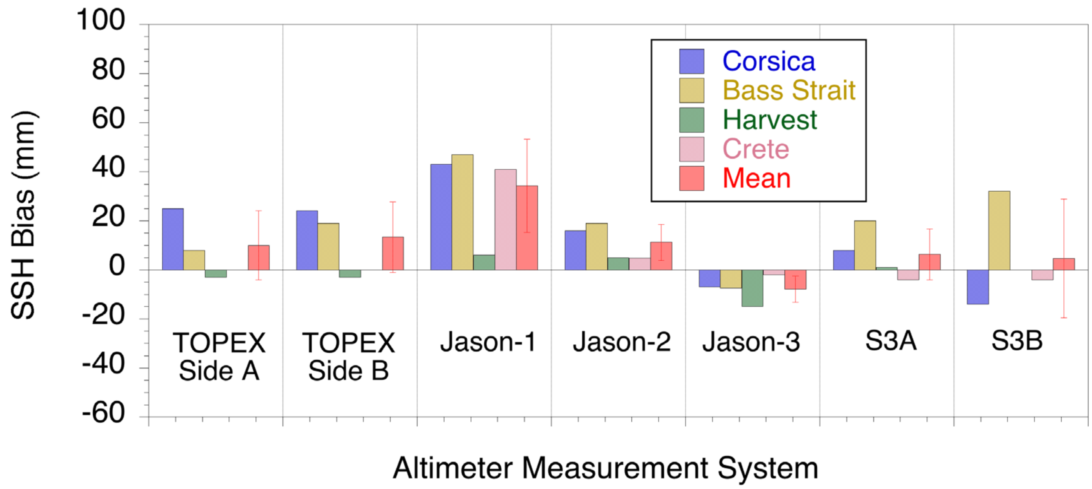


Figure 4.9-1: Absolute SSH bias values (in mm) for different missions and from the different calibration sites (using in situ SSH measurements).

The permanent transponder installed in Crete at a crossover point of the Jason and Sentinel-3 ground tracks continues to provide absolute calibration results focused on the altimeter range component of the measurement systems. Mertikas et al. reported range biases of +6 and +7 mm for Jason-3 and Sentinel-3A respectively: we must note that the range bias is by definition opposite in sign than the SSH bias). First transponder results for Sentinel 3B are promising, yielding range bias estimates of –9 and –1 mm respectively for two overflights. 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.

Highlighted in this year's session was the maturing role of new technologies, especially GNSS (GPS) buoy systems, in supporting the altimeter calibration initiatives. Watson et al. 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 (cf. also Legresy et al., poster). Haines et al. showed the first comprehensive results from the successful 2018–19 tandem GPS buoy campaign at Harvest. Absolute SSH bias results were competitive with those from the platform, and results from differential (between buoys) SSH corroborated those from prior Bass Strait tests, except over a wider range of sea states. Results from the buoy campaigns at Bass Strait, Corsica and Harvest have particular implications for verification of high-resolution (swath) measurements from the future SWOT mission. The GPS buoys can be used not only for SSH calibration, but also for monitoring SWH and wet path delay (e.g., to compare with retrievals from spaceborne radiometers).

Providing a bridge to the session on global validation studies, Leuliette et al. detailed new comparisons of Jason-3 and Sentinel-3A with tide gauges. No significant drift is detected for the current Jason-3 time series, or for the complete T/P-Jason legacy time series (Figure 4.9-2). The tide gauge comparisons, however, indicate a Sentinel-3A SAR mode drift, in part from the processor change in early 2019. This warrants reassessment after the next full-mission reprocessing.

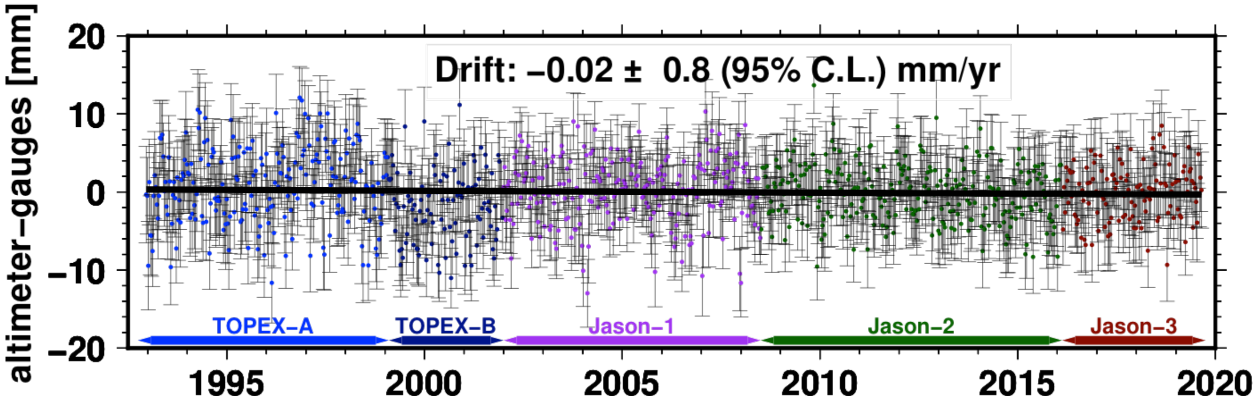


Figure 4.9-2: Altimeter/tide gauge comparisons for entire TOPEX/Poseidon and Jason series of reference missions (Leuliette et al.)

4.9.3 Global validation studies

Jason-2 and Jason-3 products continue to demonstrate nominal performance (Roinard et al., Talpe et al.), though Jason-2 reached its end-of-life in October 2019. Of note is that Jason-3 operational data products transitioned from version E to version F precise orbit determination solutions. This transition has been shown to provide a noticeable reduction in sea surface height crossover differences of ~20 mm^2 (Roinard et al) (see Figure 4.9-3) and improved consistency with independent GPS-based precise orbit determination solutions (Talpe et al.).

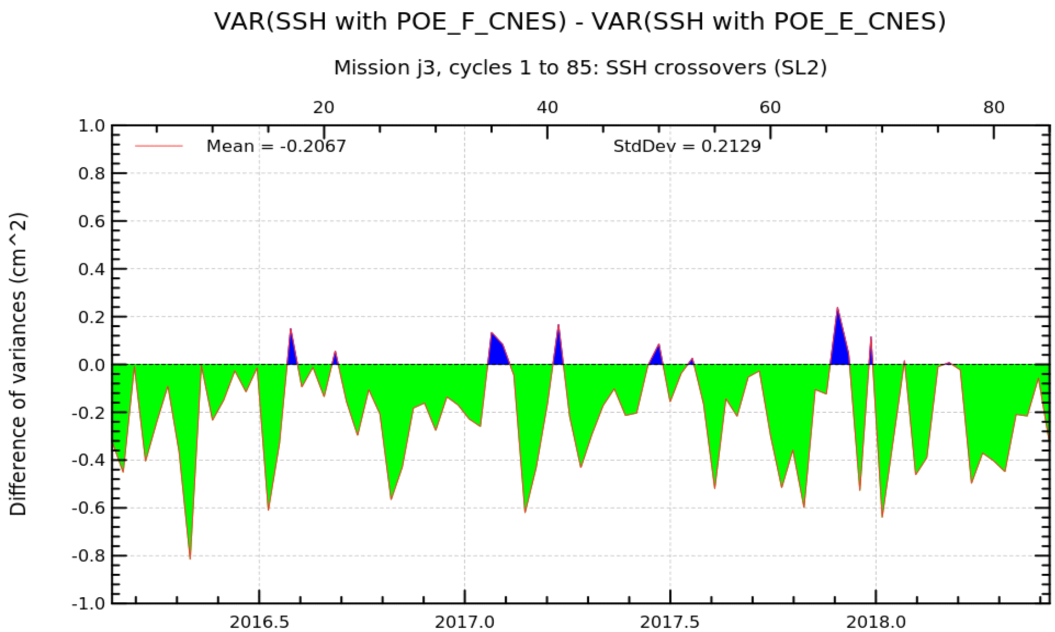


Figure 4.9-3: Variance gain when using POE-F standard on Jason-3 mission (Roinard et al).

A reprocessing of the TOPEX/Poseidon data record by NASA/JPL and CNES is now underway, with reprocessing products expected to be available by mid-2020. Preliminary results from this reprocessing show very promising results. Well-known systematic errors in the TOPEX measurements have been significantly reduced through the use of numerical retracking methods that explicitly also account for features of the instrument itself (Desjonqueres et al.) (see Figure 4.9-4). In addition, the application of modern GDR-F geophysical standards and orbit determination solutions enables significant improvement in the consistency with the Jason-series (see Figure 4.9-5).

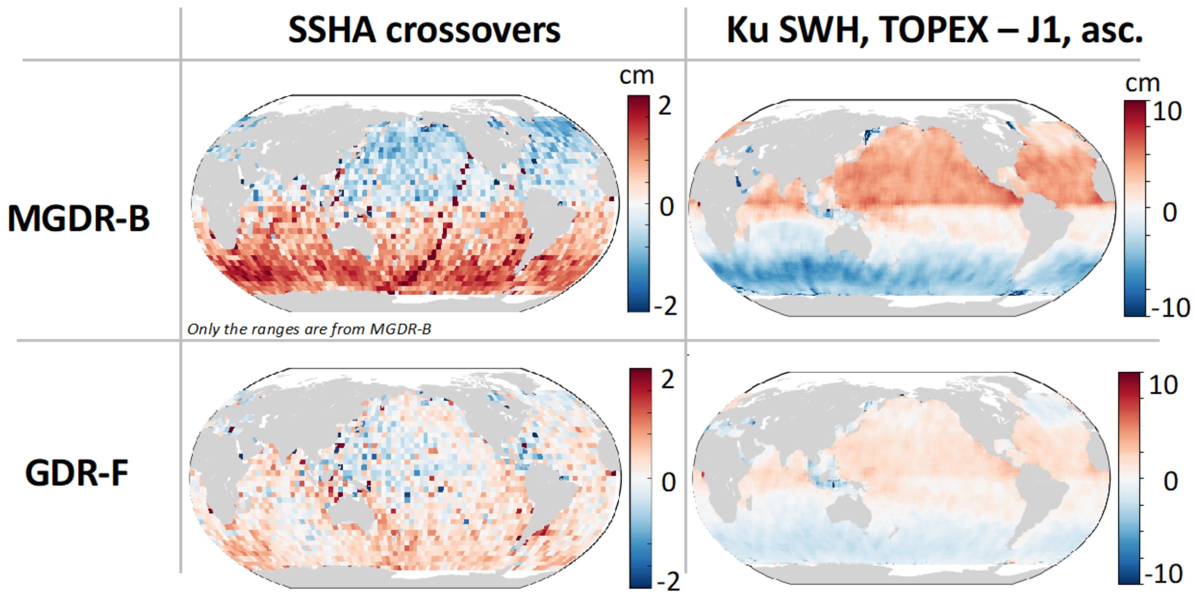


Figure 4.9-4: Numerical retracking of the TOPEX altimeter measurements (GDR-F) has significantly reduced hemispherical biases in reported range, SWH, and sigma0 from MGDR-B that were correlated with range rate (Talpe et al.)

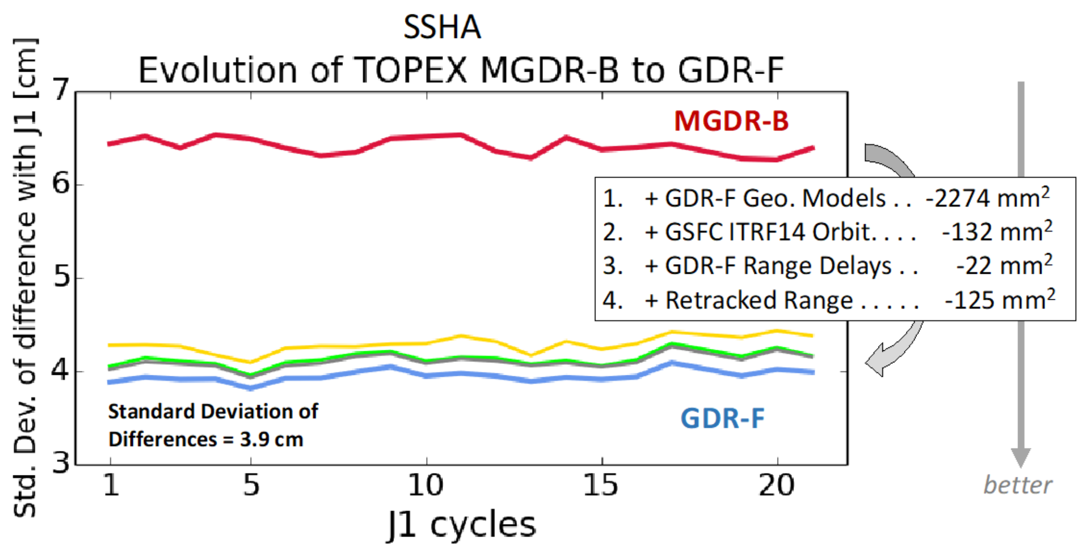


Figure 4.9-5: Application of modern GDR-F standards for geophysical models and new orbit determination solutions from GSFC, together with new TOPEX retracked solutions, enable improved consistency between the TOPEX and Jason-1 (J1) data records (Talpe et al.).

The most recent versions of the Sentinel-3A and -3B data products demonstrate good data quality for operational oceanography and numerical weather prediction models (see Figure 4.9-6). Some improvements are still needed to achieve full climate quality usage of SAR and PLRM data. A new reprocessing of the Sentinel-3 data products is expected by the end of 2019.

An additional reprocessing by the end of 2020 is expected to correct some of the drifts detected in the Sentinel-3 data products (Figure 4.9-7).

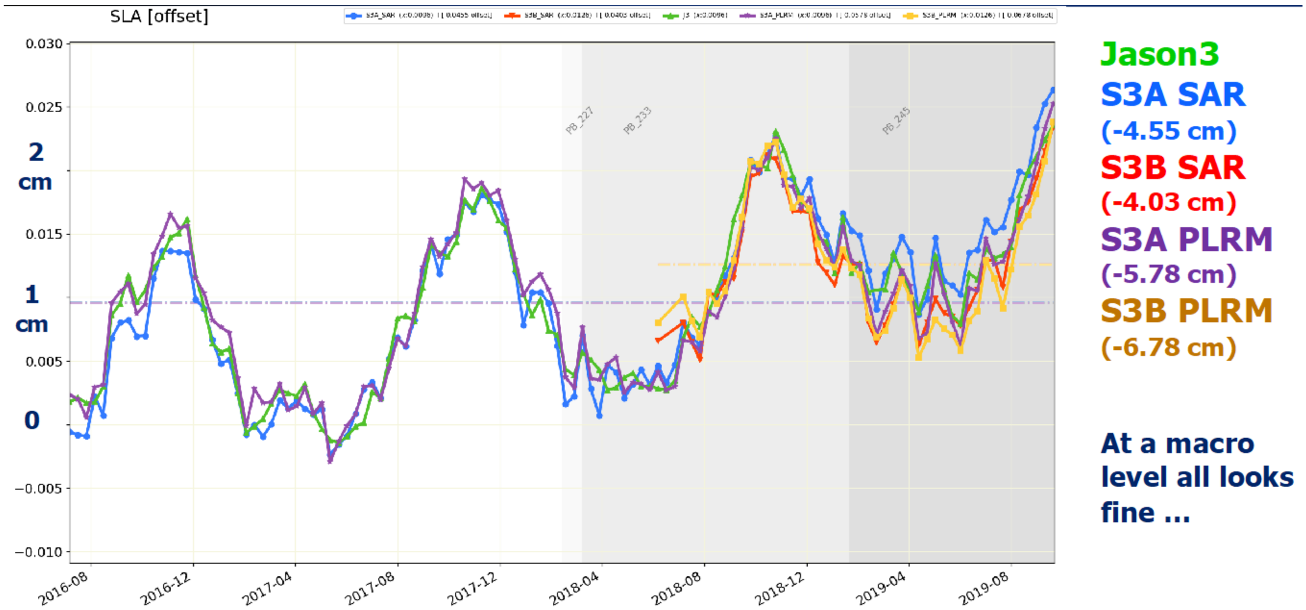


Figure 4.9-6: The most recently available Sentinel-3A and -3B data products show good consistency with Jason-3 measurements (Lucas et al.)

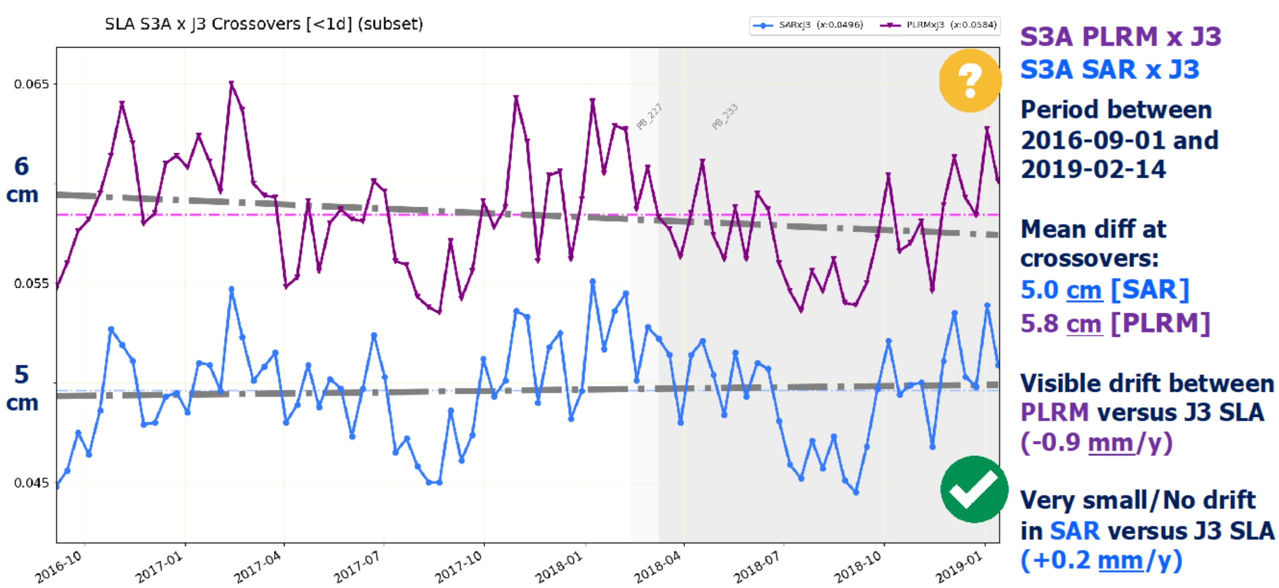


Figure 4.9-7: Visible drifts between Jason-3 and Sentinel-3A are observed when considering inter-satellite sea surface height crossover differences, with PLRM data showing larger drifts than SAR measurements (Lucas et al).

The HY-2B satellite was launched in October 2018, with the HY-2A satellite having been moved to a geodetic orbit in 2016. An assessment of the HY-2B data products shows good data availability over the ocean, large amounts of missing measurements over land, but good tracking performance over large lakes. Dedicated on-ground processing is shown to improve performance of the sea surface height measurements for wavelengths < 100 km, and HY-2B demonstrates a lower noise floor than Jason-3 (see Figure 4.9-8). Nevertheless, measurements of SWH appear to be slightly over-estimated with a dependence on SWH itself. Tests to incorporate HY-2B data into the CNES DUACS system show promising results.

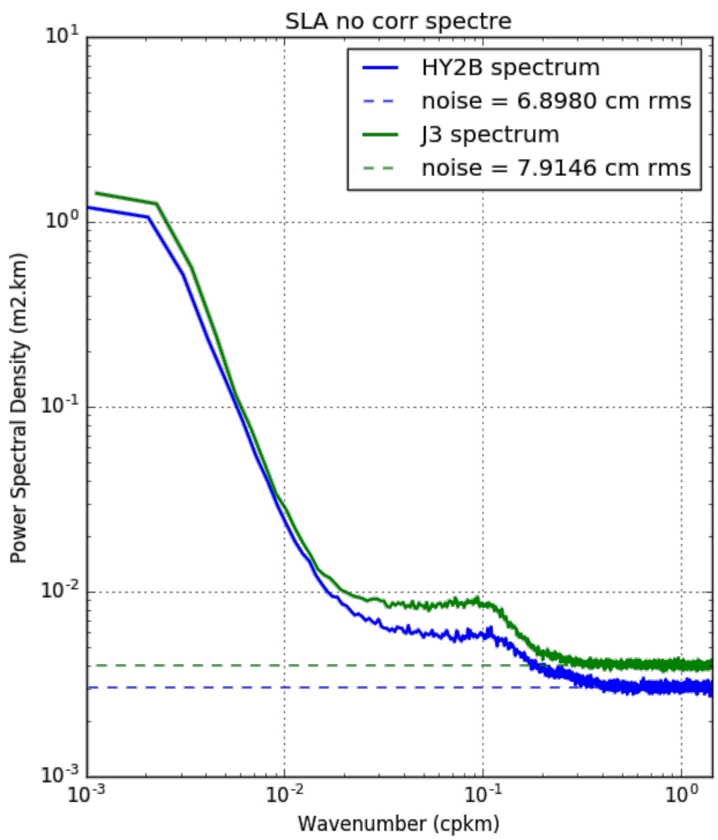


Figure 4.9-8: Dedicated on-ground processing enables improved performance of the HY-2B measurements, resulting in a lower noise floor than Jason-3 (Labroue et al.).

The SARAL/AltiKa mission continues to operate since its launch in 2013. A reprocessing of its science data products is underway and expected to be completed with GDR-F standards by June 2020. This includes retracking to account for the actual altimeter aperture, new radiometer processing algorithms, updated altimeter calibration schemes, and GDR-F geophysical model standards. Early assessment of GDR-F SARAL/AltiKa products shows significant improvement over the previous GDR-T products (see Figure 4.9-9).

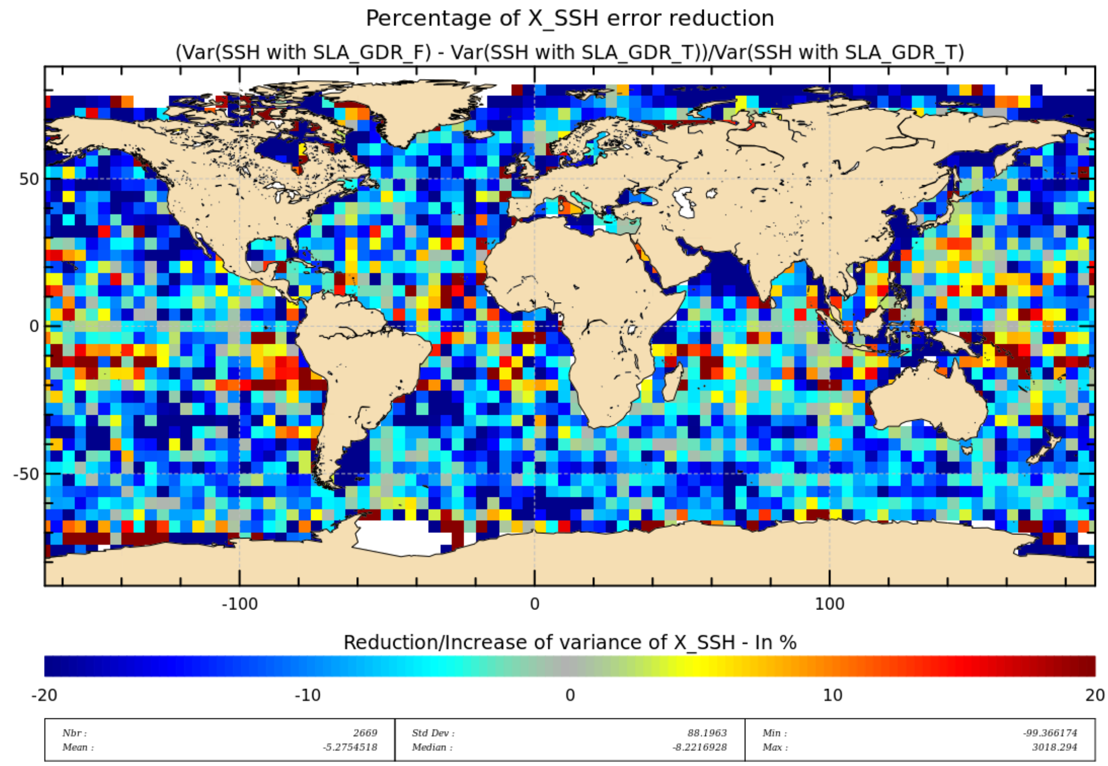


Figure 4.9-9: GDR-F versions of SARAL/AltiKa products reduces the variance of internal SARAL/AltiKa sea surface height crossover differences by an average of 5% globally, and up to 20% in some regions (Jettou et al.)

CryoSat-2 ocean products have been available operationally since April 2014 from ESA, and then reprocessed from the start of the mission. The ocean products have excellent performance over the ocean, comparing well with tide gauges, ARGO, and Jason-2 and -3. An operational change to “Baseline C” including SAR and SARIn is currently being reprocessed. As shown in Figure 4.9-10, sea surface height anomaly noise appears to increase almost linearly with SWH for all tracking modes.

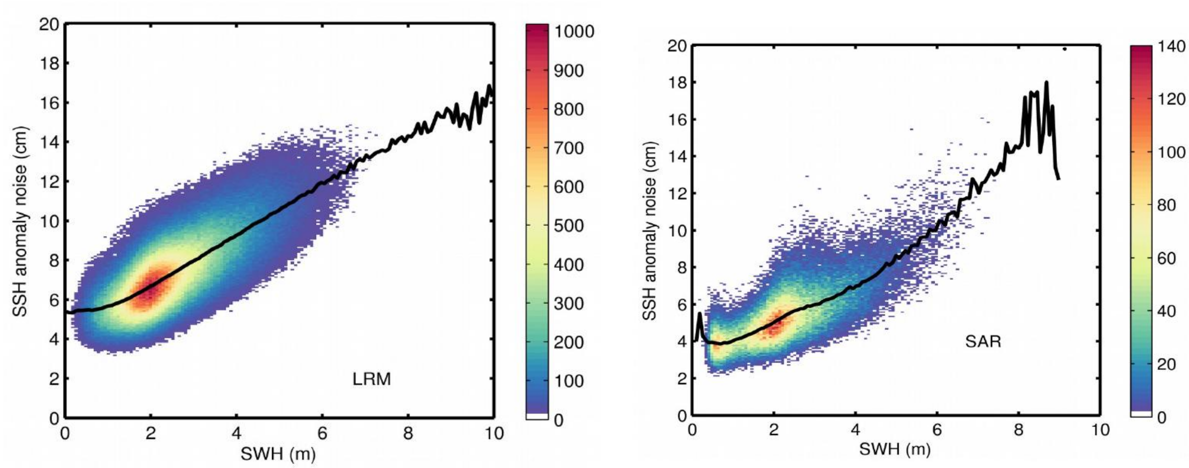


Figure 4.9-10: CryoSat-2 sea surface height anomaly noise increases almost linearly as a function of SWH for all altimeter tracking modes (Banks et al.).

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

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 SAR mode and pseudo LR mode data which is not understood so far. 0.4mm/yr is likely due to the point target response deformation. This later drift 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 has been identified and known for a long time.

In addition, 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, etc.) 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.

The recent research in sea level science shows a better understanding of the internal variability in sea level is emerging, in particular of climate modes' impact on sea level in the Pacific and the Arctic. In particular, there are new promising methods to evaluate and potentially remove natural, internal and even intrinsic variability in the sea level record. These methods should allow for improved estimates of the forced sea level response and help in constraining projections of future sea level.

Beyond the technical aspects of the session, we feel that the science at the OSTST would benefit from more interaction at science team meetings with different communities and different science teams. While we know that this is a logistical challenge, an occasional overlap with ARGO, GRACE-FO or ICESat-2 science teams (for example), could greatly benefit the science that is discussed at these team meetings.

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

Chairs: LuAnne Thompson and Thierry Penduff

This session had 13 submissions, with 6 oral and 7 poster presentations. The research covered the globe with regional studies throughout the tropics and Southern Ocean with a focus on understanding the variability of surface and boundary currents by combining in situ measurements with altimetric sea surface height (SSH) measurements either through process studies, or through the use of reanalyses. In addition, satellite altimetry is also being used to study air-sea interaction both in the mid-latitudes and in the tropics. Some overall themes and highlights are given below.

- SSH along with in situ observations are important in building understanding of remote atmospheric forcing of boundary current and coastal regions (Strub, Lazar, Fewings, Saraceno).
- SSH as an essential component of ocean reanalyses such as GLORYS that allow new insight into boundary current regions such as the Malvinas Current (Artana talk and poster).
- New machine learning and statistical techniques are being developed to separate out the chaotic and deterministic parts of the SSH variability, or to integrate in situ and satellite observations (Penduff and Mulet)
- Altimetric SSH is increasingly being used to study air-sea interactions, both as a proxy for thermocline depth in the tropics (Han) and as a proxy for upper ocean heat content in the mid-latitudes (Thompson). These studies show the potential for using SSH in investigations of the role of the ocean below the surface mixed layer in coupled ocean-atmosphere variability.

The presentations and discussions lead to the following **recommendations**:

- There is less differentiation of Large and Mesoscale oceanography science presentations, examples being the interactions between both ranges of timescales in boundary current regions, or the broad range of space scales of the oceanic chaotic variability. Bringing together the communities that are using altimetry to investigate largescale, mesoscale, and submesoscale variability would allow deeper understanding of the interaction of the different scales of motions and their consequences for the ocean variability.

There are also dynamical connections between coastal and open ocean altimetry across boundary currents. The study of these connections would be facilitated by the development and distribution of altimeter products describing this coastal-to-open ocean continuum in a consistent way.

4.12 Science III: Mesoscale and sub-mesoscale oceanography

Chairs: Jinbo Wang, Clement Ubelmann, [Lee-Lueng Fu and Rosemary Morrow]

Recent reprocessing of along-track altimeter data has led to lower along-track errors and smaller space scales being revealed in Jason Ku-band class altimeters, as well as the Saral/ALtiKa and Cryosat-2 and Sentinel-3 –SAR data. New mapped products also have smaller space scales and higher eddy energy levels. This session addressed the recent progress in observing the smaller ocean mesoscale signals in along-track data, and in observing the eddy dynamics with mapped altimeter data. This session includes studies that address the synergy between altimetry and other satellite data (SST, SSS and ocean colour), in-situ data or models in order to reveal the mesoscale or sub-mesoscale fields. The interaction between the mesoscale and large-scale circulation via the eddy effects on ocean transport, water mass modification and mixing are also encouraged. A new topic concerns the interaction of high-frequency internal tides and internal waves with the mesoscale eddy field, and their imprint in SSH. There are results that will help pave the way for high-resolution swath altimetry, in particular on the merging of the anticipated SWOT observations with conventional altimetry database. There were 6 oral presentations and 14 posters. These presentations include (1) studies about smaller mesoscale and submesoscale processes towards high-wavenumber regime, (2) applications of altimetry in regional/coastal ocean dynamics and statistics of altimetry eddies, (3) data assimilation methodology and results, and (4) the dynamical studies about the forced-intrinsic variability, linear and nonlinear dynamics of oceanic eddies and nonlocal effect of equatorial instability waves. We group the presentations into these four loosely-defined topics and summarize them as follows.

4.12.1 Toward high-wavenumber/smaller-mesoscale spatial-scale regime

- High-wavenumber variability in the California Current: Evaluating sub-100-km scales with high- resolution altimetry, ADCP, and model output: Teresa Chereskin et al.
- SWOT-ACC, Satellite and ship-based investigation of mesoscale-submesoscale interactions in the Antarctic Circumpolar Current: Benoit LEGRESY et al.
- Synergetic use of altimetry and surface drifters to increase resolution and accuracy of sea level anomaly and geostrophic current maps in the Gulf of Mexico: Sandrine Mulet et al.

- High-Resolution Maps of Sea Surface Height: A new method applied to the California Current system: Matthew Archer et al.
  Spectral content of nadir altimetry at regional scales: a case study in the Bay of Biscay and New Caledonia region: Mei-Ling Dabat et al.
- Meso to sub-mesoscale variability observed by Sentinel-3A: Oscar Vergara et al.
- Improvements of Sentinel-3A altimetry data in the retrieval of sea level variability in the coastal region of the European Seas: Antonio Sánchez Román et al.
- High-wavenumber variability in the eastern tropical Pacific from ADCP, altimetry, and a high- resolution numerical model: Saulo Soares et al.

High-wavenumber altimetry signal becomes more and more important as we entering the SWOT era, and the physical processes at the small-scales to be observed by SWOT but not in current altimeter products have been demonstrated to play an important role in the oceanic heat and carbon uptake and oceanic debris transport etc. It is important to study this high-wavenumber regime using all available approaches. We have 8 presentations in this category, 3 oral and 5 posters.

Chereskin et al., used high-resolution altimetry, ADCP, and model output to study the high-wavenumber variability (sub-100km) in the California Current. Their goal is to develop a regional MITgcm adjoint assimilation for the California Current region for the SWOT CalVal. The regional model was compared to a global high-res MITgcm simulation (llc4320) and found an underestimated high-frequency field. After analyzing the difference among the regional ocean simulation and the global ocean simulation, observations from a MBARI mooring, CCE1 mooring, CalCOFI line 90, HF radar measurements, three altimeters and two ocean simulations they conclude that the remote baroclinic high-frequency forcing is important for a regional model to capture high-frequency variability within the regional domain. For the California current region, the global simulation has 539 mega-watts baroclinic energy input into the regional domain through the open-boundaries of the regional model, but the regional model loses 183 Mega-watts baroclinic energy. This energy difference is enough to account for the high-frequency difference between regional and global models.

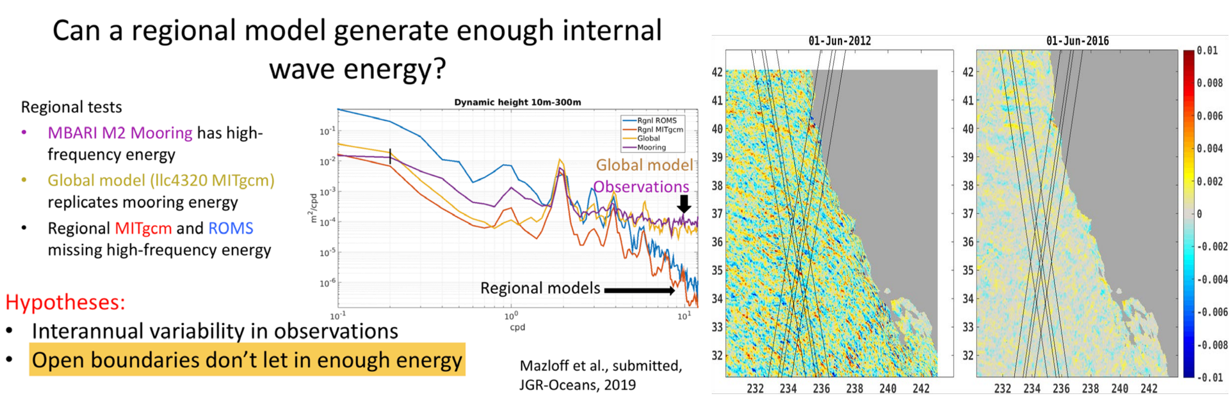


Figure 4.12-1: Chereskin et al. left: The high frequency (super-inertial) energy is less in regional models than in the global model which matches the observations. Right, the vertical velocity field from a global model (left) and a regional model (right). Paper published at https://doi.org/10.1029/2019JC015623

Legresy et al. presented a study of mesoscale and submesoscale interactions in the ACC using satellite altimetry and ADCP, aiming to conduct in-situ field campaign during SWOT fast-sampling phase in 2020. The study area is the ACC meandering south of Tasmania, an eddy hot-spot in the ACC and important in cross-ACC eddy transport. The location is also close to Tasmania and logistically convenient. They analyzed altimetry data, a 2018 cruise in-situ data and a high-res regional MITgcm simulation, and concluded that this region has submesoscale eddies with large enough signal-to-noise ratio to be seen by SWOT. SWOT fast-sampling phase will provide circulation information to provide statistics for optimizing sampling plan. The planned cruise is in 2022 to concurrent with SWOT fast-sampling phase.

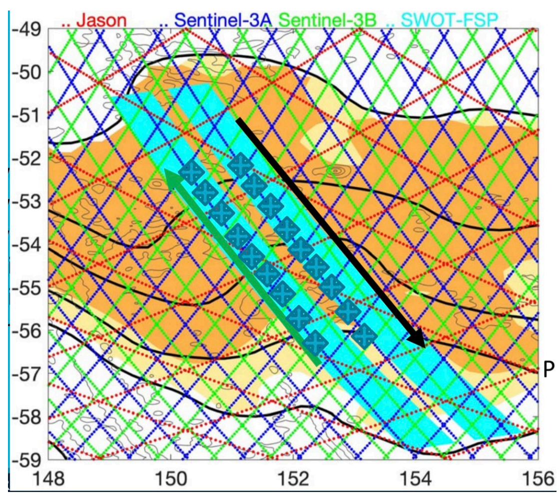
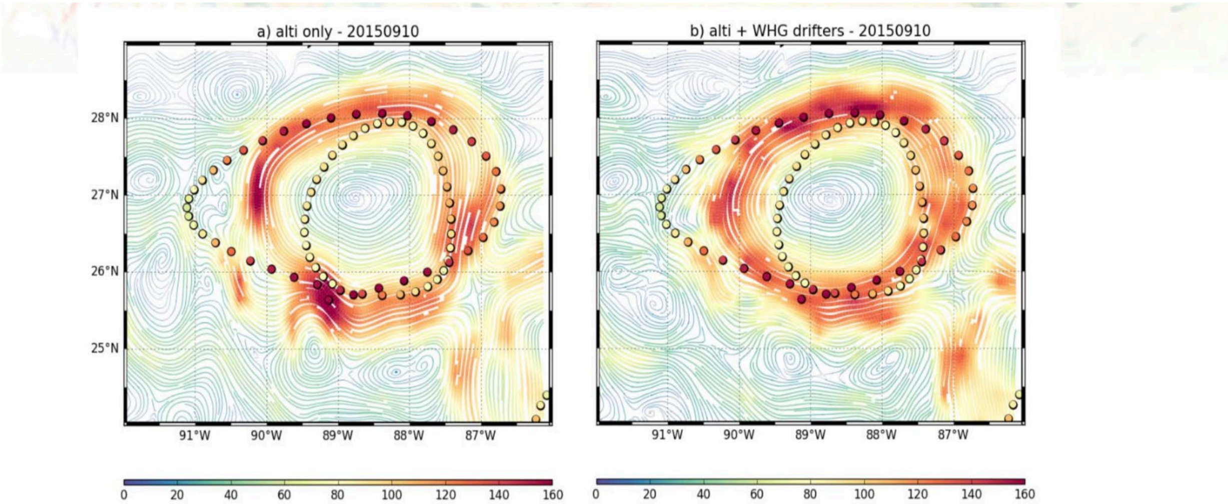


Figure 4.12-2: Legresy et al. The strawman plan for post-SWOT field campaign during the initial fast sampling phase. The cyan color indicates SWOT-swaths.

Mulet et al. presented the synergetic use of altimetry and surface drifters to increase resolution and accuracy of sea level anomaly and geostrophic current maps in the Gulf of Mexico. They combined drifters from CARTHE/LASER project and along-track altimetry to retrieve an improved geostrophic current in the GoM, and validated the reconstruction using independent (Saral/AltiKa) along-track SLA and (withhold) LASER drifters. They conclude that (1) the use of drifters helps to resolved slightly better SLA and zonal component of geostrophic current, same improvement than adding 1 satellite, (2) the use of drifters helps to improve a lot the meridional component of geostrophic current.



Streamlines and intensity of the geostrophic current (cm/s) on 10/09/2015 computed (a) from along-track SLA only and (b) from along-track SLA and WHG drifters. The dots show the intensity of the geostrophic current estimated from AOML drifters.

Figure 4.12-3: Mulet et al., shows that combining the drifter velocities with altimeters improves the reconstruction of geostrophic currents.

Archer et al. used a new multi-scale 2Dvar system and created a new gridded SSH map with a focus on the California Current system. Motivated by the upcoming SWOT Cal/Val in the California Current system, their goal is to investigate how much of the fine-scale ocean variability resolved by along-track observations can be retained in the interpolated 2D maps, while avoiding spurious off-track variance. They applied a variational interpolation technique, optimize the correlation scales for the region, and incorporate a new 'representation error' term in the observational error covariance matrix. Initial results indicate a significant improvement over AVISO in terms of the spatial and temporal resolution of the maps, which we validate with independent remote and in-situ datasets. Figure 4.12-4 shows that the new SSH map (right) has more energy in the high frequency and wavenumber regime than shown in the AVISO gridded data (left).

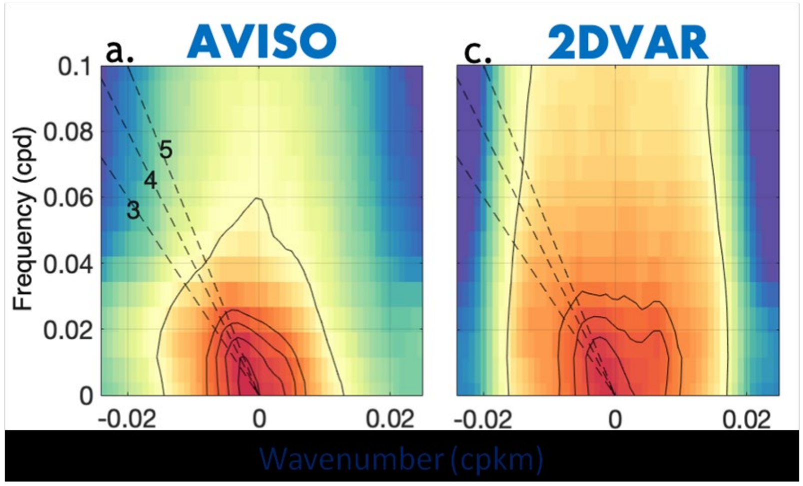


Figure 4.12-4: Archer et al., The frequency-wavenumber spectrum of SSH in AVISO L4 product and the new 2D gridded data (right).

Dabat et al. presented a new study investing the wavenumber spectral content of conventional altimeter data using high-frequency/high-resolution altimeter data from the most recent satellite missions such as Jason 2, Saral/Altika and Sentinel 3A. The motivation is to extend the previous analysis to finer scales with regard to the next SWOT mission. This work follows the studies of Fu et al., 2012; Zhou et al., 2015; Dufau et al., 2016; Vergara et al., 2019 but with a focus on coastal regions: a subtropical area around New Caledonia in the western tropical Pacific and a middle latitude area which is the abyssal plain of the Bay of Biscay in the north-east Atlantic. These regions have contrasted dynamics, but are both characterized by the presence of strong internal tides. They found that anisotropic motions such as internal tides indeed significantly alter the wavenumber spectrum at high-wavenumber end. They also concluded that in these two regions, the along-track Saral/Altika has the best spatial resolution down to 50km.

SSH wavenumber has a constant slope over the mesoscale range, but start to become shallower toward high-wavenumber due to internal gravity waves and tides. It is still a question at what wavelength the transition occurs. There are modelling studies using a high-resolution (2km) global ocean simulation using MITgcm. **Vergara** et al. used a re-processed Sentinel-3A SSH at 20Hz and find similar results as predicted in the numerical model. The lowest values (Lt < 50 km) are found at the highly energetic western boundary current systems, marking a clear asymmetry with the eastern boundaries in all the ocean basins (Lt ~100-150 km). Lt values progressively increase from the mid-latitudes (~150 km) towards the equatorial ocean (Lt > 250 km), consistent with the increased dominance of unbalanced over balanced motions in the SSH variability that is observed at low latitudes. The identified seasonal cycle of Lt shows the same phase as the one predicted by global models but the amplitude of the altimetry-derived seasonal cycle of Lt is below that computed from numerical simulations. **Saulto Soares** et al. also considered this transition scale using ADCP data over the mid-low latitude Eastern Pacific (Figure 4.12-5), the global MITgcm simulation (llc4320) and satellite altimetry. One of the keys conclusions is that the spatial scales of SSH that can be used to derive geostrophic currents will be between 100-200km over the low-latitudes.

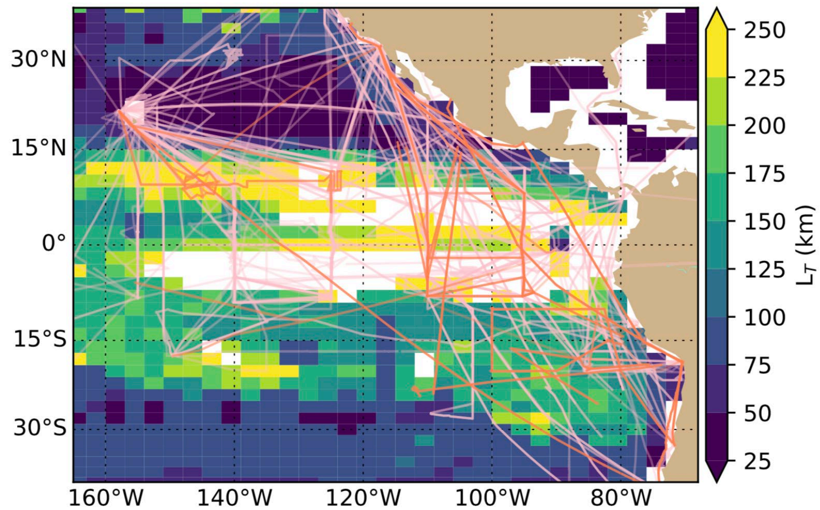


Figure 4.12-5. Map of the annual mean transition scale (L_T) overlaid with ship tracks from JASADCP (pink) and UH (coral) repositories. L_T data from Qiu et al 2018.

Román et al. compared satellite altimetry against in-situ tide gauges in the European coasts of the North Atlantic Ocean and in the Mediterranean Sea. Results show a better performance of Sentinel-3A time series with respect to Jason-3 data in the coastal region of Europe. Similar results are obtained for the different sub-regions investigated.

4.12.2 Ocean dynamics

- Forced vs Intrinsic variability of the Agulhas Bank circulation: V. Combes et al.
- The ocean mesoscale regime of the reduced-gravity quasi-geostrophic model: R. Samelson et al.
- Nonlinear short-term SSH evolution during the 2015/16 El Nino event in the tropical western Pacific: B. Qiu et al.
- Nonlocal effects of an unstable ocean current: T. Farrar et al.

The phenomenology of the oceanic mesoscale eddies has been studied extensively using satellite altimetry but the generation and dissipation mechanisms remain inconclusive. **Samelson** et al. used the eddy statistics from AVISO data to constrain a simplest reduced-gravity QG model to infer the mesoscale eddy dynamics, including questions such as "Does altimeter SSH wavenumber-frequency spectra show nonlinearity?", What does eddy identification and tracking imply when used to constrain a dynamical model?" and "can a regime be identified as a good representation of the mid-latitude mean mid-ocean mesoscale?" The study concluded that a simple data-constrained dynamical model indicates that mid-latitude eddies has forcing amplitude ¼ cm^2/day, damping rate 1/62 per week, and stochastic forcing timescale of 1 week. The altimeter wavenumber-frequency spectra show evidence of nonlinearity that removes energy along the linear dispersion relation and deposit elsewhere. The study also suggests that the altimeter ssh record likely contains largely unexplored wavenumber-frequency information at high-frequency and wavenumbers, echoing the study by Archer et al. in the poster session.

Qiu et al. also used a reduced-gravity model but studied the nonlinear short-term upper ocean circulation variability in the western tropical Pacific. They showed that while the reduced-gravity model well reproduces low-frequency sea level variability in tropical Pacific invoking wind-forced baroclinic response, the region west of Palau cannot be represented simply by linear Rossby wave dynamics in the linear reduced-gravity model. It is because that Palau is located at the northern boundary of a "shadow zone" where wind-forced linear vorticity dynamics breaks down and local nonlinear dynamics becomes important. This nonlinearity is enhanced during El Niño->La Niña transition when intense, wind-forced, downwelling Rossby Waves impinge on the seasonally poleward-migrating North Equatorial Counter-Current.

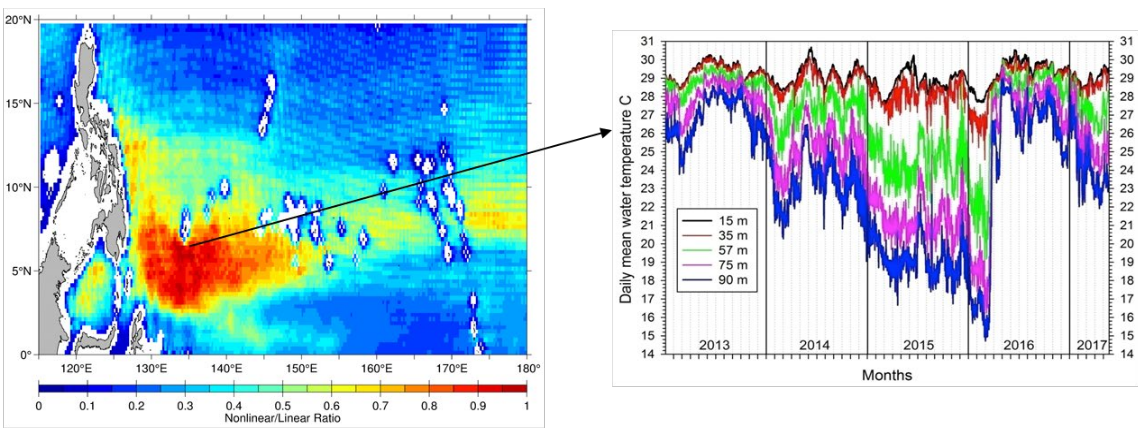


Figure 4.12-6: Qiu et al. Left: the ratio of nonlinear/linear processes. Right: daily mean water temperature at various depths.

Combes et al. investigated the driving mechanism of the variability of the Agulhas Bank circulation using altimetry and model experiments. Forced variabilities were found to be driven by local wind stress, tides and by remotely generated equatorial Kelvin waves propagating along the Atlantic coast. Intrinsic variability is principally found at the southern Agulhas Bank triggered by the passage of mesoscale eddies/pulses of the Agulhas current.

Farrar et al. presented a work that extends Farrar et al. (2011) where long-meridional and short-zonal Rossby waves are identified from altimeter data to be forced by tropical instability waves. They found that spatial variations in the DUACS temporal filtering causes a severe distortion of the global pattern of 33-day SSH variance corresponding to the timescale of the TIWs. Using their own Gaussian-kernel gridded SSH, they are able to pinpoint the meridional coherence of the radiating waves. The model simulation (Figure 4.12-7 upper left) matches that identified from altimeter (bottom left). The patches of SSH variation absent from DUACS product but evident in their own gridded SSH maps and simulation (right panel) indicates that those may be due to a combination of wave interference and topographic refraction.

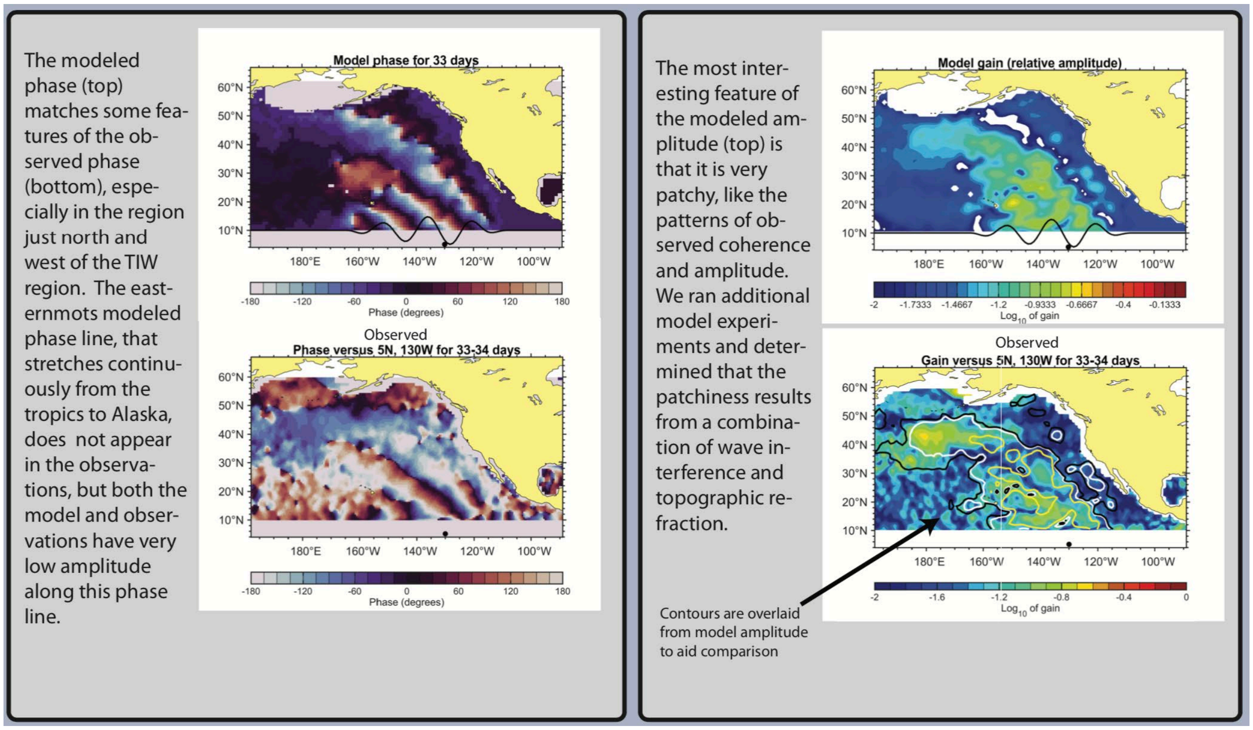


Figure 4.12-7: Farrar et al., comparison of modeled and observed Rossby waves.

4.12.3 Data assimilation

- Constrained scales in ocean forecasting: Gregg Jacobs et al.
- Nested data assimilative modeling of submesoscale variability at the Mid Atlantic Bight Pioneer Coastal Array: John Wilkin et al.
- Multiscale Data Assimilation for SWOT Ocean Application: Jinbo Wang et al.

Satellite altimetry has been demonstrated to be valuable constraint for data assimilation. The conventional data assimilation method, however, faces challenges in utilizing high-resolution altimeter data anticipated from SWOT and future missions. There are three presentations in this session addressing small-mesoscale data assimilation.

Jacobs et al. presented data assimilation results with a focus on characterizing the constrained scales. They discussed the balance of the model and data resolutions in terms of data constrain. While the model resolution is usually higher than data resolution, the latter is the limiting factor in predicting smaller scale processes. In the LASER experiment, they demonstrated that the forecast of drifter trajectory improved by 20% if the unconstrained features were removed. The predictable scale is 220km. The study recognized the future direction of using the multi-scale analyses especially in SWOT data assimilation.

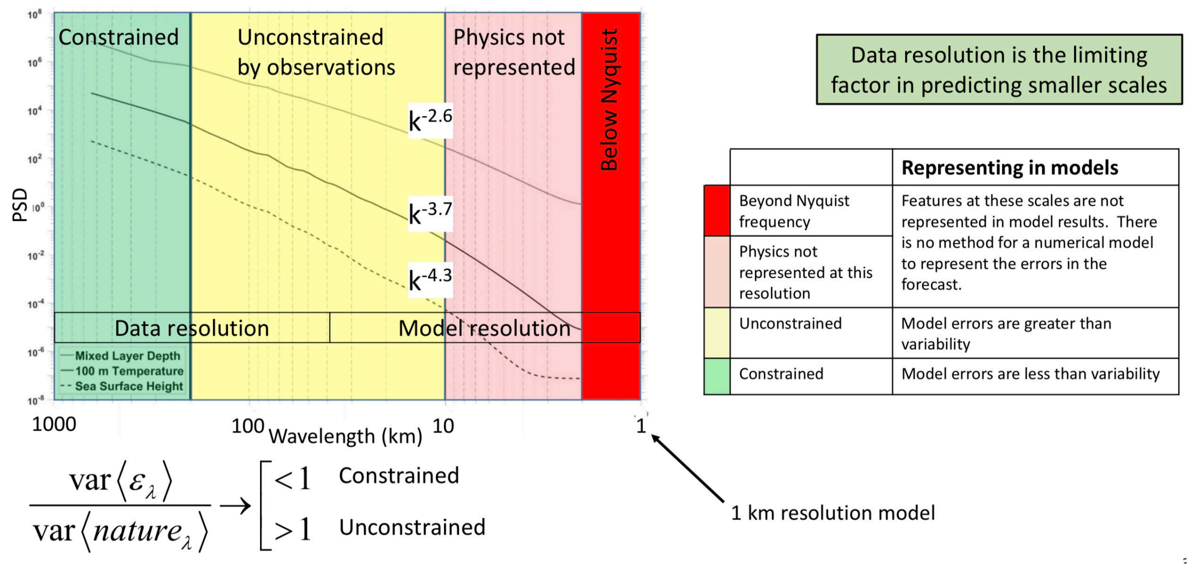


Figure 4.12-8: Jacobs et al. Schematics of the data constrain scales versus model/data resolution.

Wang et al. presented a multi-scale data assimilation system using ROMS (ROMS-MSDA) focusing on the California Current System for the application of SWOT CalVal. Different from their previous twin-experiment study (Li et al., 2019), this study used a MITgcm global ocean simulation as the *nature* to produce synthetic observations. This puts a more stringent test to the assimilation system. Preliminary results shown in Figure 4.12-9 shows effective error reduction in SSH assimilation. This system will be used for future SWOT calval campaign design and SWOT data assimilation.

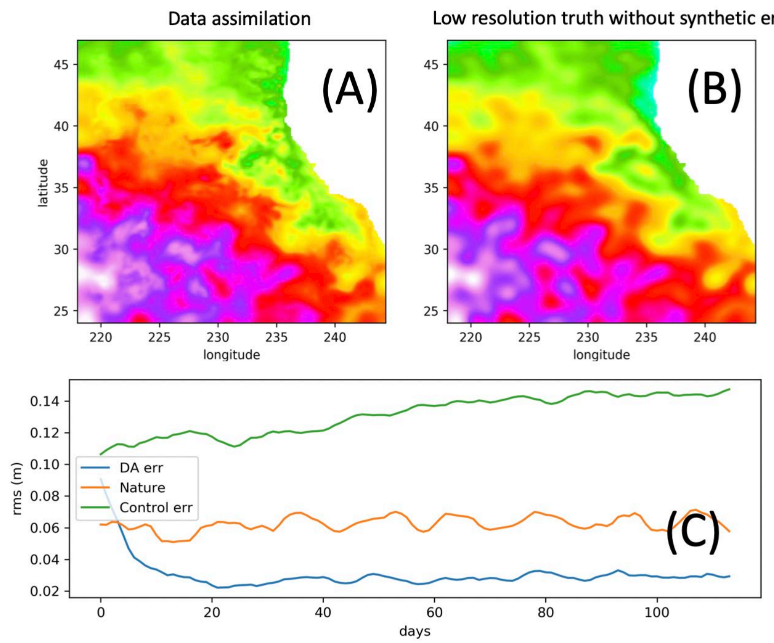


Figure 4.12-9: Wang et al., The resolution from ROMS-MSDA with the MITgcm simulation (llc4320) as the nature run. The upper panels are SSH snapshots from data assimilation (left) and the synthetic truth. The lower panel shows the error reduction by the data assimilation (compare the blue line to the green line).

4.12.4 Applications

- On the Agulhas Bank Circulation: Ricardo Matano et al.
- Understanding Regional Trends in Southern Ocean Eddy Kinetic Energy: Don Chambers et al.
- Preliminary results of FLOATECO: experimental study of physical and biological processes maintaining the floating pelagic ecosystem: Nikolai Maximenko et al.
- Particle dispersion in a multiple migrating quasi-zonal jet regime: A case study in the eastern North Pacific: Oleg Melnichenko
- Monitoring open sea and coastal ocean dynamics in the Baltic Sea and North East Atlantic: Luciana Fenoglio et al.
- Analysis of Second-Order Transverse Structure Functions of Velocity in the Southern Ocean: Don Chambers et al.
- A New NRT Mesoscale Eddy Trajectory Atlas on AVISO: Antoine Delepoulle et al.

There are 7 presentations showing various altimeter applications. **Matano** et al. studied the Agulhas Bank circulation. They used model and observations to characterize the time mean circulation and its seasonal evolution and its interannual variability. The model is evaluated against in-situ observations and satellite altimetry. A suite of process-oriented experiments has conducted to evaluate the relative contributions of local wind forcing, tides and the Agulhas Current on the shelf dynamics and on the shelf/deep-ocean exchanges. **Chambers** et al.

extended Hogg et al (JGR 2015) on the topic of the trend in the eddy kinetic energy in the Southern Ocean. Instead of averaging over a large domain like in Hogg et al. (2015), they examined the average over smaller regions over a period 1993-2018. The results suggest that the conclusions reached by Hogg et al. (2015) of the observational support for the eddy-saturation theory may be premature. Only downstream of Kerguelen Plateau exhibits EKE change and this one location alone can explain the broad Indian Ocean and Pacific Ocean estimates that Hogg et al calculated. This suggests those estimates were biased by regional extremes. In a different study, **Chambers** et al. presented a study on transverse structure functions which sort transverse velocity difference as a function of separation distance. The slope of the function will change depending on the level of turbulence and submesoscale energy in the velocity field. They used along-track altimeter data and ADCP data in the Drake Passage. The results are compared to a new turbulence spectrum theory. **Maximenko** et al. reported some preliminary results of the FLOATECO project, which is a multi-institutional and interdisciplinary project studying the oceanic processes responsible for the formation of marine debris accumulation. The project deployed a set of Lagrangian tools including nine drifting buoys and trackers attached to real debris objects. Preliminary results show that drifters with different drogue depth spread consistently with the vertical shear of Ekman currents but mesoscale and submesoscale turbulence reduces effects of the wind-induced vertical shear during later stage. Physical mechanisms of this reduction are under investigation. **Melnichenko** et al. presented particle dispersion in a multiple migrating quasi-zonal jet regime with a focus on eastern North Pacific. They used altimetry derived velocity to advect particles and calculated the spreading rate through particle dispersion. They found that despite being of weak energy quasi-zonal jets play an important role in localizing eddy pathways that are important for mixing. **Fenoglio** et al. presented a systematic approach to study ocean system of the Baltic Sea and North Eastern Atlantic area using in-situ observations, satellite altimetry and modelling. They demonstrated that mesoscale and submesoscale features are present in the North Sea – Baltic sea transition zone (Danish straits), satellite altimetry in SAR mode has accuracy of 2-4 cm. They also demonstrated that accurate models and in-situ measurements exist for SWOT CalVal purpose in that area. **Delepoulle** et al. presented a new Near Real Time (NRT) "Mesoscale Eddy Trajectory Atlas" to be released by AVISO altimetry portal. The dataset will provide locations and trajectories of detected eddies along with additional information about the amplitude, rotational speed, radius, eddy type (cyclonic/anticyclonic), contour, speed profile and a flag storing missing detections. The methodology and assessment results of this new dataset are presented in the poster.

4.12.5 Discussions

During the last 10 minutes of the session, we discussed a couple of seed questions summarized below. There were interesting discussions on having a dedicated splinter session on state estimate in the next meetings, with data assimilation challenges involving common nature run to compare the different state estimate algorithms, from interpolation to data assimilation. There are also questions identified for future research/meeting considerations.

- What is the space/time resolution of the current 5+ satellites constellation? Has the along-track resolution been fully utilized in gridded products? A new study came out about the resolution (Ballarotta et al., 2019), 400km equator and 100km high latitude.
- SWOT related
    - How to ingest SWOT and fine-scale along-track altimetry data into altimetry analysis?
    - How to handle the high-frequency motions of internal tides and waves?
    - How to handle the incoherent sampling of SWOT/fine-scale along track data, in particular its infrequent temporal sampling?
- What are the future innovations in the synergy of satellite data and in-situ observations including data assimilation method and simple statistical and dynamical interpolations?
    - Existing: Simple OI, dynamical interpolation, multi-scale data assimilation (under development), 3dVar, 4dVar
- Session or splinter dedicated to state estimate from altimetry?
    - Examples: Use SWOT pre-launch field campaign data to test data assimilation? OSSEs with a common nature run?

4.13 Science Results IV: Altimetry for Cryosphere and Hydrology

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

This session was well attended with 27 submitted presentations, splitting into 6 orals and 21 posters. Presentations touched on Jason-3, Sentinel-3A,3B, CryoSat-2 and ICESat-2 mission status as well as the availability of specific thematic data products and improvements to global DEM for enhanced surface acquisition during Open Loop (Diode/DEM mode).

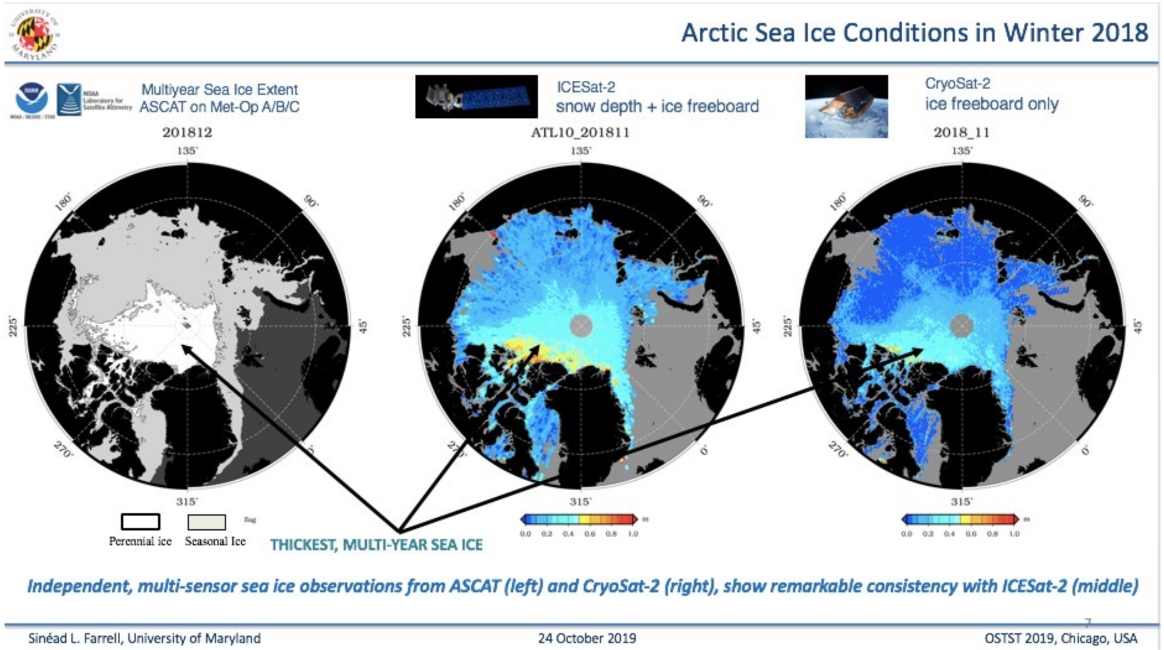
The Hydrology part of the session which touched on lake, reservoir, and river monitoring, in situ validation efforts, SWOT data assimilation exercises for modeling efforts, and tropical river basin research, also heard overviews on the new RIDESAT multi-mission river level monitoring system, and on the ESA Lake Climate Change Initiative and its request for proposals.

The Cryosphere part of the session contained updates on advances in measuring land ice elevation change, looking at polar ocean sea level anomalies, measuring sea ice freeboard and thickness, and estimating snow depth on sea ice. The latter focused on data fusion of SARAL/AltiKa with CryoSat-2, and on ICESat-2 with CryoSat-2, and found that best results were obtained from the former with respect to LRM (AltiKa) and pseudo LRM (CryoSat-2).

A review was given on the Copernicus Sentinel-3 Land Altimetry products and their intended evolutions, looking specifically at STM Land Ice and Se Ice performance. An overview on the relatively new (laser-based) ICESat-2 mission was also given. This multi-beam, high latitude photon-counting instrument, is providing excellent elevation data over all surfaces including coastal, ocean, land ice and continental waters at high spatial resolution. To certain water depths with a degree of clarity, below-water level bathymetry has also been observed at land and lakes/reservoir coastlines.

<u>Specific group responses to the OSTST questions:</u>

- There will be a potential polar altimeter data gap in the mid 2020's. There will be an associated loss of coverage over the Arctic Ocean and Antarctica, and additional impacts on high-latitude hydrology. There is an official OSTST recommendation for the continuation of Polar altimeter time series. The CryoSat-2 and ICESat-2 missions should be maintained as long as possible. The OSTST should explore the potential for exploring polar observations with HY2-A/B/C/D. Additionally it is recommended to support the proposed CRISTAL mission.
- Multi-mission synergy advances a range of scientific studies, e.g. snow depth on sea ice/land ice, SWH (SSB and lidar wave heights), and improved spatial coverage of lakes and reservoirs. Improved use of multi-mission synergies could assist in several ways, e.g., would ensue if a) there was better orbit alignment between CryoSat-2 and ICESat-2, and b) there were coordinated in situ field campaigns for CryoSat-2 and ICESat-2 cal/val in the polar regions, and c) agency data sets could be brought up to the same standard (e.g. GDR-F) and grid lines.
- Advances in hydrology and cryosphere altimetry might be better served if these groups were allowed their own separate sessions at the OSTST (noting that the Cryosphere/Hydrology session was the most subscribed session in 2019). Each session could then subdivide or organize down into different themes e.g. sea ice or land ice, lakes or rivers or product systems. There is also a strong demand to embrace the application science and communities rather than a series of presentations on technical details. Perhaps applications presentations can be held separately on their own merit. How can the OSTST encourage attendance of the applications sector? Can OST make an applications showcase at major meetings and conferences? There is also a need for documenting end user requirements, which would help future sensor development and data product generation. For example, water management agencies need to be aware of current capabilities and their requirements (accuracy, resolution, delivery latency etc.) should drive future data product revisions and goals.
- Improved coordination within the OSTST could be achieved via thematic group breakout sessions. On the subject of joint mission meetings, it was thought that extra effort might outweigh any potential collaboration that might arise.



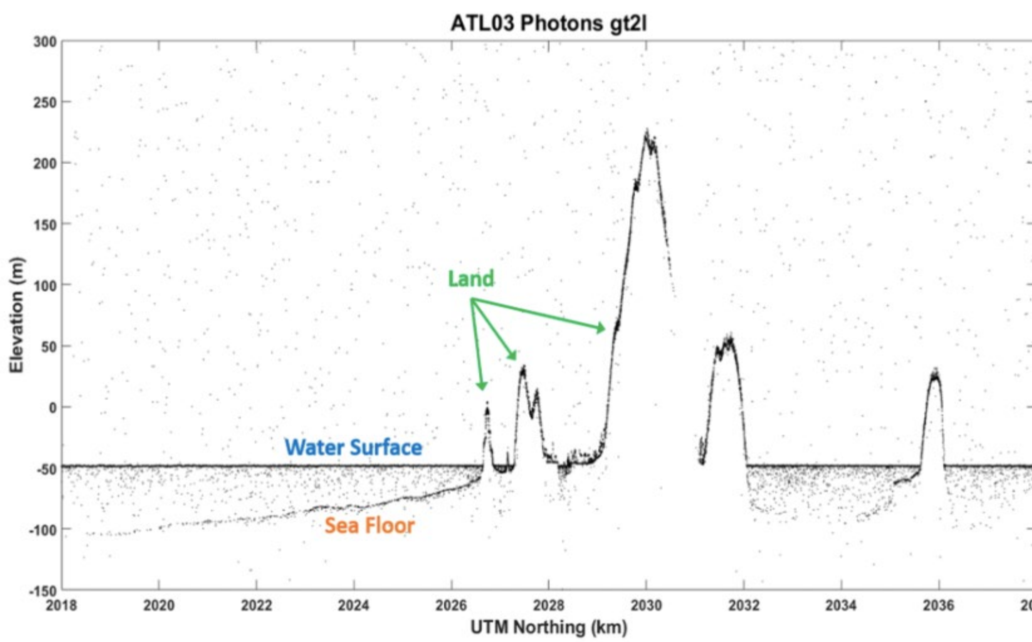


Figure 4.13-1: Contributions to Cryosphere, Hydrology, and Coastal altimetry from the new ICESat-2 mission. (Top) ICESat-2 observations of snow depth plus ice freeboard have remarkable consistency with the ice freeboard measurements of CryoSat-2 and the ASCAT sea ice extent. (Bottom) ATL03 (photon) product shows elevation variations as ICESat-2 crosses over the US Virgin Islands. The land and water surfaces are clearly defined, as is the near-shore submerged topography. The ability to acquire bathymetry to a certain depth is of interest to both the

coastal and inland water communities. Figures courtesy of S. Farrell (2019 OSTST) and McGruder et al., (EOS, 2019).

4.14 The Future of Altimetry

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

A special splinter session was included in the 2019 OSTST Program to discuss the future of satellite altimetry. The session included 5 plenary talks and 7 posters. The topics included both near term and long-term plans and proposals regarding missions that will span the next decade and beyond.

Oral presentations included talks on Sentinel-6 data products (Remko Scharroo, EUMETSAT); CRISTAL, a candidate ESA polar altimeter for the cryosphere (Sinead Farrell, University of Maryland); calibration and validation of the SWOT high-resolution altimeter (Lee-Lueng Fu, JPL); the proposed SKIM Mission at ESA to measure surface currents, ice drift and waves (Clement Ubelmann, CLS); and use of GNSS reflections measured by Spire CubeSats for ocean and ice altimetry (Dallas Masters, Spire Global, Inc.).

Discussions during the splinter sessions covered several topics, but arrived at two separate recommendations. The first was regarding the availability of low resolution "LRM" data from the Sentinel-6 mission. The proposed recommendation read "For Sentinel-6 L2P product should be provided so that LRM data users have continuity with earlier Jason and TOPEX data record." Additionally, there was a discussion regarding the possibility of a gap in high inclination polar altimetry, given the aging of existing missions and the current schedule for CRISTAL. In light of this discussion, the splinter suggested the following recommendation, which was discussed by the entire OSTST during the closing plenary session, and a version of it was eventually adopted.

The final **recommendation** read:

- To minimize likelihood of a gap in polar ocean and ice monitoring, the OSTST encourages Agencies to strive to launch CRISTAL in the early 2020s and to maintain operation of CryoSat-2, ICESat-2, and SARAL/AltiKa as long as possible.

4.15 The Geoid, Mean Sea Surfaces and Mean Dynamic topography

Chairs: Ole B. Andersen and Yannice Faugere

This splinter was slightly smaller this year and had a total of 5 oral presentations and 4 posters.

Oral presentations	
Andersen & Abulaitijiang	Marine Gravity from the first two cycles of the Jason-2 LRO extension of Life mission
Bruinsma et al	ESA's new satellite-only gravity field model via the direct approach (DIR-R6)
Mulet et al	New CNES-CLS18 Mean Dynamic Topography of the global ocean from altimetry, gravity and in-situ data
Knudsen et al	A new combined mean dynamic topography model – DTUUH19MDT
Pujol et al	Improvements and limitations of recent mean sea surface models: importance for Sentinel-3
Poster	
Knudsen et al	GOCE User Toolbox and Tutorial
Schaeffer et al	New CNES CLS 2019 mean sea surface: first validation
Schaeffer et al	The new CNES CLS 2019 marine gravity anomaly model: first validation in the Mediterranean.
Bruinsma et al	Geomed2: High-Resolution Geoid Models of the Mediterran

As the previous years the session covered the three topics of the session, Geoid, Mean Sea Surfaces and Mean Dynamic Topography.

First, Ole Andersen et al. presented the evaluation of a new gravity field using Jason-2 geodetic measurements. In a comparison with gravity field from the Jason-1 extension of life, Jason-2 is the only geodetic mission which can decrease the track distance below 8km (past GM's) in a systematic way to 4km after 2 years and 2km after 4 years. Hence it will enable mapping of finer and finer scale in the gravity field not mapped before and likely enable us to map bathymetry with finer scale than ever before (Figure 4.15-1).

Sean Bruinsma presented the ESA's new satellite-only gravity field model via the direct approach (DIR-R6) developed in spherical harmonics to degree and order 300, computed by GFZ Potsdam and CNES Toulouse within the framework of GOCE High Level Processing Facility. GOCE-DIR-R6 is significantly more accurate than previous GOCE model releases (Figure 4.15-2).

Then, Sandrine Mulet presented the new CLS18 MDT which is derived with higher resolution (1/8°) than the previous CNES-CLS13 MDT (1/4°). She presented validation results that illustrate the overall improvement and in particular huge improvements of the coastal and western boundary currents. She mentioned however that in future work we should go on improving coastal area, high latitudes and go toward higher resolution (Figure 4.15-3). The preliminary results of another MDT, DTUUH19 MDT, as been presented by Per Knudsen et al. (Figure 4.15-4). A recommendation of a cross comparison of the two MDT in the coming year was recommended during the session.

Finally, different Mean Sea Surface models were assessed by Pujol et al. with focus at short wavelengths [15, 100 km]. The authors showed that the recent MSS models SCRIPPS (Sandwell et al., 2016) and DTU_2018 (Andersen et al., 2018) allow to significantly reduce the omission errors compared to the CNES_CLS_2015 (Pujol et al., 2016) model with up to -37% error reduction observed with SCRIPPS model. On another hand, commission errors still contribute to the MSS error budget at short wavelengths as underlined for instance with DT_2018 model. The Hybrid Mean Profile (HMP) that can be estimated along repetitive tracks, gives a refined solution of the MSS along theses tracks. Results obtained along uncharted tracks Sentinel-3A (Dibarboure et Pujol, 2019) showed that this solution remains more performing than all the gridded MSS models tested (Figure 4.15-5). Such HMP solution is thus recommended and used for along-track operational processing within CMEMS. Finally, the improvement and assessment of the different MSS/HMP solutions remains an important issue for the future of altimetry since the MSS remains an important source of error when focusing on the small-scale signal that should be sampled with the future SWOT mission.

Data	Std	Percent improvement Wrt Jason1 GM gravity
Jason-1 GM (1 year)	2.76	0 %
Jason-2 (1st LRO)	2.77	~-1 %
Jason-2 (2nd LRO)	2.78	~-1 %
Jason-2 (all)	**2.68**	**4%**
C2 only (8 years)	**2.66**	**5%**
SA only (3 years)	**2.67**	**4%**
Combinations:		
C2+SA+J1	**2.58**	**7%**
C2+SA+J2	**2.57**	**7%**

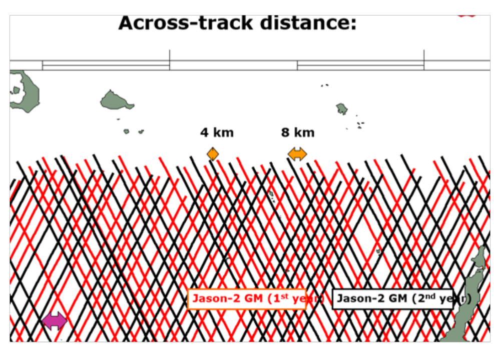


Figure 4.15-1: Illustration from (Andersen & Abulaitijiang) on the impact of Jason-2 geodetic measurements on the improvement of the gravity field

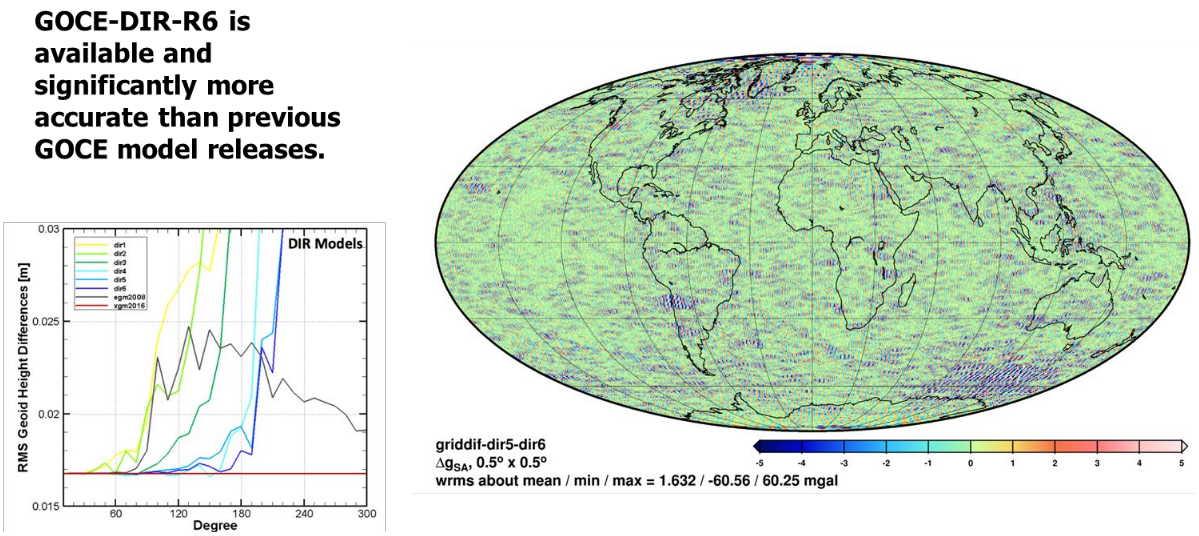


Figure 4.15-2: Illustration from (Bruinsma et al) Improvement of dir-6 gravity field

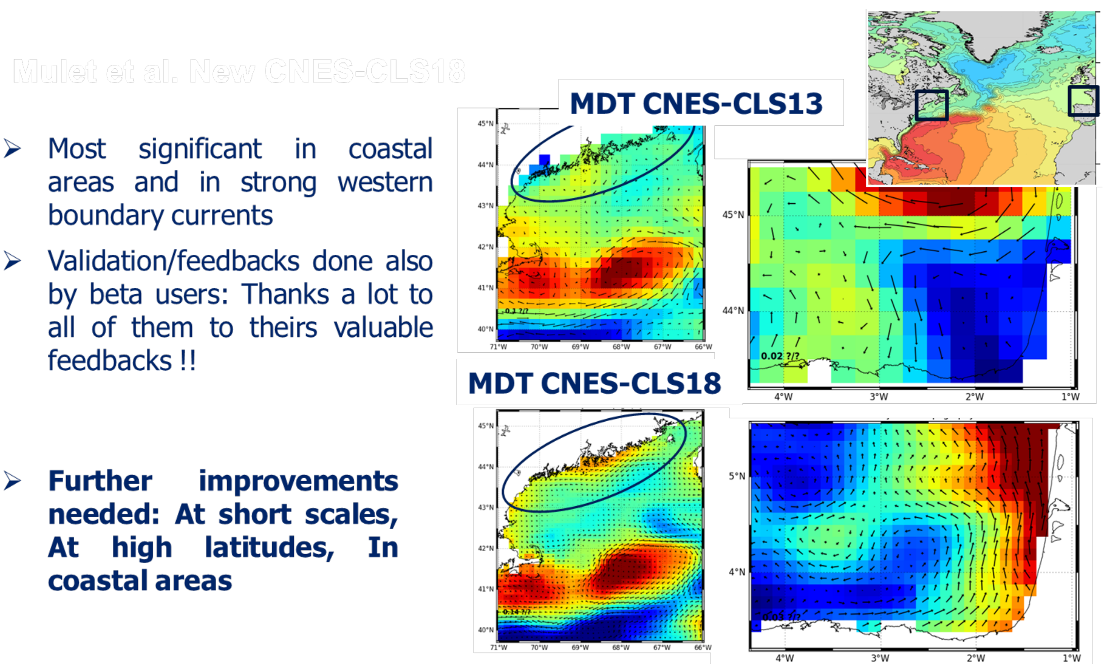


Figure 4.15-3: Illustration from (Mulet et al) illustrating the improvement in coastal current determination through the new CLS18MDT.

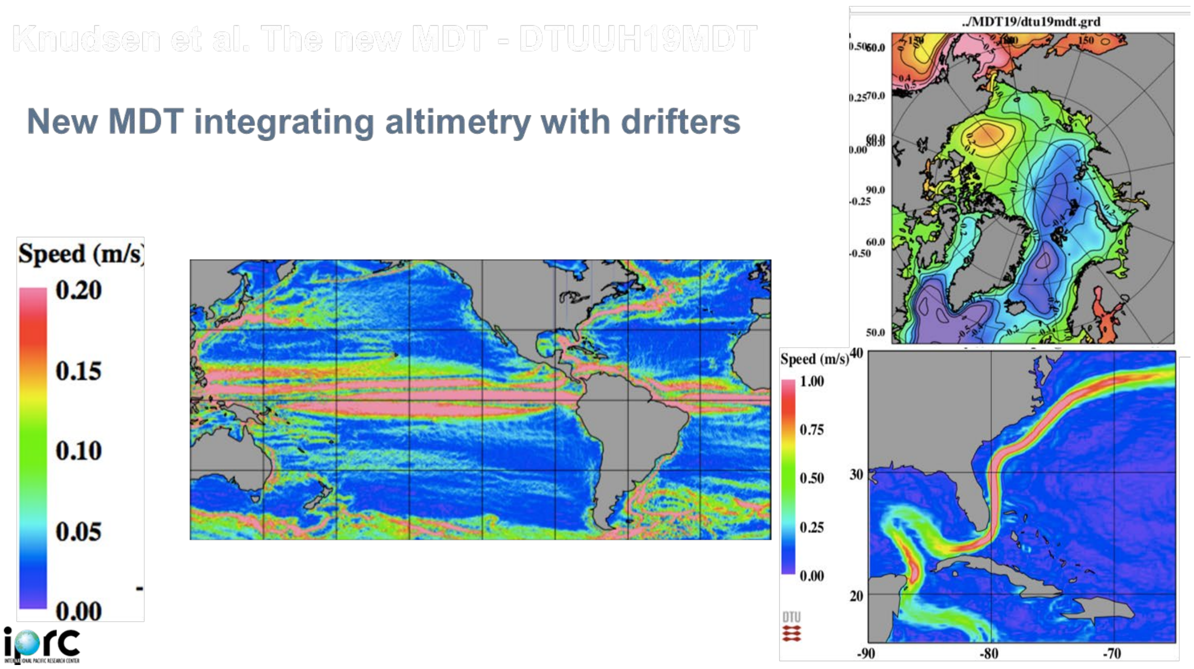


Figure 4.15-4: Illustration from (Knudsen et al) on the improvement of DTUUH19 MDT

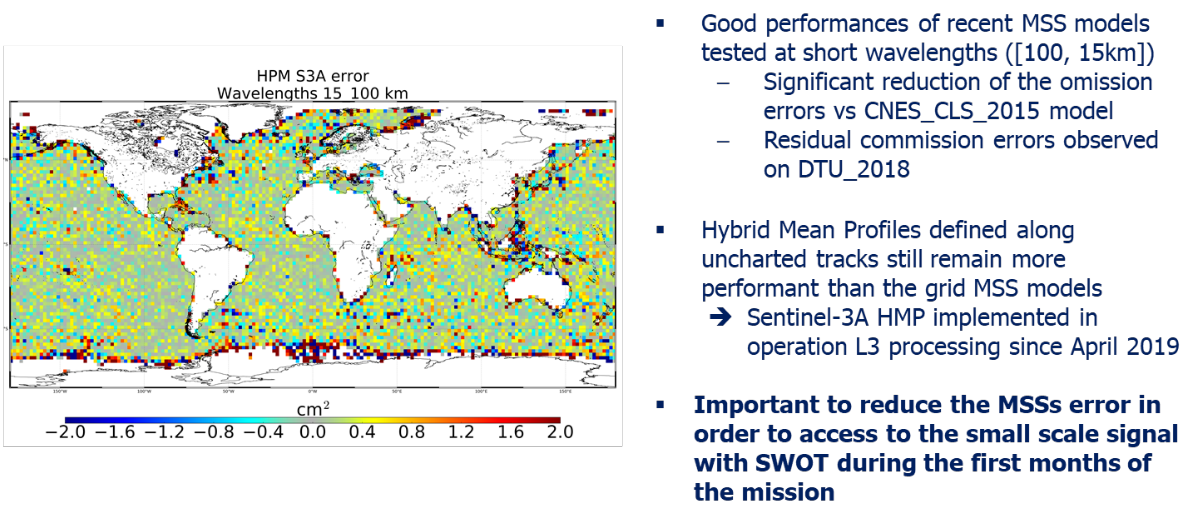


Figure 4.15-5: Illustration from (Pujol et al) et al illustrating the impact of a mean profile for Sentinel3A

Recommendations:

The discussion in the splinter focused on preparing recommendations for the question posed by the organizers on the extension of life for Jason-3.

The splinter **recommends** the following:

- Reconstitute the Jason EoL group to initiate the study of possible moving J-3 into a "controlled" geodetic orbit after the S6 commission phase and to maximize the benefit to both oceanography and geodesy (mean sea surface).
- Study possibilities to use and continue the Jason-2 LRO to gain 2 km across-track spacing.
- Acknowledging that by 2021 there will be at least 3 operating ERM missions, recommend to study the value of putting Jason-3 in an interleaved mission vs geodetic mission for operational usage and for oceanographic purposes.

4.16 Tides, internal tides and high-frequency processes

Chairs: Loren Carrere, Florent Lyard and Richard Ray

This year the Tides, Internal Tides and HF splinter counted 5 oral presentations and 8 posters dedicated to barotropic tides, internal waves and high-frequency corrections, but again the main focus of the splinter was internal tides in the perspective of the coming SWOT mission.

Oral presentations: Four talks focused on internal tides, and one was dedicated to barotropic tides.

Y. Faugère et al. presented some results about the impact of internal tide correction on the DUACS maps. The along track altimeter products used to generate the DUACS gridded Sea Level Anomalies products currently disseminated in CMEMS are not corrected from the internal tide effects. Recent studies highlighted the existence of residual tidal variability in the grids (Zaron, 2019), representing a pollution of the 2D mesoscale signal retrieved. An experimental dataset has been produced using a prior internal tide correction (Zaron model) for the along track data following the OSTST 2018 recommendation. The impact of this correction on the DUACS maps accuracy has been assessed over a 5-years period. Various diagnoses have been implemented including comparisons to independent dataset to quantify the improvement. The results show the positive impact of using the Ed. Zaron IT model on the maps quality (DT2018 mapping configuration):

- Better consistency of corrected maps with independent measurements (CryoSat-2)
- Error reduction is low in average but locally >1cm2
- Hawaii focus: the signal removed represents 33% of the variance of the corrected map for the main IT wavelength
- EKE is reduced by 20 cm^2/s^2, representing 10% of the signal in some areas.

This IT correction is already available in 5Hz DUACS "high resolution" products available on AVISO, and it will be implemented in new level-2 products (Jason GDR-F, S3 …) and in next DUACS 2021 reprocessing.

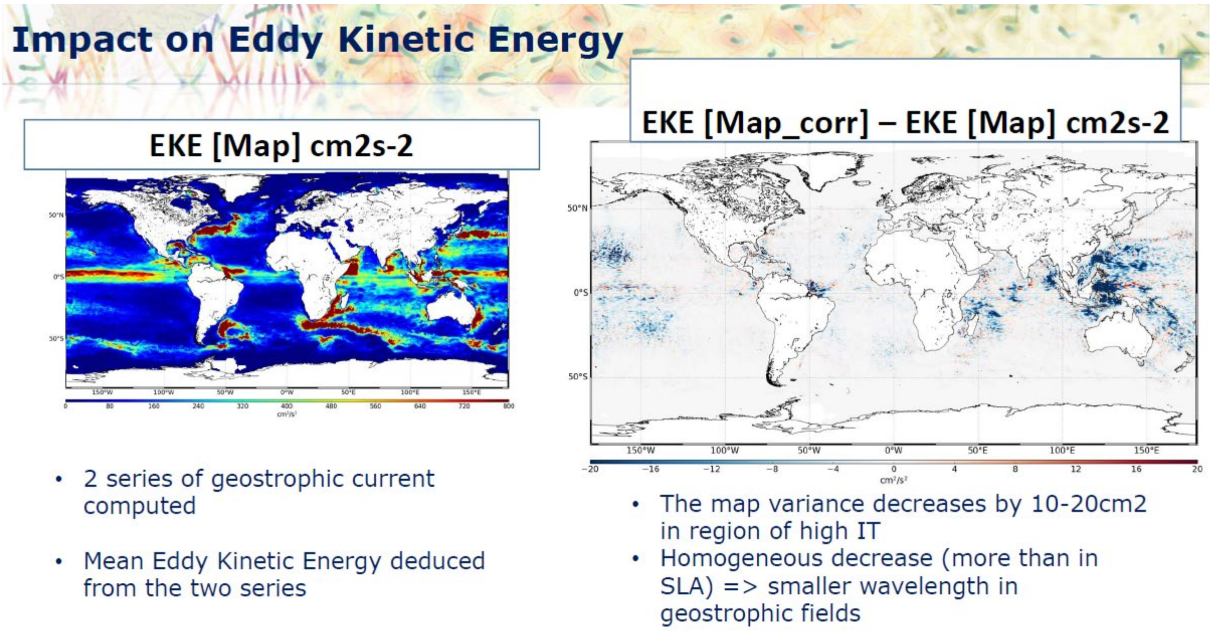


Figure 4.16-1: impact of applying the Ed. Zaron IT model on the EKE estimation on global ocean.

R. Ray et al. presented new progress towards GOT5 concerning high latitudes and minor constituents. The talk focused on some minor tidal constituents in diurnal, semi-diurnal and terdiurnal bands which are not so critical for tide prediction purposes, but which are of interest in their own right. Some estimations of these minor tides have been presented and the talk addressed the question: do we need to infer them or estimate directly? An accuracy assessment of the deep-ocean minor tides was done using 150 bottom-pressure stations on global ocean. Finally, some recommendations have been raised for handling minor tides:

- Tides in middle of bands can still be inferred (admittances interpolated, not extrapolated): M1, nu2
- Tides affected by nonlinearity must be directly estimated (but not everywhere?): mu2 (2MS2), L2 (2MN2), tau1 (MP1)
- Tides at edges of bands can now be directly estimated (depending on SNR): 2Q1, sigma1, J1, OO1

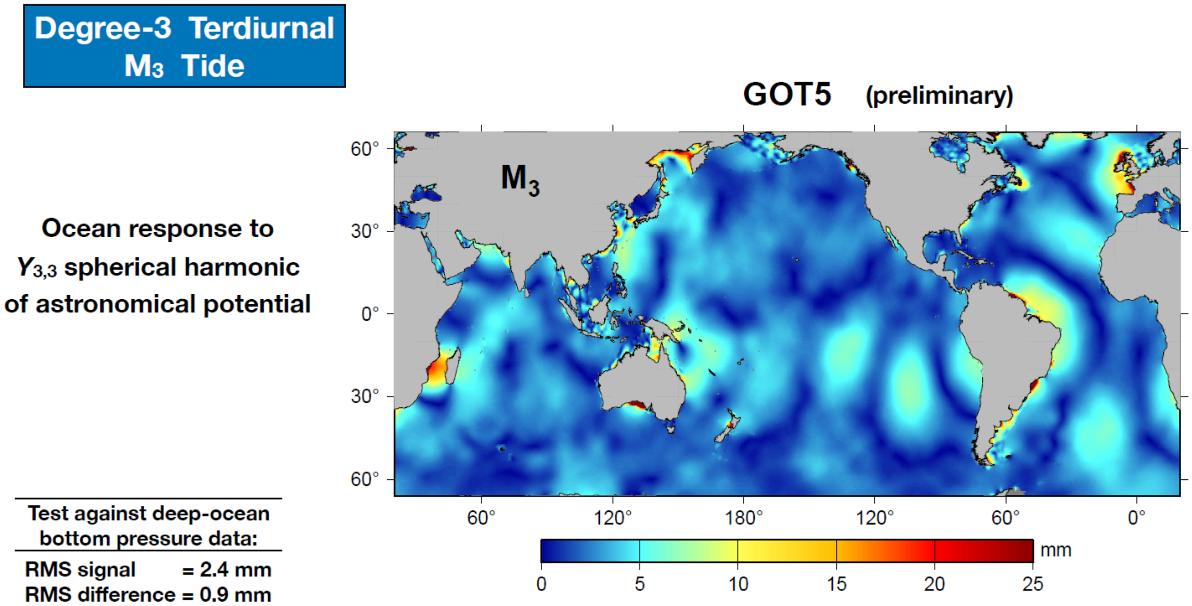


Figure 4.16-2: global amplitude map of the preliminary estimation of M3 tide from GOT5 model. Amplitude is greater than 1 cm locally.

Internal tides fate and energy budget off the Amazonian shelf (Tchilibou M., Koch-Larrouy A., Lyard F. et al.). In the perspective of the forthcoming SWOT mission, the NEMO hydrodynamical model performances in reproducing realistic tidal dynamics, barotropic and baroclinic are being investigated and hopefully improved in a CMEMS financed project. In parallel with global ocean experiments, we conduct more detailed diagnostics using regional experiments. The presentation shows an analysis the internal tides generation, propagation and dissipation and examine the associated energy budget off the Amazonian shelf. The analysis is based on regional NEMO high-resolution simulations (1/36°) and the vertical modes decomposition. The coherent versus incoherent internal tides issue is addressed, as well as the limitations of the harmonic approach in characterizing the full internal tides dynamics. Results show that the baroclinic energy flux is maximum for the first modes (1 and 2) in the area, and the signal captured by the harmonic analysis corresponds to the areas where the energy flux is strong. The IT energy flux extension appears «stopped» by the mesoscale dynamic for high EKE regime, and the interaction between the baroclinic energy fluxes and the cyclonic/anti-cyclonic eddies is pointed out but needs some more investigation.

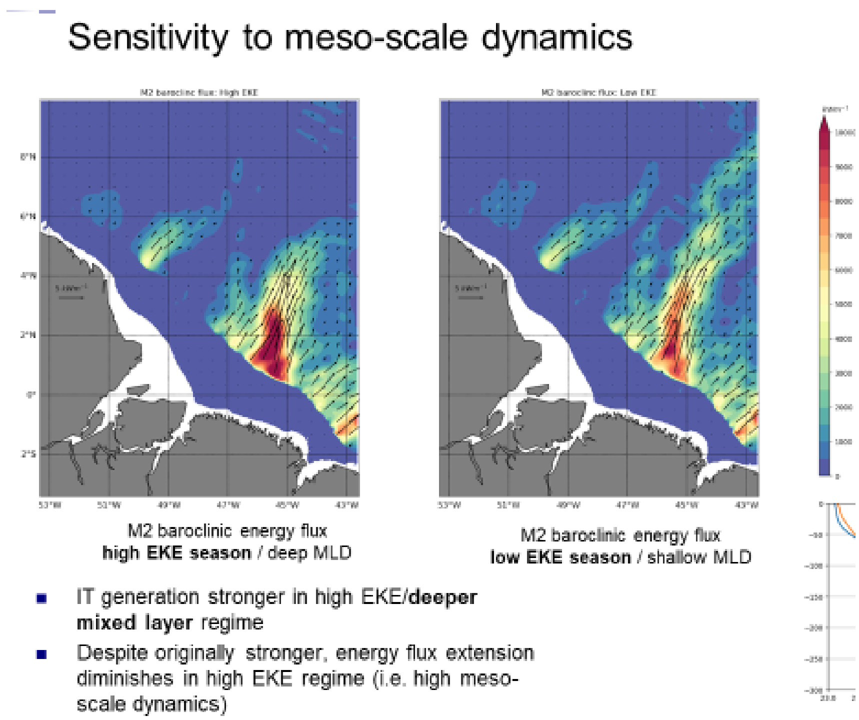


Figure 4.16-3: M2 baroclinic energy flux estimated for two different oceanic regimes (high EKE and low EKE).

Decomposition of the multimodal multidirectional M2 internal tide field (Zhao et al.). The M2 internal tide field contains waves of various baroclinic modes and various horizontal propagation directions. The talk presents a technique for decomposing the sea surface height (SSH) field of the multimodal multidirectional internal tide. The technique consists of two steps: First, different baroclinic modes are decomposed by two-dimensional (2D) spatial filtering, utilizing their different horizontal wavelengths; second, multidirectional waves in each mode are decomposed by 2D plane wave analysis. The decomposition technique is demonstrated using the M2 internal tide field simulated by the MITgcm. The analysis focuses on a region lying off the US West Coast ranging 20–50N, 220–245E. The lowest three baroclinic modes are separately resolved from the internal tide field; each mode is further decomposed into five waves of arbitrary propagation directions in horizontal. The decomposed fields yield unprecedented details on the internal tide's generation and propagation, which cannot be observed in the harmonically fitted field. The results reveal that the mode-1 M2 internal tide in the study region is dominantly from the Hawaiian Ridge to the west, but also generated locally at the Mendocino Ridge and continental slope. The mode-2 and mode-3 M2 internal tides are generated at isolated seamounts, as well as the Mendocino Ridge and continental slope. The Mendocino Ridge radiates both southbound and northbound M2 internal tides for all three modes. Their propagation distances decrease with increasing mode number: Mode-1 waves can travel over 2000 km; while mode-3 waves can only be tracked for 300 km. The decomposition technique may be extended to other tidal constituents and to the global ocean. In the end, its application to 1-year synthetic SWOT data is demonstrated.

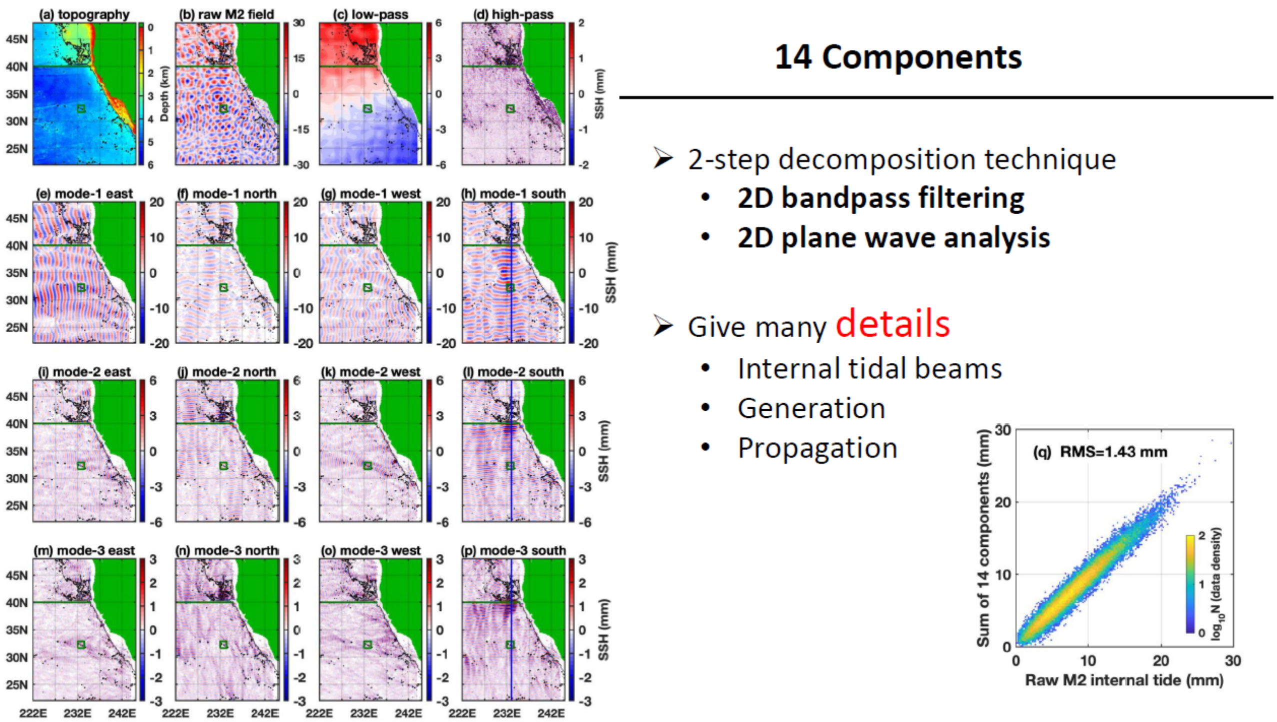


Figure 4.16-4: decomposition of the baroclinic tide signal in 14 components on the region of interest: low-pass and high-pass fields and then 4 horizontal propagation directions for each of the first 3 IT modes.

Comparison of global and regional internal tide and gravity wave models with observations (Arbic et al.). In recent years a growing number of modeling groups have included tidal forcing in high-resolution, three-dimensional global ocean general circulation models (OGCMs). Inclusion of tides in high-resolution OGCMs allows for modeling of non-stationary internal tides, and a partially resolved supertidal internal gravity wave (IGW) continuum spectrum, both new additions to the list of phenomena that global models can simulate. Such models have been, or are being, applied to problems in satellite altimetry, field experiment design, basin-scale ocean acoustics, and (soon) achieving a better understanding of ocean mixing. Because they are being used for a growing number of applications, it is very important to validate these models against available altimetric and in-situ observations. This talk shows comparisons of four high-resolution OGCMs with explicit tidal forcing --HYCOM, MITgcm, NEMO, and MOM66-- to an array of observations. The stationary internal tides in all four models is compared to altimetry, the non-stationary internal tide in HYCOM is also compared to altimetry, and the IGW continuum kinetic energy spectrum in global HYCOM and MITgcm is compared to McLane profiler spectra. HYCOM and MITgcm temperature variance and kinetic energy, integrated over several frequency bands of interest, are compared to values computed from an archive of thousands of moorings. The surface ocean geostrophic kinetic energy in HYCOM and MITgcm is compared to AVISO. The surface kinetic energy in HYCOM and MITgcm are compared to drifters. General conclusions emerging from these comparisons are:

- Higher horizontal and vertical resolution (especially in MITgcm) make for a better-represented internal gravity wave continuum spectrum
- HYCOM has a higher spatial correlation with observations than MITgcm, probably due to substantial tuning done for operational purposes
- MITgcm, MOM6, HYCOM, NEMO internal tides run without extra damping such as topographic wave drag are larger than in altimetry
- HYCOM tide simulations predict the geography of non-stationary internal tides relatively well
- Preliminary HYCOM comparison to surface drifters indicates closer agreement than MITgcm in near-inertial and tidal bands

Note that a very large number of co-authors contributed to this work.

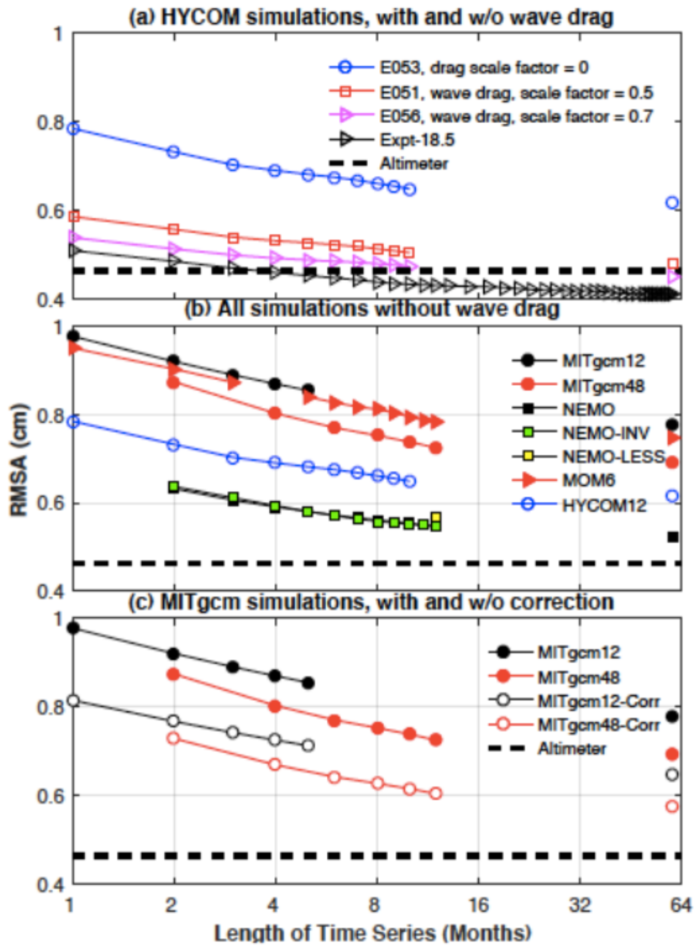


Figure 4.16-5: globally averaged M2 stationary internal tide SSH amplitude given by several global hydrodynamic models and along-track altimetry (cm) [Ansong et al., in preparation].

<u>Poster presentations</u>: 4 posters focused on the internal tide signals, 3 on barotropic tide and one poster focused on the Dynamic Atmospheric Correction. Posters' summaries are gathered hereafter.

TID_001: Bathymetry improvement and tidal modeling in the North East Atlantic Ocean and in the Mediterranean Sea (Cancet et al.). The aim of this project (CNES funded) is to improve the bathymetry and the tides in the North-East Atlantic Ocean and in the Mediterranean Sea. The increase in the grid resolution, combined with local model tuning, is one of the means to improve the tidal model performance in the coastal regions and large improvements have been achieved thanks to this approach. However, increasing the resolution of the model grid implies consistent bathymetry quality and accuracy, which is today the main limiting factor to accurate high-resolution tidal modelling. The work presented is divided in several steps: 1) an inventory of the existing bathymetry datasets in the regions of interest; 2) the integration of the collected datasets into a reference global bathymetry dataset; 3) the evaluation of this new bathymetry dataset through hydrodynamic modelling; 4) the assimilation of tidal observations into the model and the production of high resolution regional tidal atlases. The most recent results obtained within this project are presented and show some improvement compared to the FES2014-non assimilated solution on both areas.

TID_002: Coastal tides and sea level variations at high latitudes from GNSS-R and satellite altimetry (Andersen et al.). The ability to determine ocean tides are still limited in coastal regions due to the limited space-time sampling and ocean tide errors remain the largest source of range error in satellite altimetry today in the coastal zone. SAR altimetry from Cryosat-2 and Sentinel 3A/B is capable of providing altimetry closer to the coast than conventional altimetry and in this presentation we aim at presenting result from the ESA GOCE++ project which looks at the ability to add information about sea level and tides from GPS reflectometry in high latitude regions where tide gauges are sparse and where GPS reflectrometry is a promising alternative to measure sea level close to the GPS stations. We have currently identified some high latitude stations on Greenland where tide gauges are sparse, but where the Danish GNET system of coastal GNSS stations operated and have identified and processed the GNSS data to determine sea level variation. We will present results from these co-located GPS reflectrometry data and Cryosat-2 and Sentinel 3A SAR altimetry with respect to both sea level variations and estimation of the residual tide signal at those locations.

TID_003: The effect of horizontal resolution and wave drag on tidal baroclinic mode waves in realistic global ocean simulations (Buijsman et al.). The M2 tidal energetics are studied for two realistically forced global ocean HYCOM simulations with horizontal resolutions of 8 km (H12) and 4 km (H25) and 41 layers. In both simulations the M2 SSH RMS error with TPXO is 2.7 cm. To optimize the tidal accuracy, the wave drag is tuned differently: in H12 the wave drag scale is 0.5, while in H25 it is 0.3. In HYCOM, the wave drag dampens both the barotropic and baroclinic tidal waves. The M2 baroclinic fields are decomposed into the first 5 vertical modes. In H12 the first 2 modes are resolved, while in H25 the first 5 modes are resolved. From H12 to H25, the M2 barotropic energy conversion to the resolved baroclinic wave modes increases by 47%, mainly due to the increased resolution in H25. At the same time, the barotropic energy lost to the wave drag decreases in H25 due to the reduction in drag scale. In both simulations, the sum of the resolved conversion and wave-drag dissipation, which represents the unresolved high-mode conversion, is the same (about 1 TW), in accordance with both simulations having identical tidal accuracy. The M2 barotropic energy conversion to the first 5 modes agrees with analytical models based on Bell's theory. The reduction in wave drag scale also reduces the damping on the resolved baroclinic modes in H25, which are too energetic when compared to satellite altimetry and altimetry-inferred fluxes. The resolved, low-mode, internal tide dissipation rates in H25 are in agreement in magnitude and spatial distribution with dissipation rates inferred from Argo and Mirco- and Finestructure data. However, when the parameterized high-mode dissipation is included, the tidal internal tide dissipation is larger than the rates inferred from Argo and Fine/Microstructure. These findings suggest that HYCOM needs barotropic and baroclinic wave damping terms that can be tuned separately.

TID_004: Using Complex-Demodulation to Identify Non-Phase-Locked Tides from Reference-Mission Altimetry (Zaron et al.). Modulations of the internal tide are caused by both large-scale, seasonal-to-interannual, changes in ocean stratification and also by smaller-scale mesoscale currents and stratification. The magnitude and frequency spectrum of the tidal modulations is hardly known, but it is clear that this information may be crucial to the interpretation of ocean topography measured by SWOT and it may provide a useful record of climate statistics which are currently poorly measured by direct means. Complex-demodulation, which may be implemented with short-term harmonic analysis or other techniques, can be combined with spatial analyses of along-track altimetry data to reveal changes in internal tides and distinguish them from broadband mesoscale variability. In this talk I will show examples of these kinds of analysis which identify seasonal-to-interannual variability of internal tides. By looking at variability as a function of the demodulation window, it is possible to infer the total variance associated with the non-phase-locked internal tide. These results provide a view of internal tide variability which complements previous approaches based on analysis of the wavenumber spectrum.

TID_005: De-aliasing of tidal signals using wide-swath sun synchronous orbits (Carrere et al.). Some errors The tides and tidal currents are predominant signals in shallow and shelf regions which have critical applications and societal interests; tidal models have now a very good accuracy in deep ocean but some errors still remain mainly in shelf seas and in polar regions where availability of new databases is worthful for the development of future tide models. In this context, we analyze the interest of new satellite missions for the observation of tidal signals. It is well-known that sun-synchronous orbits (SSO) do not sample properly the tidal signal, leading to bad aliasing frequencies of most tidal waves, and some solar waves are not even observable (S1 and S2). But as some of future SSO will benefit from wide-swath measurements of SSH or even surface currents (WISA, SKIM), we propose an estimation of the observability of tidal signals while taking into account the local multiple sampling allowed by the wide-swath of those new missions. Different WISA constellation flying contexts are taken into account. The analysis is based on OSSE experiments using the IBI36 regional simulation of the North-East Atlantic Ocean (provided by Mercator-Ocean), which includes the tidal signal as well as other oceanic variability which can prevent a proper tide estimation from satellite measurement due to crossed aliasing issues. Results of this tidal desaliasing analysis are presented, and show first the interest of the proposed method to investigate the tidal accuracy of a given wide-swath orbit/constellation (SSO or not SSO) and secondly that a wide-swath SSO orbit can provide useful tidal information.

TID_006: Last TUGO model simulations and perspectives of evolution of the Dynamic Atmospheric Correction for altimetry (Carrere et al.). The Dynamic Atmospheric Correction (DAC) allows for the removal of high frequency ocean variability induced by the atmospheric forcing and aliased by the altimetric measurements. The accuracy of the DAC has been much improved over the last 25 years leading to centimeter accuracy in open ocean. However significant errors still remain mainly in shallow waters and in polar regions, due to bathymetric errors, to atmospheric forcing errors, to local lack of resolution of the grid, or even to sea ice effects ... In this context and taking into account the new challenges of DAC for the coming high-resolution altimetry missions, several ways of improvements are being tested, including: replacing the barotropic model MOG2D by TUGO-M version, using higher frequency temporal sampling provided by the new ERA-5 ECMWF meteorological database, using a higher resolution mesh, or generating higher frequency maps of DAC to take into account a better propagation of the high frequency surge signal. Including the gravitational tide forcing within the barotropic model used to compute the DAC is also investigated to try to improve the bottom friction dissipation in the simulations. Validation results show a significant improvement in many regions of interest. The poster describes the tests performed and some validation results and presents an implementation plan for a new version of the DAC for altimetry in 2020.

TID_007: Mapping Internal Tides from Satellite Altimetry without Blind Spots (Zhao et al.). Satellite altimetry may be the only practical technique for observing internal tides on the global scale. However, it is a challenge to mapping the global complicated internal tide field using satellite altimeter data, mainly due to the low spatiotemporal sampling rate of nadir-looking satellite altimetry. The next-generation wide-swath altimetry will also have low temporal resolution. Therefore, it is important to develop new techniques for better mapping internal tides from the current- and next-generation satellite altimetry. This study addresses a problem caused by along-track high-pass filtering in previous studies, which is used to remove long-wavelength nontidal noise and barotropic tidal residual. However, the filter removes internal tides having large angles with respect to satellite ground tracks and thus causes blind spots in the resultant internal tide field. Satellite ground tracks are generally in south-north direction at low latitudes; therefore, westbound and eastbound internal tides are either underestimated or totally missed. This study presents a new technique that replaces the one-dimensional (1D) along-track high-pass filter with a two-dimensional (2D) bandpass filter. The latter extracts internal tides in all directions without blind spots. Westbound and eastbound internal tides can be retrieved by the new technique. The new internal tide models are presented and compared with previous models. The improvement is shown by SSH variance reduction explained by applying different models to independent Cryosat-2 altimeter data. However, the new technique makes no improvement in boundary current systems or energetic equatorial zones. The application of this new technique to other observational and modeled datasets are also demonstrated.

TID_008: Temporal variability of the mode-1 M2 internal tide (Zhao et al.). This work aims to (1) construct time-variable internal tide models accounting for the incoherent component and (2) monitor ocean heat change in the upper ocean over various time scales. For these goals, seasonal, annual and decadal variations of the mode-1 M2 internal tide are studied using 25 years of multi-satellite altimeter data from 1992–2017. A series of global internal tide maps are constructed using a subset of altimeter data. A new mapping technique is employed to better suppress nontidal noise and retrieve westbound/eastbound internal tides. The resultant maps enable us to explore the temporal and spatial variability of internal tides (1- and 2-order derivatives). By dividing the data into two decades: 1992–2004 and 2005–2017, we construct two global internal tide fields that have almost identical spatial patterns. Interestingly, global statistical analysis reveals that there is a 6-degree phase difference between them (about 10 minutes in time), suggesting that the ocean stratification strengthened from the first to the second decade, which is mainly attributed to upper ocean warming. However, the phase difference is very complicated in space. In addition, four seasonal internal tide maps are constructed and all have similar spatial patterns. Systematic phase differences mainly occur in equatorial zones and marginal seas, consistent with the seasonal speed change of internal tides estimated from World Ocean Atlas 2013. We also construct global internal tides using yearly subsetted data. Due to limited data length and thus large uncertainties, annual variations are mainly studied in regions of strong internal tides. Significant phase changes are observed to be associated with numerous long-range internal tidal beams in different years.

Recommendations:

- Jason-3 Extension of Life
    - Recommendation from OSTST 2018 was to continue an interleaved orbit (as per usual)
    - OSTST 2019 also recommends the interleaved orbit but we need to provide some quantitative estimation of what extension is needed (how many years ? …)
- Internal tides
    - OSTST 2018 recommended an internal tide model for use by the community (e.g., in CMEMS processing, in RADS, ...): the recommendation is to use Ed. Zaron's model
    - We recommend applying this IT correction on the GDRs SLA
    - We still need studies to better understand/estimate/model internal tides variability and non-stationary part
- We should start to worry/investigate about barotropic tides non-stationarity or long-term change (linked with ice-cover change, sea level rise, ...)
- We should model also some minor tides
- We want to continue efforts to make tidal correction errors and HF correction more homogeneous with dedicated efforts toward shallow water/high latitudes regions, including:
    - bathymetry improvements in coastal/shallow water regions
    - improving data and tide estimation in shallow waters/high latitudes to get better assimilation databases
    - regional modeling configurations studies

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, Shailen Desai (JPL/NASA) gave an update on the status of the effort to retrack and reprocess data from the TOPEX/Poseidon mission. Several long-standing issues in the TOPEX/Poseidon are finally being addressed and corrected. These include the so-called “Wallops Range Correction”, which has finally been understood and recreated, as have the slow changes in the evolution of the radar behavior, or waveform. In addition, the retracked data have improved stability in terms of the observed significant wave height and radar return brightness, and the hemispheric biases have been understood and largely corrected. Finally, improved agreement with Jason-1 during the TOPEX/Poseidon – Jason-1 tandem period suggest that the reprocessing has resulted in a significant improvement in the overall data quality.

Nicolas Picot (CNES) discussed the current GDR status for altimetry missions. He recalled that we have currently 8 flying altimeters, with a very homogenous processing baseline (thanks to coordination between all agencies) and overall very good data quality. He also noted that Sentinel-6 will begin to produce data in late 2020 using the GDR-F standard. Highest priority will be the migration of Jason-3 to GDR-F for easy comparison with Sentinel-6 during the Cal/Val phase. TOPEX data will also be reprocessed to GDR-F standards during 2020. Beyond 2020, it will be important to migrate Jason-1 and 2 to GDR-F standards as well. Nicolas also noted that SARAL has implemented GDR-F standards and is in the process of reprocessing past data to this standard as well.

Finally, Annick Sylvestre-Baron (CNES) gave a brief presentation on the Committee on Earth Observations Satellites (CEOS). CEOS is the primary forum for international coordination of space-based observations. For altimetry, the Ocean Surface Topography Virtual Constellation (OST – VC) helps coordinate systems to meet measurement requirements for ocean topography. At present, this body (currently chaired by CNES and EUMETSAT) is in the process of updating its document “Next 15 years of altimetry – OST Constellation User Requirement Document” and will be seeking comments and reviews of the document in the coming months.

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

Recommendations:

- To minimize likelihood of a gap in polar ocean and ice monitoring, the OSTST encourages Agencies to strive to launch a high-resolution polar altimeter in the early 2020s (such as the proposed HPCM** CRISTAL) and to maintain operation of CryoSat-2, ICESat-2, and SARAL/AltiKa as long as possible.

- In order to maintain consistency across multiple missions, the OSTST recommends that the Sentinel-6 data product suite should include Level 2P & 3 products for Low-Resolution data.
- The OSTST recommends that the Jason Projects apply the internal tide correction to the sea surface height anomaly variable in GDR-F and future evolutions of the GDR standards.
- Although the OSTST recognizes the importance of the 5G spectrum for advances in telecommunications, use of this spectral band has the potential to interfere with critical observations used by climate scientists, oceanographers, meteorologists and operational users. In light of this, the OSTST recommends that governments and agencies take steps to mitigate interference from 5G communications by regulation and enforcement as well as improvements to future satellite designs.
- In light of the need to maintain the continuity and integrity of the 26 year record of sea level, the OSTST recommends that agencies continue to support ongoing reprocessing of the TOPEX and Jason records as new improvements become possible, and so that regular reprocessing of new missions does not impact the continuity and homogeneity of the climate record.
- The OSTST recommends that agencies and mission advisory groups developing future radar altimeter missions consider including the three independent positioning systems (SLR, GNSS, DORIS) to ensure highest possible orbit accuracy and widest possible use of the data over all surfaces
- The OSTST recommends pursuing study, understanding and potential correction of the drift in Sentinel-3A SAR measurements of sea surface height in anticipation of Sentinel-6, which will embark instruments of similar design.

OSTST Appreciations:

The OSTST would like to express its appreciation…

- …to Eric Lindstrom and François Parisot for their leadership in satellite oceanography.
- …for the successful transfer of Sentinel-3B into the operational phase and the launch of CFOSAT and the timely release of data.
- …for the excellent operation of Jason-2 and its scientific and operational legacy.
- …for the Project conducting Jason-2 redundant instrument experiments before decommissioning.
- …for the progress in reprocessing the TOPEX data, which anchors the global mean sea level record.
- …for the continuing effort to implement a consistent GDR-F standard across the missions
- …to the agencies for maintaining the launch schedule for Sentinel-6 Michael Freilich (Nov 2020), which is critical to maintaining the climate data record.

- …to the agencies for continuing to improve and develop the next generation of satellites with extended capabilities compared to conventional altimetry (e.g., SKIM, SWOT, CRISTAL, WiSA on Sentinel-3 Next Generation).

Due to the ongoing COVID-19 pandemic, no in-person OSTST meeting will be held in 2020.