OBJECTIVES OF THE STUDY

HYDROCOASTAL is an ESA project aimed to maximize the exploitation of SAR and SARIn altimeter measurements in the coastal zone and inland waters. As part of the HYDROCOASTAL project, several impact assessment studies are envisaged. One of them regards the coastal lagoons and the coastal zone of northern Adriatic Sea (NAS): the Marano-Grado Lagoon; the Venice Lagoon; the estuarine coastal zone of the Po River.

Coastal lagoons are a geographically well-defined typology of lagoons, often fed by rivers, possibly protected from wave action and exposed to weaker and less persistent winds. As they are connected to the open sea, they constitute an advantageous laboratory for developing and evaluating coastal altimetry in the transition zone between the open sea and inland waters. They may contribute to the definition of a (needed) methodological unicum for the study and quantification of some of the most dynamic processes regarding the interaction of inland waters and the coastal zone.

Moreover, during the 2022 spring and summer and the preceding winter, unusual climatic conditions in northern Italy caused a deep drought of the Po River, with saltwater intrusion up to 40 km from its mouth. This situation caused significant biological and economical damages of a large part of the country. In this context, the current study evaluates the impact of the new satellite coastal altimetry dataset, produced with advanced algorithm standards within the HYDROCOASTAL project, with respect to the reference altimetry products, in the transition zone between inland waters, coastal lagoons, coastal zone and open sea in the NAS.

HOW USING TOOLS AND DATA WITHIN CLOUD HELPED TO ACHIEVE THE GOALS

At present, Sentinel-3 and CryoSat-2 altimetry data are available at global scale only with the ground segment data processing. This situation is particularly limiting in the case of coastal altimetry, as the assumptions made for the processing of altimetric data for the open ocean are not respected.

The EarthConsole® Altimetry Virtual Lab (EC_AVL), funded by ESA, provides a virtual space to support the Altimetry community in the development & operation of new Earth Observation applications, offering established altimetry processors (the SARvatore family) as well as other innovative and fully customizable altimetry data processing services, as for example:

- ALES+ SAR Retracker – developed by the Technical University of Munich
- FF-SAR (Fully Focused SAR) for CryoSat-2 – developed by Aresys srl
- TUDaBO SAR-RDSAR – developed by the University of Bonn
- Sentinel-6 GPP L1 – isardSAT
- Fully-Focused SAR for Sentinel-6 and Sentinel-3 – Aresys Srl
- SMAP for Sentinel-3 – CLS

This solution avoids the need for users to download large quantities of L1 data onto their computers, and at the same time the need to install the processing algorithms locally is avoided, overcoming, among other things, the problem of non-open software licenses.

HIGHLIGHTS OF ANY BENEFITS TO SOCIETY DERIVED FROM THE STUDY

1. Coastal Zone Monitoring:
Satellite coastal altimetry contributes to the monitoring of coastal zones, having a preeminent role in detecting changes in sea level at spatial scales from local to regional and global. It also helps understanding coastal dynamics, and identifying potential hazards.

2. Lagoon Monitoring:
Satellite coastal altimetry is useful for monitoring lagoons. It represents the most suitable remote sensing tool able to coherently observe the hydrodynamic of the water from inland to the coastal zone, at global scale, and to establish causal relationship between the dynamics of such different environments.

3. River Mouth Monitoring:
It is also relevant in monitoring river mouths, as well as the fate of river outflows, at the meeting point between freshwater discharge and the coastal environment.

4. Societal Benefits:
Once the dynamics of river outflows are better understood, there would be direct societal benefits derived from the use of satellite coastal altimetry data, including improved coastal planning, early warning systems for natural disasters, sustainable resource management, and support for navigation and transportation.

COASTAL LAGOONS

Coastal lagoons are shallow transition zones characterized by intertidal marshes, slow water flow, direct connection with open sea, and partially shielded from the wind.

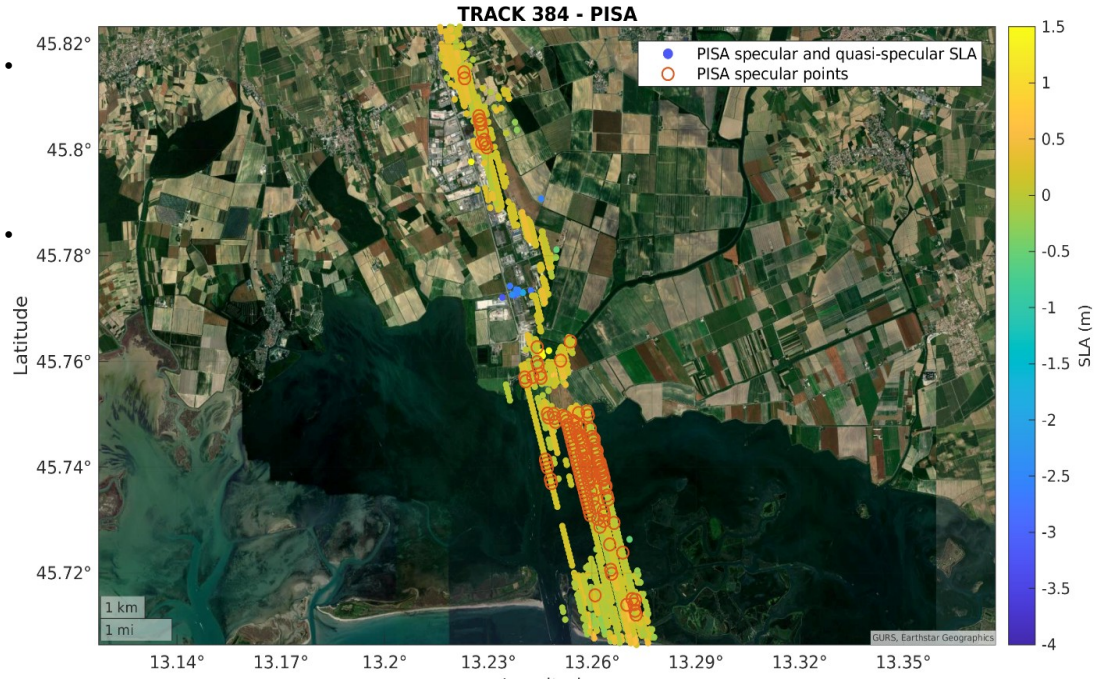
- Around 32,000 lagoons (Carter et al., 1996) are identified along 13% of the world's coastline (Barnes, 1980)
- They are vulnerable to changes of the water surface level, due to storm surges and climate change, in combination with anthropogenic causes
- Because of sparse in situ measurements, especially in developing countries, the usage of satellite radar and lidar altimetry is currently the only option to monitor those changes

Objectives of this study:

- What: to assess the HYDROCOASTAL radar altimetry dataset over coastal lagoons (GRADO-MARANO and VENICE)
- How: by using independent observations (Tide gauge, SARvatore data, PISA data (Abileah and Vignudelli, 2021))

PRELIMINARY ANALYSES GRADO-MARANO

- **Specular echoes in S3B track 384 and 250**
- **PISA classification permits to recover also several quasi-specular**

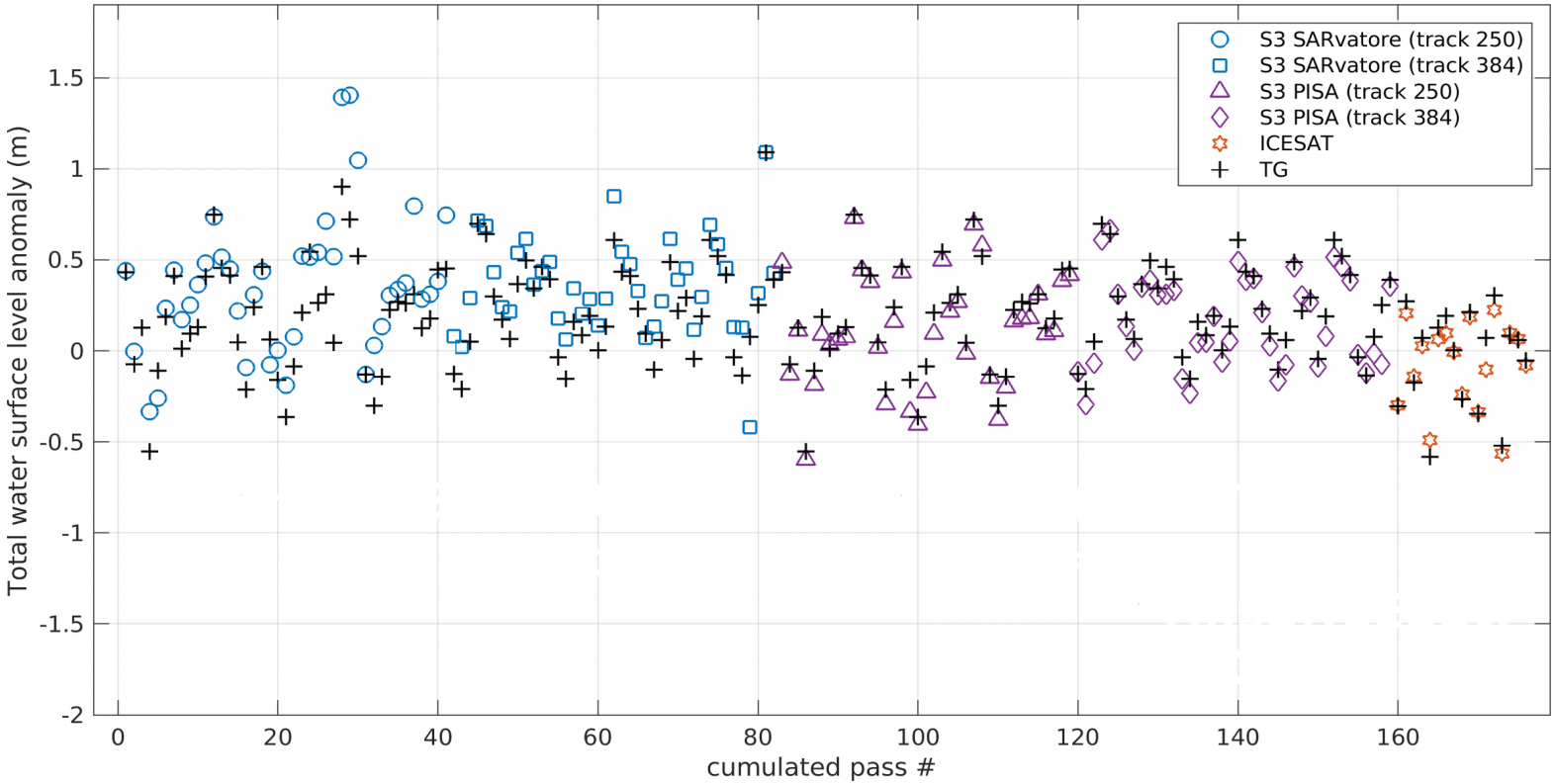


SEA LEVEL ANOMALY

Instantaneous comparison of the surface level anomaly means of each cycle, supplied by the SARvatore and PISA methodology, against ICESat-2 and tide gauge observations.

PISA and SARvatore (HPR) have 75 and 82 revisiting cycles respectively that can be exploited (ICESAT keeps only 17 cycles due to shorter observational period). **There is a clear consistency between the three satellite-based independent products**.

PISA comparison against tide gauge results in a very good agreement, with correlation of 0.98 and RMS difference of the mean levels of the passes of 8 cm (aggregation by pass). For GPOD the correlation is lower (0.77) and RMS difference much higher (36 cm). ICESat-2 has somewhat less performances than radar estimates (correlation of 0.96 and RMS difference of 8 cm).



TIME SERIES OF OBSERVED LEVELS

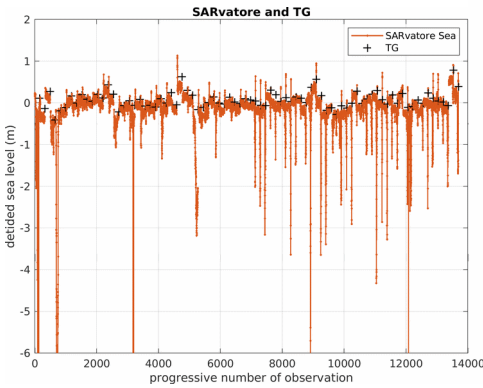
A step-in advance: in this study we propose a new comparison approach using only altimetry bursts over Lagoon that are specular and quasi-specular.

Metrics:

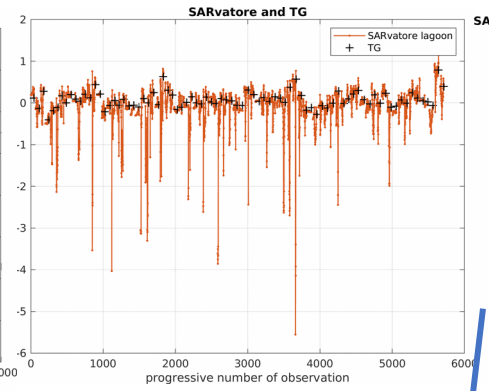
The precision of PISA and SARvatore derived SL is measured from burst-to-burst variability with respect the TG

The accuracy is measured by matching measurements

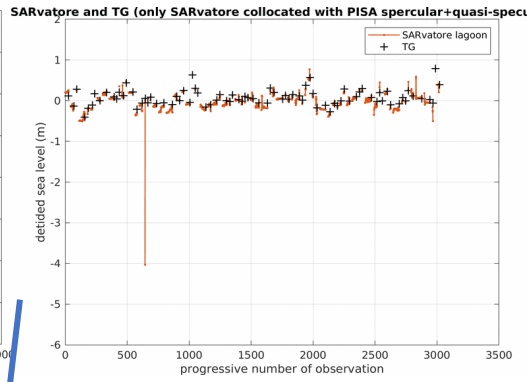
Many lagoons un-gauged in the world: the method can be replicated and we can have altimetry measuring precisely



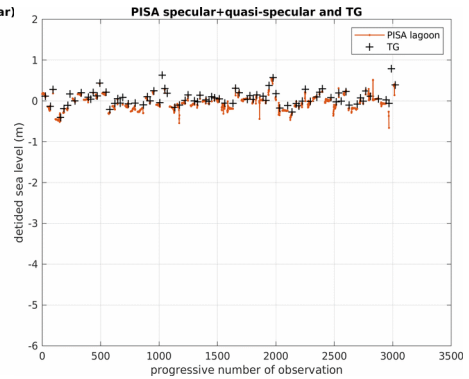
SARvatore HPR: using all bursts offshore



SARvatore HPR: better inside lagoon, but still remarkable noise



SARvatore HPR collocated with PISA: dramatic reduction of noise. Echoes in specular or quasi-specular conditions



PISA specular and quasi-specular echoes are more precise

Approach: we expect specular surfaces more precise, so the idea is to select only specular and quasi specular burst.

Specular echoes are less: what is better, to have one precise measurement or many measurement of lower precisions?

	PISA	SARvatore
PRECISION: RMSE of consecutive detided residuals ALT-TG (m)	0.051	0.157
PRECISION: MAE of consecutive detided residuals ALT-TG (m)	0.022	0.026
ACCURACY: RMSE(ALT,TG) (m)	0.091	0.143
ACCURACY: MAE(ALT,TG) (m)	0.072	0.076

RESULTS IN MARANO-GRADO LAGOON

In the SEA region, DTU and UBONN retrackers perform similarly well. SAMOSA+ suffers for a small bias which penalises BIAS and RMSD, and for some outliers which enlarge the value of the CRMSD. ESA has more outliers than the other retrackers penalising the CRMSD and the RMSD.

In the LAGOON region, ESA shows low precision and accuracy (high BIAS and MAE, high MAD and CRMSD). DTU exhibits scarce accuracy (high BIAS and MAE) but high precision (low MAD and CRMSD). GPOD and UBONN have similar performances.

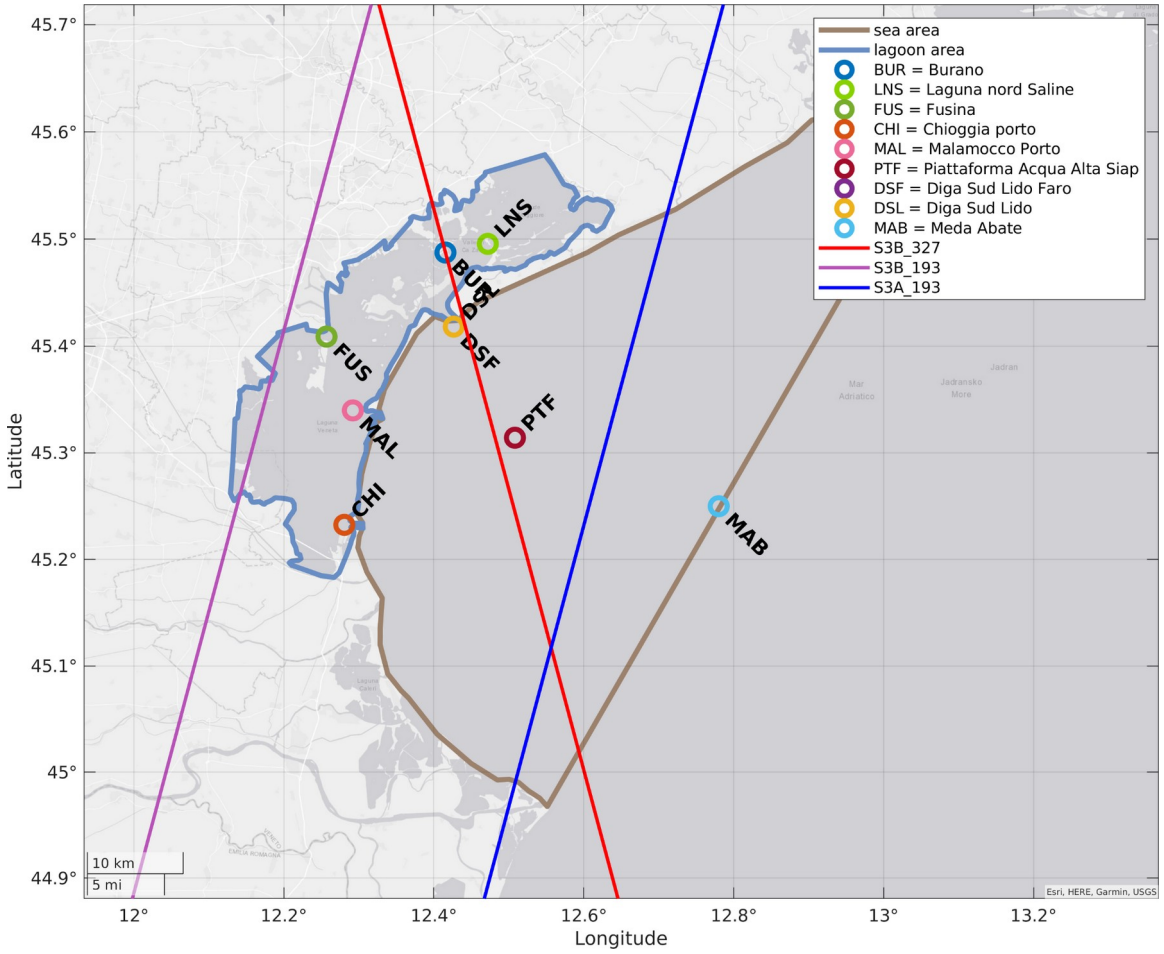
SEA	**ESA**	**UBONN**	**DTU**	**GPOD**
BIAS	0.10	0.09	0.06	0.16
MAE	0.06	0.09	0.05	0.14
MAD	0.05	0.08	0.03	0.04
CRMSD	0.42	0.09	0.12	0.15
RMSD	0.43	0.13	0.13	0.21

LAGOON	**ESA**	**UBONN**	**DTU**	**GPOD**
BIAS	-0.56	0.06	-0.37	0.09
MAE	0.70	0.09	0.37	0.07
MAD	0.14	0.08	0.03	0.05
CRMSD	0.45	0.14	0.06	0.14
RMSD	0.72	0.15	0.37	0.17

VENICE LAGOON

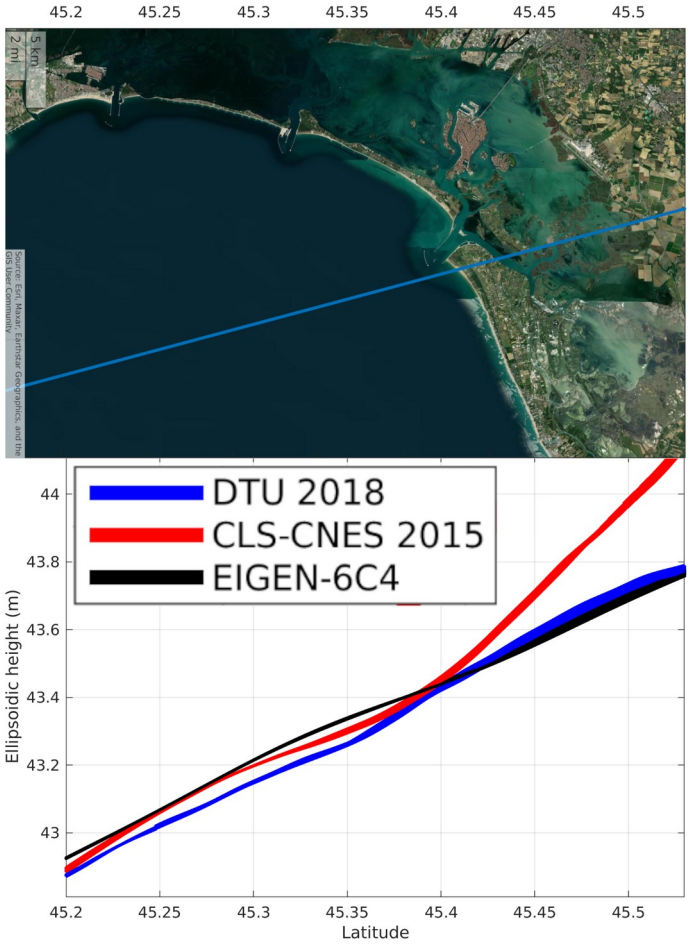
Venice lagoon offer a wide network of tide gauge and meteorological stations: it is possible to assess the quality of the altimetry sea level and of significant wave hight and wind

STATION	STATION LONG NAME	LAT (°N)	LON (°E)	SEA LEVEL	WIND SPEED	SW H
BUR	Burano	45.48750	12.41549	X		
LNS	Laguna nord Saline	45.49559	12.47197	X	X	
FUS	Fusina	45.40889	12.25694	X		X
CHI	Chioggia porto	45.23254	12.28060	X	X	
MAL	Malamocco porto	45.33980	12.29197	X	X	
PTF	Piattaforma	45.31425	12.50825	X	X	X
DSF	Diga sud Faro	45.41823	12.42655		X	
DSL	Diga sud Lido	45.41823	12.42655	X		
MAB	Meda Abate	45.25000	12.78000	X	X	X



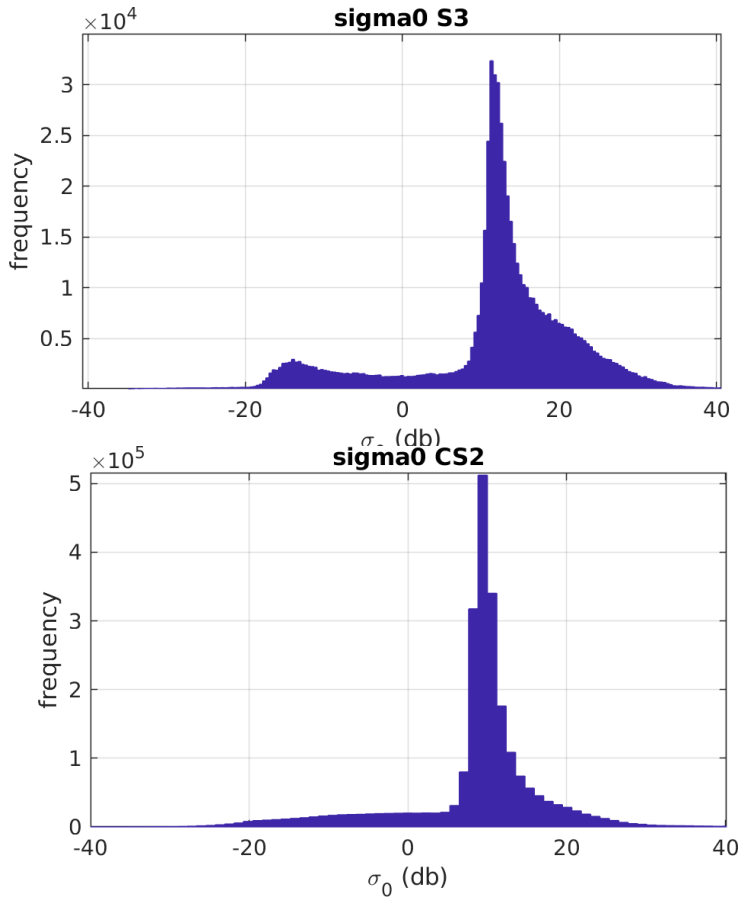
COASTAL ZONE: ALTIMETRY MEAN SEA SURFACE IS OFTEN UNREALISTIC

Auxiliary data, as the mean sea surface, are central for the exploitation of altimetry observations. In the coastal zone we observed that different MSSs can differ substantially from each other, impacting the interpretation of geophysical variables. The Figure shows the profiles of the DTU 2018 and CLS-CNES 2015 MSSs, as well as the profile of the EIGEN-6C4 geoid (Foerste et al., 2014), along track S3B 327 for all cycles. While at open sea the two MSSs differ by a limited quantity, near coast they rapidly diverge, reaching about 30 cm where the satellite track crosses land.



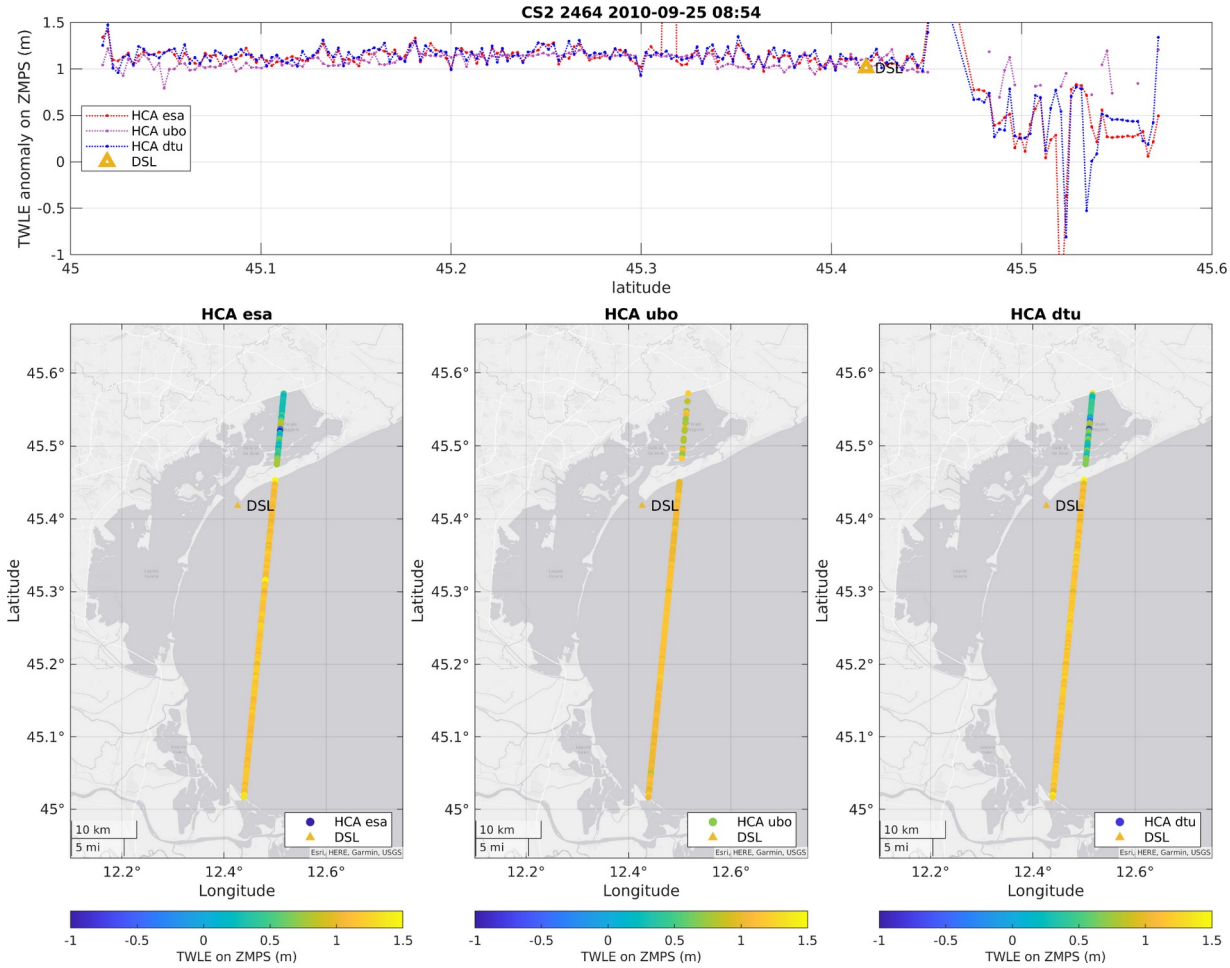
COASTAL ZONE: WIND

The wind speed calculated from the radar backscatter following Abdalla's algorithm (Abdalla, S., 2007). Wind calculated from HYDROCOASTAL S3 retracked σ_0 has to be considered as indicative in the coastal zone.
CS2 files do not contain the atm_cor_sig0 parameter, and thus the wind could not be derived at all. In order to provide an approximate value of wind speed also for CS2 mission, we fed the wind algorithm with a constant atmospheric attenuation correction evaluated as the most probable one, in the median sense, from the S3 mission.
The value of atm_cor_sig0 used here is 0.17 db.
Unfortunately, for CS2 the calculated wind speed did not match that of the in situ stations. The main reason for this disagreement could be identified on the distribution of the $\sigma 0$ of CS2 in the northern Adriatic Sea, which significantly differs from that of S3 for the same area (see Figure)



HYDROCOASTAL MEASURES SEA LEVEL IN COASTAL LAGOONS

A storm surge happened on 25 September 2010, producing a storm surge of 104 in the venice Lagoon.
CS2 crosses the northern Adriatic sea and approaches the land near DSL, finally flying over the lagoon.
The altimeter clearly captures the surge signal, and compares well with TG level.
At the interface between SEA and LAGOON, retrackers fail due to the need of a more precise land/water mask.
Inside the lagoon the HYDROCOASTAL products observe a lower sea level: the drop is compatible with the level that the sea would have considering the lag in time for the water to travel from the open sea to the edges of the lagoon.

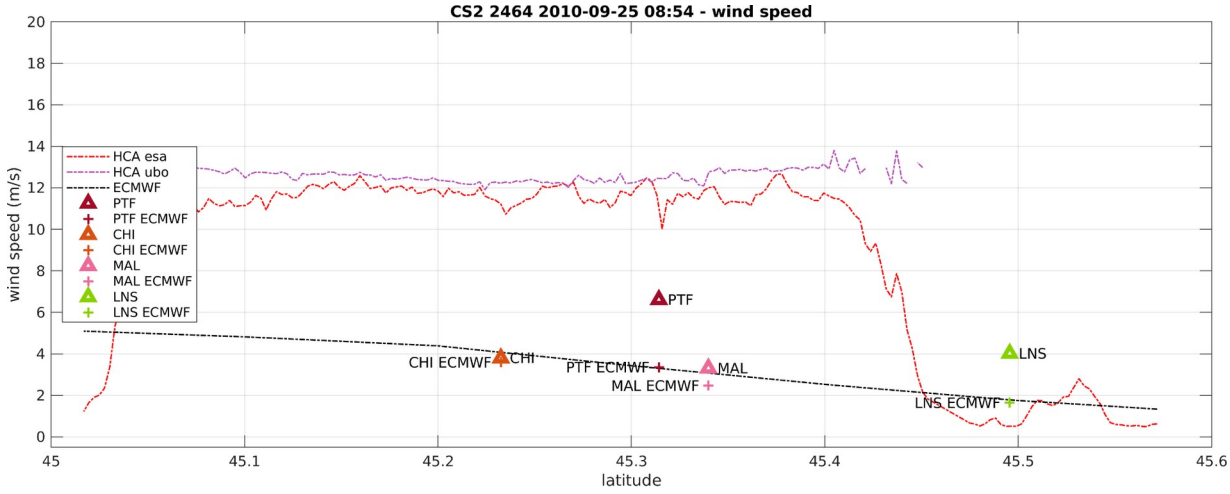


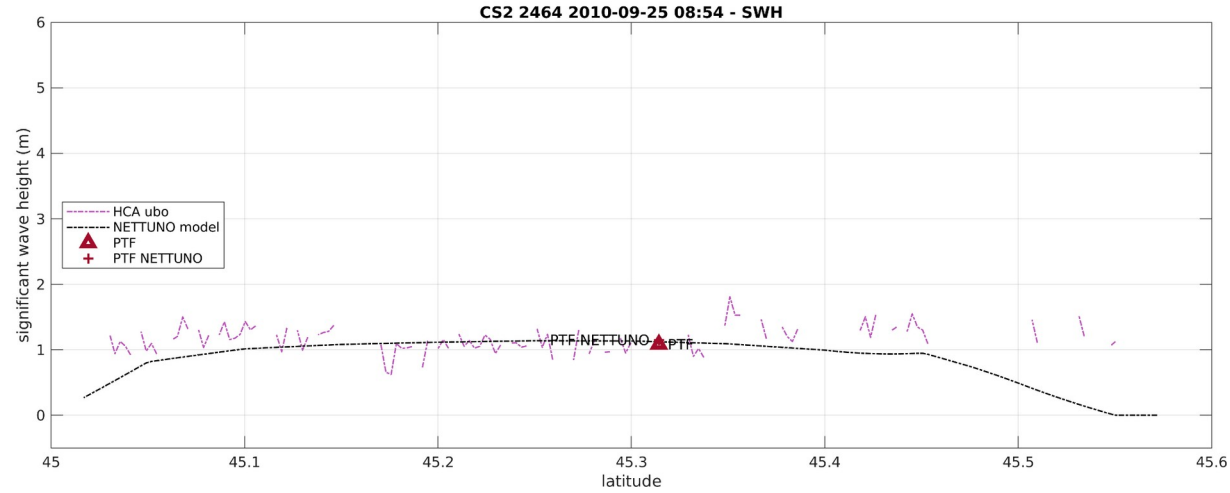
WIND AND SIGNIFICANT WAVE HEIGHT

Estimated along track wind and SWH w.r.t local gauges. Evident overestimation of the wind at SEA: the σ_0 retracked values for CS2 are about 3 db lower than S3, returning too high winds.

SWH agrees with the measured value at a local station.

It is promising that SWH can be measured with such spatial detail outside and inside LAGOON: a distinct improvement compared to ESA official products





PO RIVER'S MOUTH

Four S3 tracks have been selected passing over or close to the Po River mouth:

- S3B track 327
- S3B track 250
- S3A track 193
- S3A track 270

We considered the major drought and flood events on the years 2018-2022.

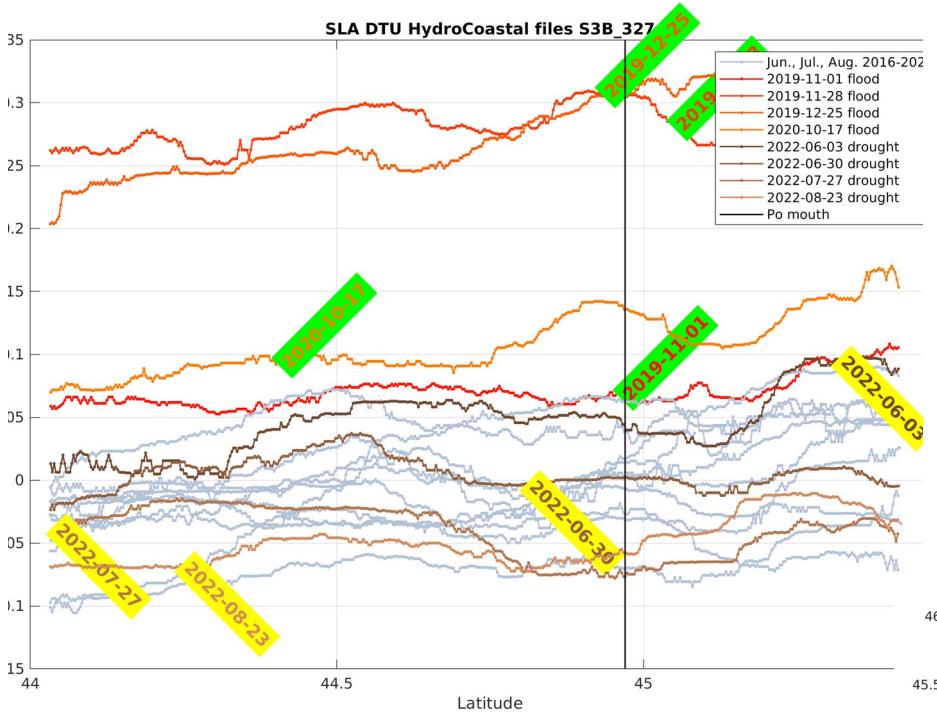
For the flooding events:

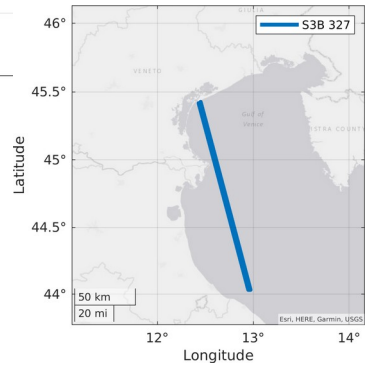
- ❑ November 2018
- ❑ November 2019
- ❑ December 2019
- ❑ October 2020

For drought events:

- ❑ June 2022
- ❑ July 2022
- ❑ August 2022

ALONG TRACK HYDROCOASTAL SEA LEVEL ANOMALY (SLA) PROFILES (S3B 327)





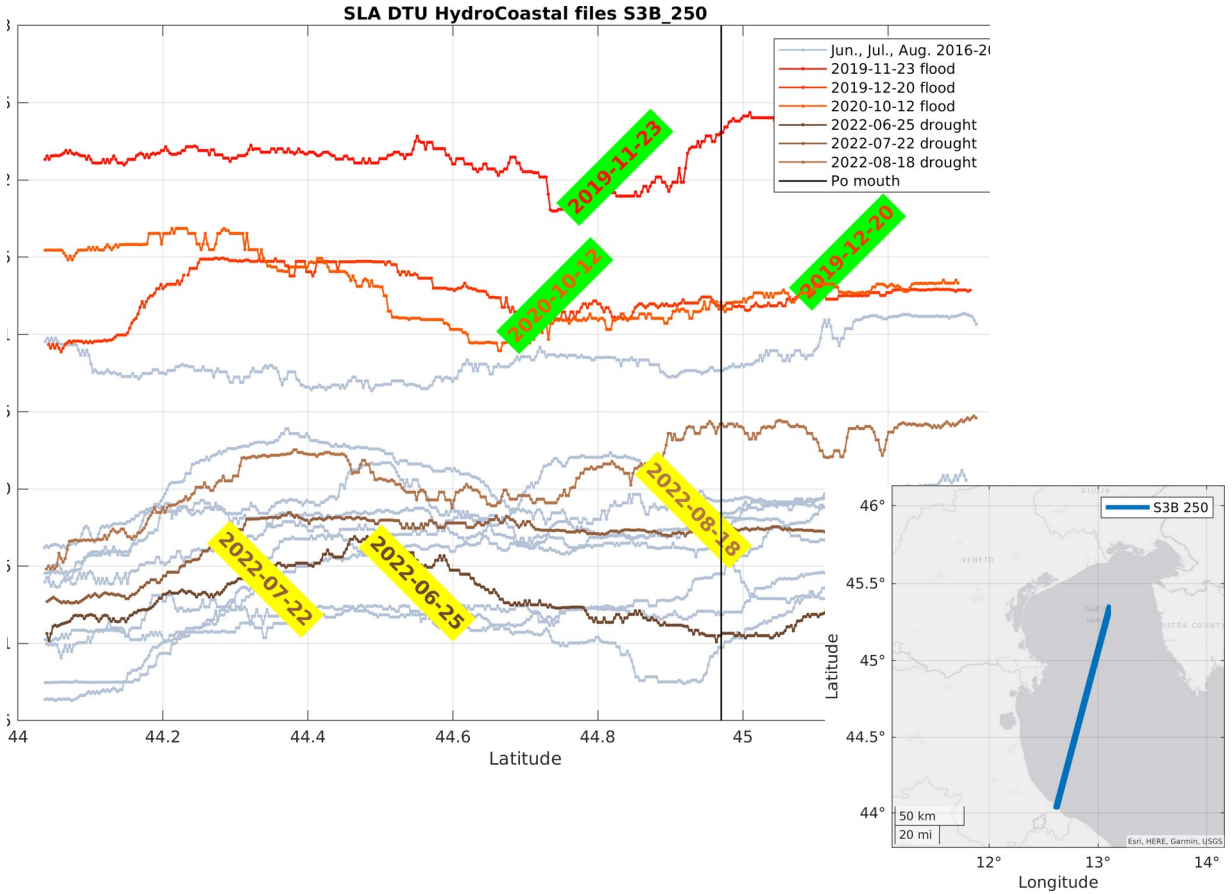
Warm colors → flood events

Brown colors → drought events

Gray colors → summer periods in 2019-2021

- The flood profiles are vertically isolated from the drought profiles, reflecting the increased fresh water discharged from Po and surrounding rivers in northern Adriatic Sea;
- The profiles of the drought in 2022 of the summer months are found in the same bottom portion of the plot of the preceding years (in gray);
- The two profiles of June 2022 are higher than those observed in July and August 2022, as the river discharge is not at its minimum value;
- The level difference between the two June 2022 profiles and those of July and August 2022, is roughly 5-10 cm;
- The difference between the flood and drought levels is at least threefold (about 20-35 cm)
- The along track variability of SLA profiles in proximity of the river mouth is probably modelled by the flood plumes

ALONG TRACK HYDROCOASTAL SEA LEVEL ANOMALY (SLA) PROFILES (S3B 250)



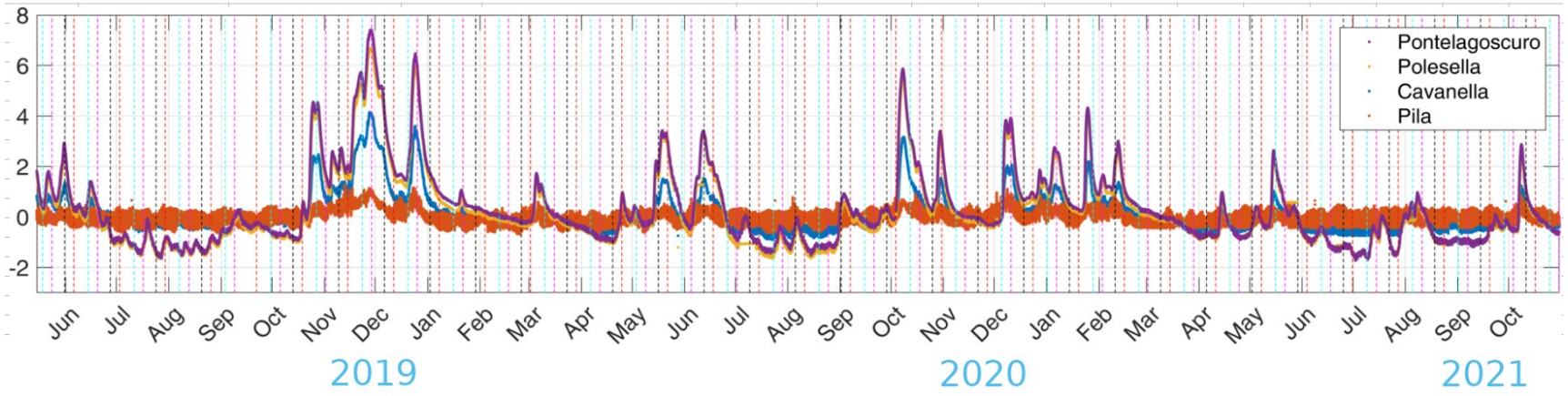
- The scenario observed along the track S3B 250 remains similar to the previous one along track S3B 327;
- The signature of the Po River discharge during the flood events manifests itself also farther from the mouth;
- The water level bulges near the mouth are more smoothed.

Warm colors → flood events
Brown colors → drought events
Gray colors → summer periods in 2019-2021

MEASURED LEVEL ALONG PO RIVER

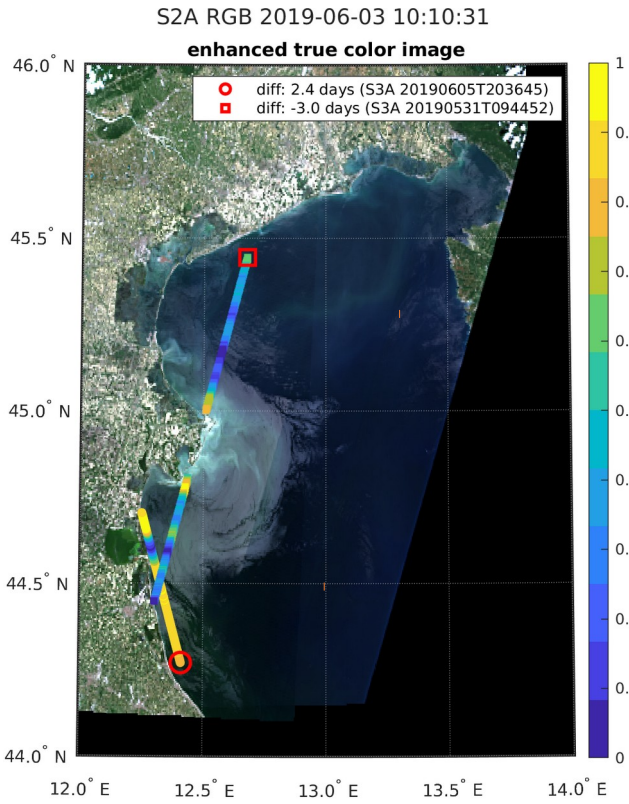
We considered several flood events on the years 2019-2020, looking at similarities between optical features and altimetric sea level anomaly (SLA). All the needed corrections to the were applied (DAC, TIDES, IONO, WET & DRY TROPOSPHERE). The range was retracked with the DTU algorithm

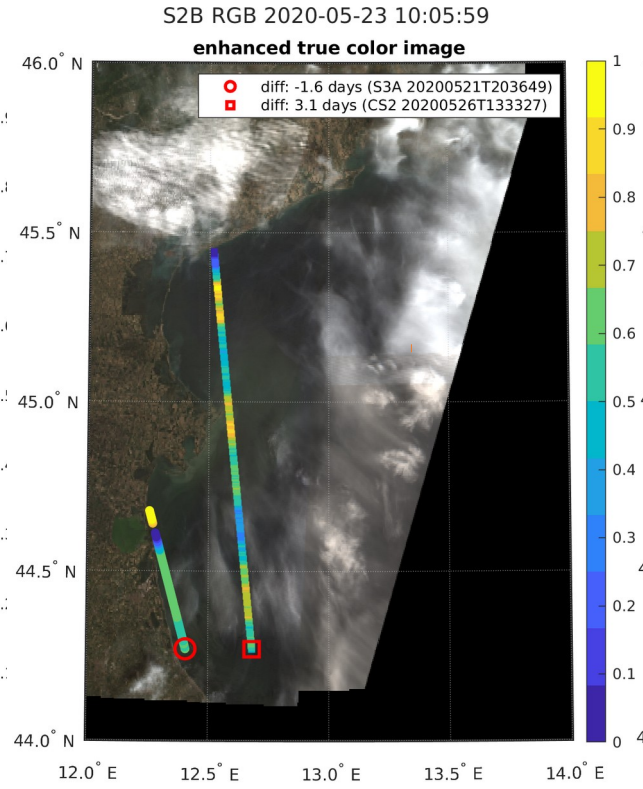
Time series of water level at several gauges along the Po River were retrieved

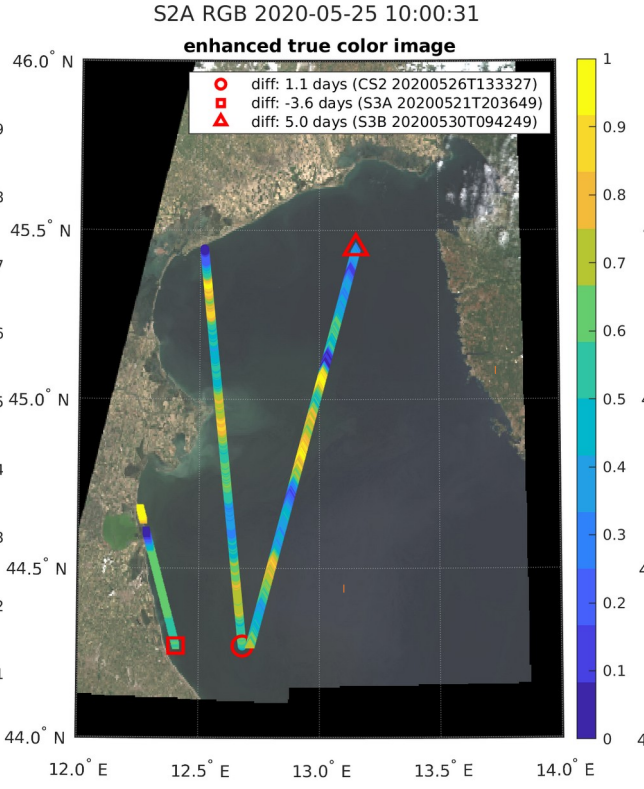


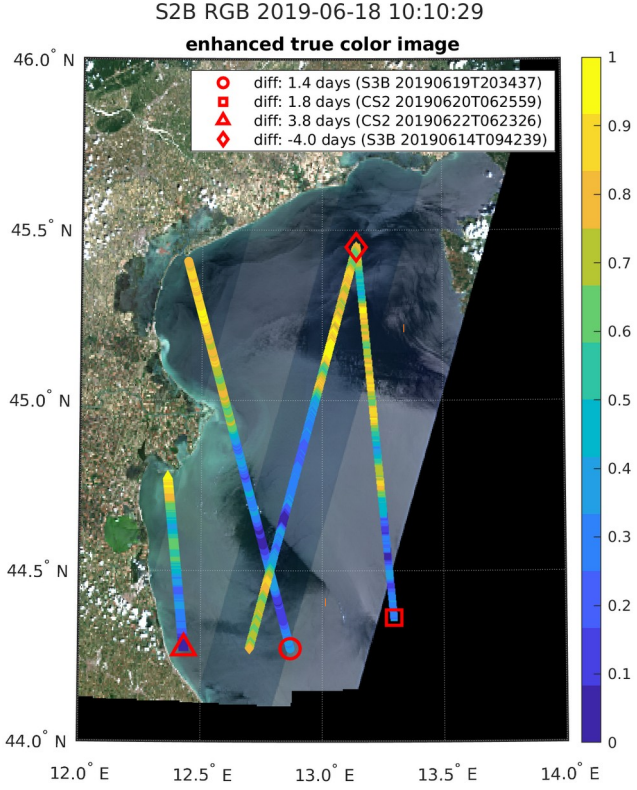
PO RIVER PLUME: HAS IT AN IMPACT ON SEA LEVEL ANOMALY (SLA)?

In some of the acquired images close to the flood dates, correspondences are visible between the plume and the SLA, but not in all.



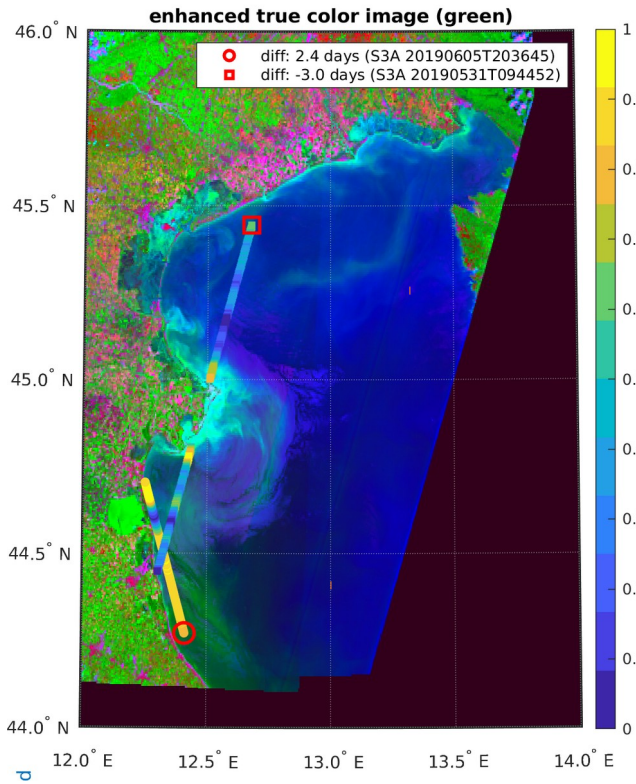


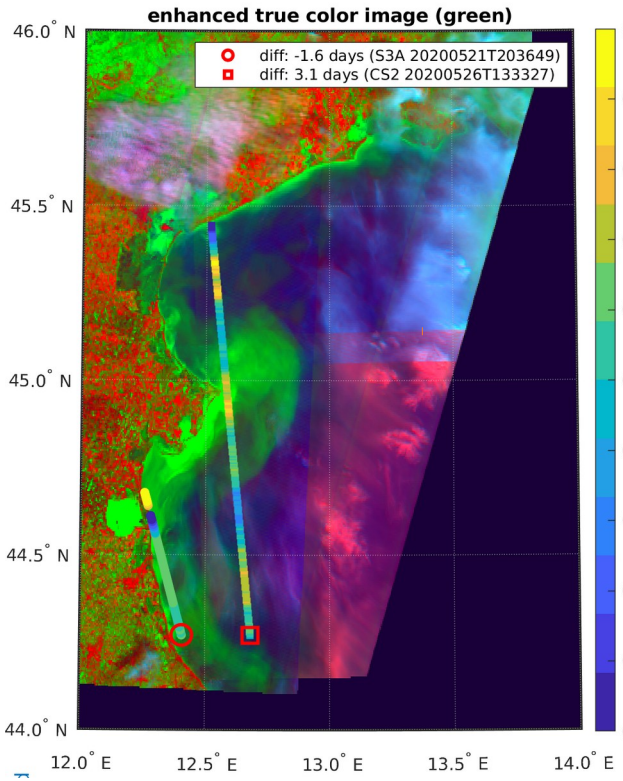


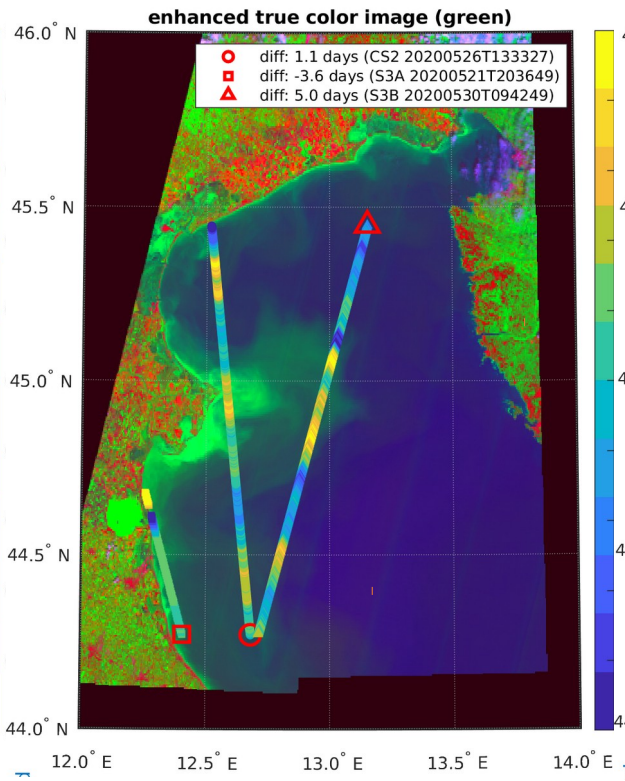


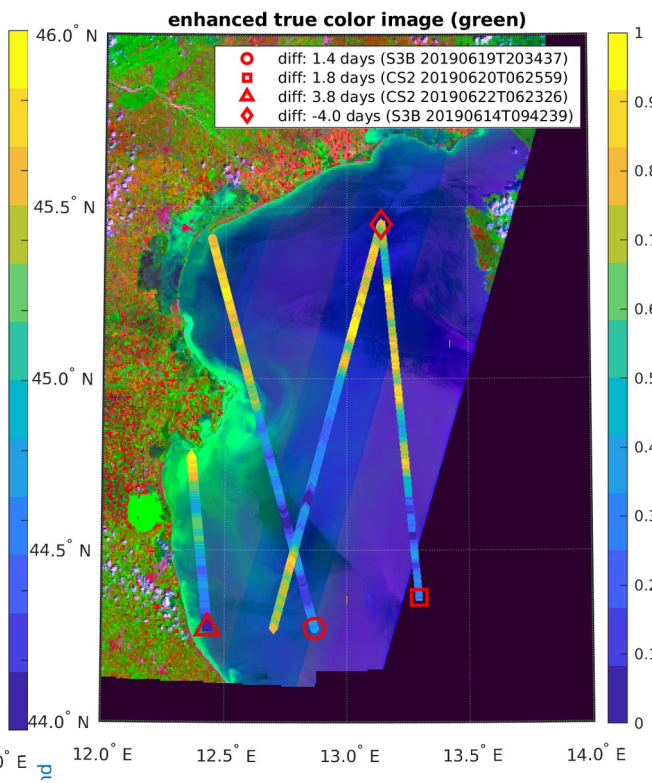
DOES ALONG TRACK SLA MATCH THE PROFILE OF VISIBLE GREEN?

We looked at the green band in contrast-enhanced S2 images, to find correlation between SLA and image values along track



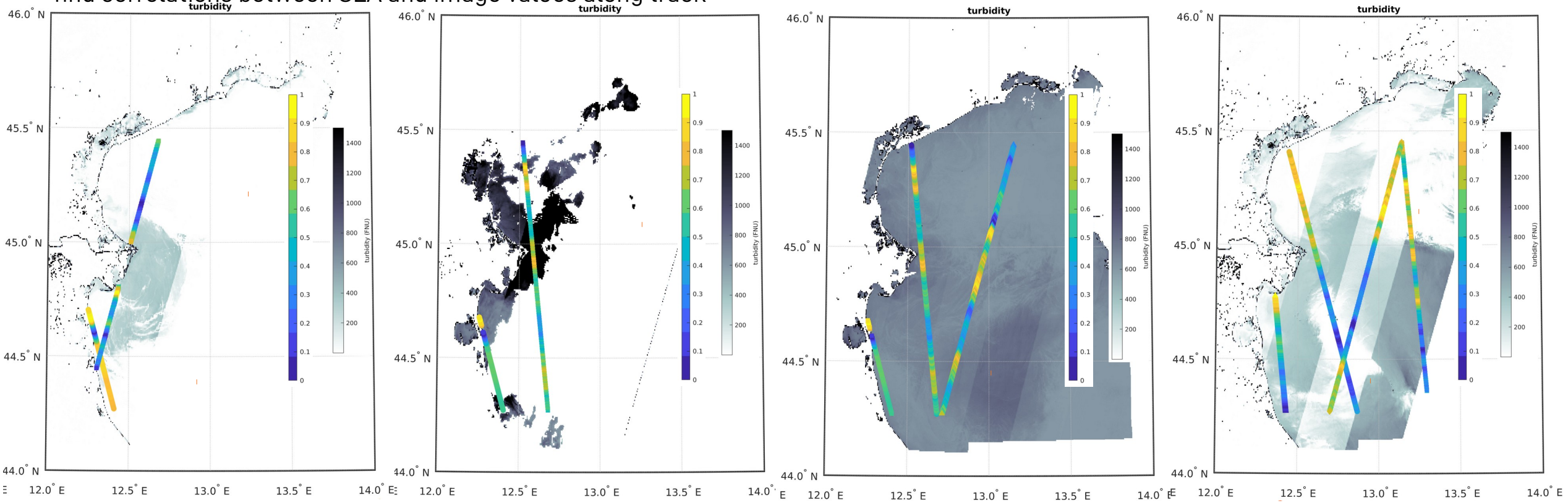






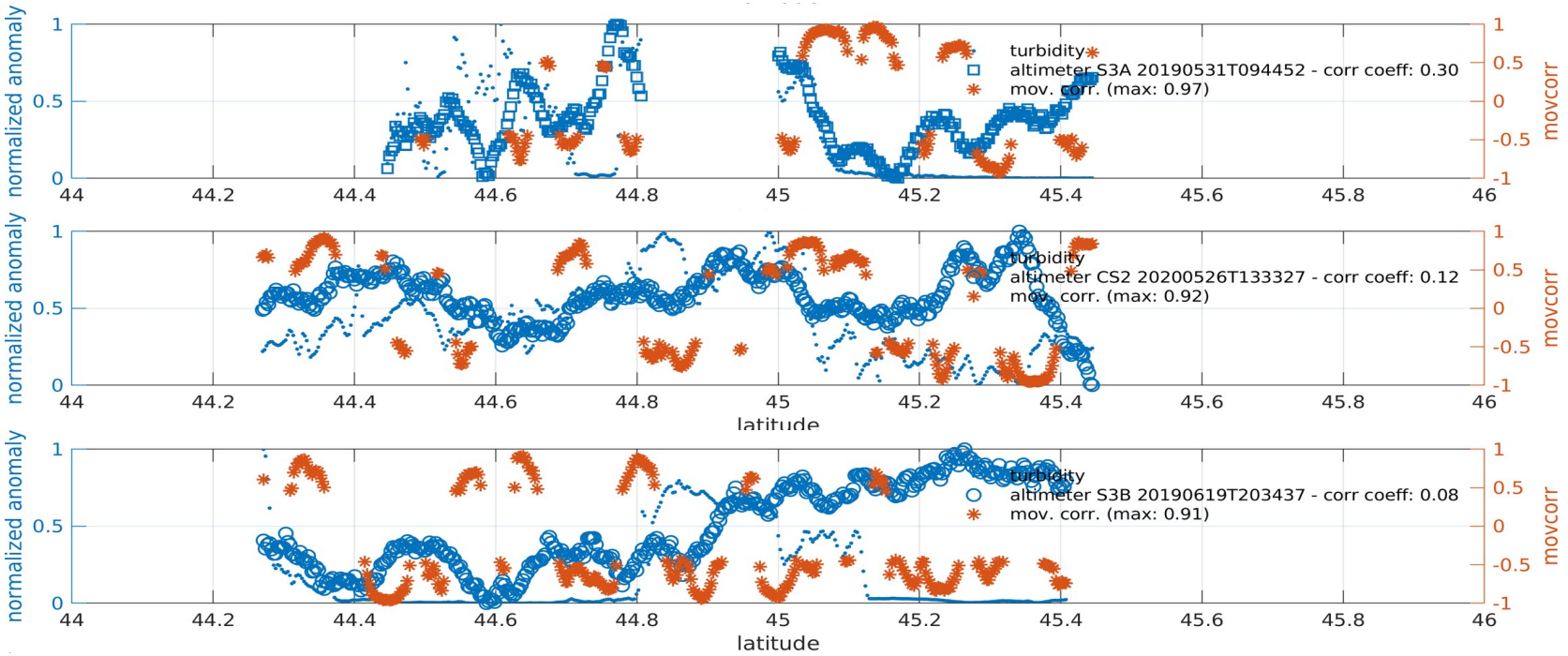
DOES ALONG TRACK SLA MATCH THE PROFILE OF TURBIDITY?

We looked at turbidity maps as well. Turbidity was derived from the same images using the one-band algorithm of Dogliotti et al. (2015), to find correlations between SLA and image values along track



SLA-TURBIDITY CORRELATION

The correlation between SLA and along-track sections of turbidity was even more difficult to assess.
Water bulges produced by other phenomena (coastal currents, bathymetry etc.) do not contribute to turbidity, but they are detected by satellite altimetry.



CONCLUSIONS AND RECOMMENDATIONS

Single altimetric along track profiles of sea level height, wind amplitude and SWH are useful for verification and support during the interpretation of storm surge at sea, or flooding events inland, in synergy with in situ data; moreover, satellite data are captures well spatial variability. They can provide a proper forecasting for the coastal settlements all around the world.

In particular, the following recommendations are advised for future scientific activities:

- Wind amplitude and SWH are not mature for exploitation yet. The wind algorithm is tuned for the global ocean, and SWH does not always agree with ground-truth
- A common vertical datum (geoid) for storm surge studies at regional level is needed
- An accurate coastal MSS at high-resolution is needed
- Novel methodologies for sea surface height determination, based on specular reflection can be more accurate for geodetic and cal/val applications
- Exploiting the extra resolution (80 hz or less) possible by reprocessing individual echoes;
- Improving the revisiting and exploring the possible advantage of constellation of small altimeters
- The correlation between satellite altimetry SLA and turbidity should be analyzed, and several factors have to be clarified: what is the connection between turbidity and the SLA? How to disentangle the height contribution of non visible altimetric features in optical images, from the visible ones? Thermal, organic and chemical-phisycal properties detectable in remotely sensed images can be used to this end?