HYDROCOASTAL

SAR/SARin Radar Altimetry for Coastal Zone and Inland Water Level

AI_PM12_03: CNR to make recommendation for which mean sea surface and geoid should be used for northern Adriatic Sea studies

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1 Scope of this document

At the HYDROCOASTAL (HC) progress meeting n. 12 (PM12), the action (AI_PM12_03) was raised about the mean sea surface (MSS) and geoid to be used in the studies involving the northern Adriatic Sea. The purpose of this technical note is to describe the motivations of this action and the reasons for the proposed solution.

2 List of acronyms

ALT	altimeter
DAC	Dynamic Atmosphere Correction
Dry	dry tropospheric correction
ET	earth tides
G	geoid
GPT	Geocentric Polar Tide
HC	Hydrocoastal
IGM	Istituto Geografico Militare
Iono	ionospheric correction
L	sea level
MDT	mean dynamic topography
MSS	mean sea surface
OET	Ocean Equilibrium Ocean Tide Correction
OLPT	Ocean Equilibrium & Non-Equilibrium Long Period Ocean Tide
OLT	Ocean Tide Loading
S3	Sentinel-3
SET	Solid Earth Tide
SSB	sea state bias
TG	tide gauge
T/P	TOPEX/Poseidon
Wet	wet tropospheric correction
WGS	Word geodetic system 84
WT	water tides

2 Introduction

During the preliminary analysis of the final HC products provided for the impact assessment study dedicated to the Venice Lagoon (WP3230, [1]), a method has been adopted for comparing altimetric determinations of the sea surface height with tide gauge observations. The method permits direct measurement of anomalies with respect to mean sea surfaces, conveniently adopted for both the time series (altimeter and tide gauge).

While tide gauges (TG) record changes in the height of the sea surface but are insensitive to the vertical movements of the earth's crust to which they are attached, satellite altimeters (ALT) register the composite movements of the seabed and the water above it. For this reason, to compare tide gauge observations to altimetry measurements, earth tides have to be modeled and subtracted from the altimetry records.

The water tide (WT) is the resultant of all the tides components producing oscillations of the sea surface. It is composed by:

$$WT = OET + OLPT + 0.532\,GPT$$

OET = Ocean Equilibrium Ocean Tide Correction

OLPT = Ocean Equilibrium & Non-Equilibrium Long Period Ocean Tide

GPT = Geocentric Polar Tide

The earth tide (ET) is the resultant of all the tides components producing oscillations of the earth's surface:

$$ET = SET + OLT + 0.468\,GPT$$

SET = Solid Earth Tide

OLT = Ocean Tide Loading

GPT = Geocentric Polar Tide

The geocentric polar tide signal (GPT), due to the oscillations of the earth's rotation axis, reflects in both the sea surface and the solid earth, but with different weights, given by combinations of the Love numbers, following [2]:

$$GPT_{WT} = (1 - h2 + k2)/(1 + k2)\,GPT = 0.532\,GPT$$
$$GPT_{ET} = h2/(1 + k2)\,GPT = 0.468\,GPT$$

The same approach has been adopted before [3] for such a type of comparison between in situ and remotely sensed observation of the sea level height.

As the WT is observed by both platforms (TG and ALT) it does not need to be removed from both the sea level height time series before comparison, as long as the observation points are close enough. The ET, instead, has to be removed from the altimeter time series, because only the altimeter is sensitive to this tidal contribution.

Finally, the altimetry observations can match the TG observation, up to an additive constant, after applying the set of corrections reported below:

$$L_{ALT} = Altitude - Range_{uncorr} - (Wet + Dry + Iono) - (SET + OLT + 0.468\,GPT) - SSB - MSS_{ALT}$$

where MSS_{ALT} is the averaged mean sea surface (MSS) over a given period and is commonly used to determine the sea level anomaly.

The role of such an additive constant, can be transferred in the TG expression of the sea surface level height:

$$L_{TG} = L_{obs} + K$$

It is natural to assume -K to be the mean sea surface observed by the TG during the same period used to calculate MSS_{ALT}:

$$L_{TG} = L_{obs} + MSS_{TG}$$

This type of comparison is not based on absolute values (geocentric heights), as a MSS is subtracted to both the ALT time series and the TG one; however, it retains an absoluteness meaning, as all the variables in play are referenced to well defined absolute height systems.

While the official Sentinel-3 L2 product provides two mean sea surface solutions, CNES-CLS 2015 and DTU 2015 [4] (baseline land) / DTU 2018 [5] (baseline water), the HYDROCOASTAL L2 product at the moment contains only one of them, namely CNES-CLS 2015 [6]. The CNES-CLS 2015 MSS model is referenced to the 20-year period 1993-2012 [7], while the DTU 2018 is referenced to the 25-years period 1993-2017 [8].

Since the comparisons between TG and ALT sea level signals are made subtracting the MSS from both, we conducted a preliminary analysis about the characteristics of the MSS given in the HC L2 final product in the coastal zone, and similarly for the MSS included in the official S3 L2 product. The analysis is reported in the next section.

3 Mean sea surface in S3 products

Altimetry mean sea surface values are given with respect to a reference ellipsoid. Since these are altimetric surfaces, they usually refer to the mean tide system (See Appendix A). Two different reference ellipsoids are used nowadays: TOPEX/Poseidon (T/P), preferred ellipsoid for the TOPEX/Poseidon mission, and World Geodetic System 1984 (WGS84), which is the reference ellipsoid for the ESA missions. By definition, their major and minor semiaxes differ by about 71 cm, the T/P ellipsoid axes being shorter than the corresponding ones of WGS84. The result is that the height difference between the two ellipsoids is about

71 cm almost everywhere [9], as can be seen in Fig. 1, where the difference is expressed as a function of the latitude.

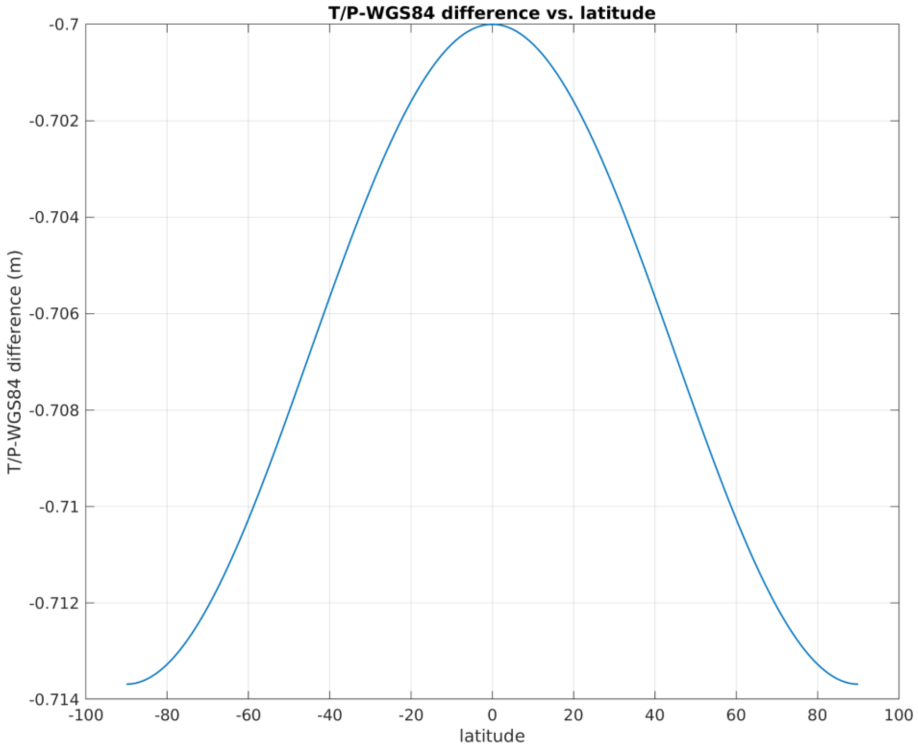

Figure 1: The difference between the T/P and the WGS84 ellipsoids as a function of the latitude

As the reference ellipsoid model in the SENTINEL-3 mission is WGS84, the geodetic coordinates (longitude, latitude and altitude) of each point measurement are referenced to WGS84 reference ellipsoid [10], and thus also the MSS included in the S3 products are expressed w.r.t. WGS84. The WGS84 reference ellipsoid is defined in [11]. The defining parameters are reported for completeness in Table 1.

Parameter	**Symbol**	**Value**	**Units**
Semi-major Axis	a	6378137.0	m
Flattening Factor of the Earth	1/f	298.257223563	
Geocentric Gravitational Constant	GM	$3.986004418 \times 10^{+14}$	m^3 / s^2
Nominal Mean Angular Velocity of the Earth	ω	7.292115×10^{-05}	rads / s

Table 1: Defining parameters of WGS84

As a first test before comparison, we focused on the S3B track 250 over the northern Adriatic Sea. S3B track 250 is a descending track passing over the Marano-Grado Lagoon in northeastern Italy, and then over open sea (Adriatic Sea): see Fig. 2.

Figure 2: S3B track 250, descending over the Marano-Grado Lagoon in the Gulf of Venice, northern Italy.

We plotted the CNES-CLS 2015 MSS from some S3 L2 files and from the official gridded product distributed by AVISO, along the S3B track 250. The plot is reported in Fig. 3.

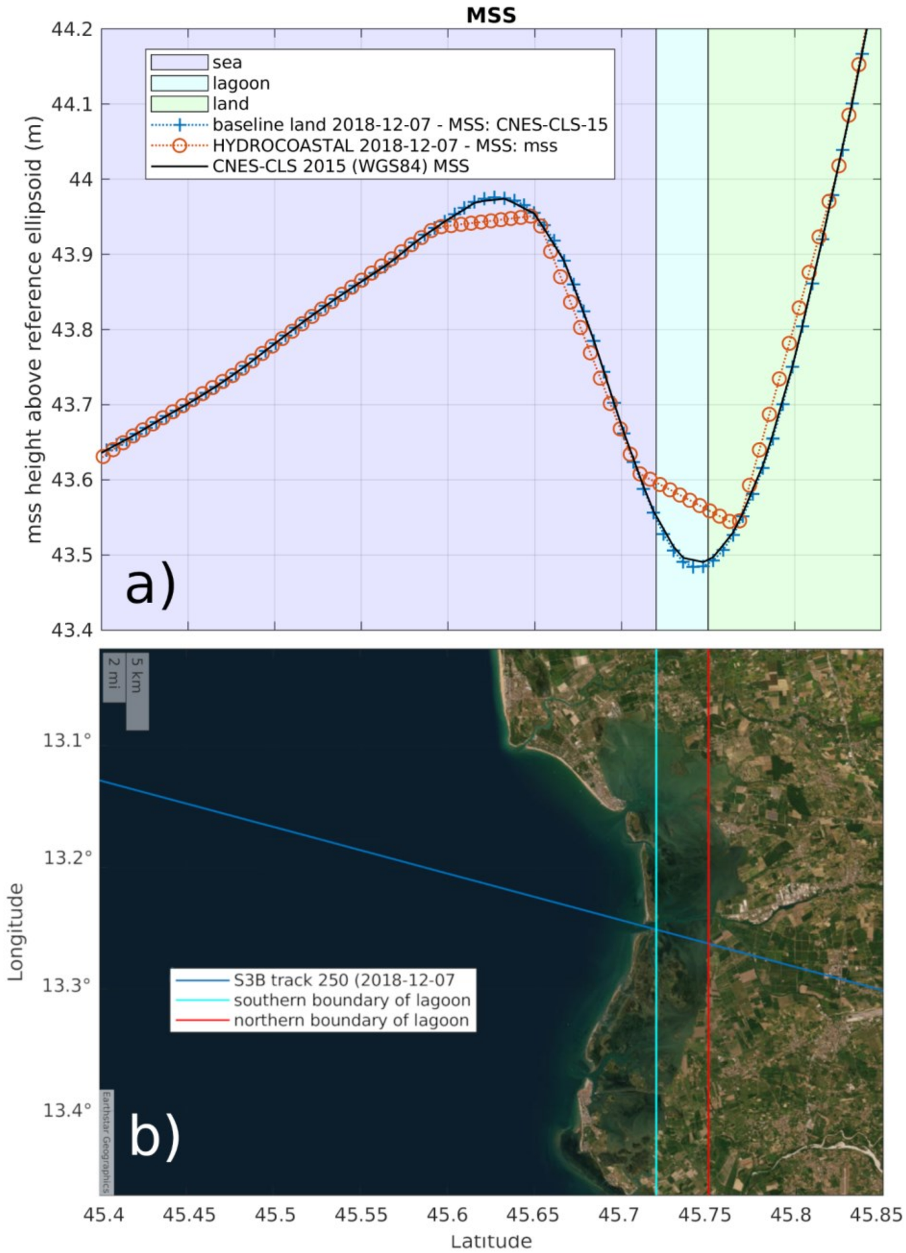

Figure 3: a) the CNES-CLS 2015 MSSs plotted from two S3B track 250 L2 product files and from the official AVISO release, over the Marano-Grado Lagoon in northern Italy. Markers are inserted at 10 Hz for clarity. The original products are the 20 Hz version; b) the track 250 overimposed to the geographic region of interest, showing the sea, lagoon and land boundaries, and the northern and southern latitude limits of the lagoon

The CNES-CLS 2015 MSS was taken from the following sources:

- S3B_SR_2_LAN____20181207T093010_20181207T102039_20190101T202924_3029_019_250______LN3_O_NT_003.SEN3 (standard_measurement.nc): from Copernicus Open Access Hub, it is a L2 land baseline S3 file - blue dotted line with “plus” markers
- combined_FULL_combined_FULL_L2E_S3B_SR_1_SRA_A__20181207T093010_20181207T102040_20190101T200954_3029_019_250______LN3_O_NT_003_default.nc: from the HYDROCOASTAL S3 L2 product files - orange dotted line with “circle” markers

- the third MSS is the official CNES-CLS 2015 MSS gridded product (1/60° x 1/60°), interpolated on the coordinates of the previous files - solid black line

In Fig. 3 we can observe some features of the various MSSs:

- the 20 Hz MSS included in the S3 L2 Copernicus official product (drawn at 10 Hz) forms a smooth curve
- the 20 Hz MSS included in the HC L2 product (drawn at 10 Hz) has been linearly interpolated from 1 Hz data and is composed of linear segments instead of following a smooth curve
- the 20 Hz official CNES-CLS 2015 MSS (drawn at 10 Hz) follows closely the Copernicus official product
- the three MSS have a local maximum at 45.63°N and a local minimum around 45.74°N. The difference between the two extremes is more than 45 cm in around 11 km

A first observation from this preliminary analysis is that, according to how the original gridded MSS has been interpolated along the track, the resulting SLA will be different.

A second and more important observation regards the abrupt change of the CNES-CLS 2015 MSS in the coastal zone, visible in Fig 3a, in the latitude range 45.6°N-45.8°N. In [12] a similar artifact was noted in another coastal site for a previous edition of the CNES-CLS MSS; in the same paper, the authors recall that similar scenarios had been identified in other coastal areas. In the same area as [12], the artifact has been identified also by [13], where the MSS version is the present one (CNES-CLS 2015). With the aim of understanding if this abrupt MSS trough was present also in the second MSS included in the official S3 L2 altimetry products, we plotted the second MSS solution from two official S3B L2 files on track 250 over the Marano-Grado Lagoon, for the day 2018-12-07:

- S3B L2 baseline land (ESA): DTU 2015
- S3B L2 baseline marine (EUMETSAT): DTU 2018

The second MSS solution of the two official products, together with the previous MSS plot of Fig. 3 are shown in Fig. 4.

The second mean sea surface solution, whether DTU2015 or DTU2018, has a totally different behavior in the latitude range of the trough shown by CNES-CLS 2015, which corresponds to the coastal zone and the lagoon interior. The height difference between the MSS of the two different providers is about 45 cm, CNES-CLS being the lower. In the open sea the height difference shortens to about 3 cm (not shown). With the aim of understanding the origin of the discrepancy between the two sets of MSS (CNES-CLS and DTU), we investigated how the underlying geoid looks like.

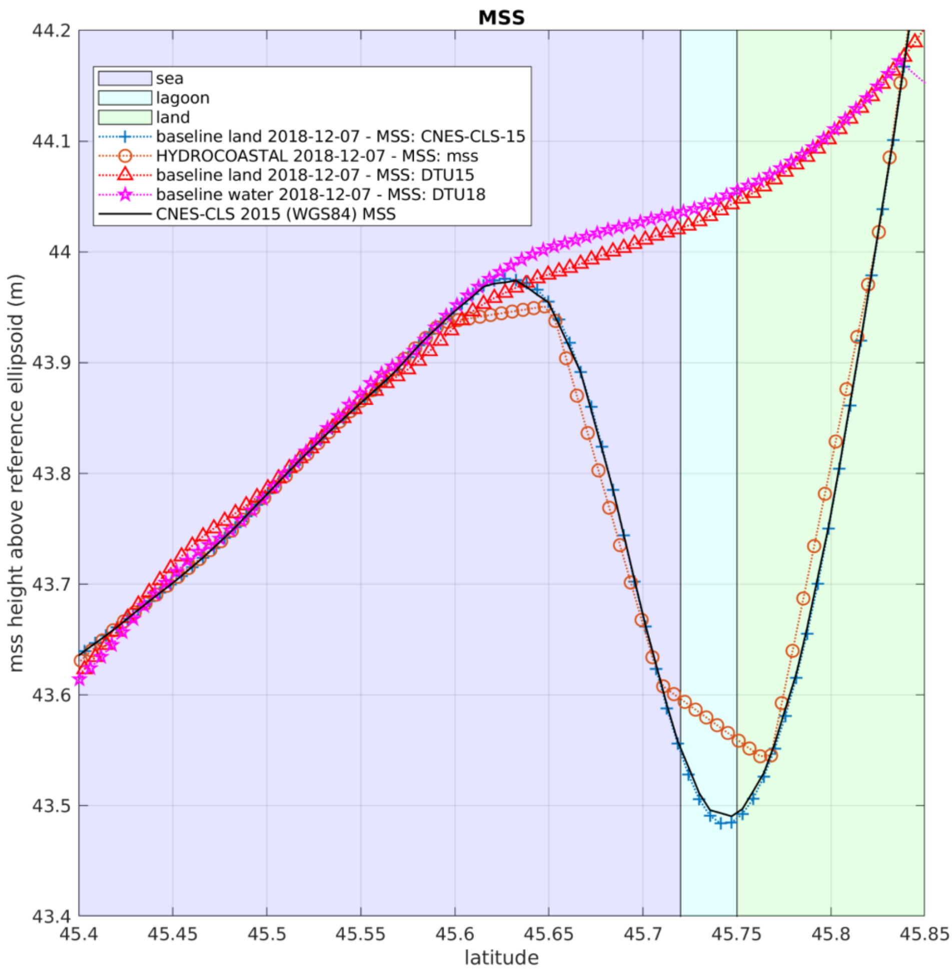

Figure 4: the CNES-CLS 2015 MSS, plotted from two S3B track 250 L2 product files and from the official AVISO release, over the Marano-Grado Lagoon in northern Italy, and the DTU 2015 and DTU 2018 MSSs plotted from the official S3B L2 official product of the land and marine baselines respectively, for the same day as the first two files (2018-12-07). Markers are inserted at 10 Hz for clarity: the original products are the 20 Hz version.

4 The mean sea surface and the geoid

Among others, [14] defines the relationship between the geoid (G), the mean sea surface and the mean dynamic topography (MDT). The relationship is reported in eq. 1 of [14]:

$$MSS = G + MDT$$

The Marano-Grado Lagoon is a shallow water lagoon where the maximum depth of a few meters is reached, inside the basin, by narrow canals. All over the rest of the lagoon the water is not deeper than a couple of meters. Fig. 5 a) shows the Marano-Grado Lagoon bathymetry, kindly provided by the government authority of Friuli-Venezia Giulia [15], with superimposed the S3B track 250. In Fig. 5 b) the profile of the GEBCO bathymetry [16] along the same S3B track is also reported, along with the CNES-CLS 2015 and DTU 2018 MSS profiles. There is clear evidence that the usage of the global GEBCO bathymetry would lead to an overestimation of depths within the lagoon. Bathymetry has important implications in models used to correct for tidal field and wind & pressure effects (aka Dynamic Atmospheric correction, DAC), but also in coastal ocean models used for coastal studies.

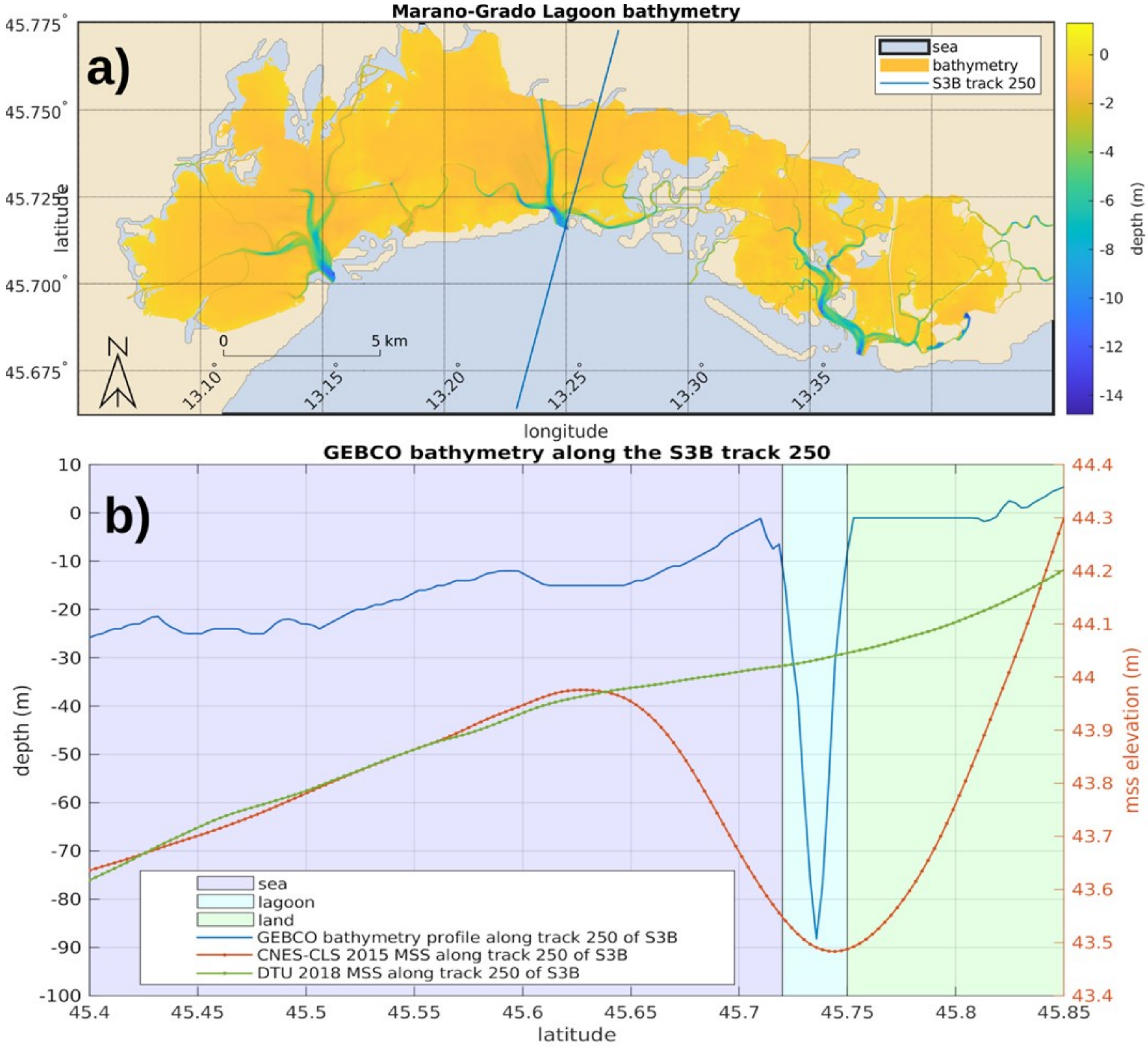

Figure 5: a) high resolution bathymetry of the Marano-Grado Lagoon (kindly provided by dr. Marco Lipizer, Friuli-Venezia-Giulia autonomous region, Italy); b) GEBCO bathymetry profile along S3B track 250, superimposed to the CNES-CLS 2015 and DTU 2018 MSS profiles along the same track: an artifact in the bathymetry profile is visible inside the lagoon, at 45.72°N.

Being the lagoon a semi-enclosed basin with low water input from the tributaries, we would expect the MDT level to not vary significantly from the southern end to the northern end of the lagoon at the intersection with track 250. Thus, if a trough in the mean sea surface is expected, it should derive from the geoid. For this reason we have interpolated the official EGM2008 global geoid model [11], expressed in the mean tide system (the official 1'x1' EGM2008 geoid undulation is given in the zero-tide system), along the S3B track 250 path over the lagoon, and plotted it, along with the CNES-CLS 2015 MSS, the DTU 2018 MSS and the ITALGEO2005 local geoid model [17] of the Istituto Geografico Militare (IGM), the official local geoid for Italy, in Fig. 6. EGM2008 has an absolute accuracy of about 20 cm [18].

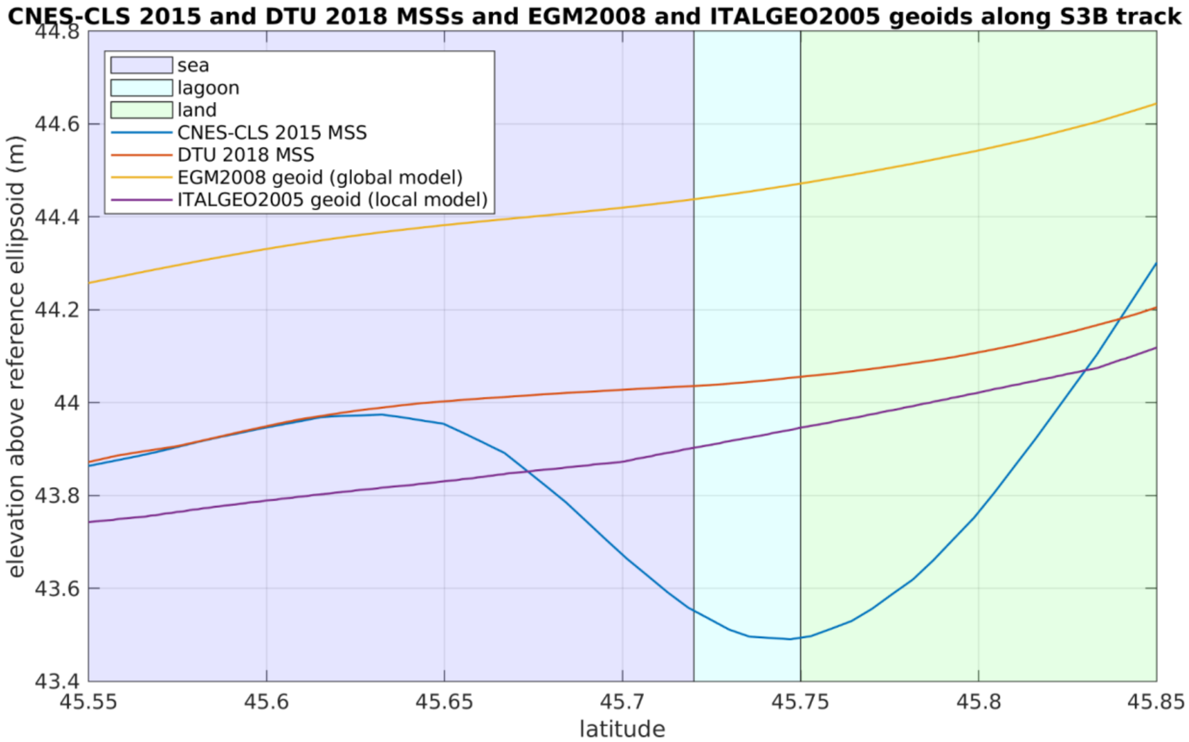

Figure 6: the CNES-CLS 2015 MSS along with DTU 2018 MSS, EGM2008 global geoid model and ITALGEO2005 local geoid model, expressed in the mean tide system, linearly interpolated on the S3B track 250 (2018-12-07). The interpolation has been performed from the official product grids at 1/60° x 1/60° resolution.

All geoid undulations and mean sea surfaces cited in this study are expressed in the mean-tide system, as far as we know from the bibliography and from direct inquiries to the interested people. Apart from an almost constant bias of about 40 cm between the geoid and the two MSS, DTU 2018 seems to follow closely the slope of the EGM2008 geoid, while CNES-CLS 2015 deviates, due to the trough inside the lagoon. While EGM2008 is a global geoid model, ITALGEO2005 is a local geoid model. Local models are valid for limited areas, but their accuracy is usually greater than that of the global ones. The ITALGEO2005 model is the official local geoid model of Italy. It has been estimated with the classic remove-solve-restore technique from gravimetric measurements integrated by GPS and leveling observations and vertical deviation measurements, and the terrain topography is also considered in the formulation of the geoid [19]. The accuracy attributed to ITALGEO2005 is of the order of 5 cm or less over the Italian territory [19,17]. The undulation differences between EGM2008 and ITALGEO2005 have been estimated over another Italian region (Campania), with a mean of -22 cm and a standard deviation of 9 cm, and maximum and minimum values of -76 cm and 52 cm respectively [19]. Similar experiments were conducted also in northwestern

Italy against GNSS/GPS measurements, with similar statistics: min 24 cm, max 66 cm, mean 47 cm and standard deviation 11 cm [20]. The results of such studies could explain the bias found between EGM2008 and ITALGEO2005 over the Marano-Grado Lagoon.

During this study we also used the geoid heights included in the S3 L2 official products of the land and marine baseline, and that distributed with the HC L2 product, which derives from the land baseline.

Fig. 7 shows the EGM2008 geoids, plotted along the S3B track 250, for a limited set of such files.

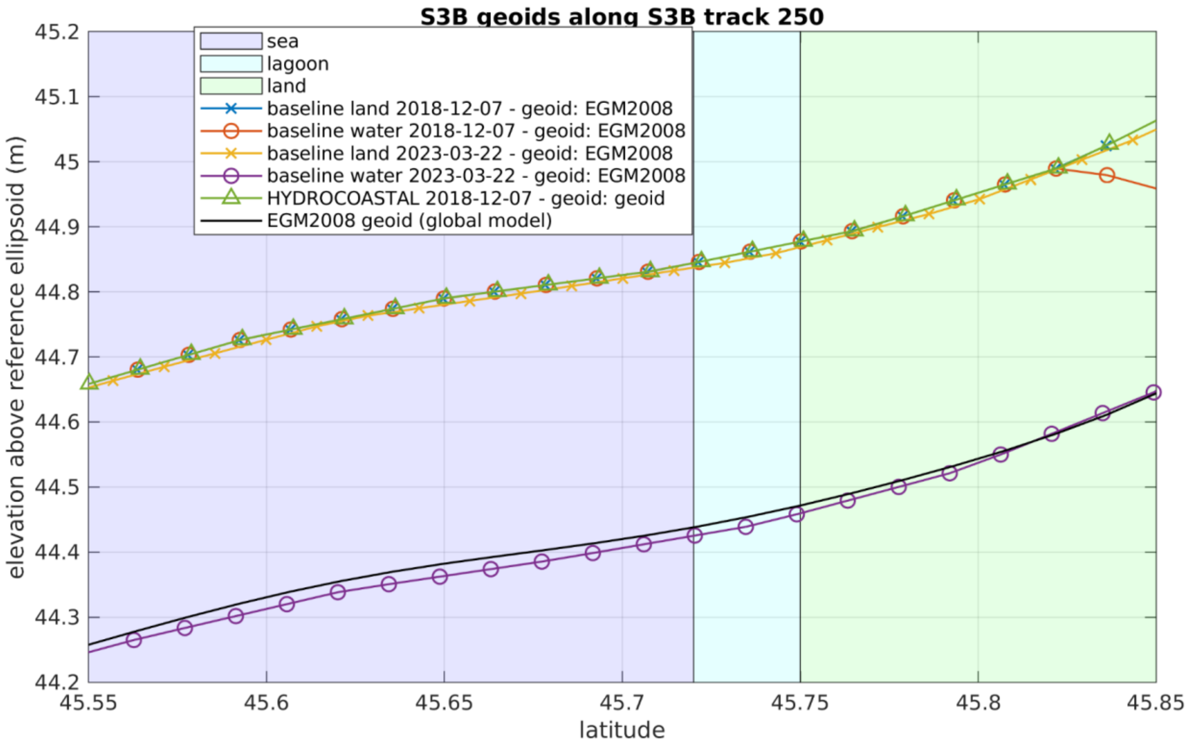

Figure 7: the EGM2008 global geoid model as found in the S3B L2 official products of the land and marine baselines, and in the Hydrocoastal L2 product, compared with the official gridded product, interpolated on the S3B track 250.

The files considered are as it follows:

- S3B L2 land baseline (2018-12-07)
- S3B L2 water baseline (2018-12-07)
- S3B L2 land baseline (2023-03-22)
- S3B L2 water baseline (2023-03-22)
- S3B L2 Hydrocoastal (2018-12-07)

As can be seen, all the geoid undulations included in the files except the water baseline 2023-03-22, are biased high of about 41 cm with respect to the original EGM2008 geoid (black solid line). The reason is that the auxiliary file containing the official EGM2008 geoid grid, used for deriving the geoid height in the S3 L2 altimetry products, has been erroneously coded with such a bias. EUMETSAT identified this error (see the product notice [21], EUM/Sen3/AR/7504 - Incorrect Geoid information) and corrected it with the processing baseline SM__WAT.005.02, which operates for the EUMETSAT L2 global altimetry products. This is the reason why only the S3B L2 water baseline (2023-03-22) product contains the correct EGM2008 geoid (see Fig. 7), while all the other products including the old one, have the wrong version of the geoid.

Some of the S3 L2 altimetry products also contain the EIGEN_6C4 geoid [22] among the parameters coded in the netCDF structure. For sake of completeness we show in Fig. 8 all the geoids available along with the CNES-CLS 2015 and DTU 2018 mean sea surfaces interpolated on the S3B track 250.

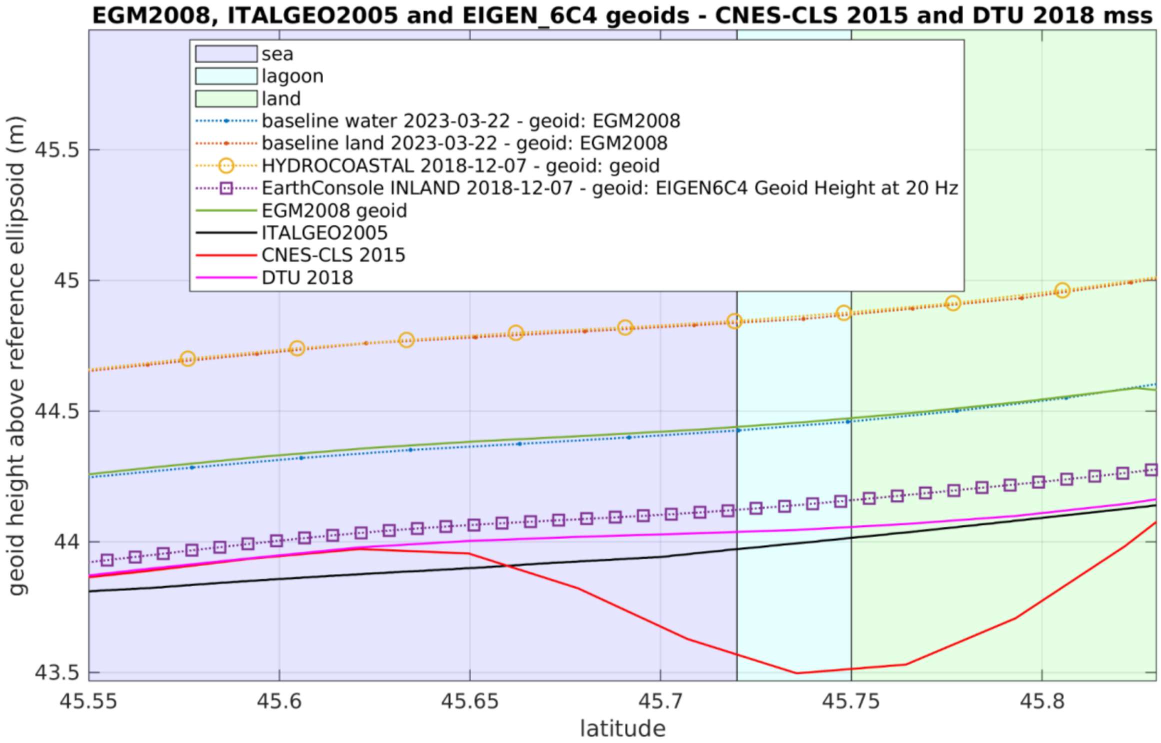

Figure 8: the EGM2008 global geoid model as found in the S3B L2 official products of the land and marine baselines, and in the Hydrocoastal L2 product, along with the EIGEN_6C4, included in S3 L2 altimetry products made available by the ESA EarthConsole virtual altimetry laboratory, the ITALGEO2005 local geoid, and the CNES-CLS 2015 and DTU 2018 mss official gridded products interpolated on the S3B track 250.

The geoids and mean sea surfaces plotted in Fig. 8 are taken from these sources:

- EGM2008 from S3B L2 water baseline (2023-03-22, new SM__WAT.005.02 baseline EUMETSAT)
- EGM2008 from S3B L2 land baseline (2023-03-22, ESA)
- EGM2008 from S3B L2 Hydrocoastal (2018-12-07)
- EIGEN_6C4 from S3B L2 ESA EarthConsole AVL (2018-12-07)
- EGM2008 from the official gridded product of NGA, interpolated on S3B track 250
- ITALGEO2005 from the official product of IGM, interpolated on S3B track 250
- CNES-CLS 2015 mean sea surface from the official grid, interpolated on S3B track 250
- DTU 2018 mean sea surface from the official grid, interpolated on S3B track 250

In Fig. 8 the ITALGEO2005 geoid and the DTU 2018 MSS appear very close, as well as the EIGEN_6C4 geoid from the S3B L2 EarthConsole product. The CNES-CLS 2015 MSS follows DTU 2018 up to 46.63°, but goes down as it approaches the coast, forming a local minimum inside the lagoon, and finally realigns to DTU 2018 over land. The EGM2008 geoid from the official gridded product and from the S3 L2 files of the new SM__WAT.005.02 EUMETSAT lies about 40 cm over DTU2018. The EGM2008 geoid included in the ESA land baseline S3 L2 product and the HYDROCOASTAL product are found about 40 cm higher than the official one. The EIGEN-6C4 geoid, as plotted from the EarthConsole data, lays a few centimeters above the DTU2018 MSS, determining for the local MDT a negative value:

$$MSS - G = MDT$$

The MDT of the northern Adriatic Sea is reported in Fig. 9. As the MDT is obtained by differencing MSS and G, the same tidal system (mean tide in the satellite altimetry context) must be adopted for those two quantities.

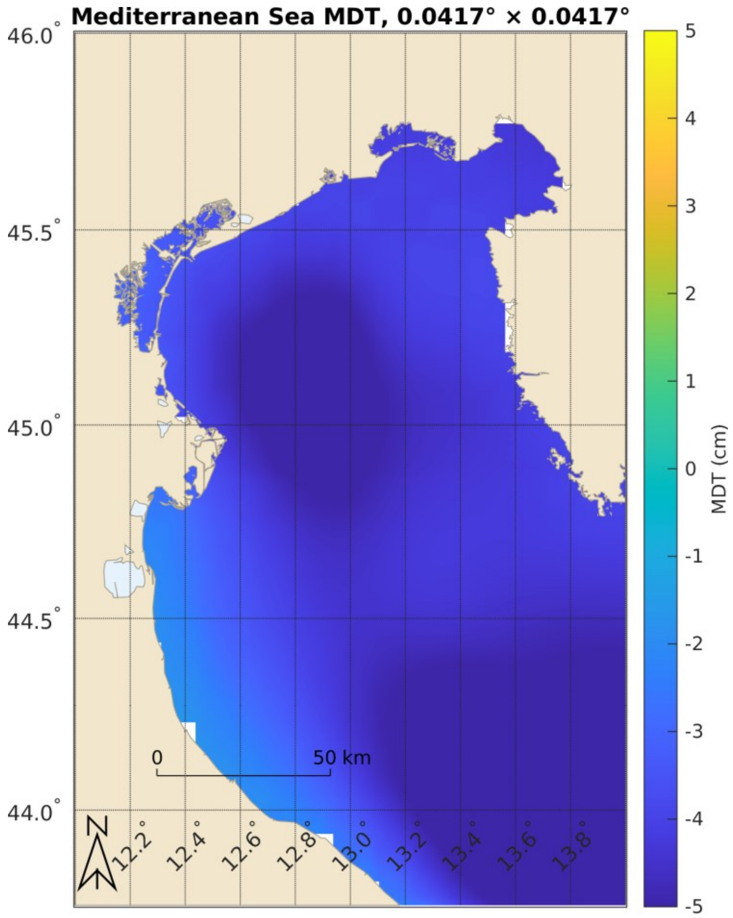

Figure 9: Copernicus CMEMS mean dynamic topography in the northern Adriatic Sea.

The MDT in Fig. 9 is provided by the E.U. Copernicus Marine Service (CMEMS) and is the regional product SEALEVEL_MED_PHY_MDT_L4_STATIC_008_066, which has a spatial resolution of 0.0417° × 0.0417° [23]. In the Marano-Grado Lagoon and in proximity to the coast the MDT is about -4 cm. Even if the spatial resolution of this MDT is not suitable to infer any detail about the spatial variability of the MDT at the spatial scale considered (1 Km), it can be chosen as an indication that the DTU 2018 MSS and the EIGEN_6C4 are consistent with the expected values of the local MDT. For this reason, we interpolated the EIGEN_6C4 geoid along the S3B track 250, using the calculation service offered by the International Centre for Global Earth Models (ICGEM, http://icgem.gfz-potsdam.de/home), in the mean tide system, on the geometrical WGS84 ellipsoid. This means that the zero-degree term has not been applied: for the EIGEN-6C4 geoid calculated by ICGEM to be comparable with the EGM2008 geoid, a constant -41 cm term must be applied (E. Sinem Ince, director of the ICGEM service, personal communication). To explain the situation of the geoids found in the altimetry products examined so far, two more images are reported in Fig. 10.

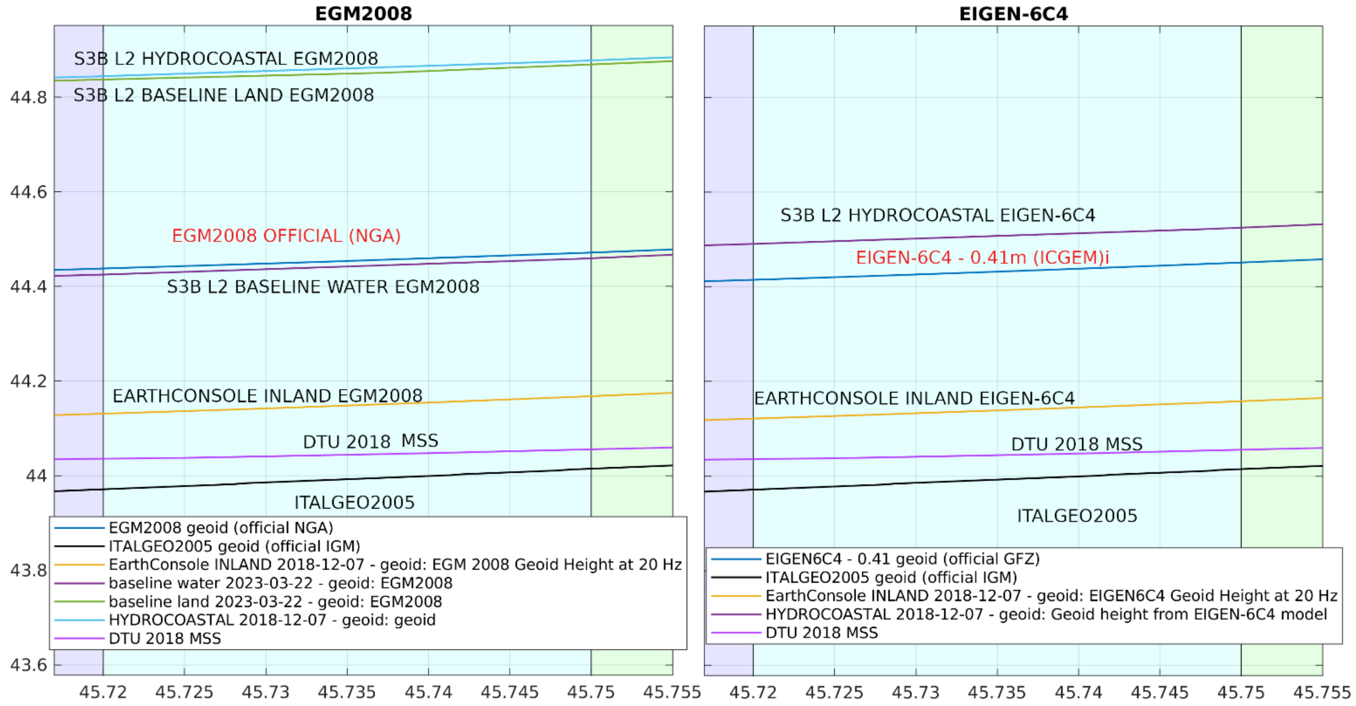

Figure 10: Comparison of the two official global geoids EGM2008 and EIGEN-6C4, with the geoids contained in the S3B L2 altimetry products examined so far, along a portion of track 250. The EIGEN-6C4 geoid has been biased low by 41 cm, as indicated by the provider, to be consistent with the EGM2008 geoid.

The two images show that:

- The official EGM2008 and EIGEN-6C4 (-41 cm) are consistent in slope and quote
- EGM2008 in S3B L2 baseline water after SM__WAT.005.02 is consistent with the previous two
- EIGEN-6C4 in S3B L2 HYDROCOASTAL is almost consistent with the previous two, but biased by 8-10 cm
- EGM2008 in S3B L2 products from HYDROCOASTAL, baseline land and EARTHCONSOLE, are biased several tens of centimeters w.r.t. the official EGM2008 geoid
- EIGEN-6C4 in S3B L2 product EARTHCONSOLE is biased several tens of centimeters w.r.t. the official EIGEN-6C4-0.41 geoid

5 Summary

Height determination at land-sea interface requires careful attention in the vertical references used. Heights from radar altimetry and GPS use the ellipsoid that, however, does not have equal gravity potential. As water flows according to gravity potential the geoid (a surface with equal gravity potential at every point) is the right datum for physical heights.

There are a wide range of geoid models which have been developed to permit the conversion of geometric ellipsoidal heights to physical heights. Over the ocean, another reference is often used, the MSS that was introduced when multiple satellite radar altimetry missions were flying. An along-track MSS profile was generally used with the early satellite missions. This is the approach used today in X-TRACK coastal altimetry product [24], which is available from AVISO at 1 Hz (around 7 km spacing along the track). The MSS is computed using all the available corrected SSH data along the repeated ground tracks of the specific satellite radar altimetry mission by taking into account the cross track gradient of the SSH from one cycle to the other. However, the product cannot be applied to drifting missions (e.g., CryoSat-2) and Sentinel-3B is not available from AVISO yet. In the context of the ESA Climate Change Initiative, a new coastal sea level product called X-TRACK/ALES has been generated at 20 Hz, but only for Jason series missions [25].

In this note, we have analyzed different MSS and geoids in the Marano-Grado lagoon. At present MSS are only available as global products, while countries have developed national or local geoid models which use a global gravity model, and augment it with local data such as terrestrial and airborne gravity data.

When MSS and geoids are used with satellite radar altimetry the consistency is required, in terms of ellipsoids (e.g., WGS84, TOPEX/Poseidon) and tidal system (free-tide vs mean-tide). Also, the zero-order geoid undulation value (“zero degree term”) should be taken into account.

It should be noted that MSS and geoid data that are available in the official altimetry products are considered auxiliary information being produced by third parties. However, their usage with altimeter data would require that the user is provided with detailed information in the product manual to exploit correctly.

The analyses that has been carried out so far leads us to conclude that the CNES-CLS 2015 MSS presents an unexpected trough in correspondence of the coastal zone in front of and inside the Marano-Grado Lagoon, while the DTU 2018 MSS follows the almost linear slope, in this region, of the ITALGEO2005 local geoid model, with a mean bias of 12 cm inside the lagoon, and also the slope of the EGM2008 global geoid model, even if with a larger bias, which is expected for global geoids used at the local or regional scales, and that depends also from the constant gravity potential attributed to the chosen reference ellipsoid.

The impact in the SLA when using MSS with artifacts has been already documented in the literature. Although updated MSS are stated to have better performances in the coastal zone on a global average (e.g., see [26]), our results confirm that, when zooming locally, these models must be scrutinized before exploiting them in the coastal studies.

Another important observation from this preliminary analysis is that, according to how the original gridded MSS has been interpolated along the track, the resulting SLA will be different.

The analysis also shows some inconsistencies between the same MSS and geoid available in the various baseline and experimental satellite radar altimetry products. Table 2 provides a summary that shows what is known from the documentation and what is supposed (e.g., products that are generated for usage with altimetry are always expected to be provided in the mean-tide system).

MSS	Type	Product	Ellipsoid system	Tidal system	Note
	CNES-CLS 2015	AVISO native grid	WGS84	supposed mean	
	CNES-CLS 2015	EUMETSAT L2 ocean baseline	WGS84	supposed mean	
	CNES-CLS 2015	HydroCoastal	WGS84	supposed mean	
	DTU 2015	ESA L2 land baseline	WGS84	mean	
	DTU 2015	DTU native grid	WGS84	mean	
Geoid					
	EGM2008	NGA native grid	WGS84	free	transformed to Mean
	EGM2008	EUMETSAT L2 ocean baseline	WGS84	supposed mean	
	EGM2008	ESA L2 land baseline	WGS84	supposed mean	
	EIGEN-6C4	ESA Earth Console	WGS84	supposed mean	
	ITALGEO2005	Italian Army	GRS80/WGS84	supposed free	transformed to Mean
MDT					
	MDT-CMEMS_2020_MED	Copernicus CMEMS	supposed WGS84	Consistent with MSS and G (supposed mean)	

Table 2: Type of MSS, Geoid and MDT found in the products and consistency.

We have observed DTU MSS not aligned between the land and marine baselines (DTU2015 vs DTU2018); the same geoid (EGM2008) that underwent a correction after a certain date, is updated previously as the reprocessing follows-up, however, the user if not aware of this would use different geoid values. Moreover, while a bias correction for the EG2008 geoid has been applied in the marine baseline, it has not been taken over in the land baseline.

6 Recommendations

The recommendations from the previous analyses for the Marano-Grado lagoon are:

- Better assessment of global MSS products at land-sea boundary (coastal zone, coastal lagoons, river estuaries);
- Defining the best method to have accurate MSS for studies at land-sea boundary;
- Better assessment of global and local geoid products in selected areas (round-robin exercise). The Northern Adriatic Sea would be excellent place to collect ground-truth measurements for logistical reasons and possible support of the regional authorities;
- Interpolating MSS and geoids at higher resolution than 1 Hz directly from the native grids and not from the along track data;
- Providing more detailed documentation about MSS and geoids included in the distributed products. Some products are not published, and the interpretation of results becomes quite difficult. The user needs to understand which source data sets are used to generate the product, how those data sets are processed, which reference systems are used, etc.;
- Avoid inconsistencies between MSS and geoid available in the official marine and land baseline products, as at land-sea interface there is overlapping;
- Bathymetry is fundamental for coastal models and should be supplemented with local data that are often owned by national or local authorities;
- Better assessment of the MDT which is fundamental for assimilation of SLA in coastal ocean models.

7 Appendix A

Following the treatment given in [27], the temporal average of the tide-generating potential of the Sun and the Moon is not zero. In order to deal with the permanent deformation they cause, three concepts for the gravity field were introduced:

Non-tidal or tide-free system

The permanent deformation is eliminated from the shape of the Earth: from the potential field quantities (gravity, geoid etc.) both the tide-generating potential, and the deformation potential of the Earth (the indirect effect) are eliminated. This corresponds to physically moving the Sun and the Moon to infinity.

The mean tidal system

The permanent effect is not removed from the shape of the Earth; the shape therefore corresponds to the long-time average under tidal forcing. The potential field retains the potential of this average Earth, and also the time-average of the tide-generating potential. Mean-tide potential field describes how water flows.

The zero tidal system

A “middle alternative” Eliminates the tide-generating potential but retains its indirect effect, i.e., the potential of the permanent deformation of the Earth. In this alternative, the gravity field is generated only by the masses of the Earth (plus the centrifugal force).

Satellite radar altimetry has been designed for the oceans. It needs a reference surface on which the tidal forcing is averaged over a long time, and the mean-tide potential field has zero effect on the horizontal movement of the water. For this reason, the mean tide system is generally adopted, and all the potential surfaces are expressed in such tidal systems. On the contrary, geoids have to do with crustal movements, and reference surfaces are expressed in the tide-free system. To pass from the tide-free to the mean-tide system for undulation heights, a simple formula is used:

$$h_{mean\ tide} = h_{tide-free} + (\mathbf{1}+\boldsymbol{k}) \cdot (\mathbf{9.9} - \mathbf{29.6}\ \cdot \boldsymbol{sin}^{\mathbf{2}}(\boldsymbol{\varphi}))\ (\boldsymbol{cm})$$

where 1+k = 1.3 is the appropriate Love number. For the area of interest of this study, the latitude in play is 45.7°N, and the anomaly to be added to geoid undulation heights is -6.8 cm. The anomaly height as a function of the latitude, for undulation heights (positional heights are a bit different), is reported in Fig. 11.

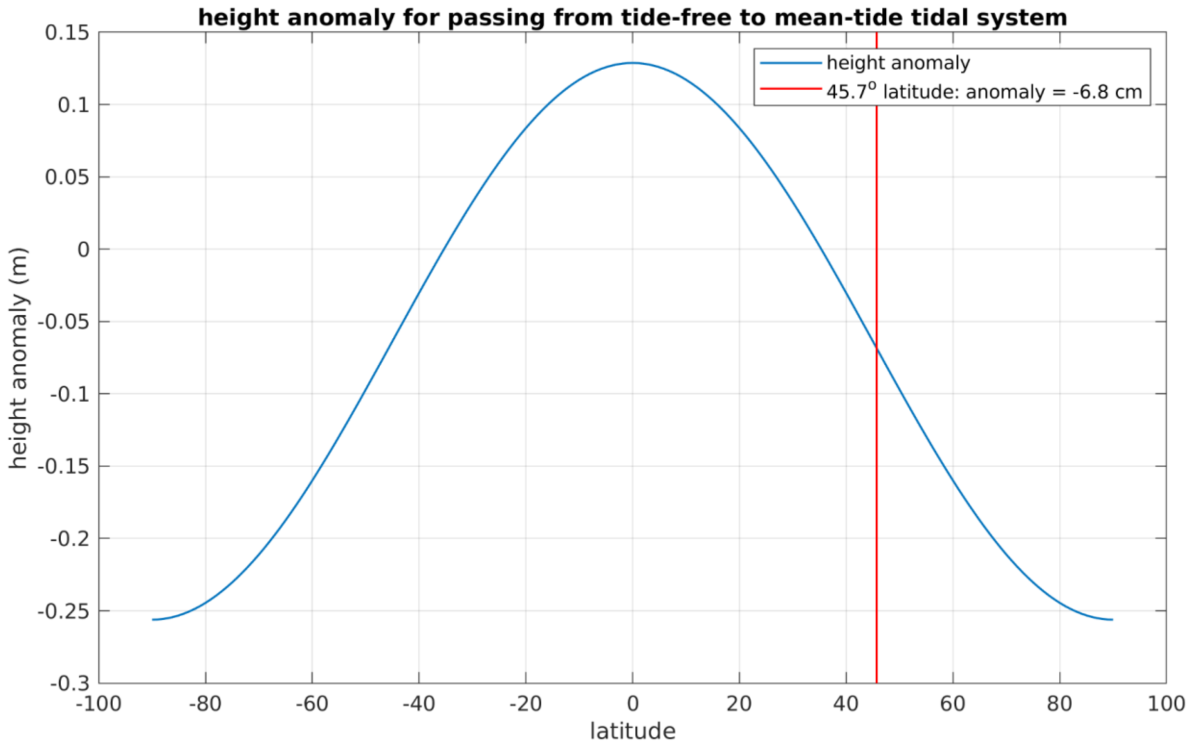

Figure 11: the tide-free to mean tide undulation height anomaly as a function of latitude.

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