D.3.3.1 –
Regional high-resolution Maps of Sea-level

Document Control Sheet

Project number:	10048765
Project acronym	ASTERIS
Project Title	Adaptation to Saltwater inTrusion in sEa level RIse Scenarios
Start of the project	January 2019
Duration	24 months

Related activity:	3.3 – Definition of future sea level scenarios for the Adriatic Area
Deliverable name:	Regional high-resolution maps of sea-level
Type of deliverable	Report
Language	English
Work Package Title	Modelling present and future salt ingression in Adriatic coastal aquifers
Work Package number	3
Work Package Leader	University of Urbino "Carlo Bo" – (UNIURB)

Status	Final
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Version	1
Due date of deliverable	31 June 2020
Delivery date	31 June 2020

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1. Introduction

Sea level is currently rising and it is expected to increase from 25 to 100 cm (global average) by the end of the century. Sea-level rise is not uniform but affected by a strong spatial variability. The Mediterranean Sea, due to its characteristic of semi-enclosed basin, has not been well represented in global ocean circulation models so far developed, which consider the Mediterranean as a closed Sea, without exchange with the Atlantic Ocean across the Gibraltar Strait.

In this activity, sea-level changes are modelled by taking into account all the interrelated physical mechanisms that characterize glacial isostatic adjustment processes and taking regional variability into consideration. As a consequence, the activity will predict regionally varying relative sea-level (RSL) changes that might locally be significantly different from eustatic (i.e., spatially uniform) sea-level variations. Previous studies of saline intrusion in coastal aquifers relied on the eustatic approximation, which implies a globally uniform sea-level rise.

The objective is to predict the actual local RSL changes within the study area and, in a subsequent step, the local response in terms of saline intrusion.

2. Methodological approach

The long-term sea-level variations at a given place and time stem from the combination of several contributions. Assuming that these are acting independently, following the general approach outlined by Mitrovica et al. (2001), the total variation is given by the combination of different factors including GIA component of sea-level change, the contribution associated with mass exchange (referred to the current melting of terrestrial ice masses), the component due to the ocean response (this includes the ocean circulation contributions and thermosteric plus halosteric effects), the contribution of other factors (including, for instance, sediment compaction, co- and post-seismic deformations and other tectonic effects). To obtain scenarios for the evolution of future sea level, all these components have to be modelled. A first attempt of future sea-level scenarios at 2050 for Mediterranean Sea was presented by Galassi and Spada (2014); here their work is expanded to develop sea-level scenarios to 2100.

The AR5 IPCC report analyzed different Representative Concentration Pathway (RCP) pathways, i.e. greenhouse gas concentration trajectory, to which correspond sea-level scenarios at 2100. Among those published, here we consider RCP8.5 (continued growth of gas emissions) to estimate a possible upper bound of future RSL variation in the study area. For that reason, both steric and current ice melting component of sea level, have been modelled according to the RCP 8.5. The GIA component is not influenced by the current evolution of climate and it is independent from scenarios.

The scenario so obtained is compared with other two scenarios obtained with different approaches:

- A low-hand "business as usual" scenario that has been developed based on a projection "business as usual" of sea-level trend detected during the last decades at tide gauges located in Adriatic basin;
- A "semi-empirical" scenario, obtained following the approach described by Rahmstorf (2007), based on the relationship between temperature and sea-level rise: this has been obtained adopting the highest temperature scenarios for Mediterranean Sea at 2100.

The analysis of tide gauges signals has the further advantage of introducing a local component for the comparison of modelled scenarios. This is useful for testing the model at the case study areas.

At the basis of the analysis, the ocean's mean dynamic topography (MDT), calculated as the filtered difference between an altimeter mean sea surface and a geoid model, has been introduced in the model. Here, the MDT modelled by Rio et al. (2014) for Mediterranean has been used. **(Fig. 1)**. The MDT is of low importance at coastal level. Nevertheless, the use of MTD in the analysis is important to show the overall variability at basin level.

2.1 Geodynamic model of sea level components

The geodynamic components of sea level account for the deformation of solid Earth as consequence of ice melting. Here two different geodynamical processes are taken into consideration: the current melting of the ice sheets, glaciers and ice caps and the Glacial Isostatic effects deriving from the melting of ice at Last Glacial maximum. For both, sea-level projections have been modelled with the aid of an improved version of program SELEN (Spada and Melini, 2019), which solves the “sea-level equation” (Farrell and Clark, 1976) assuming a spherically symmetric, rotating, elastic and isotropic Earth model, with a PREM structure.

The glacial isostatic adjustment (GIA) component of sea-level change is originated by the ongoing mass redistribution still caused by the melting of the late-Pleistocene ice sheets. GIA effects average to zero across the surface of the oceans, but they will be the source of local and regional sea-level variations, both in the formerly glaciated areas at the Last Glacial Maximum (LGM, ~ 21,000 years ago) and in key-areas such as the Mediterranean Sea (Galassi and Spada, 2014). The pattern of the sea-level change expected from future mass loss from glacial and ice caps and continental ice sheets shows significant variations even at the 100-km spatial scale (Spada et al., 2013). To model GIA effects, it will make use of the gravitationally self-consistent Sea Level Equation formalism and account for solid Earth deformations, gravitational and rotational perturbations. GIA is estimated by the ICE-6G (VM5a) global model of Peltier et al. (2013).
Sea level is also influenced by the effect of the current terrestrial melting (hereinafter TIM) of glaciers, ice caps (GIC), and ice sheets (Antarctica - AIS - and Greenland - GIS). For the AIS and the GIS, the surface mass balance (SMB) and the ice dynamic (DYN) components of TIM are considered separately. The projection of melting of glaciers and ice caps has been taken from Slangen et al (2014). The glacier estimate is computed using CMIP5-based projections of temperature and precipitation changes over glaciered regions in combination with a glacier area inventory (Radi´c and Hock 2010) in a model for glacier mass loss that is based on volume-area considerations (Slangen and van de Wal, 2011). The SMB change has been combined with the projected CMIP5 global mean surface temperature change to calculate the CMIP5-SMB. Since

ice-melting dynamical processes are complex (accounting for calving and melt of marine-terminating glaciers, ice flow-SMB feedback, melting of ice shelves from below for changes in circulation cause warmer water, etc.), the projection modelled by Slangen et al (2014) uses an RCP-independent scenario bounded by two different estimates: a lower bound taken from a scaled-up estimate of IPCC AR4, and upper bound corresponding to the estimates presented in Katsman et al. (2011). For this project, the TIM mass balance included in the model is that projected according to the scenario B described in Slangen (2014), corresponding to the RCP 8.5 of IPCC; the model has been developed accordingly with Spada et al. (2013), to obtain sea-level pattern (fingerprint) at 2100.

2.2 Steric component

Steric component of sea-level change describes the effects of water density variations. These can be separated into thermosteric and halosteric components, where the first accounts for temperature variations assuming a constant salinity, and the second represents the effect of salinity variations at constant temperature (Jordà and Gomis, 2013). While at global scale the thermosteric effects dominate the steric sea-level variations, at a regional scale and in particular in the Mediterranean Sea halosteric and thermosteric effects can be comparable (see e.g. Tsimplis and Rixen, 2002). In this work, data obtained from the Euro-CORDEX run - MOHC-HadGEM2-ES*-SMHI-rcp85 (Struglia, ENEA, personal communication, 2019).

2.3 Linear model based on tide gauges data

Tide gauges (hereinafter TGs) are the oldest instruments for measuring sea-level changes. In its basic form, a TG is a graduated staff in which the sea-level can be visually observed. At present, staffs have been replaced with more elaborate instruments that allow to eliminate the wave effects and to obtain a continuous recording of sea-level. However, the idea behind remains the same: a TG is an instrument capable to detect the height (and its variations) of the free surface of the ocean relative to the solid Earth. As a consequence, TGs measure the “relative sea-level” (RSL, defined as the sea level referred to a benchmark on the solid Earth, differently from the “absolute sea-level”, referred to the Earth’s center of mass and measured by altimeter).

For TG measurements, we employ observations obtained from the Permanent Service for the Mean Sea Level (PSMSL, see http://www.psmsl.org/) that collects sea-level data from individual national authorities since 1933 (Holgate, 2013).

In Northern Adriatic Sea there are 29 TGs in the PSMSL database. These recorded sea level for different periods, the oldest starting from 1875 (Trieste, Id 154), and their records have different length (the shortest at Manfredonia id 1262, and the longest 145 years, at the above-mentioned TG of Trieste). The level of completeness (i.e. the presence of gaps in information in the record) also varies from a TG to another. For these reasons, the linear trends obtained at single TGs' location cannot be compared each others straightforward.

The approach used here is to combine TGs belonging to a same "zone", having divided the Northern Adriatic Basin into 5 zones, as shown in **Fig. 2**. The distribution of TGs in the zones and their basic information are shown in the following table. TG's records falling in the same zones have been stacked to obtain a unique curve for each zone. The stacking allows to cover, at least partially, the gaps in time series and to filter out signals associated to local phenomena. In addition, stacking the available records allows to obtain a sea-level signal of a sufficient length so to avoid disturbances due to decadal and inter-decadal fluctuation in the computation of linear trend (the minimum length is 60 years, see Spada & Galassi 2012 for details). Only sea-level records longer than 60 years are adequate to represent sea level trend at century scale. The stacked curves have been then used to obtain a linear trend for a common period (i.e. a period covered by data in all the different zones). The trends have been in turn used to obtain projection at 2100 for a "business as usual" scenario.

Table 1: List of Tide Gauges (TGs) used in this study with basic information grouped by zones

Zone 1 - NORTH Adriatic						
PSMSL ID	Name	Y_start	Y_end	Period (years)	% of missing value	Linear trend (mm/yr)
2099	TRIESTE_II	2001	2015	15	0,56%	-7,05
154	TRIESTE	1875	2019	145	13,20%	1,33

2100	VENEZIA_II	2001	2015	15	0,00%	14,29
39	VENEZIA_S.STEFANO	1872	1920	49	1,37%	2,64
87	VENEZIA_ARSENALE	1889	1913	25	4,33%	2,58
168	VENEZIA_PUNTA_SALUTE	1909	2000	92	5,89%	2,44
1009	KOPER	1962	1991	30	4,44%	-0,04
Zone 2 - EAST CENTRAL Adriatic						
1578	ZLARIN	1883	1988	6	0,00%	6,98
1859	ZADAR	1994	2018	25	0,68%	2,39
1577	GAZENICA	1983	1988	6	0,00%	-0,64
761	ROVINJ	1955	2018	64	1,18%	0,76
353	BAKAR	1930	2013	84	13,10%	1,10
Zone 3- WEST CENTRAL Adriatic						
2098	ANCONA_II	2001	2015	15	0,00%	6,54
101	ANCONA	1966	1972	7	10,50%	-9,18
2144	PORTO_GARIBALDI	2009	2018	10	0,00%	-0,01
100	PORTO_CORSINI	1969	1972	4	4,26%	-6,21
Zone 4- EAST SOUTH Adriatic						

352	SPLIT_GRADSKA_LUKA	1954	2018	65	0,00%	1,05
685	SPLIT_RT_MARJANA	1952	2008	57	0,93%	0,61
1574	VIS-CESKA_VILA	1983	1991	9	4,90%	-6,33
1706	SUCURAJ	1987	2005	19	1,33%	5,55
1718	UBLI	1987	1991	5	0,00%	-18,11
1945	PLOCE	2006	2018	13	0,64%	6,51
760	DUBROVNIK	1956	2018	63	0,93%	1,58
1075	BAR	1956	2018	63	0,00%	1,36
Zone 5- WEST SOUTH Adriatic						
2075	BARI	2001	2015	15	1,11%	8,05
1262	MANFREDONIA	1969	1971	3	2,78%	-44,44
2087	VIESTE	2001	2015	15	1,11%	7,16
2097	ORTONA_II	2001	2015	15	1,67%	8,96
972	ORTONA	1960	1972	13	50,30%	-0,53

2.4 The "Semi empirical" model

The semi-empirical model proposed by Rahmstorf (2007) hypothesizes that there is a (semi-empirical) relationship connecting sea-level rise to the mean ocean surface temperature. According to Rahmstorf, the increase of temperature and sea-level changes during the 20th century are linked by a proportionality constant of 3.4 mm/yr per °C. This, at global level, results in a projected sea-level rise in 2100 of 0.5 to 1.4 meters above the 1990 level.
A similar approach has been used by Lambeck et al. (2011) where, however, authors used the upper bound of sea-level projection estimated at global level by Rahmstorf (2007) (1400 mm at 2100), and correcting this figure for glacial isostatic and seismic processes estimated at locale level. Here, the semi-empirical model proposed by Rahmstorf, with its proportionality constant, is applied considering the expected increase in temperature at 2100 (as the difference between the average 2071-2100 relative to 1986-2015) proposed by Sakalli (2017). In particular, different zones of SST at 2071-2100 for the Mediterranean Sea, as shown in Sakalli's figure 8.b) and the difference to the 30-year study time period 1986-2015 (figure 8.d), have been applied for the computation. In the Adriatic Basin the ∆SST range between 3.25 and 3.50 °C.

3. Results

3.1 Geophysical modelling

3.1.1 Glacial Isostatic Adjustment

Model output shows that GIA contribution to sea level at 2100 is modest and that GIA signal in Adriatic Basin is smooth (**Fig. 3**). Values range between -0.8 cm in the northern part and 0.5 cm in the central-southern part of the Basin. The slight negative value in the North Adriatic, corresponding to an annual trend of -0.1 mm/yr, is partly due to the ongoing rebound following the melting of glaciers from Last Glacial Maximum.

Compared with the other variables involved in the modelling of the total sea-level projection, GIA provides a minor contribution.

3.1.2 Current ice melting

The modelled sea-level projection expected at 2100 from the current ice melting is shown in **Fig. 4**. Since the basin is located in the intermediate far-field of the ice sources employed here, these sea-level variations exhibit sub-eustatic values (i.e. they do not exceed the ocean-averaged values) and show only very modest variations across the basin. By 2100 the current ice melting component of sea-level change across Adriatic Basin.

By 2100, the TIM component of sea-level change across the Adriatic Basin ranges between 2.2 cm in the northern part to 6.2 in the southern. The lower value at the upper Adriatic Seas is the effect of the melting of the nearby Alpine glaciers.

3.1.3 Steric component

The steric component refers to Eta, thermosteric and halosteric variation of sea level. Thermosteric changes relate with changes in the density of sea water induced by temperature changes, whereas halosteric refers to change in density by salinity changes. The Eta variable is proportional to the mean pressure change.

The total contribution to sea-level change at 2100 in Mediterranean Sea, according with RCP 8.5, is larger than 80 cm (**Fig.5**). The contribution associated to change in temperature and in pressure (thermosteric and Eta, respectively) are the most relevant.

3.2 Tide gauges - based model: the “business as usual” scenario

For each zone, the records of TG have been stacked (**Fig. 6)**.

For **Zone 1**, of the seven TGs available, only two with a record longer than 60 years: Trieste (ID. 154, length 145 years) and Venezia Punta della Salute (ID. 168, length 92 years). Nevertheless, all the TGs in this Zone have recorded for more than 10 years and then all have been used for the stack. The resulting stacked curve has a total length of 148 years with a completeness of 99.4%.

The five TGs included in **Zone 2** have only in two cases records longer than 60 years: Rovinj (ID. 762, length 64 years) and Bakar (ID 353, length 84 years). The two TGs shorter than 10 year (Zlarini, ID 1578 and Gazenica, ID 1577, both having a record 6 years long) have not been considered for the stacking. The resulting stacked curve covers a period of 89 years, with a completeness of 87.6%. Missing values are concentrate in the period may 1940- August 1949.

Zone 3 contains four TGs, all of them shorter than 60 years (the longest is Ancona II, ID. 2098, with 15 years of data). For the stacking, only Ancona II and Porto Garibaldi (ID 2144 , 10 years of data) have been used, being tother two even shorter than 10 years (Ancona, ID 101, length 7 years, and Porto Garibaldi, ID 101, length 4 years). The resulting stacked curve has a length of 18 years, too short for being accounted in the computation.

Zone 4 has eight TGs, three of which longer than 60 years (Split Gradska Luka, ID.352, length 65 years, Dubrovnik, ID. 760, and Bar, ID 1075 both length 63 years). Since the TGs with record shorter than 10 years have been removed (Vlis-Ceska Vila ID 1574 and Ubli ID 1718). Six TGs have been then used for the stack. The resulting stacked curve has a length of 67 years and it is complete (no missing values).

Zone 5 has five TGs, all with short records (maximum length 15 years). The three years long curve of Manfredonia, ID. 1262 has not been included for the computation of the stack. Even if the four TGs remaining have data referred to different time span (from 1960 to 1072 the oldest, Ortona ID. 972 and from 2001 to 2015 the newest three), considering the total period covered of 65 years (<60 years) and a completeness of 77.2%, the stacked curve of Zone 5 is not adequate to obtain a trend representative for the past century.

				Whole period		From 1952 to 2015		SL at 2100 (mm+ in respect to 2015)	
ZONE	Y_start	Y_end	Period (years)	Linear trend	Standard error	Linear trend	Standard error	Central estimate	Upper bound (+2σ)
ZONE 1	1872	2019	148	0,78	0,05	0,90	0,17	76,50	105,40

				Whole period		From 1952 to 2015		SL at 2100 (mm+ in respect to 2015)	
ZONE 2	1930	2018	89	1,14	0,09	0,62	0,16	52,70	79,90
ZONE 3	2001	2018	18	2,86	1,13	-	-	-	-
ZONE 4	1952	2018	67	-0,20	0,14	-0,12	0,15	-10,20	15,30
ZONE 5	1960	2015	56	0,25	0,17	-	-	-	-

3.3 The “semi-empirical” scenario

According with equation 2 in Rhamstorf (2007) the sea-level variation H(t) with respect to a reference time, due to temperature increase is

$$H(t) = a \int_{t_o}^{t} \Delta T(t') dt'$$

where *a* is the proportionality constant (3.4 mm/yr), *t,* is time and ΔT is the difference in SST. In Our computation ΔT represents the difference in SST between the average 1986-2015 and 2071-2100, as computed by Sakalli (2017) for the Adriatic Sea.

The values of *H(t)* at 2100 for the two extremes in ΔT for the Adriatic Sea (3.25 and 3.50 °C) are 469.62 mm and 505.75 mm, respectively.

The values obtained with the Rahmstorf (2007) method for “semi-empirical” scenario, have been then averaged **across each ZONE**. The results are shown in the following table.

ZONE	SL at 2100 (mm + in respect to 2015)
ZONE 1	487,19

ZONE	SL at 2100 (mm + in respect to 2015)
ZONE 2	500,57
ZONE 3	469,62
ZONE 4	498,88
ZONE 5	489,98

3.3 Sea level scenarios

The most reliable scenario is the “model-based” scenario, presented in Annex 1. The expected sea level variation at 2100 ranges between 72 and 80 cm above the 2015 heigh. This result is of comparable magnitude of that obtained with the “semi-empirical” scenario, which ranges between 47 and 50 cm.

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ANNEXES

Annex 1: Model based sea-level scenario

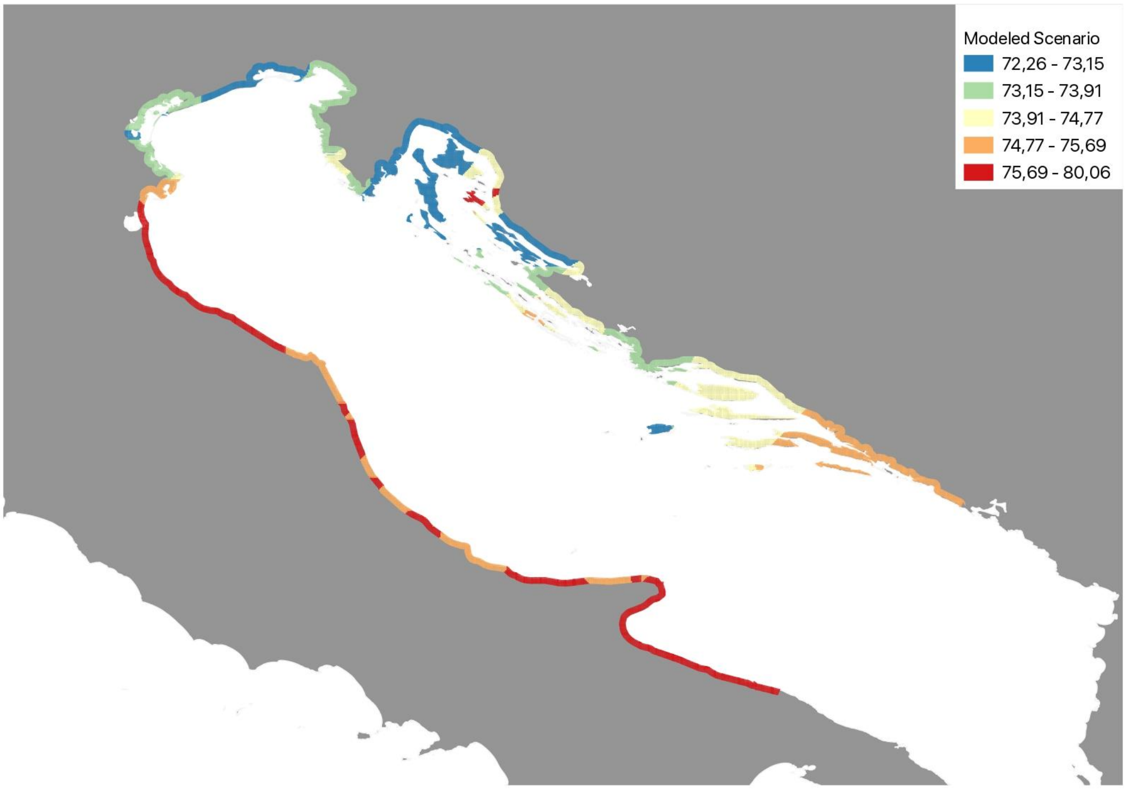

Figure 1: Mean dynamic topography (MDT) as modeled by Rio et al. (2014). The grid at the oasis of MDT has been used to rescale the output form geo dynamic and steric models.

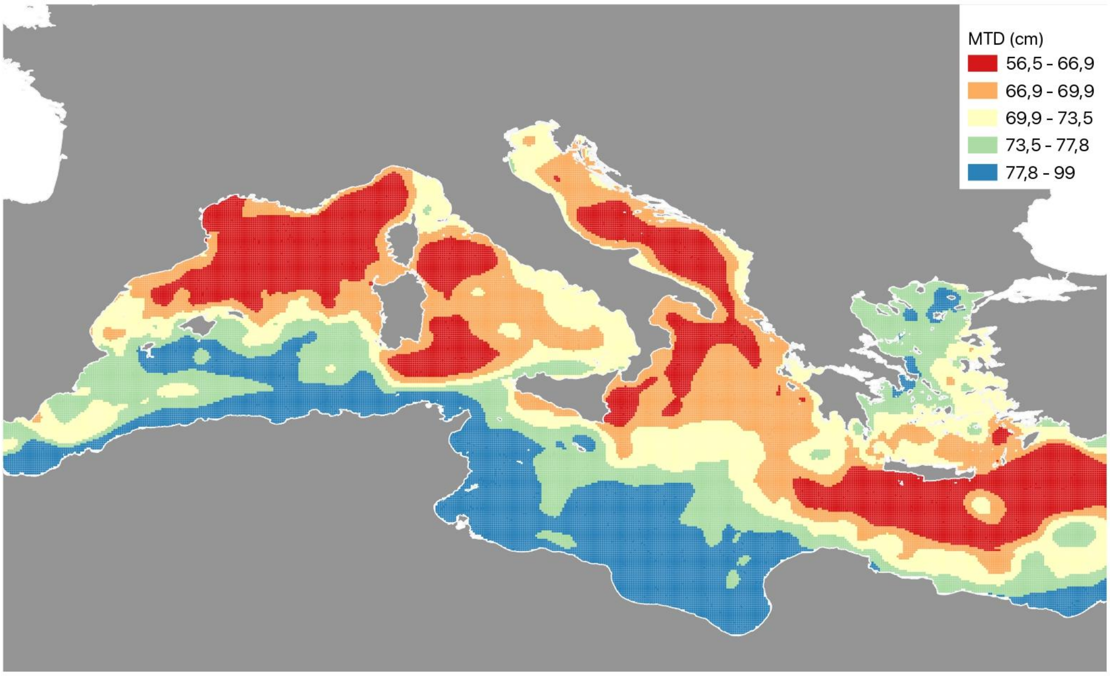

Figure 2: Distribution of tide gauges in Adriatic Sea (numbers represent the PSMSL code) and identification of the 5 zones for the analysis of tide gauges' data

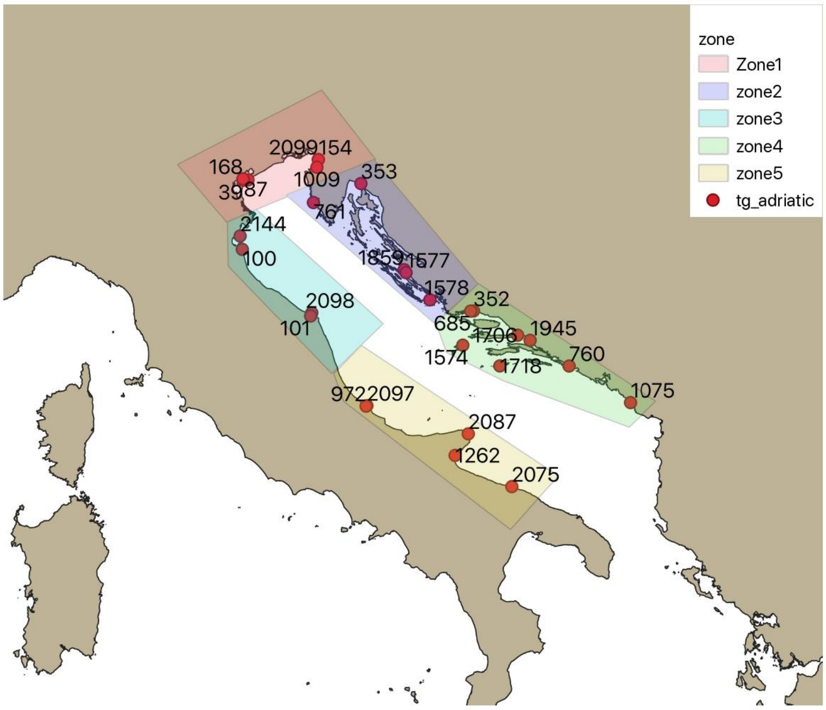

Figure 3: GIA-induced sea level change at 2100 in respect to 2015, modeled using ICE-6G (Peltier et al. 2013) with the code SELEN (Spada and Melini, 2019)

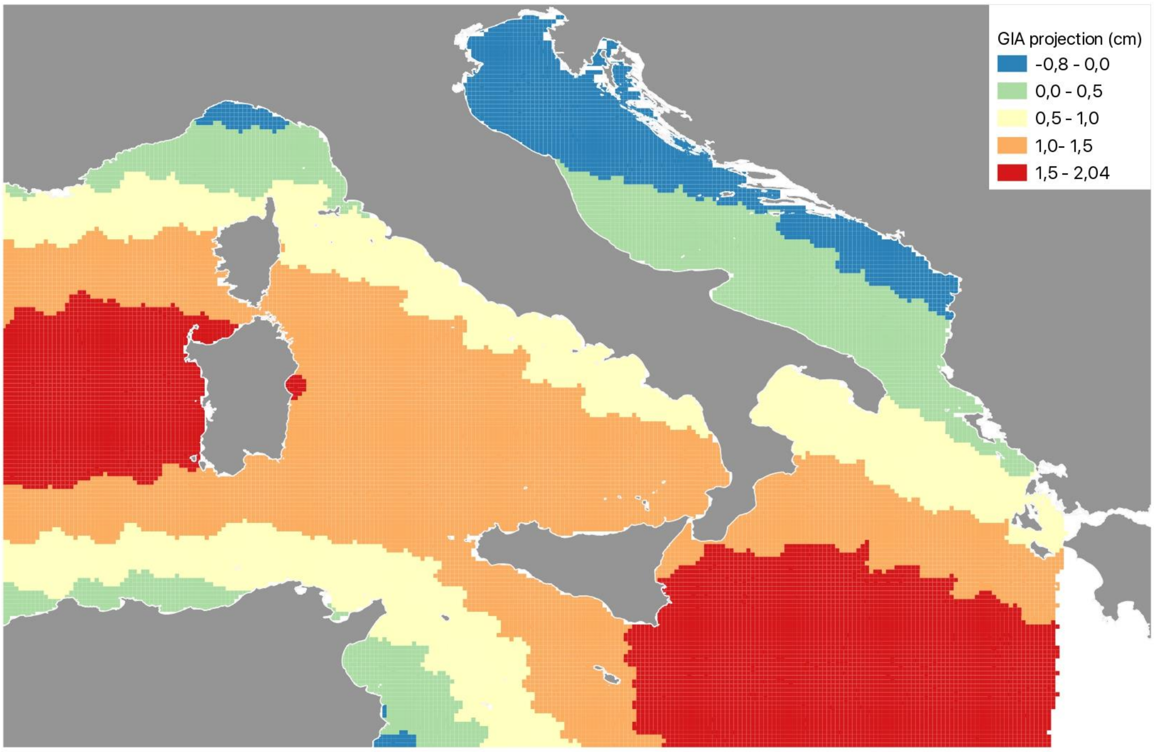

Figure 4: Sea level height at 2100 above 2015 (in cm) due to current ice melting (mass contribution), modelled according the "high end" scenario in Spada et al. (2013)

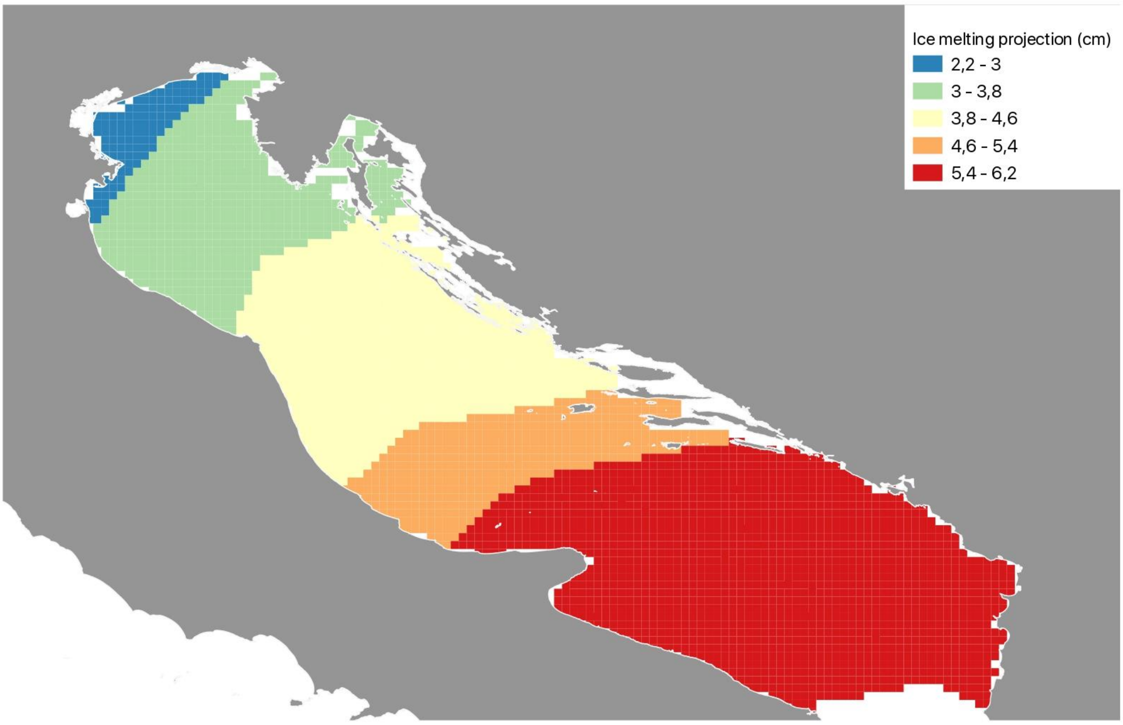

Figure 5: Trend of steric sea level in Mediterranean Sea according to Euro-CORDEX run - MOHC-HadGEM2-ES*-SMHI-rcp85 (M.V. Struglia, ENEA, personal communication, 2019)

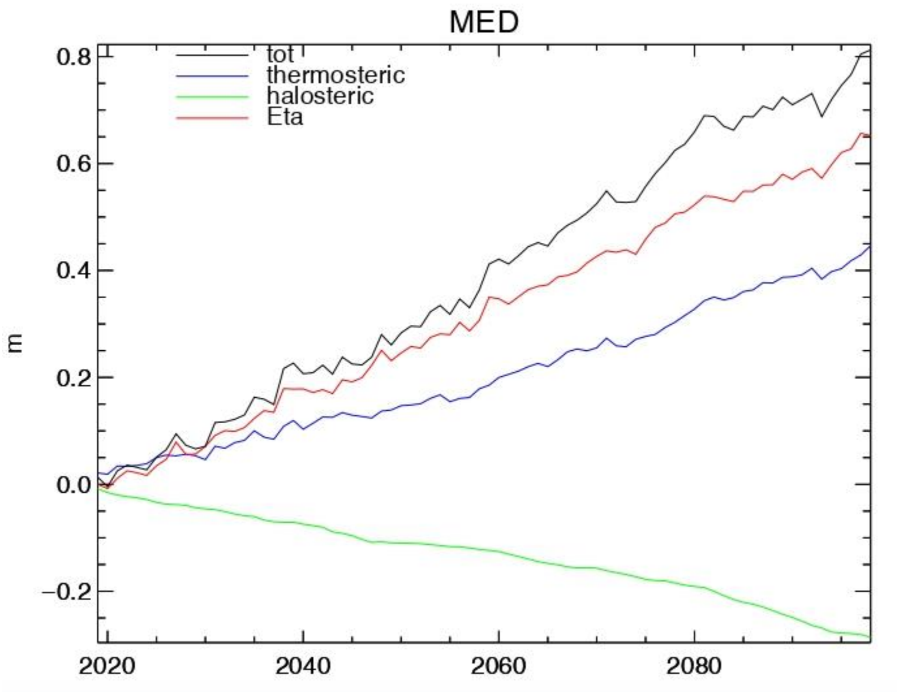

Figure 6: Stacked curves