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A GIS-based investigation of different Sea Level Rise (SLR) Scenarios in Messinia (SW Greece)

Abstract

This research work focuses on the investigation of different Sea Level Rise (SLR) scenarios, linked to Climate Change, for the terminal years of 2050 and 2100. The study area concerns the regional unit of Messinia in Southwestern Greece and especially three tourist spots; the beach of Navarino Dunes, the Voidokoilia beach and the coastal zone of Kalamata. SLR estimations are based on the up-to-dated scenarios of Bonaduce et al. (2016), E.E.A. (2017) and IPCC (2013a), as well as, on an additional scenario, developed in the context of the present study, which takes into consideration the regional change between two historic coastlines (1945, 2009), as they are depicted in the corresponding orthophotomaps provided by the National Cadastre and Mapping Agency. The aforementioned scenarios were developed and analyzed in a GIS environment. Based on the comparison of the results, it was found that the differences in SLR trends of the examined scenarios lead to variant inundation areas both for 2050 and 2100. It should be mentioned that the spatial resolution of the digital elevation model and the morphology of the beach (i.e., the slope at the shoreline) play important role in the entire procedure.

Keywords: GIS, sea level rise, climate change, Messinia, coastal vulnerability

Introduction

Climate change and sea lever rise (SLR) are two strongly connected issues, as they both affect the human activities and the natural ecosystems. On a global scale, the 20^{th} century SLR was approximately 0.18 m, (i.e., a mean rate of 1.8 mm y^{-1}). Particularly, the rate of the Global Mean Sea Level (GMSL) rise was 2 mm y^{-1} during the period between 1971 and 2010 and 3.2 mm y^{-1} during the years 1993 - 2010 (IPCC, 2013b). Among the future predictions, recent global forecasts show that by the year 2100 the lower rise of the GMSL will be between 0.17 and 0.28 m, while the higher rise will be between 0.28 and 1.31 m (IPCC, 2013b; Kopp et al., 2016; Mengel et al., 2016). The estimations for the Mediterranean Sea differ from the global average and, even the rate is lower, the sea level rising trend is existent. The estimations for the previous century show that the mean sea level (MSL) in the Mediterranean has been increased by 0.12 - 0.15 m with a rate of 1.2 - 1.5 mm y^{-1} (Marcos and Tsimplis 2008). The estimations for the last 20 - 25 years vary significantly, with an indicative rate of 1.9 ± 0.4 mm y^{-1} (Calafat and Jordà 2011), 2.44 ± 0.5 mm y^{-1} (Bonaduce et al. 2016) and 2.8 ± 0.5 mm y^{-1} (Tsimplis et al. 2013).

Regarding Greece, sea level variations are not homogenous for the entire coastline, considering the complexity of the territory and the combination of climatic, geodynamic and geomorphologic processes that take place. More specifically, the study area, which is the Region of Messinia (southwestern Greece), shows a spatial diversity both in the historic SLR and in the future estimations for SLR. This phenomenon is linked to the geodynamic regime of the Eastern Mediterranean and to the distance from the Atlantic Ocean (Papanikolaou et al. 2011).This distinction is obvious when comparing the Eastern and Western parts of the Mediterranean Sea, with the first generally characterizing by smaller SLR; about 17% in present and future process (e.g., Akylas et al. 2005; Woodworth and Player, 2003). It is estimated that, by the year 2050, SLR for the Western and Eastern part of the Mediterranean Sea will be about 0.6 m and 0.5 m, correspondingly.

Relevant research for the historic SLR in the Messinian Region shows a rise of 5.7 ± 1 mm y^{-1} (Flemming and Woodworth, 1988) for the period 1969 - 1983 and of 4.7 mm y^{-1} (Akylas et al., 2005; Woodworth and Player, 2003), when considering a longer period (1973 – 2000). Particularly for the period 1985 - 2005, other findings estimate a higher rate of SLR, which is about 7.3 mm y^{-1} (Akylas et al. 2005; Woodworth and Player, 2003). However, the findings of Marcos and Tsimplis (2008) propose a trend of 0.6 ± 1.0 mm y^{-1}. This estimation is based on the correlation of the nearest tide gauge station (named 'Kalamai') with the station 'Antalya', from which the trends are determined. Bonaduce et al. (2016) analyzed satellite measurements for Messinian gulf and determined a SLR rate of 2.21 ± 0.08 mm y^{-1}, while, their results from sea level measuring stations showed a rate of 3.77 ± 0.1 mm y^{-1}. Finally, the European Environmental Agency (E.E.A., 2017) estimated a SLR for the Messinian region of 3 - 4 mm y^{-1} (reference period: 1992 -2014). E.E.A. (2017) also provides estimations for the sea level in the last 20 years of 21st century (a rise up to 0.4 m). The aforementioned estimations for the study area are summarized in Table 1.

In the context of this research work, three vulnerable coastal areas are investigated for the influence of different SLR scenarios, as they are characterized by different geomorphological attributes. The three areas belong to the Region of Messinia, which is located at the Southwestern part of Peloponnesus (Fig. 1). The first area is the «Navarino Dunes» beach at the Western Messinia and its total area that analyzed is 133 m^2. Among the human activities, the main is the tourism during summer months and a number of luxurious hotels and apartments. The second area is the beach of Voidokilia, which is located Southern the previous one, it is near the Divarion lagoon and its total area is 21 m^2. This is popular as a tourist attraction due to its strange shape with extended sandy dunes that gives it the title of the most beautiful beach of Messinia. It is also included in the Natura 2000 network, the largest network of protected areas in the world. The third area is the beach of Kalamata, which is located in the southeastern of the city (total area: 69 m^2). This area hosts a lot of accommodation facilities and a high number of tourists. Its current good condition and natural beauty gives an aesthetic advantage in the city of Kalamata.

Table 1. Historic SLR estimations for Messinia (SW Greece)

Reference Period	SLR	Reference(s)
1969 - 1983	+ 5.70 ± 1 mm y^{-1}	Flemming and Woodworth 1988
1973 - 2000	+ 4.70 mm y^{-1}	Akylas et al. 2005; Woodworth and Player 2003
1985 - 2000	+ 7.30 mm y^{-1}	Akylas et al. 2005; Woodworth and Player 2003
1985–2001	+ 0.60 ± 1.0 mm y^{-1}	Marcos and Tsimplis (2008)
1993 - 2012	+ 3.77 ± 0.1 mm y^{-1}	Bonaduce et al. 2016 *(tide gauge records)*
1993 - 2012	+ 2.21 ± 0.08 mm y^{-1}	Bonaduce et al. 2016 *(satellite altimetry measurements)*
1992 - 2014	+ 3.50 ± 0.5 mm y^{-1}	E.E.A. 2017

Figure 1. Study areas

The analysis is concentrated in the implementation of different SLR scenarios for 2050 and 2100, based on the SLR estimations of Bonaduce et al. (2016), E.E.A. (2017) and IPCC (2013a). An additional scenario, developed in the context of the present study, which takes into consideration the regional change between two historic coastlines of 1945 and 2009, which are provided by the National Cadastre and Mapping Agency orthophotomaps (Fig.2). The aforementioned scenarios were developed and analyzed in a GIS environment. McLeod (2010) describes the different models that are capable for SLR applications (i.e., inundation models, SLAMM, BTELSS, SimCLIM, etc). Among them, the inundation models that are based on geographical/geospatial informations are selected for the current application due to their simplicity and their ability to reach a result with only requiring a small number of geographical data. The disadvantage of this method should be noted, as it cannot take into consideration complicated natural processes (i.e., coastal ecosystems, etc.). Findings are compared and discussed, while estimations using different SLR scenarios vary significantly. Furthermore, factors such as the spatial resolution of the digital elevation model (DEM) and the morphology of the beach (i.e., the slope at the shoreline) play an important role in the entire procedure, and regarding this, an indicative analysis for Kalamata beach is presented.

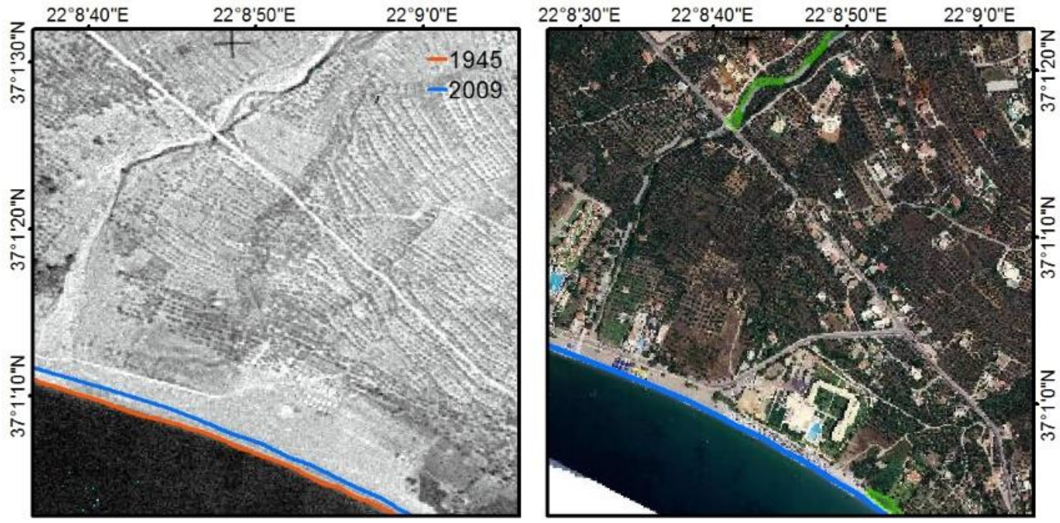


Figure 2. The National Cadastre and Mapping Agency orthophotomaps for 1945 (left) and 2009 (right) and the historic coastline of 1945 and 2009

Examined SLR Scenarios

A GIS-based inundation model implementation requires a short number of data, with the most important among them the digital elevation model (DEM) of the study area. The higher the resolution of the DEM is, the more accurate estimations are provided. The entire procedure is done with the aid of the Map Algebra Tool from the ArcToolbox Spatial Analyst (ESRI, 2014). Different SLR scenarios were investigated, based on the relevant literature and they are summarized in Table 2. As the available scenarios are refered to wider areas, the SLR information is not distributed and, in the context of this study, the relevant SLR rates were assumed as same for the three cases. The only scenario that attaches different values per study area, is the referred to as Digitized Scenarion (hereinafter 'Dig.Scen.'), which is an additional scenario that is based on the observed different between two historic coastlines; this from 1945 and this from 2009. These coastlines were created in a GIS environment with the aid of two aerial orthophotomaps provided by the National Cadastre and Mapping Agency (Fig.2). According to this analysis, it was found that the mean rate of sea level change during the period 1945 - 2009 for the three study areas is positive, however, it differs significantly from region to region with an upward trend directed from the Western to Eastern. Indicatively, the mean SLR rate is (i) 4.5 mm $y^{-1}$for the beach of Navarino, (ii) 6.9 mm y^{-1} for Voidokilia Beach and (iii) 8.6 mm y^{-1} for the beach of

Kalamata. These rates were assumed to be stable in the future and the corresponding aggregated SLR, as implemented, are summarized in Table 2.

Table 2. SLR scenarios investigated for the years 2050 and 2100

#	Source	Character	SLR by 2050 (m):	SLR by 2100 (m):
1	Bonaduce et al. (2016)	Lower	0.087	0.194
2	E.E.A. (2017)	Lower	0.123	0.273
3	Bonaduce et al. (2016)	Higher	0.159	0.352
4	E.E.A. (2017)	Higher	0.164	0.364
5	RCP8.5 (IPCC, 2013a)	Lower	0.190	0.530
6	RCP8.5 (IPCC, 2013a)	Mean	0.250	0.740
7	RCP8.5 (IPCC, 2013a)	Higher	0.320	0.980

Apart from the different SLR scenarios impact, another issue that investigated was the influence of the spatial resolution of the DEM in the results. The implementation was conducted for a DEM of 5 x 5 m and of 1 x 1 m spatial resolution. The 'Dig.Scen.' (Tab. 3) requires the information of the slope along the shore, in order to transform the horizontal displacement into vertical (i.e., SLR). This fact adds a second assumption in the entire procedure. Finally, in order to quantify the impact on the results, findings that correspond to different slopes (i.e., 1°- 3°) are compared.

Table 3. 'Dig.Scen.' for the three study areas

#	Study area	SLR by 2050 (m):	SLR by 2100 (m):
1	Beach of Navarino Dunes	0.184	0.408
2	Beach of Voidokilia	0.282	0.626
3	Beach of Kalamata	0.351	0.778

Results and Discussion

The eight SLR scenarios (Tables 2 and 3) for Messinian region correspond to different rates of SLR, a factor that generally results in different impact for coastal areas. The analysis show that about the half of the scenarios meet the general trend that the 'Dig.Scen.' provides. Nevertheless, the SLR scenario of Bonaduce et al. (2016) appears to be the most optimistic among them. The higher scenario of RCP8.5 (IPCC, 2013a) is the one that leads to the highest impact, with an exception of the Kalamata beach, where the 'Dig.Scen.' is the worst concerning the beach area reduction. More specifically, the beach of «Navarino Dunes» is the area with the lowest percent of area reduction but with the highest in absolute sizes, as the other two areas have smaller size. One of the most likely scenarios compared to the 'Dig.Scen.' for this area is based on this of E.E.A. (2017), i.e., a total SLR of 0.123 m for 2050 and 0.273 m for 2100 (Fig.3a). The beach of Voidokilia is a small closed bay (Fig. 3b), but both the scenarios of Table 2 and the 'Dig.Scen.' (Tab.3) showed significant losses. The rate that results from the displacement of the historic coastlines is closer to the RCP8.5 Mean Scenario (IPCC, 2013a). An effect behind the rise of the sea level on the beach of Voidokilia is the loss of its soil after a limit of rise at the level of the Divarion lagoon located behind Voidokilia. The height of this boundary between the sea and the lagoon is about 0.5 m. As a result, the system is in balance and any SLR may create ecological problems such as loss of nesting sites for migratory birds and conversion to swamp. The system is particularly complex and the estimations need further analysis. The Beach of Kalamata, which is an open and straight bay exposed to waves, shows the largest beach loss compared to the other two cases (Tab. 4). Furthermore, for this area, the 'Dig.Scen.' (Fig. 3c) led to the highest SLR rate.

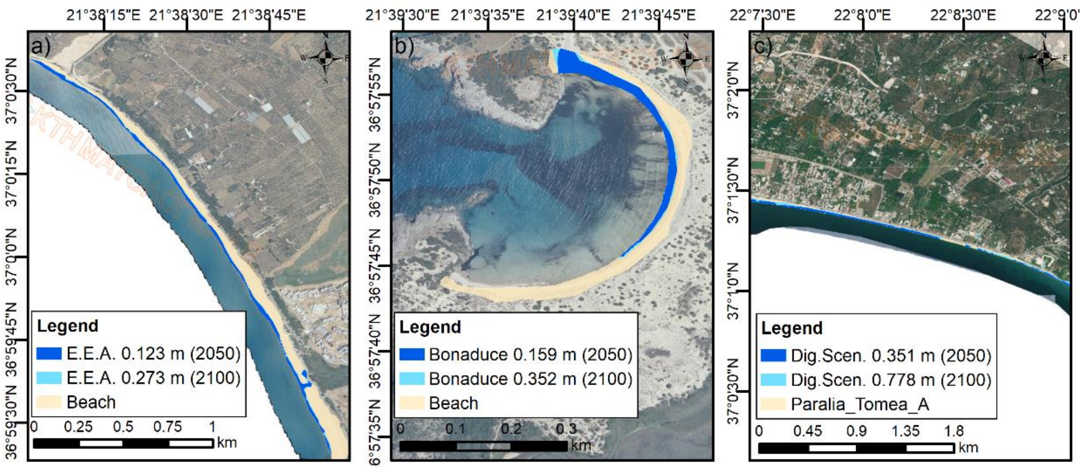


Figure 3. Indicative results for the three study areas and for different SLR scenarios (blue and light blue for 2050 and 2100, correspondingly)

Table 4. Percentage of beach area reduction (%) with respect to the current extend of the Navarino, Voidokilia and Kalamata beach according to the eight scenarios

#	SLR scenario by 2050 (m)	Navarino		Voidokilia		Kalamata	
		2050	**2100**	**2050**	**2100**	**2050**	**2100**
1	Bonaduce et al. (2016) - Lower	19.7	22.8	27.1	28.5	30.2	32.5
2	E.E.A. (2017) - Lower	20.8	25.2	27.9	29.5	31.4	37.6
3	Bonaduce et al. (2016) - Higher	21.8	27.1	28.2	30.5	32.0	41.8
4	E.E.A. (2017) - Higher	21.9	27.6	28.3	30.6	32.2	42.2
5	RCP8.5-I.P.C.C. (2013a) - Lower	22.6	28.6	28.5	32.2	32.6	54.3
6	RCP8.5-I.P.C.C. (2013a) - Mean	22.7	32.6	29.3	33.4	36.3	68.0
7	RCP8.5-I.P.C.C. (2013a) - Higher	24.4	38.3	29.8	35.0	39.9	70.4
8	Dig.Scen.	26.4	44.2	30.2	39.4	41.6	87.4

The investigation of SLR scenarios for the study areas using DEMs of different spatial resolution led to generally lower values in the percentage of beach area reduction. However, there is no systematic difference among the results. As expected, the influence of the shore slope, as a reference for the 'Dig.Scen.' implementation, is obvious. In Figure 4, where a part of the Kalamata beach is presented, one can observe the different estimations by comparing different spatial resolutions (1m, 5m) and shore slopes (1°, 3°).

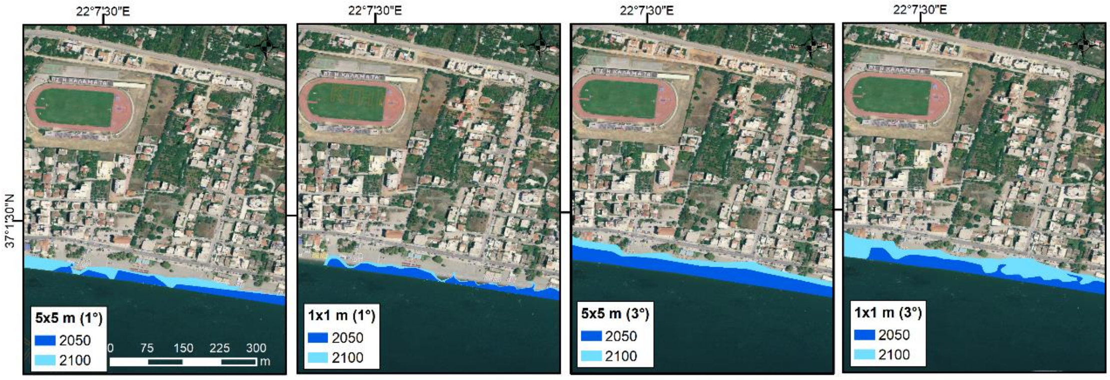
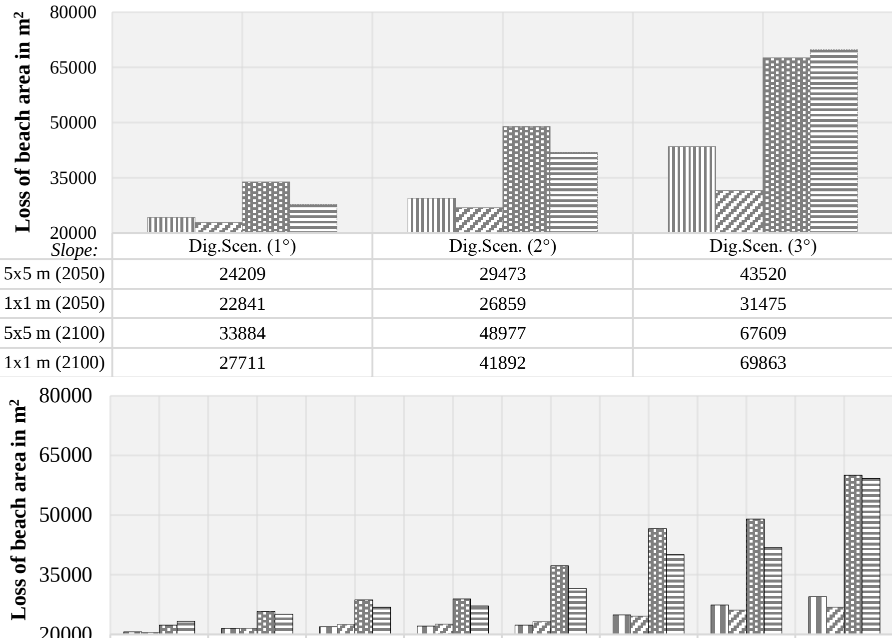


Figure 4. 'Dig.Scen' results the beach of Kalamata using different DEM and slope

This comparison is also illustrated in Figure 5, which includes the entire results for all the scenarios that have been analyzed for the beach of Kalamata.



Slope:	Dig.Scen. (1°)	Dig.Scen. (2°)	Dig.Scen. (3°)
DEM 5x5 m (2050)	24209	29473	43520
DEM 1x1 m (2050)	22841	26859	31475
DEM 5x5 m (2100)	33884	48977	67609
DEM 1x1 m (2100)	27711	41892	69863

Scenarios:	Bonaduce (2016) - Lower	E.E.A. (2017) - Lower	Bonaduce (2016) - Higher	E.E.A. (2017) - Higher	RCP8.5 - I.P.C.C. (2013a) - Lower	RCP8.5 - I.P.C.C. (2013a) - Mean	Dig.Scen. (2°)	RCP8.5 - I.P.C.C. (2013a) - Higher
DEM 5x5 m (2050)	20700	21546	21971	22073	22351	24882	27399	29473
DEM 1x1 m (2050)	20502	21584	22481	22586	23197	24571	26149	26859
DEM 5x5 m (2100)	22325	25807	28678	28960	37283	46636	48977	59970
DEM 1x1 m (2100)	23302	25117	26886	27156	31606	40072	41892	59187

Figure 5. Comparison between DEM of different spatial resolution using (a) different mean shore slopes for the Dig.Scen., (b) for the eight SLR scenarios

Conclusions

In this research, different scenarios of sea lever rise were implemented for three vulnerable coastal areas in Messinia. The main findings are summarized as follows:

- Messinian coastal areas appear an existent risk regarding SLR. The mean trend resulted from the comparison between the two historic coastlines of the region show that there is a systematic, increasing trend from the Western to the Eastern parts of the region.
- Generally, Kalamata appears to be the most vulnerable area among the examined but scenarios differ greatly among the case studies. According to the scenarios that have been analyzed, it was found that the loss of beach surface is extensive in this beach (about 48% of the current beach up to 2100). Voidokilia and Navarino Dunes beaches follow with 31% and 27% loss by 2100, correspondingly.
- Concerning the specific results of the analysis, an issue that affects the estimations is the cell size of the DEM, with generally lower losses when using the higher spatial resolution. The comparison of various SLR scenarios from the global literature with the 'Dig.Scen.' scenario, which has been created in the framework of this study and that takes into consideration the historic evolution of this coastal areas, is particularly important. It is illustrated that no general rate is observed and that each region appears rates close to different scenarios.

References

Akylas E., Lykoudis S. & Lalas D. (2005), Climatic change over Greece: Observations analysis: trends of the past 100 years, Athens, National Observatory of Athens, (Report In Greek).

Bonaduce, A., Pinardi, N., Oddo, P., Spada, G., & Larnicol, G. (2016). Sea-level variability in the Mediterranean Sea from altimetry and tide gauges. *Climate Dynamics*, *47*(9-10), 2851-2866.

Calafat, F. M., & Jordà, G. (2011). A Mediterranean sea level reconstruction (1950–2008) with error budget estimates. *Global and planetary change*, *79*(1-2), 118-133.

Environmental Systems Research Institute (ESRI), (2014). ArcGIS for Desktop v. 10.2.

E.E.A., European Environmental Agency (2017, May 03). Global and European sea level. Retrieved from https://www.eea.europa.eu/data-and-maps/indicators/sea-level-rise-4/assessment-2.

Flemming, N. C., & Woodworth, P. L. (1988). Monthly mean sea levels in Greece during 1969–1983 compared to relative vertical land movements measured over different timescales. *Tectonophysics*, *148*(1-2), 59-72.

IPCC, (2013a). Annex II: Climate System Scenario Tables [Prather, M., G. Flato, P. Friedlingstein, C. Jones, J.-F. Lamarque, H. Liao and P. Rasch (eds.)]. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

IPCC, (2013b). Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kopp, R. E., Kemp, A. C., Bittermann, K., Horton, B. P., Donnelly, J. P., Gehrels, W. R., ... & Rahmstorf, S. (2016). Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences*, *113*(11), E1434-E1441.

Marcos, M., & Tsimplis, M. N. (2008). Coastal sea level trends in Southern Europe. *Geophysical Journal International*, *175*(1), 70-82.

Mcleod, E., Poulter, B., Hinkel, J., Reyes, E., & Salm, R. (2010). Sea-level rise impact models and environmental conservation: A review of models and their applications. *Ocean & Coastal Management*, *53*(9), 507-517.

Mengel, M., Levermann, A., Frieler, K., Robinson, A., Marzeion, B., & Winkelmann, R. (2016). Future sea level rise constrained by observations and long-term commitment. *Proceedings of the National Academy of Sciences*, *113*(10), 2597-2602.

Papanikolaou M., Papanikolaou D. & Vassilakis E. (2011). Climate Change Impacts Study Committee: Sea level changes and coastal impacts, Athens: Bank of Greece, (Report In Greek).

Tsimplis, M. N., Calafat, F. M., Marcos, M., Jordà, G., Gomis, D., Fenoglio-Marc, L., ... & Chambers, D. P. (2013). The effect of the NAO on sea level and on mass changes in the Mediterranean Sea. *Journal of Geophysical Research: Oceans*, *118*(2), 944-952.

Woodworth, P. L., & Player, R. (2003). The permanent service for mean sea level: an update to the 21stCentury. *Journal of Coastal Research*, 287-295.