COASTAL HAZARDS UNDER CLIMATE VARIABILITY AND CHANGE THE CASE OF SANTORINI AND CRETE (AEGEAN SEA)

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Abstract

The objective of the present contribution is to examine some of the potential hazards and threats for the coastal zone, induced by Climate Variability and Change (CV&C), using as case studies two Greek islands: Santorini and Crete. Beach retreat/inundation due to mean and Extreme Sea Level (ESL) rise was assessed using cross-shore morphodynamic model ensembles. The results were used in conjunction with information (geo-spatial and human development features) from readily available satellite imagery to assess the impacts on the beach carrying capacity and the backshore assets/infrastructure. Potential impacts on critical transport infrastructure (e.g. airports, seaports) under ESL and heat waves were also discussed. By 2100 under a moderate emission scenario (RCP4.5) it is projected that up to 23% of Santorini beaches and 53% of Cretan beaches will be completely eroded under relative sea level rise (RSLR); the 100-year ESL event may overwhelm up to 93% of Santorini and 94% of Cretan beaches, causing damages to the backshore infrastructure/assets. The results show that both ESL_{100} and heat waves at the locations of 6 seaports and 3 airports in Crete will increase significantly in both magnitude and frequency, raising the potential for flooding, operational disruptions and possibly damages to the infrastructures.

Keywords: Beach erosion, Morphodynamic models, Extreme sea levels, Heat waves.

1. Introduction

Coastal areas, by their exposure to many hazards, such as rising mean sea levels, storm surges and waves, increasing temperatures, cyclones etc, are threatened by increasing land loss and flooding that can severely impact their ever-increasing populations, infrastructure, assets and economy. In Greece, coastal areas also form the pillar of tourism, a vital sector for the Greek economy. Tourism is increasingly associated with beach recreational activities according to the 'Sun-Sea-Sand-3S' model (Philips & Jones, 2006), at the same time beach erosion, which is projected to greatly increase under Climate Variability and Change (CV&C), poses a significant threat especially to island beaches; as they have limited dimensions and sediment supply (Monioudi *et al.*, 2017). Beaches are not only significant habitats in their own right, but they also provide protection from marine flooding to the coastal assets, infrastructure and activities they front. CV&C also poses significant challenges for the critical infrastructure located at the coastal front, such as airports and seaports, involving impacts from both flooding under extreme events and operational disruptions from e.g. the increasing magnitude and frequency of extreme heat waves. The objective of the present contribution is to examine some of the potential hazards and threats, induced by CV&C, for the island coastal zone, using as case studies two Greek islands: Crete and Santorini.

2. Material and Methods

2.1 Beach retreat/inundation projections

The geo-spatial characteristics (i.e. max. width, area, sediment type) and human development features (i.e., the density of backshore assets) of all the beaches of Santorini (30 were identified) and Crete

(828) were recorded on the basis of the images and other related optical information available in the Google Earth Pro application. The 'dry' (subaerial) parts of these beaches were digitized as polygons bounded on their landward side by either natural boundaries (vegetated dunes and/or cliffs) or permanent artificial structures (e.g. seawalls, roads, and buildings) and on their seaward side by the shoreline. Constraints in the approach can stem from the accuracy/resolution of the (not properly georectified) images and the varying hydrodynamic conditions during the image collection that can affect shoreline delimitation. These may introduce uncertainties which, however, cannot be avoided in regional studies.

Beach retreats under CV&C were projected using 1-D (cross-shore) morphodynamic model ensembles, following the methodology described in Monioudi *et al.* (2017). Specifically, beach retreat/inundation was assessed with regard to; (a) long-term relative sea level rise (RSLR) and (b) 1-100 year Extreme Sea Level (ESL, i.e. storm-induced water levels superimposed on RSLR and high tide), projected for the year 2100 under the IPCC RCP4.5 scenario. Projections of the RSLR, tide and ESL_{100} along the coasts of Santorini and Crete were abstracted from the JRC (Joint Research Centre) database (Vousdoukas *et al.*, 2017). Given the large scale of the application (Island scale), the input data of the models could not be based on in situ measurements. Therefore, the models were set up using a plausible range of environmental conditions (i.e. combinations of different beach slopes, wave conditions and sediment size) and they produced a range of beach erosion projections. The lowest and highest projections were compared with the recorded beach maximum width (BMW) to assess the impacts on the 'dry' beach width (and consequently the beach carrying capacity) under RSLR and the impacts on the backshore assets under ESL. It is noteworthy that the use of the reduction in BMW as the erosional impact indicator may result in conservative estimations.

2.2 Impacts on critical transport infrastructure

Transport infrastructure and related operations that are situated at the coast are likely to be seriously affected by the impacts of CV&C. Coastal flooding may inundate low-lying coastal airports/seaports, whereas higher mean temperatures and more frequent heat waves can affect runways (heat buckling) and aircraft lift, resulting in payload restrictions and disruptions. Also seaport/airport operations (and possibly, the infrastructure itself) could be seriously impacted due to increasing health and safety concerns and energy needs (and costs) for cooling (Monioudi *et al.*, 2018). Projections of heat wave changes in magnitude and frequency, under mean temperature increase scenarios of 1.5, 2 and 3 ^{o}C above the pre-industrial times (Special Warming Level – SWL), were abstracted from Dosio *et al.* (2016).

3. Results

3.1 Beach Erosion and impacts in Santorini

For the year 2100 under RCP4.5, it appears that Santorini beaches would be seriously affected due to the projected sea level rise (0.53 m); beach retreat is estimated between 5.5 m and 16.5 m causing 73% and 23 % (high prediction) of the beaches to be reduced by up to 50% and 100 % of their current BMW (Fig. 1a,b, Table 1). Many of these beaches lack the accommodation space to retreat landwards and, thus, will suffer coastal squeeze without appropriate replenishment.

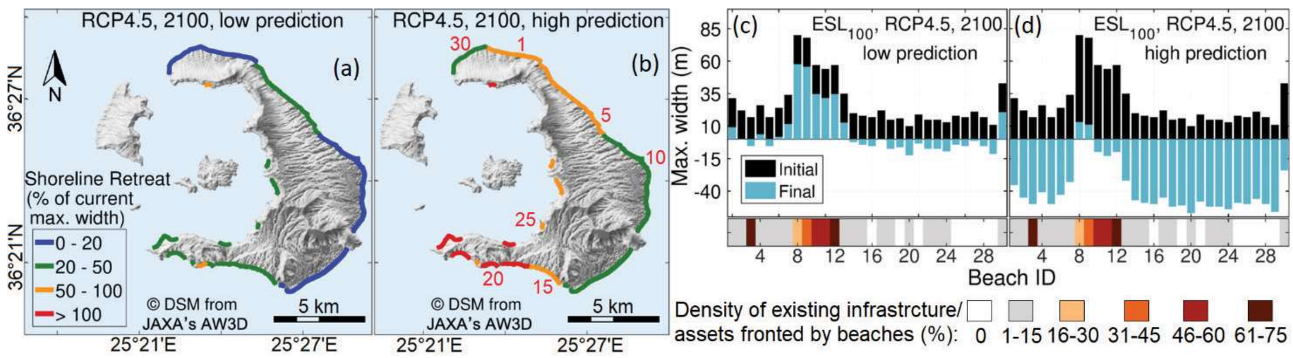

Fig. 1: The percentages of the current BMWs of the 30 Santorini beaches projected to be eroded under RSLR based on the (a) low and (b) high model projections. The current (initial) BMWs (black bars) are compared with those resulting from temporary inundation/retreat (blue bars) under ESL_{100} based on the (c) low and (d) high predictions and are shown together with the recorded density of the backshore assets (as a percentage of the beach length). The negative values indicate total beach inundation.

The 100-year ESL (ESL_{100}) in 2100 will result in storm beach inundation of up to about 22.3 and 66.9 m, under the RCP4.5 scenario based on the low and high model estimates respectively. The impacts could be devastating since 63 - 93% of all beaches will be completely (at least temporarily) inundated under the low and high projections, respectively. In terms of asset exposure, 50 - 91% of the beaches presently fronting assets are projected to be overwhelmed during the event (Fig. 1c, d, Table 1). These frontline backshore assets will sustain damages even in the case of a partial (or total) post-storm beach recovery as they are located within the beach erosion-recovery envelop.

Table 1. The low and high beach retreat/inundation estimates of Santorini beaches by the model ensembles. Percentages of the beaches that will be retreated/inundated more than 50% of their current BMW and more than their current BMW. Numbers (N) and percentages of beaches where backshore infrastructure and assets are projected to be impacted are also shown.

Sea Level Rise (m) under RCP4.5, 2100		Retreat (R)/ Inundation(I) (m)		R/I to 50 % of max. width (%) N	R/I to max. width (%) %	Beaches with assets affected	
RSLR	0.53	Low	5.5	7	0	0	0
		High	16.5	73	23	5	23
ESL_{100}	1.66	Low	22.3	83	63	11	50
		High	66.9	100	93	20	91

3.2 Beach Erosion and other coastal hazards in Crete

Under sea level rise of 0.55 m, projected for the year 2100 under RCP4.5, the model results show that the Cretan beaches would be seriously affected; beach retreat is estimated between 5.8 m and 19.6 m and 53 % of the beaches might see (high prediction) their BMW reduced by up to 100 % (Table 1). Similar to Santorini, many of these beaches will suffer coastal squeeze due to the absence of adequate inland accommodation space. Inundation due to the RCP4.5 ESL_{100} is predicted between 18 and 68.5 m and represents a catastrophic scenario, since 53-94% of all the Cretan beaches will be completely inundated causing damages to the backshore infrastructure/assets.

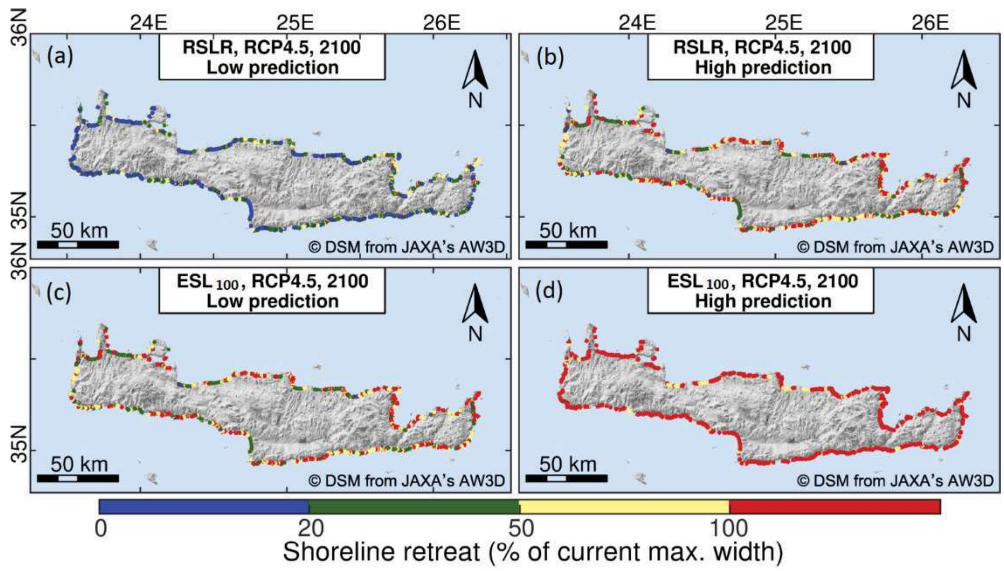

Fig. 2: The percentages of the current BMWs of the 828 Cretan beaches projected to be eroded under RSLR ((a) and (b)) and to be inundated under ESL_{100} ((c) and (d)) based on the low and high model estimates.

Regarding the flood hazard under extreme events, the results show that the baseline ESL_{100} (mean of the period 1980-2014) varies along the Cretan coastline, with the highest values found along the southern and eastern coast (up to 1.6 m above the mean sea level) (Fig. 3). By 2100, ESL_{100} at 6 seaports and 3 airports in Crete will increase on average by 45 cm under the RCP4.5 and medium ice melt scenario and by 93 cm under the high-end scenario (RCP8.5 and high ice- melt scenario) (Table 2). The assessment of future extreme heat waves for the same seaports/airports indicates that heat wave events will increase in both magnitude and frequency. Heat waves having the magnitude of the baseline 1 in a 100 years heat wave (the mean of the 1976-2005 period) are projected to occur on average every 12.8 years under SWL scenario of 1.5 °C (expected to be reached by the 2030s, see IPCC (2018)); every, 5.4 years under a SWL of 2 °C (expected by the 2050s), and every 1.4 years under a SWL of 3 °C (expected in the beginning of the next century) (Table 2). It is also projected that the 100-year heat wave will increase in magnitude on average by 2, 3 and 7 times respectively under the same scenarios.

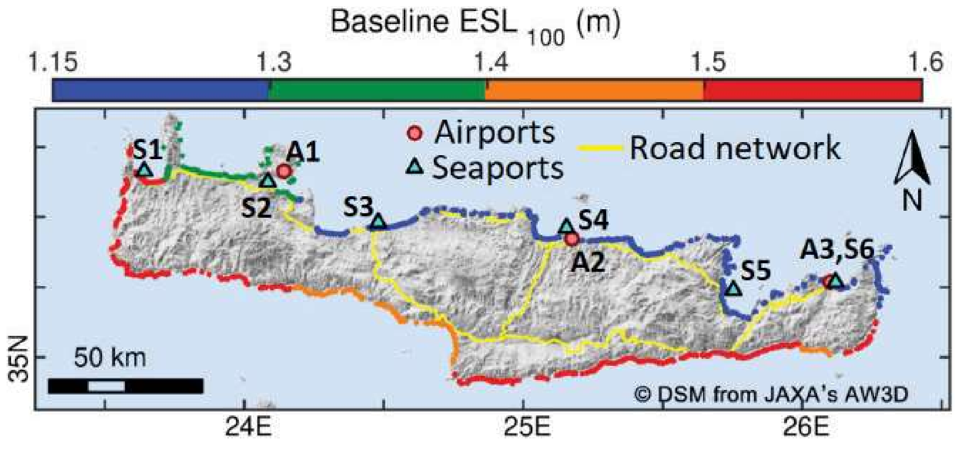

Fig. 3: Baseline ESL_{100} (mean of the period 1980-2014) along the coast of Crete. 6 seaports (S1: Kissamos, S2: Souda, S3: Rethymnon, S4: Heraklion, S5: Agios Nikolaos, S6: Sitia) and 3 airports (A1: Chania, A2: (current) Heraklion, A3: Lassithi).

Table 2. Future changes of ESL_{100} and 1-100 year Heat Wave at 6 seaports and 3 airports of Crete. Key: T_r = return period.

Seaports/ Airports ID	ESL_{100} increase (cm) for 2100		1-100 year Heat wave					
		Increase (times)			New T_r (years)			
	RCP4.5 med. ice	RCP8.5 high ice	1.5 °C	2°C	3°C	1.5 °C	2°C	3°C
S1	38	79	3	5	12	1	1	1
S2, A1	45	90	2	2	3	12	7	1
S3	46	92	2	3	8	4	1	1
S4, A2	49	102	1	2	2	36	15	3
S5, A3	46	99	2	2	3	19	8	1
S6	45	98	3	5	13	4	1	1

4. Conclusions

The results show that the coastal zone of Santorini and Crete faces significant threats from different hazards, which are projected to be exacerbated by CV&C. In the absence of adequate inland accommodation space for beaches to roll-over and/or effective coastal protection schemes, the RSLR will potentially have devastating effects on coastal natural and human systems. Tourism, for example, will be particularly affected by the projected large decreases in dry beach width, a critical control of the beach resilience and recreational use, and the long-term recreational value of the Santorini and Crete beaches and the value of associated assets may decrease considerably (e.g. Gopalakrishnan et al., 2011). Future extreme events will further exacerbate these impacts, with very severe flood damages and losses projected for the backshore infrastructure and assets, even if the fronting beaches would eventually recover. There will be also significant challenges for the critical infrastructure located at the coastal front, such as airports and seaports. The results show high and increasing potential impacts from climatic changes involving both flooding under extreme events and operational disruptions from the increasing magnitude and frequency of extreme heat waves.

5. Acknowledgements

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