Coastal hazard risk assessment for small islands: assessing the impact of climate change and disaster reduction measures on Ebeye (Marshall Islands)

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Abstract

Small island states around the world are among the areas most vulnerable to climate change and sea level rise. In this paper, we present results from an innovative methodology for a quantitative assessment of multiple hazards on coastal risks, driven by different hydro-meteorological events, and including the effects of climate change. Moreover, we take an additional step by including in the methodology the option to assess and compare the effectiveness of possible disaster risk reduction measures. The methodology is applied to a real case study at the island of Ebeye (the Republic of the Marshall Islands). An example is provided in which a rock revetment is implemented as a risk reduction measure for the island. Results show that yearly expected damages may increase, by the end of the century, by a factor of three to four, depending on the sea level rise scenario considered, while the number of yearly affected people may double. Putting a cap on the temperature increase (e.g. 1.5 vs. 2 °C) according to the Paris Agreement may reduce damages and number of affected people by about 20 and 15%, respectively. However, impacts for same warming levels can vary substantially among different emission scenarios. Disaster risk reduction measures can be useful for mitigating risks in current and future situations but should be incorporated within long-term adaptive planning for these islands.

Keywords Multi-hazard risk assessment · Numerical modelling · Climate change · Small islands · Disaster risk reduction measures · The Marshall Islands

Introduction

In most islands around the world, people, agriculture, infrastructure and recreational activities are concentrated in the coastal zones and are thus especially vulnerable to any change

in climate and rise in sea level. Two thirds of the countries with the highest disaster losses relative to gross domestic product (GDP) are small island states, with average annual losses between 1 and 9% of the GDP. These averages hide extremes, since a single disaster can sometime cripple an island's entire economy (GFDRR 2016).

Extensive literature is available on the quantification of individual coastal hazards and the consequent risks resulting from those hazards. For example, Vousdoukas et al. (2016a, b) and Muis et al. (2016) focused on the modelling of coastal risks resulting from storm surges at European and global scale, respectively. Hinkel et al. (2013) focused on a global assessment of land loss and coastal erosion due to sea level rise. On the other hand, the relevance for adopting a multi-hazard risk approach has been proposed and discussed for more than two decades by international organisation and in high-level policy documents (UNEP 1992; Dilley et al. 2005). Gallina et al. (2016) provided a complete review of multi-risk methodologies for natural hazards. As one of the main outcomes of their review, the authors pointed out how multi-risk approaches

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often do not consider the effects of climate change and mostly rely on the analysis of static vulnerability. However, in contrast to single-hazard analyses, the assessment of multiple hazards poses a number of additional challenges related to the interaction and combination between those hazards at different spatial and temporal scales (see for example, Kappes et al. 2012). For this reason, the impact of different combined hazards is often resolved by describing the hazards by empirical formulas (e.g. Hinkel and Klein 2009 and Hinkel et al. 2010). As part of the recent EU-funded RISC-KIT project, methodologies and applications have been proposed to carry out coastal risk assessments at different scales (e.g. Ferreira et al. 2017; Van Dongeren et al. 2017). These include the use of Bayesian Network analysis to describe the interaction of multiple hazards with the socio-economic system (Poelhekke et al. 2016; Plomaritis et al. 2017).

In the present paper, a quantitative methodology for coastal multi-hazard risk assessment, including the effects of climate change, is proposed and applied to a small island case study: the island of Ebeye (The Republic of the Marshall Islands). The methodology is based on results from process-based numerical modelling simulations, explicitly solving all major sources of offshore forcing affecting the island, including wind waves, swell waves, typhoons and tsunamis. In particular, the effects of short- and infragravity waves, generally omitted in those types of assessments but very relevant for coral reef environments (Gawehn et al. 2016), are explicitly taken into account by this approach. Effects on both flooding and coastal erosion are assessed. Finally, direct, indirect and intangible damages are estimated and translated to yearly monetary and social risks under different climate change scenarios. The methodology is then used to identify areas at higher risks and where disaster risk reduction (DRR) measures are required. Moreover, the same methodology is used as a basis to assess the effectiveness of possible interventions in reducing those risks, as well as the risks which may be associated to different global warming pathways.

Terminology

By definition, risk is described as a product of hazard, exposure and vulnerability (Kron 2005). While hazards are related to the physical aspect of risks, i.e. natural events with negative impacts, exposure and vulnerability encompass socio-economic characteristics (Vousdoukas et al. 2018). In particular, hazard is the probability and magnitude of an event with negative impacts (e.g. island flooding or erosion). Exposure refers to the assets present on the territory which may be impacted by the event. Vulnerability refers to the damage inflicted upon the exposed property, and it is often assessed using depth-damage curves (i.e. vulnerability curves).

Gallina et al. (2016) distinguished between multi-hazard risk assessments and multi-risk assessments. Multi-hazard risk

assessments provide an analysis of different hazards and aggregate them into a multi-hazard index (Forzieri et al. 2016), while multi-risk assessments comprise both multi-hazard and multi-vulnerability concepts, taking into account interactions between hazards and vulnerability. Our analysis will focus on setting up a multi-hazard risk assessment methodology. A further distinction relates to how multiple hazards are treated, either as independent variables, as done in this study, or considering their combined probability of occurrence (Poelhekke et al. 2016).

Different approaches exist for quantifying risks. In the present paper, monetary risks are quantified as damages in USD. Damages can be further distinguished in different categories (Lekuthai and Vongvisessomjai 2001; Messner and Meyer 2006; Kind 2014) as follows:

- Tangible damages: financial
- Direct damages: economic damages to human assets
- Indirect damages: disruption to economic activities
- Intangible damages: social and environmental (e.g. disruption of ecosystem services and loss of lives)

The damage calculations presented in the paper include an estimation of all three damage categories.

Study area

The Republic of the Marshall Islands (RMI) consists of an atoll archipelago located in the central Pacific Ocean, stretching approximately 1130 km north to south and 1300 km east to west (Fig. 1). The archipelago consists of 29 atolls and 5 reef platforms arranged in a double chain of islands named Ratik and Ralik (Owen et al. 2016). The atolls and reef platforms are host to approximately 1225 reef islands, which are characterised as low lying with a mean elevation of 2 m above mean sea level.

Ebeye is built on a small islet on the south eastern side of Kwajalein Atoll. The part above sea level stretches about 2 km from north to south, and it is approximately 250 m wide bordering a large lagoon to the west and the open ocean to the east. The lagoon is shallow with an average depth of approximately 40 m. On the eastern ocean side, the islet is fronted by a reef flat. This reef flat varies slightly in width between 100 and 130 m. From there on, the depth increases rapidly, reaching depths of ~6000 m just a few kilometres away from the coast. The islet is covered entirely with buildings and infrastructure and hence densely populated. The last available census from 2011 reported that 9614 people lived on the island, in an area of merely 0.36 km², i.e. 1 person per 30 m² (Economic Policy, Planning, and Statistics Office 2012). Based on personal communication with the local government, we have estimated that about 12,000 inhabitants

Fig. 1 Geographical location of The Marshall Islands (a, b) and the island of Ebeye (c)

currently live on the island. The island is connected, via a causeway in the north, to the island of Gugeegue.

The tidal range at Ebeye varies between 0.48 and 1.86 m, at neap and spring tide, respectively. The wind climate at Ebeye is characterised by trade winds blowing from the east, leading to wind-sea and swell waves from that direction. Typical monthly offshore wave heights range between 1.4 and 2.4 m, and wind speeds between 4 and 9 m/s (Giardino et al. 2017).

Pacific typhoons generally develop around the RMI and then move towards the northeast. For this reason, most of the typhoons hitting Ebeye are not yet fully developed. Following the Saffir-Simpson hurricane scale, out of the 162 events which passed the island between 1946 and 2013, 133 were tropical storms and depressions, 26 were characterised as Category 1, one as Category 2 and one as Category 3.

In the current situation, the island is nearly unprotected from extreme events, except for a rock revetment next to the causeway towards Gugeegue. Sediment characteristics around the islands are highly non-uniform and characterised by a non-erodible reef, a few short sandy stretches and mainly gravel and rocks with some rudimentary seawalls.

Material and methods

Data collection

In order to carry out the hazard and risk assessment, the following data types have been compiled: bathymetry, topography, wind, waves, water levels, typhoon tracks and intensity,

information on tsunamis from regional sources, climate change effects and exposure data.

Deep-water bathymetry data were derived by combining bathymetric data of the Republic of the Marshall Islands and Vicinity (Hein et al. 2007) and GEBCO 2008 global bathymetric data sets (resolution of $\approx 1 \text{ km} \times 1 \text{ km}$). Higher-resolution nearshore bathymetry data were collected with an echosounder, with a vertical resolution of 0.10 m, at a number of cross-shore transects over the reef flat and out to a depth of 80 m.

Detailed topographic data are essential to carry out coastal hazard and risk assessments on low-lying atoll islands. Unfortunately, no digital elevation data were available for the island from literature or other data sources. Therefore, high-resolution topographic data (maximum vertical resolution $\approx 10 \text{ cm}$) were collected with a GPS device (Trimble CenterPoint-RTX) at ≈ 1500 locations over the island and interpolated in order to create a digital elevation map of the entire island.

Tidal levels were derived based on the global TOPEX/Poseidon dataset (i.e. TPXO 8.0; Egbert and Erofeeva 2002) and were combined with information from the Kwajalein NOAA tidal gauge (station ID 1820000; lat. $8^\circ 43.9' \text{ N}$; lon. $167^\circ 44.2' \text{ E}$). A harmonic analysis was carried out on the measured water levels available every 6'. Residual water levels were derived as the difference between measured water levels at Kwajalein tidal gauge and predicted tidal water levels.

Offshore wave and wind conditions were extracted from the ERA-Interim (European ReAnalysis) global wave reanalysis (Dee et al., 2011). The data are six hourly, starting in 1979, and are available on a global grid with a resolution of $0.75^\circ \times 0.75^\circ$ ($\approx 80 \times 80 \text{ km}$). The dataset contains information on winds (wind speed and direction) and wave conditions (wave height, period and direction). ERA-Interim global wave data were validated using wave data information available at Majuro via the NOAA website (National Oceanic and Atmospheric Administration).

The effect of typhoons was analysed based on historical typhoon tracks derived from the IBTrACS (“International Best Track Archive for Climate Stewardship”) database. Typhoon events between 1979 and 2015 are listed in the database.

No tsunami events caused by local sources (i.e. landslides or nearby earthquakes) have been previously reported. Most of the recorded tsunami waves were driven by mega thrust earthquakes (e.g. 2011 Tohoku tsunami) and resulted in minor impact to the RMI (i.e. limited to no island flooding). For example, tsunami waves generated by the Tohoku event in 2011 were estimated at less than 1 m in the RMI and occurred at low tide therefore not causing remarkable damages (Hess et al. 2015).

Sea level rise (SLR) projections were available through the Australian Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organisation (CSIRO

2014). According to these projections, the mean sea level may increase 0.42 to 0.78 m by 2100, for the more conservative Representative Concentration Pathway (RCP) 2.6 scenario and the “business-as-usual” RCP 8.5 scenario, respectively. The intermediate RCP 4.5 and RCP 6.0 were also considered. Changes in wave conditions due to future climate change scenarios were derived from Hemer et al. (2013). According to these projections, an increase up to + 2% in wave height by the end of the century may be expected. No significant changes in wave direction are expected.

Since the scope of the present study is to assess impacts under specific warming levels (SWLs) compared to pre-industrial levels, projections of global temperature were used, available from CMIP5 GCMs (Coupled Model Intercomparison Project Phase 5, Global Climate Models) (Taylor et al. 2011). For each GCM, the initial time series were averaged to obtain annual mean series and were then bias-corrected according to the present day warming. Next, all model series were ensemble averaged to create time series of annual mean temperature spanning from 1970 to 2100 for all the studied RCPs. These were also used to estimate the years at which SWLs of 1.5, 2.0 and 2.5 °C are reached.

Exposure data (location, construction type and value in USD) were derived from PCRAFI 2015 (“Pacific Catastrophe Risk Assessment and Financing Initiative”).

Numerical models

Process-based numerical models were used to quantify and propagate the offshore forcing to nearshore and to compute the impacts over the island (Fig. 2).

The coupled hydrodynamics and waves Delft3D modelling system (Lesser et al. 2004) were used to compute wave conditions and storm surges resulting from wind wave events from the lagoon, as well as the generation and propagation of typhoons and tsunamis from the ocean. Wind waves from the lagoon, as well as due to typhoons, are not included in ERA-Interim due to the spatial resolution of this global dataset and therefore had to be simulated separately. Standard default parameters were used in the model.

Wind conditions from the ERA-Interim dataset were used to simulate wind-induced waves from the lagoon. A model covering the lagoon extent was built with a spatial resolution of 300 m.

The generation and propagation of typhoons were computed based on coupled Delft3D-FLOW and Delft3D-WAVE simulations. The model domain covered the area ranging between lon. 160 to 180° and Lat. -5 to -15° on a computational grid with a spatial resolution of 0.1° . Each individual typhoon track was simulated separately using a spider web grid, in order to generate the space- and time-varying wind and pressure fields within the model domain. No additional boundary condition was used to force the model. The same

Fig. 2 Multi-hazard and risk assessment methodology as applied in this study

model setup was first validated in a different case study for Hawaii, and for which measurements were available (Hurricane Iniki, 1992). Based on the validated model, all tracks from the IBTrACS database and with a category of tropical storm or higher (i.e. categories 1 until 5) were modelled, resulting in a set of 30 simulated events.

Water levels generated specifically from the Tohoku tsunami event, the most recent recorded past event, were also simulated with Delft3D.

The offshore forcing was then translated into impacts on the island (i.e. flooding and erosion). The XBeach model (Roelvink et al. 2009; surf beat version) was used to propagate waves (i.e. short and infragravity) and water levels across the reefs towards the shore and to compute the flooding over the island (Fig. 2). The model has been successfully applied to compute wave transformation and water levels in reef environments (Pomeroy et al. 2012; Van Dongeren et al. 2013), including the nearby Roi-Namur island at Kwajalein Atoll (Quataert et al. 2015). Given the very similar settings, the model was selected for this application using the same parameters as in Quataert et al. (2015). Waves and water level boundary conditions for the XBeach model were derived from the ERA-Interim offshore wave data (i.e. for swell events) and from Delft3D simulations (i.e. for wind waves from the lagoon and typhoon events), as shown in Fig. 2. The model covered the entire island with alongshore resolution of 20 m and cross-shore resolution ranging between 50 m offshore and 1 m on the island. The model was forced with time-varying water levels and wave conditions in order to simulate a design storm with a duration of 30 h. The maximum in water level and wave condition of the design storm was dependent on the return period of the simulated event.

Storm erosion due to episodic (extreme) events and long-term land loss due to SLR were estimated separately by means of empirical formulas on nine representative cross-shore profiles of known steepness and sediment characteristics.

Namely, the Van Rijn (2009) formula was used to provide an estimate of the dune erosion resulting from individual storms of different return periods, and the Bruun Rule (Bruun 1962) to assess the effect of coastal retreat induced by SLR. It is important to note that these formulas were originally derived for closed sandy coastlines. Although their application for this specific case study may stretch beyond their limit of validity, given the very specific geomorphological settings of Ebeye, we believe that the use of empirical formulas was the optimal solution in terms of computational times and accuracy.

Multi-hazard assessment

The two main coastal hazards at the island are flooding and coastal erosion. However, those hazards are generated by a number of inherently different, independent, hydro-meteorological events, namely, (a) wind waves and surge from the lagoon, (b) oceanic swell waves, (c) wind waves and surge during typhoon events and (d) tsunamis. Therefore, an important step of the methodology consists of the combination of those different processes.

An extreme value analysis based on a peak-over-threshold approach was at first carried out in order to derive wave heights and storm surge levels for different return periods (i.e. $T = 1, 5, 10, 30$ and 50 years) for each individual process. This resulted in a matrix of 15 conditions (i.e. 5 return periods and 3 processes, namely, wind waves, swell waves and typhoons). Since there was only evidence of one minor past tsunami at the island, no return period could be derived for tsunami events. Therefore, water levels generated from the past Tohoku event were treated as constant for the different return periods. In any case, tsunami events are a minor source of risks for the island, in comparison with swell waves and typhoons.

Each individual combination of wave height and storm surge level, for each individual process, was then used to compute the flooding and coastal erosion hazard over the island. An example of a flooding map, resulting from swell wave events with a return period of 10 years, in the present and in 2100, is shown in Online Resource 1. In order to reduce the number of scenarios and to combine the effect of different forcing mechanisms on each return period, maps were generated showing the greatest flood depth at each grid node and the greatest erosion distance at different representative cross-shore transects. This resulted in a total of five flood maps and five erosion maps corresponding to the different return periods (i.e. $T = 1, 5, 10, 30$ and 50 years) for each time horizon (current situation, 2030, 2050 and 2100). The SLR scenarios analysed were derived from different RCP scenarios, namely, RCP 2.6, 4.5, 6.0 and 8.5.

Relative percentages describing the portion of the island inundated by, an arbitrarily chosen, threshold water depth equal to 20 cm are summarised in Online Resource 2.

Risk assessment

Separate damage computations were carried out to quantify the effects of flooding and coastal erosion.

Direct damages due to flooding were estimated by combining inundation maps, exposure data and a depth-damage function describing the damages to houses and infrastructure at different flood depths. In particular, one depth-damage curve derived for America Samoa was selected and applied to all types of assets on the island (Paulik et al. 2015). Damages (D) for different return periods were derived and then integrated over the different probabilities of occurrence (P), to compute the expected annual damages (EAD), following Eq. (1). EAD describes an expected yearly averaged damage.

$$\text{EAD} = \int_0^1 D(p) \cdot dP \quad (1)$$

EAD/m^2 was also derived, to be used as a basis for the prioritisation of disaster risk reduction measures. Direct damages due to erosion were derived by multiplying the area loss by the estimated land value ($400 \text{ USD}/\text{m}^2$). The land value was estimated based on land reclamation costs, required to counteract island erosion.

Indirect and intangible damages were estimated as a percentage of the direct damages. Moreover, a separate indirect damage was added to account explicitly for the number of days when one of the major roads on the island (i.e. the causeway towards Gugeegue) is not accessible due to flooding and debris caused by wave overtopping. Inaccessibility of the road also results in additional indirect damages as inhabitants in Gugeegue are not able to reach their work place and students

cannot attend school. The different sources of damage were then summed up to derive the total damages.

The population affected by flooding was estimated by overlaying flood maps and population maps. Expected annual affected people (EAAP) was computed similarly to the EAD, but using a 20 cm threshold depth value to consider individuals actually affected by flooding. This threshold takes into account the fact that local inhabitants have learnt to cope with minor and more frequent flooding events, which they do not necessarily consider as major problem.

Results

Coastal risk assessment

The total baseline EAD over the island is estimated at about \$2.4 million, of which about \$2.1 million results from flooding and \$0.3 million from erosion. Those values were validated against yearly damages provided by the local government and were within the same order of magnitude. The total baseline EAAP amounts to a total of about 5000 yearly affected people. However, when including the effect of SLR, the total EAD at the end of the century is projected to increase to \$5.7–9.1 million, depending on the SLR scenario (RCP 2.6 or 8.5), while the projected EAAP reaches 8800–10,800.

Flood risk, defined as EAD to the island (USD/m^2) for different time horizons and under SLR scenario RCP8.5, is shown in Fig. 3. The figure shows how damages in the present are generally higher on the ocean side (east of the island) as a result of the highest hazards affecting the island from this side. The most important are swell waves, for low return periods, and typhoon events, for the highest return periods (see also table provided in Online Resource 2). Moreover, the figure clearly shows how SLR is projected to increase damages in the future. The information on Fig. 3 can also be used to plan risk reduction measures at locations where those risks are the highest, in the current and future scenarios.

Assessment of the efficiency of risk reduction measures

In order to reduce coastal risks, different types of DRR measures are available. Referring to the original definition of risks = hazard $\times$ vulnerability $\times$ exposure, the first option consists of reducing the hazards, for example, by implementing a suitable coastal protection measure (e.g. a beach nourishment and a rock revetment). A second possibility consists of reducing the vulnerability of the assets (e.g. by designing houses on poles, so that they will not be damaged during a flooding event). A third option consists of reducing the exposure value of the assets affected by flooding or erosion (e.g. by designing set-back lines and promoting relocation).

Fig. 3 Expected annual damages (EAD) under SLR (sea level rise) scenario RCP 8.5 (Representative Concentration Pathway), for different time horizons (current, 2030, 2050 and 2100). Sub-areas define sectors

characterised by homogeneous exposed assets. Values are given per areal unit (USD/m²)

In this paper, we show the suitability of the proposed methodology for assessing the efficiency of one potential risk reduction measure; at the same time, the methodology could be used as a basis for the comparison of different options. As an example, we assume that part of the east side of the island, where risks are higher, will be protected using a revetment with a cross section as sketched in the figure attached (Online Resource 3). The location of the revetment is indicated in the figure provided as Online Resource 4.

As a result of the rock revetment, computed flood depths and coastal erosion will decrease considerably. As an example, the maximum flooding levels for combined events with a return period of 10 years, before and after implementation of the revetment, are shown in the figure attached (Online Resource 4). The figure shows that the revetment reduces flood levels on the island and prevents erosion. However, although to a smaller degree, some flooding can still occur from the lagoon side.

The change in EAD and EAAP over time, as result of different SLR scenarios, in the current situation (no coastal protection) and after construction of the revetment, is shown in Fig. 4. The figure shows how EAD are expected to increase by a factor of three to four when no DRR measure is implemented and depending on the SLR scenario. By constructing the revetment, the EAD are reduced by about 30%.

The EAAP is expected to double without any additional adaptation measure. In this scenario, nearly the entire population is expected to be exposed at least once per year to flood depths exceeding 20 cm. However, the revetment is effective in reducing the future EAP approximately by 40%.

It is important to stress that EAD and EAAP at Ebeye are already substantial in the current situation. Therefore, relative changes due to SLR with respect to the current situation may be lower than according to other global predictions (e.g. Hinkel et al. 2014).

Sea level rise and impacts of global warming pathways

The proposed methodology is applied to estimate EAD and EAAP, for different SWLs, under different RCP scenarios. The results show that the timing when 1.5, 2 or 2.5 °C warming will be reached varies among RCPs (Fig. 5a) and so does the resulting SLR (Fig. 5b). As an example, following RCP 4.5, a temperature increase equal to 1.5 °C will be reached in year 2034, with a corresponding SLR equal to 15 cm. The temperature is expected to rise by 2.0 °C in 2058 with a SLR equal to 28 cm. On the other hand, following RCP 8.5, the temperature will rise by 1.5 °C in 2029 (SLR = 14 cm) and by 2 °C in 2043 (SLR = 21 cm).

Fig. 4 Development of expected annual damages (EAD) and expected annual affected people (EAAP) indicators as a function of time, in the situation without revetment (dashed line) and after construction of the

revetment (continuous line). The different colours represent different RCP (Representative Concentration Pathways) scenarios. The circles indicated the computed values

Figure 5c shows change in EAD under different RCP scenarios, and with the yearly damages associated with SWLs of 1.5, 2 and 2.5 °C, respectively. As an example, under RCP 4.5, damages associated with a 1.5 °C warming are estimated around 3.4 million USD, while they will rise to 4.3 million USD under 2.0 °C warming. On the other hand, damages associated with a 1.5 and 2.0 °C warming under RCP 8.5 are around 3.3 million USD and 3.8 million USD, respectively. This means that not only is the temperature increase important but also the pathway to reach this temperature increase. This aspect is discussed in more details in the Discussion Section.

Fig. 5d shows the results in terms of EAAP. The figure shows that under RCP 4.5 and 1.5 and 2.0 °C warming, the number of people affected will reach 6400 and 7600, respectively. Under RCP 8.5, the same values are around 6300 and 7000 respectively.

Discussion

General remarks

One of the main strengths of the methodology is related to the combined analysis of multiple offshore forcings with climate

change scenarios. Among the climate change-related effects, SLR and change in wave height were explicitly included in the analysis. Nevertheless, other effects may contribute to further exacerbate this trend (e.g. coral degradation, changes in frequency and intensity of extreme events).

Additionally, the extensive assessment of coastal flood hazard has been improved in several aspects compared to the current state-of-the-art, and for similar studies. The effect of waves is often omitted in such analyses, since their assessment requires computationally expensive simulations and technical expertise. Waves are an important hazard component as they lead to an additional elevation in mean water level near the coast (Bertin et al. 2012), drive coastal erosion (Vousdoulas et al. 2012) and wave induced flooding (Storlazzi et al. 2018). Moreover, most assessments of flood risk in view of climate change are based on the static inundation approach (Hinkel et al. 2014; Hinkel et al. 2010), which has been shown to overestimate flood extents (Bertin et al. 2014; Gallien 2016; Ramirez et al. 2016; Vousdoulas et al. 2016a). The Delft3D/XBeach modelling chain presently used allows a robust simulation of all the major nearshore hydrodynamic processes from storm surge generation from tropical cyclones to wave nearshore processes and inundation.

Fig. 5 Time development of temperature (a), sea level rise (SLR) (b), expected annual damages (EAD) (c) and expected annual affected people (EAAP) (d) for different RCP (Representative Concentration Pathways) scenarios. Temperature limits of 1.5, 2 and 2.5 °C are explicitly indicated in the figure. Colour lines indicate average values, while shaded areas indicate the 95% confidence interval around those average values

Global warming and emission scenarios

Recent discussions have focussed on the options to limit global warming and the impacts that SWLs may have at the global and local level. Nevertheless, available literature on this topic related to small islands is still very scarce. A milestone in this debate is the Paris Agreement which has, as a central aim, the strengthening of the global response to the threat of climate change; this is by keeping the global temperature rise this century well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 °C. Within this discussion,

the Alliance of Small Island States (AOSIS) has been advocating strongly for a cap of 1.5 °C on global warming above pre-industrial levels (AOSIS 2015). The consequences of exceeding this temperature cap on coastal ecosystems, coral reefs, SLR, freshwater availability, etc. may have drastic consequences on small island developing states (SIDS) countries. However, Fig. 5a shows that the temperature increase is expected to rise above 1.5 °C for all RCP scenarios analysed, with exception of RCP 2.6. This is consistent with the majority of recent research, which points out that global warming levels of less than 2 °C may be unlikely (Raftery et al. 2017).

The present findings show that impacts for the same warming levels can vary substantially among different emission scenarios. The reason is that SLR is a phenomenon which has a certain time-lag in relation to increases in temperature, rendering the pathway to warming an important parameter and implying that slower warming will result in additional SLR for a given temperature (Jevrejeva et al. 2016). Despite its importance, this aspect is generally neglected in similar studies and in the public debate, mainly focussing on the limitation of global warming, while neglecting that consequences may be substantially different when considering the pathways leading to this temperature increase.

Moreover, the present study highlights the possible benefits resulting from a limitation in the temperature increase to 1.5 or 2 °C, as following the Paris Agreement. By limiting the temperature increase to 1.5 °C with respect to 2 °C, damages may be reduced by about 20%, while yearly affected people may be reduced by 15%. However, additional benefits (i.e. on coastal ecosystems, freshwater availability and health of local population) may arise by limiting this temperature increase, aspects which were not taken into account in this analysis.

Disaster risk reduction measures and adaptive planning

The methodology proposed in the paper can also be used to assess and compare the effectiveness of different DRR measures. In this paper, as an example, the methodology was applied to assess the effectiveness of a DRR measure in the form of a rock revetment. The construction of an adaptation option in the form of a rock revetment can be useful to reduce risks and “buy time”, by delaying the effects of an increase in sea level. This is clearly shown in Fig. 4: EAD can be maintained below current levels until year 2040 by using the revetment, while EAAP will reach current levels in 2070–2100, depending on the SLR scenario. However, by the end of the century, this measure will also be ineffective, and alternative (more sustainable) solutions should be explored. The methodology could also be used as a basis to carry out a full cost-benefit analysis, required to assess the financial feasibility of a possible adaptation option and to design a long-term coastal adaptation plan for the island (e.g. Haasnoot et al. 2013; Smallegan et al. 2017). Adaptive planning is, in general, the most effective way of dealing, in a sustainable way, with the effects of climate change and SLR on these islands, by identifying a set of adaptation options which can be applied at different times in response to changing conditions.

Factors of uncertainties

As the methodology is generic, any model could be used to derive the hazard values. The accuracy of the results will, of course, depend on the accuracy of the input data. The study

area was characterised by very poor data coverage. Several data sources were combined in order to validate the different modelling components. In particular, global data sources (i.e. waves, bathymetry, tides and cyclone tracks) were used in combination with local data. Given the spatial scale of these islands, the combination of these two data sources is an absolute requirement. Most of all, local topographic and bathymetric data are a very important requisite in addition to global data.

A depth-damage function was used in the study to translate flooding depths to damages. However, large uncertainties in results exist depending on the type of function used (Vousdoukas et al. 2018). Wagenaar et al. (2016) estimated that uncertainties in computed damages may vary between a factor 2 and 5, according to the flood damage function and maximum damages used. Computed damages should also be compared and validated based on databases with recorded yearly damages over the study area. Unfortunately, those data often do not exist or they are very scattered, especially in small or developing countries.

Conclusions

In this paper, a methodology is proposed to assess, in a quantitative way, coastal risks due to multiple hazards driven by various hydro-meteorological events, also accounting for the effects of climate change. In particular, monetary risks were defined as expected annual damage (EAD), while the population affected was defined as expected annual affected people (EAAP). The methodology was applied to a small island case study (i.e. the island of Ebeye). However, the methodology is generic and could be applied to any other coastal region.

The results highlight that without additional adaptation measures, the EAD over the island will increase by a factor three to four, by the end of the century, due to the effects of climate change. On the other hand, the number of yearly affected people will increase by a factor two.

The methodology could also be used to assess and possibly compare the effectiveness of different disaster risk reduction measures. In this case, an example was provided in which a rock revetment was implemented as a risk reduction measure for the island in order to mitigate short-term risks.

The study has also shown the unlikelihood that a temperature cap of 1.5 °C can be achieved and the possible consequences that this may have, in terms of additional damages and affected people, for the island of Ebeye. A further increase in temperature from 1.5 to 2 °C, may lead to an increase in damages of about 20% and an additional increase in affected people equal to 15%. However, additional consequences, not taken into account in this analysis, may arise such as (irreversible) damages to coastal ecosystems, freshwater availability and health of local population. Another important

observation from this study, often neglected in the public debate, is the consideration of different emission pathways, resulting from different temperature increases and the implication that this may have on damage estimation. Higher damages, for a given temperature, are to be expected for lower emission scenarios.

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References

- AOSIS (2015). Submission by AOSIS on the outcome of the structured expert dialogue and the 2013–2015 review
- Bertin X, Bruneau N, Breilh J-F, Fortunato AB, Karpytchev M (2012) Importance of wave age and resonance in storm surges: the case Xynthia, Bay of Biscay. *Ocean Model* 42:16–30. <https://doi.org/10.1016/j.ocemod.2011.11.001>
- Bertin X, Li K, Roland A, Zhang YJ, Breilh JF, Chaumillon E (2014) A modeling-based analysis of the flooding associated with Xynthia, Central Bay of Biscay. *Coast Eng* 94:80–89. <https://doi.org/10.1016/j.coastaleng.2014.08.013>
- Bouziotas D (2016) Upscaling coastal flood risk assessment. Insight into the uncertainty of a continental-scale model. Master thesis, TUDelft, The Netherlands
- Bruun P (1962) Sea level rise as a cause of shore erosion. *J Waterways Harb Div ASCE* 88:117–130
- CSIRO (2014). Climate variability, extremes and change in the Western Tropical Pacific: New Science and Updated Country Reports 2014
- Dee DP et al (2011) The ERA-interim reanalysis: configuration and performance of the data assimilation system. *Q J R Meteorol Soc* 137(656):553–597. <https://doi.org/10.1002/gj.828>
- Dilley M, Chen U, Deichmann RS, Lerner-Lam A, Arnold M (2005) Natural disaster hotspots: a global risk analysis. In: *Disaster Risk Management Series*, 5. Bank, The World
- Economic Policy, Planning, and Statistics Office (2012). The RMI 2011 census of population and housing. Summary and Highlights Only
- Egbert GD, Erofeeva SY (2002) Efficient inverse modeling of barotropic ocean tides. *J Atmos Ocean Technol* 19:183–204. [https://doi.org/10.1175/1520-0426\(2002\)019<0183:EIMOB>2.0.CO;2](https://doi.org/10.1175/1520-0426(2002)019<0183:EIMOB>2.0.CO;2)
- Ferreira O, Viavattene C, Jiménez JA, Bolle A, das Neves L, Plomaritis TA, McCall R, van Dongeren AR (2017) Storm-induced risk assessment: Evaluation of two tools at the regional and hotspot scale. *Coastal Eng* 2018 134:241–253. <https://doi.org/10.1016/j.coastaleng.2017.10.005>
- Forzieri G, Feyen L, Russo S, Voudoukas M, Alfieri L, Outten S, Migliavacca M, Bianchi A, Rojas R, Cid A (2016) Multi-hazard assessment in Europe under climate change. *J Climate Change* 137:105–119. <https://doi.org/10.1007/s10584-016-1661-x>
- Gallien TW (2016) Validated coastal flood modeling at Imperial Beach, California: comparing total water level, empirical and numerical overtopping methodologies. *J Coastal Eng* 111:95–104. <https://doi.org/10.1016/j.coastaleng.2016.01.014>
- Gallina V, Torresan S, Critto A, Sperotto A, Glade T, Marcomini A (2016) A review of multi-risk methodologies for natural hazards: consequences and challenges for a climate change impact assessment. *J Environ Manag* 168:123–132. <https://doi.org/10.1016/j.jenvman.2015.11.011>
- Gawehn M, van Dongeren A, van Rooijen A, Storlazzi CD, Cheriton OM, Reiniers A (2016) Identification and classification of very low frequency waves on a coral reef flat, vol 121. *Oceans, Journal of Geophysical Research*, pp 121–7574. <https://doi.org/10.1002/2016JC011834>
- Giardino A, Nederhoff CM, Gawehn M, Quataert E, Capel A (2017) Coastal risk assessments for Ebeye. Technical Report Deltares, Delft, The Netherlands
- GFDRR, (2016). “The small island states resilience initiative (SISRI)”, SISRI knowledge note no. 1. Small island states resilience initiative, the World Bank and Global Facility for Disaster Reduction and Recovery (GFDRR), Washington DC. <https://www.gfdrr.org/small-island-states-resilience-initiative>
- Haasnoot M, Kwakkel JH, Walker WE, ter Maat J (2013) Dynamic adaptive policy pathways: a method for crafting robust decision for a deeply uncertain world. *J Global Environ Change* 23(2):485–498. <https://doi.org/10.1016/j.gloenvcha.2012.12.006>
- Hein, J.R., Florence, L.W., Dan, L. M. (2007). Bathymetry of the Republic of the Marshall Islands and vicinity. U.S. Geological Survey
- Hemer MA, Yalin F, Nobuhito M, Alvaro S, Xiaolan LW (2013) Projected changes in wave climate from a multi-model ensemble. *Nat Clim Chang* 3:471–476. <https://doi.org/10.1038/nclimate1791>
- Hess, D., Hwang, D., Fellenius, K., Robertson, I., Stege, M., and Chutaro, B. (2015). Republic of the Marshall Islands homeowner’s handbook to prepare for natural hazards. Published by University of Hawaii Sea Grant Program, June 2015, p. 81
- Hinkel J, Klein RJT (2009) Integrating knowledge to assess coastal vulnerability to sea-level rise: the development of the DIVA tool. *Glob Environ Chang* 19:384–395. <https://doi.org/10.1016/j.gloenvcha.2009.03.002>
- Hinkel J, Nicholls RJ, Vafeidis A, Tol RSJ, Avagianou T (2010) Assessing risk of and adaptation to sea-level rise in the European Union: an application of DIVA. In: *Mitig Adapt Strateg Glob Chang* 5(7):1–17. <https://doi.org/10.1007/s11027-010-9237-y>
- Hinkel J, Nicholls RJ, Tol RSJ, Wang ZB, Hamilton JM, Boot G, Vafeidis AT, McFadden L, Ganopolski A, Klein RJT (2013) A global analysis of erosion of sandy beaches and sea-level rise: an application of DIVA. *J Global and Planet Change* 111:150–158. <https://doi.org/10.1016/j.gloplacha.2013.09.002>
- Hinkel J, Lincke D, Vafeidis AT, Perrette M, Nicholls RJ, Tol RSJ, Marzeion B, Fettweis X, Ionescu C, Levermann A (2014) Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc Natl Acad Sci* 111:3292–3297
- Jevrejeva S, Jackson LP, Riva REM, Grinsted A, Moore JC (2016) Coastal sea level rise with warming above 2 °C. *Proc Natl Acad Sci* 113:13342–13347
- Kappes MS, Keiler M, von Elverfeldt K, Glade T (2012) Challenges of analyzing multi-hazard risk: a review. *J Nat Hazards* 64:1925–1958. <https://doi.org/10.1007/s11069-012-0294-2>
- Kind JM (2014) Economically efficient flood protection standards for the Netherlands. *J Flood Risk Manag* 7:103–117. <https://doi.org/10.1111/jfr3.12026>

- Kron W (2005) Flood risk = hazard values vulnerability. *Water Int* 30(1): 58–68. <https://doi.org/10.1080/02508060508691837>
- Lekuthai A, Vongvisessomjai S (2001) Intangible flood damage quantification. *J Water Res Manag* 15(5):343–362. <https://doi.org/10.1023/A:1014489329348>
- Lesser GR, Roelvink JA, van Kester JATM, Stelling GS (2004) Development and validation of a three dimensional morphological model. *J Coastal Eng* 51:883–915. <https://doi.org/10.1016/j.coastaleng.2004.07.014>
- Messner F, Meyer V (2006) Flood damage, vulnerability and risk perception-challenges for flood damage research. *J Flood Risk Manag: Hazards Vulnerability and Mitigation Measure* 67:149–167. https://doi.org/10.1007/978-1-4020-4598-1_13
- Muis, S., Verlaan, M., Winsemius, H.C., Aerts, J.C.J.H., Ward, P.J. (2016). A global reanalysis of storm surges and extreme sea levels. *J Nat Commun* 7 doi: <https://doi.org/10.1038/ncomms11969>
- Owen SD, Kench PS, Ford M (2016) Improving understanding of the spatial dimensions of biophysical change in atoll island countries and implications for island communities: a Marshall Islands' case study. *J Appl Geogr* 72:55–64. <https://doi.org/10.1016/j.apgeog.2016.05.004>
- Paulik, R. Smart, G., Turner, R., Bind, J. (2015). Development of preliminary depth-damage functions for Samoa buildings. National Institute of Water and Atmospheric Research
- PCRAFI (2015). Advancing disaster Risk Financing & Insurance in the Pacific
- Plomaritis TA, Costas S, Ferreira O (2017) Use of Bayesian Network for coastal hazards, impact and disaster risk reduction assessment at a coastal barrier (Ria Formosa, Portugal). *J Coastal Eng* 134:134–147. <https://doi.org/10.1016/j.coastaleng.2017.07.003>
- Poelhekke L, Jäger WS, van Dongeren A, Plomaritis TA, McCall R, Ferreira O (2016) Predicting coastal hazards for sandy coasts with a Bayesian Network. *Coastal Eng* 118:21–34. <https://doi.org/10.1016/j.coastaleng.2016.08.011>
- Pomeroy A, Lowe RJ, Symonds G, Van Dongeren AR, Moore C (2012) The dynamics of infragravity wave transformation over a fringing reef. *J Geophys Res* 117:C11022. <https://doi.org/10.1029/2012JC008310>
- Quataert E, Storlazzi C, van Rooijen A, Cheriton O, van Dongeren A (2015) The influence of coral reefs and climate change on wave-driven flooding of tropical coastlines. *J Geophys Res Lett* 42:6407–6415. <https://doi.org/10.1002/2015GL064861>
- Raftery AE, Zimmer A, Frierson DMW, Startz R, Liu P (2017) Less than 2°C warming by 2100 unlikely. *J Nat Climate Change* 7:637–641. <https://doi.org/10.1038/NCLIMATE3352>
- Ramirez JA, Lichter M, Coulthard TJ, Skinner C (2016) Hyper-resolution mapping of regional storm surge and tide flooding: comparison of static and dynamic models. *Nat Hazards* 82:571–590. <https://doi.org/10.1007/s11069-016-2198-z>
- Roelvink JA, Reniers A, Van Dongeren A, Van Thiel de Vries J, McCall R, Lescinski J (2009) Modelling storm impacts on beaches, dunes and barrier islands. *J Coastal Eng* 56:1133–1152. <https://doi.org/10.1016/j.coastaleng.2009.08.006>
- Smallegan S, Irish L, van Dongeren A (2017) Developed barrier islands adaptation strategies to hurricane forcing under rising sea levels. *J Clim Change*. 143:173–184. <https://doi.org/10.1007/s10584-017-1988-y>
- Storlazzi CD, Gingerich SB, van Dongeren A, Cheriton OM, Swarzenski PW, Quataert E, Voss CI, Field DW, Annamalai H, Piniak GA, McCall R (2018) Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Sci Adv* 4(4):eaap9741. <https://doi.org/10.1126/sciadv.aap9741>
- Taylor KE, Stouffer RJ, Meehl GA (2011) An overview of CMIP5 and the experiment design. *Bull Am Meteorol Soc* 93:485–498. <https://doi.org/10.1175/BAMS-D-11-00094.1>
- UNEP (1992). Agenda 21. Technical report, United Nations Environment Programme
- Van Dongeren A, Lowe R, Pomeroy A, Minh Trang D, Roelvink D, Symonds G, Ranasinghe R (2013) Numerical modeling of low-frequency wave dynamics over a fringing coral reef. *J Coastal Eng*. 73: 178–190. <https://doi.org/10.1016/j.coastaleng.2012.11.004>
- Van Dongeren A, Ciavola P, Martinez G, Viavattene C, Bogaard T, Ferreira O, Higgins R, McCall R (2017) Introduction to RISC-KIT: resilience-increasing strategies for coasts. *J Coastal Eng* 134: 2–9. <https://doi.org/10.1016/j.coastaleng.2017.10.007>
- Van Rijn LC (2009) Prediction of dune erosion due to storms. *J Coastal Eng*. 56(4):441–457. <https://doi.org/10.1016/j.coastaleng.2008.10.006>
- Vousdoukas, M.I., Almeida, L.P., Ferreira, Ó., 2012. Beach erosion and recovery during consecutive storms at a steep-sloping, meso-tidal beach. *Earth Surf. Processes Landforms* 37, 583–691. <https://doi.org/10.1002/esp.2264>
- Vousdoukas MI, Voukouvalas E, Annunziato A, Giardino A, Feyen L (2016a) Projections of extreme storm surge levels along Europe. *J Clim Dynam* 47:3171–3190. <https://doi.org/10.1007/s00382-016-3019-5>
- Vousdoukas MI, Voukouvalas E, Mentaschi L, Dottori F, Giardino A, Bouziotas D, Bianchi A, Salomon P, Feyen L (2016b) Developments in large-scale coastal flood hazard mapping. *J Nat Hazards and Earth System Sci* 2016:1841–1853. <https://doi.org/10.5194/nhess-16-1841-2016>
- Vousdoukas MI, Bouziotas D, Giardino A, Bouwer LM, Voukouvalas E, Mentaschi L, Feyen L (2018) Understanding epistemic uncertainty in large-scale coastal flood risk assessment for present and future climates. *Nat Hazards Earth Syst Sci*. <https://doi.org/10.5194/nhess-2018-127> (in review)
- Wagenaar DJ, Bruijn KM, Bouwer LM, de Moel H (2016) Uncertainty in flood damage estimates and its potential effect on investment decisions. *J Nat Hazards* 16:1–14. <https://doi.org/10.5194/nhess-16-1-2016>