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Loss of cultural world heritage and currently inhabited places to sea-level rise

Ben Marzeion[1] **and Anders Levermann**[2,3]

[1] Institute for Meteorology and Geophysics, University of Innsbruck, Austria
[2] Potsdam Institute for Climate Impact Research, Potsdam University, Germany
[3] Institute of Physics, Potsdam University, Germany

E-mail: ben.marzeion@uibk.ac.at

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Abstract

The world population is concentrated near the coasts, as are a large number of Cultural World Heritage sites, defined by the UNESCO. Using spatially explicit sea-level estimates for the next 2000 years and high-resolution topography data, we compute which current cultural heritage sites will be affected by sea-level rise at different levels of sustained future warming. As indicators for the pressure on future cultural heritage we estimate the percentage of each country's area loss, and the percentage of current population living in regions that will be permanently below sea level, for different temperature levels. If the current global mean temperature was sustained for the next two millennia, about 6% (40 sites) of the UNESCO sites will be affected, and 0.7% of global land area will be below mean sea level. These numbers increase to 19% (136 sites) and 1.1% for a warming of 3 K. At this warming level, 3–12 countries will experience a loss of more than half of their current land surface, 25–36 countries lose at least 10% of their territory, and 7% of the global population currently lives in regions that will be below local sea level. Given the millennial scale lifetime of carbon dioxide in the atmosphere, our results indicate that fundamental decisions with regard to mankind's cultural heritage are required.

Keywords: sea-level rise, cultural heritage, chlimate impacts

S Online supplementary data available from stacks.iop.org/ERL/9/034001/mmedia

1. Introduction

Increasing global mean temperature leads to sea-level rise (SLR) predominantly due to increased oceanic thermal expansion and the loss of continental ice (Stocker *et al* 2013). Transport of heat into the deep ocean and continental ice loss especially of the large ice sheets on Greenland and Antarctica have a millennial response time to atmospheric temperature increase (Levitus *et al* 2000, Gregory 2000, Church *et al* 2011). Unless global mean temperature is restored to pre-industrial levels, future sea level will continue to rise over several centuries (Zickfeld *et al* 2013, Meehl *et al* 2005, Nicholls and Cazenave 2010, Pardaens *et al* 2011, Williams *et al* 2012). At the same time, carbon dioxide has been shown to have a multi-centennial to multi-millennial residence time in the atmosphere, and global mean temperature declines on an even longer time scale (Solomon *et al* 2009, Zickfeld *et al* 2009, Allen *et al* 2009). As a consequence, the SLR that is to be expected if temperatures are sustained over a millennial time scale is much larger than that projected for the year 2100 (Goelzer *et al* 2012, Fettweis *et al* 2013, Li *et al* 2013, Levermann *et al* 2013). Studies on the socio-economic impact of climate change (Hsiang *et al* 2011) and specifically SLR (Pardaens *et al* 2011, Nicholls *et al* 1999, Nicholls 2004, Hinkel *et al* 2013) are generally limited to the 21st century, because of the time horizon of socio-economic development and planning (Moss *et al* 2010, van Vuuren *et al* 2011, Leggett *et al* 1992, Nakicenovic *et al* 2000). Cultural heritage needs to

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be considered on a longer time scale when informing societal decisions.

Here, we attempt to illustrate the potential impact of warming-induced SLR on the cultural world heritage, considering three indicators: first, as a measure of the impact on the past cultural heritage, we determine future SLR at the sites presently included in the UNESCO's list of cultural world heritage (UNESCO World Heritage Convention 2012). Second, we determine future loss of land surface area for each of the world's countries, using boundaries (Esri, DeLorme Publishing Company, Inc. 2012) as very rough proxies for regions of similar cultural heritage. Third, we take the present distribution of the global population (CIESIN *et al* 2011) as a proxy for the locations where future cultural world heritage may develop.

We consider SLR over the next 2000 years. On this time scale, ocean heat content and glacier ice mass can be considered to be in equilibrium with global temperatures, and relatively independent of the warming path of the initial 100 years. Thus the largest uncertainty from the temporal evolution is mainly restricted to the contributions from the Greenland and Antarctic ice sheets. To facilitate the advantage of equilibrated ocean heat content and glaciers ice mass, we do not try to quantify the timing of a potential impact from SLR on the cultural heritage within the next 2000 years, but instead quantify the global mean temperature anomaly which will eventually lead to an impact anytime within the next 2000 years. At the same time, a time scale of 2000 years is short enough to be relevant for the societal discussion on climate change with regard to the cultural heritage, since a number of UNESCO sites are as old as or older than 2000 years.

Basis of our analysis are the sea-level change data from Levermann *et al* (2013), providing regional sea-level change within the next 2000 years as a function of sustained global mean temperature anomalies above pre-industrial values (ΔT), considering ocean heat uptake (Stocker *et al* 2013), glaciers (equilibrium estimates from the models of Marzeion *et al* 2012 and Radić *et al* 2014), Greenland and Antarctic ice sheets (Pollard and DeConto 2009, Robinson *et al* 2012), and taking into account changes in the Earth's gravity field from mass relocation and rotation changes, and the dynamical response of the Earth's crust based on a spherically symmetric Earth model with 1D, depth-dependent viscosity structure (Mitrovica and Forte 2004, Kaufmann and Lambeck 2000). To account for glacial isostatic adjustment from the last glacial maximum, we use the Earth model of Peltier (2004). As a global digital elevation model (DEM), we use SRTM data (Farr *et al* 2007), and ETOPO1 data (Amante and Eakins 2009) north and south of the SRTM coverage. To determine the impact on UNESCO cultural world heritage sites, we use data on location and spatial extent of each site that is classified either as *cultural* or *mixed* (i.e., both of cultural and natural significance) in the UNESCO list (UNESCO World Heritage Convention 2012). Country boundaries to determine potential land surface area loss are taken from Esri, DeLorme Publishing Company, Inc. (2012). For population distribution, we rely on data from the Global Rural–Urban Mapping Project, Version 1 (CIESIN *et al* 2011), and high-resolution coastlines are taken from Wessel and Smith (1996). We consider a global mean temperature anomaly range of $0 \leq \Delta T \leq 5$ K.

2. Methods

2.1. Sea-level rise

The future sea-level commitment for different levels of global mean temperature increase is based on physical models combined with paleo-information following Levermann *et al* (2013). The oceanic thermal expansion was obtained from multi-millennial integrations of coupled climate models as used in the fourth assessment report of the IPCC Solomon *et al* (2007). The median of the six model simulations yields a quasi-linear increase of the global mean sea level of 0.42 m K^{-1}, consistent with a uniform temperature increase of the ocean. The contribution of mountain glaciers was obtained from an equilibrium integration with constant boundary conditions corresponding to different levels of warming from the CMIP5 coupled climate model intercomparison project using two different glacier models (Marzeion *et al* 2012, Radić *et al* 2008). The corresponding contribution is saturating at higher temperature anomalies and is small compared to the mass loss of the ice sheets on Greenland and Antarctica. The Antarctic contribution to the future sea-level commitment was obtained from a dynamic ice sheet simulation of the past 5 million years (Pollard and DeConto 2009) which was validated against paleo-records (Naish *et al* 2009). The correlation of the sea-level contribution with past temperature above pre-industrial levels yields a sensitivity of 1.2 m K^{-1} of Antarctic global mean sea-level contribution. The Greenland ice sheet exhibits a threshold behavior on multi-millennial time scales (Ridley *et al* 2010, Charbit *et al* 2008, Robinson *et al* 2012). On 2000-year time scale we use an ensemble of simulations that were calibrated against the reconstructed ice sheet response of the Eemian period (Robinson *et al* 2012). The simulations are consistent with long-term projections with a different ice sheet model (Huybrechts *et al* 2011) and yield a quasi-quadratic dependence on the temperature increase. Combining these four sets of simulations yields a median global mean SLR of 2.3 m per degree of global mean temperature increase. The different ice sheet contributions where used to compute sea-level patterns that account for the gravitational response of sea level to the ice loss and the dynamic response of the Earth's crust on a 2000-year time scale (Mitrovica and Forte 2004, Kaufmann and Lambeck 2000). The corresponding patterns as well as the sea-level sensitivity and its different contributions are documented in Levermann *et al* (2013). As an example of the resulting patterns, figure 1 of the supplementary material (available at stacks.iop.org/ERL/9/034001/mmedia) shows the spatially explicit sea-level rise for a warming of $\Delta T = 3$ K.

2.2. UNESCO cultural world heritage

The temperature anomaly ΔT at which each *cultural* and *mixed* heritage site (UNESCO World Heritage Convention 2012) will be impacted by SLR was estimated by (i) locating the coordinates given in the UNESCO list in the SRTM digital elevation model (Farr *et al* 2007) (ETOPO1 data (Amante and Eakins 2009) were used if the site is located north of the SRTM coverage, 60.2 N, there are no sites south of the SRTM coverage). (ii) A circle was drawn around that point, covering either the area as given for the site in the UNESCO list, or 3 km^2, whichever is greater. (iii) The land–sea mask of the global self-consistent, hierarchical, high-resolution geography database (GSHHS) (Wessel and Smith 1996) was used in order to mask out water surfaces, and retain only land grid cells. (iv) Based on the elevations of these grid cells, we estimated an upper limit of the lowest elevation of each UNESCO site by (v) finding the lowest elevation of the retained grid cells that is statistically robustly detectable. I.e., starting at the lowest grid cell, we kept adding grid cells until the error estimate of their mean elevation was lower than the difference between the elevation of the lowest grid cell and the mean elevation of the combined grid cells. We used a conservative estimate of 10 m vertical uncertainty for each individual grid cell (Farr *et al* 2007). (vi) To the elevation obtained by this method, we added the vertical displacement caused by glacial isostatic adjustment from the last glacial maximum using the ICE-5G model (Peltier 2004), and subtracted local SLR (Levermann *et al* 2013) to determine if the site is impacted by SLR at a given global mean temperature anomaly.

Sites that are situated in depressions deeper than 5 m below current mean sea level (mainly in the Netherlands and Azerbaijan) were excluded from the analysis.

The relatively small spatial extend of many of the UNESCO sites, and the relatively large error associated with the SRTM data necessitate this complex procedure: by determining the lowest robustly detectable elevation (step v), we are approximating an estimate of the ground level, given that the SRTM data provide a surface model which may overestimate the ground level in areas of dense buildings or vegetation. The SRTM data have a global horizontal resolution of 3 arc s (corresponding to about 90 m at the equator). In order to be able to obtain a robust statistical measure of the lowest detectable elevation (step v), it is necessary to include a sufficient number of elevation grid points in the analysis. This is why a lower bound of 3 km^2 area is used to estimate the distribution of elevations at the UNESCO sites. Another reason for the lower bound of the considered area is the resolution of coastlines in the GSHHS data set, where the mean distance between points is 178 m (Wessel and Smith 1996).

We do not take into account temporal sea-level variability (e.g. from tides, or storm surges). This is another potential cause for an underestimation of an impact from SLR, independent of the potential overestimation of land surface height in the SRTM data. It is therefore reasonable to assume that a site will be impacted by SLR at the latest once this lowest detectable elevation is reached by local mean sea level. Another possibility to determine whether a site is impacted by SLR would be to determine the fraction of elevation model grid cells that are below local mean sea level, ignoring the elevation uncertainty of the individual grid cells. Figure 2 of the supplementary material (available at stacks.iop.org/ERL/9/034001/mmedia) shows the result of this method. For $\Delta T < 3$ K, taking into account the uncertainty of the elevation model substantially reduces the number of sites that are considered to be affected by SLR. For $\Delta T > 3$ K, the two methods yield very similar results.

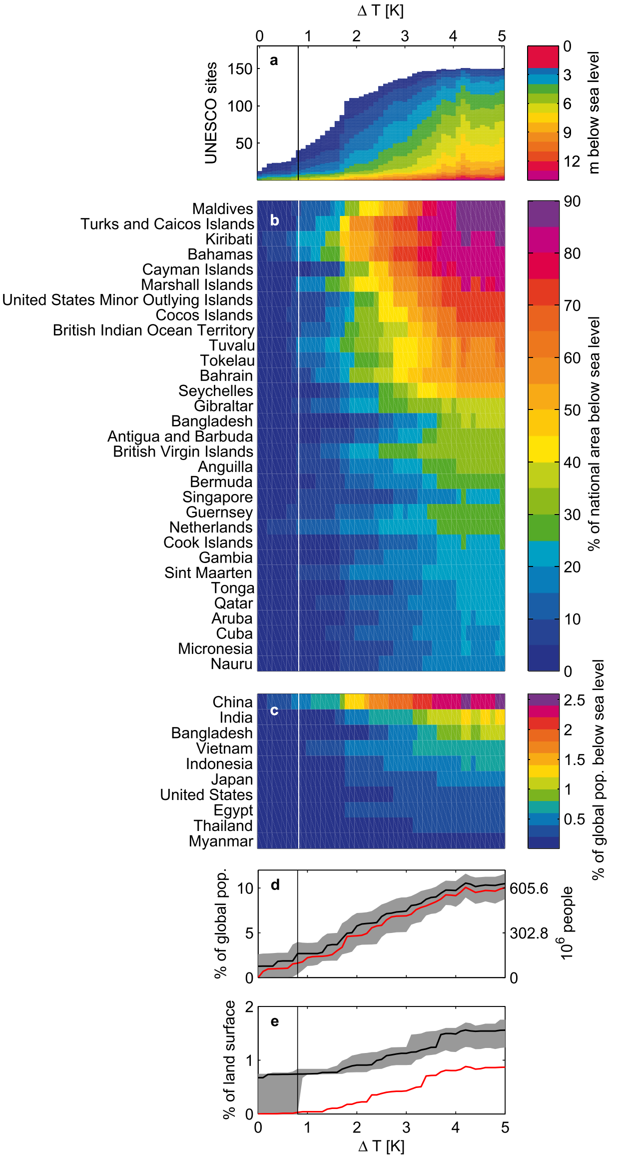

Figure 1. (a) Number of cultural UNESCO world heritage sites impacted by SLR, and depth of the sites below sea level, as a function of ΔT. (b) Increase of the percentage of national land surface lying below sea level, as a function of ΔT, sorted by descending loss of land surface. (c) Percentage of world population living in areas above current, but below future sea level, as a function of ΔT and country, sorted by descending percentage of living places affected. (d) black: global sum of (c), gray shading indicates uncertainty interval, red: the sum of (c) if glacial isostatic adjustment from the last glacial maximum is ignored. (e) Black: global percentage of land surface above current, but below future sea level, gray shading indicates uncertainty interval. Red: the same when glacial isostatic adjustment from the last glacial maximum is ignored. Vertical black/white lines indicate present day $\Delta T = 0.8$ K.

2.3. Countries

For each country in the data set of Esri, DeLorme Publishing Company, Inc. (2012), we extracted SRTM elevation data (Farr *et al* 2007) (ETOPO1 elevation data (Amante and Eakins 2009) were used if part of the country is located north or south of the SRTM coverage). To these elevations, we added the patterns of vertical displacement caused by glacial isostatic adjustment from the last glacial maximum using the ICE-5G model (Peltier 2004), and subtracted the spatially explicit SLR from Levermann *et al* (2013) (see figure 1 in the supplementary material (available at stacks.iop.org/ERL/9/034001/mmedia) for an example). We then determined the increase in the percentage of each country lying below sea level, depending on the global mean temperature anomaly. This implies that areas lying below sea level at present day are not included in our estimates. The very large number of grid cells entering this estimate renders the detailed elevation data uncertainty assessment used for the UNESCO sites unnecessary (see also argument made in Strauss *et al* (2012)).

2.4. Population

Based on the population distribution from the data set of CIESIN *et al* (2011), we determined the increase in the fraction of the population that lives within each country's boundaries, above present, and below future mean sea level, depending on the global mean temperature anomaly. We are aware that the distribution of inhabited places and boundaries may shift completely during 2000 years, but take these data as proxies for the locations where future cultural world heritage may be developing.

2.5. Uncertainty estimates

To estimate the uncertainty of our results caused by uncertainty in relative SLR, we follow two approaches: (i) (Levermann *et al* 2013) provide upper and lower bounds of the likely uncertainty range of the SLR pattern. These uncertainty bounds are based on a mixture of approaches to determine uncertainty for each of the contributions to SLR, ranging from multi-model ensemble spread to comprehensive error analysis. To determine uncertainty in our results, we repeat the procedures described above twice, once using the upper, and once using the lower bound of SLR. The uncertainty estimates corresponding to figures 1 and 2 are in figures 3–6 of the supplementary material (available at stacks.iop.org/ERL/9/034001/mmedia). (ii) We roughly estimate the uncertainty associated with glacial isostatic adjustment from the last glacial maximum by repeating the procedures described above, but not applying the ICE-5G model. We take the difference as an estimate of the upper limit of uncertainty associated with glacial isostatic adjustment from the last glacial maximum (figures 7–10 of the supplementary material available at stacks.iop.org/ERL/9/034001/mmedia). The uncertainty estimate is always within the bounds of sea-level projection uncertainty except for the global surface area below sea level.

3. Results

As sea level rises, an increasing fraction of the land surface is below sea level. For a sustained warming of $\Delta T = 3$ K over the next 2000 years, 1.1 (uncertainty range 0.9–1.2)% of the global land surface that is now above will then be below sea level (black line and shading in figure 1(e), see table 1 for the corresponding numbers at other global mean temperatures). The spatial distribution of UNESCO cultural heritage sites, of population, and of the countries impacted most by future SLR is such that the percentage of the cultural world heritage impacted by SLR is significantly greater than the percentage of land surface below sea level, as detailed below.

3.1. UNESCO cultural world heritage

There are 720 sites listed in the *cultural* and *mixed* categories in the UNESCO World Heritage List (obtained in October 2012). Of these, at a sustained warming of $\Delta T = 3$ K over the next 2000 years, 136 (111–155) sites (i.e., 19 (15–22)%) will be impacted by SLR (see table 1 for the corresponding numbers at other global mean temperatures). Figure 1(a) shows the number of sites impacted by SLR, and the depth below sea level, as a function of ΔT (see figure 4 of the supplementary material available at stacks.iop.org/ERL/9/034001/mmediafor the uncertainty of these values). Figure 2 shows the spatial distribution of these sites, and the global mean temperature anomaly above which they are impacted by SLR (see figure 3 of the supplementary material available at stacks.iop.org/ERL/9/034001/mmedia for the uncertainty of these values, and table 1 of the supplementary material (available at stacks.iop.org/ERL/9/034001/mmedia) for a detailed list of the sites). Since sea level continues to respond to the current warming level, there is a substantial number of sites (40 (12–103)) that will be impacted by SLR even without further temperature increase (see vertical lines in figure 1). Above $\Delta T = 3$ K, the number of sites impacted by SLR does not increase much, but sea level continues to rise at the sites that are impacted already. Within the considered temperature range, there is a maximum of 109 (69–143) sites that will be more than 5 m below sea level. This maximum depth below sea level occurs at different ΔT for different sites, because the spatial pattern of SLR changes over time.

3.2. Countries

Because of vastly different elevation-altitude distributions, the loss of land surface area is distributed very unevenly between different countries. Figure 1(b) shows the increase in the percentage of land surface lying below mean sea level as a function of ΔT for the countries that are affected most (see figure 5 of the supplementary material (available at stacks.iop.org/ERL/9/034001/mmedia) for the uncertainty of these values). Most, but not all of these, are small island states. At a sustained warming of $\Delta T = 3$ K over the next 2000 years, 7 (3–12) countries that will experience a loss of more than 50%, and 35 (25–36) that will lose more than 10% of their land surface currently lying above sea level (see table 1 for the corresponding numbers at other global mean temperatures).

3.3. Population

7 (5–9)% of the global population currently live on land that is now above mean sea level, but that will be below local sea level if $\Delta T = 3$ K is sustained over the next 2000 years (figure 1(d), see table 1 for the corresponding numbers at

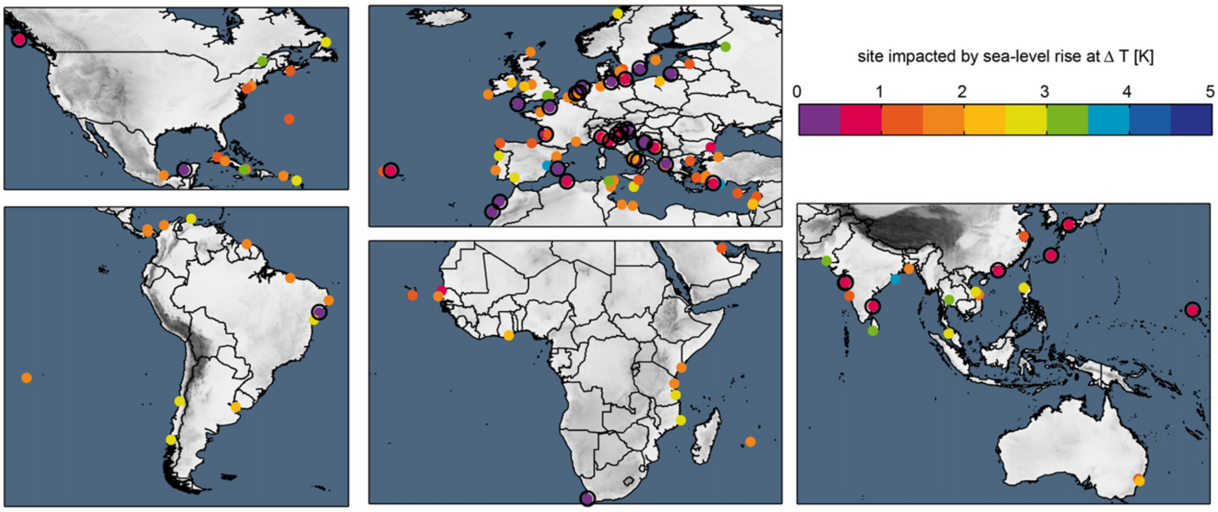

Figure 2. Location of UNESCO cultural world heritage sites affected by SLR. Colors: lowest ΔT at which the side will be impacted by SLR. Open black circles: sites which are impacted already at the present day $\Delta T = 0.8$ K.

Table 1. No. of countries and UNESCO *cultural* and *mixed* world heritage sites, and percentages of UNESCO *cultural* and *mixed* world heritage sites, distribution of current global population, and land surface area impacted by SLR at different global mean temperature anomalies ΔT. Uncertainty ranges are given in parenthesis.

			Global mean ΔT (K)				
			1	2	3	4	5
No. of	Countries	≥10%	9 (0–20)	26 (15–33)	35 (25–36)	38 (36–43)	41 (36–45)
		≥50%	0 (0–0)	3 (0–6)	7 (3–12)	12 (8–13)	13 (10–13)
No. of	UNESCO sites		47 (20–102)	110 (79–140)	136 (111–155)	148 (139–159)	149 (142–161)
% of			6.5 (2.8–14.1)	15.3 (11.0–19.4)	18.9 (15.4–21.5)	20.6 (19.3–22.1)	20.7 (19.7–22.4)
% of	Current population		2.2 (1.3–3.9)	4.7 (3.6–7.2)	6.9 (5.1–9.0)	9.1 (7.9–10.8)	10.5 (8.8–11.6)
	Surface area		0.7 (0.7–0.8)	0.9 (0.8–1.1)	1.1 (0.9–1.2)	1.5 (1.2–1.6)	1.6 (1.2–1.8)

other global mean temperatures). The affected population is very unevenly distributed between different countries, with more than 60% of the affected population lying within the 5 most affected countries (China, India, Bangladesh, Vietnam, and Indonesia, see figures 1(c), and 6 of the supplementary material (available at stacks.iop.org/ERL/9/034001/mmedia) for the uncertainties of these values).

4. Discussion and conclusion

Uncertainty enters our analysis on several levels, some that are quantifiable, and others that are not. First of all, the projections of SLR themselves are uncertain. We have taken this source of uncertainty into account by including estimates of SLR impacts for both the higher and lower bounds of SLR in our analysis (see figures 3–6 of the supplementary material available at stacks.iop.org/ERL/9/034001/mmedia). Another source of uncertainty is associated with changes in land surface elevation. The land surface area below mean sea level is greatly increased by glacial isostatic adjustment from the last glacial maximum. Over the time scale considered, this is a quasi-constant effect which does not depend significantly on the future temperature increase. If it is ignored (red line in figure 1(e)), at $\Delta T = 3.0$ K the land surface below sea level is only 0.4%, compared to 1.1% if it is included. However, the spatial distribution of UNESCO cultural heritage sites, of population, and of the countries affected most by future SLR is such that the impact of the glacial rebound from the last glacial maximum is relatively small (and within the uncertainty bounds, see figures 1(d), 7–10 of the supplementary material available at stacks.iop.org/ERL/9/034001/mmedia). This is because most cultural sites, and the current population distribution, are not concentrated near the last glacial ice masses where the rebound is strongest. Additionally, the impacts of SLR are greatest along the continental shelf edge where the glacial isostatic adjustment is typically small (Peltier 2004).

We did not account for other processes that may change land surface elevations. In particular, we neglected natural subsidence, which may be significant especially in river deltas (Stanley 1988, Ericson *et al* 2006), and we also neglected anthropogenic subsidence that can result from ground water depletion. Furthermore, the DEM we used (SRTM) is a surface model, and may overestimate the ground height in areas of dense buildings or vegetation. We also assumed a relatively high uncertainty for the DEM data in order not to underestimate the elevation of the UNESCO sites. All together, these unquantified uncertainties tend for our estimate to be rather an underestimation of the impacts of SLR than an overestimation. An example for this is the Bryggen site in Bergen, Norway, where dense buildings and surrounding steep terrain lead to an overestimation of the elevation, such that it is not included in figures 1 and 2, even though it experiences episodic flooding already under current conditions. This points to another limitation of our study: we only consider changes in local mean sea level, while episodic flooding will already impact sites at lower sea-level increases, especially if storminess, and thereby sea-level variability, increases. Furthermore, we do not consider adaptation measures like dike building, but merely illustrate the adaptive pressure caused by future SLR.

In Levermann *et al* (2013), the analysis was limited to temperature anomalies $\leq$4 K, since the SLR data get sparse for warming >4 K, decreasing the confidence in the error estimates for warmer temperatures. The situation is different here because of the spatial distribution of UNESCO sites and inhabited places: while sea level continues to rise for temperature anomalies >4 K, the number of affected sites and inhabited places hardly increases (figures 1(a) and (d)), which also implies that potentially greater uncertainty in the sea-level data does not translate into greater uncertainty in the numbers presented here.

Our analysis illustrates that the spatial distribution of the existing and potential future cultural world heritage makes it vulnerable to SLR. Future generations will face either loss of these sites, or considerable efforts to protect them.

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