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Potential impact of sea level rise on French islands worldwide

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Abstract

Although sea level rise is one of the most certain consequences of global warming, yet it remains one of the least studied. Several studies strongly suggested that sea level rise will accelerate in the future with a potentially rise from 0.5 to 2 m at the end of the century. However, currently island conservation programs do not take into account the potential effects of sea level rise. Therefore, we investigated the potential consequences of sea level rise for 1,269 French islands worldwide, by assessing the total number of island that will be totally submerged for three different scenarios (1, 2 and 3 m). Under the worst scenario, up to 12% of all islands could be entirely submerged. Two regions displayed the most significant loss of island: New Caledonia and French Polynesia. Focusing on New Caledonia, we highlighted that endemic plant species that are already classified as critically endangered by the IUCN will be the most vulnerable to sea level rise. Losses of insular habitats will thus be important in the next decades for the French islands. Given that French islands covers all latitudes in the Pacific, Indian and Atlantic oceans and in the Mediterranean, our results suggested that the implications for the 180 000 islands around the world should be considered. Therefore, decision makers are required to define island conservation priorities that will suffer of the future sea level rise.

Keywords

French islands, sea level rise, insular biodiversity, climate change

Introduction

Despite considerable attention to global change effects, few studies focused on the consequences of sea level rise (Menon et al. 2010; Wetzel et al. 2012; Schmidt et al. 2012). Many studies showed that global warming will be one of the biggest threat to future biodiversity, and predictions could play an important role in alerting scientists and decision makers to support the development of proactive strategies to reduce climate change impacts on biodiversity (Bellard et al. 2012). Potential effects of sea level rise are of considerable interest because of its potential impact on biodiversity and society. By 2030, 50% of the world population will live within 100 km of the coast (Small and Nicholls 2003; Bindoff et al. 2007). The two major causes of global sea level rise are thermal expansion of the oceans (water expands as it warms) and the loss of land-based ice due to increased melting. During recent years, for which the observing system is much better, thermal expansion and melting of land ice each account for about half of the observed sea level rise (Solomon et al. 2007). Several recent studies strongly suggest that sea level rise will increase by 0.5 to 2.3 m at the end of the century (Rahmstorf 2007; Pfeffer et al. 2008; Grinsted et al. 2009; Jevrejeva et al. 2010; Nicholls and Cazenave 2010; Traillet et al. 2011). Most dramatic scenarios of ice sheet melting and sliding lead to potential sea level rise of 4 to 6 m (Overpeck et al. 2006). Sea level increases could lead to the total immersion of many low-lying islands, associated with potential important consequences for biodiversity. Surprisingly, few studies have focused on consequences of sea level rise on islands and their biodiversity, only specific archipelagos that represent very limited subsets of existing islands (Baker et al. 2006; Webb and Kench 2010; Wetzel et al. 2012; Bellard et al. 2013), or on continental coastlines (Menon et al. 2010; Hinkel et al. 2010; Traill et al. 2011) have been studied. Yet, islands are generally considered as important hotspots of biodiversity due to very high endemism richness, about 70,000 vascular plant species are endemic to islands (Kier et al. 2009). In particular, among French territories, four of them are present in biodiversity hotspots. Although French islands only represent 0.08% of Earth land surface, they contain 1.4% of the plants, 3% of the molluscs, 2% of fishes, 1% of reptiles and 0.6% of birds of the world. Therefore, one could expect significant loss of insular biodiversity due to sea level rise. For example, the endangered Lower Keys Marsh rabbit (*Sylvilagus palustris hefneri*) already lost 64% of its habitat, the majority due to sea level rise (>48%) (Schmidt et al. 2012). While actions to mitigate climate change and its consequences in islands are being debated, few studies regard the potential impact of an increase of sea level on insular habitats.

Here, we assessed impacts of sea level rise on islands ($n = 1269$) under French jurisdiction. This sample includes islands of various sizes, geological types and elevations, and covers all latitudes in the Pacific, Indian and

Atlantic oceans and in the Mediter-ranean. We investigated three scenarios of projected sea level rise on these islands, to provide estimations of loss of entire islands. First, we considered a global sea level rise by 1 m that is slightly below the average of six recent projections of sea level rise for 2100 (Overpeck et al. 2006; Rahmstorf 2007; Pfeffer et al. 2008; Grinsted et al. 2009; Jevrejeva et al. 2010; Nicholls and Cazenave 2010). We also explored another

realistic upper bound of 2 m sea level rise (Nicholls and Cazenave 2010) and an extreme scenarios of 3 m (Hansen 2007). In addition, we studied sea level rise of two different types: a uniform increase over the globe or a recent projection that considers the regional variability of sea level rise based on a synthesis of 16 sea level rise models (see Figure 2B for details). The latter projection is more realistic because heterogeneous ocean warming will lead to non-uniform thermal expansion (Cazenave and Llovel 2010) and leads to average rises of 1.05, 2.10 and 3.15 m, hereafter termed ~1 m, ~2m and ~3 m in order to compare with homogeneous rises.

For each scenario, we assessed the number of islands that would be entirely submerged, which was estimated by overlying maximal island elevation with local sea level projections. These must be considered very conservative estimates of biodiversity impacts of sea level rise on islands because we only consider losses on islands that are totally submerged. Finally, we also highlighted a case study of New Caledonia taking into account partial habitat losses of islands and potential loss of endemic plant species area distribution due to sea level rise.

Materials and methods

French islands

In order to be exhaustive, we defined both islands and islets as “islands”, the only difference being the size (islet have a smaller area). The majority of islands represent single land masses, but in some cases, mostly for atolls like Tuamotu, islands may consist of numerous islets sharing a common geological origin. France possesses around 2,000 islands across the world, but many are located in rivers or lakes. Among oceanic islands, topographic data are available for 1,269 islands that encompass all latitudes and geologic types of island ecosystems. Moreover, French islands are present in 4 of the 25 hotspots of global biodiversity including the Caribbean islands, Indian Ocean islands, Polynesia Micronesia islands, and New Caledonia islands (Myers et al. 2000). Furthermore, the French maritime domain encompasses 10% of the coral reefs and 20% of the atolls of the planet.

Elevation data

Island coordinates were derived mostly from the Geonames database (<http://www.geonames.org/>) and inspection of satellite imagery on Google earth. To obtain data on maximal elevation (*i.e.*, the difference in meters between sea level and the highest point) of each island, we used two different

databases: IGN map (National Institute of Geographic information) where maximum elevation is provided for most of the studied islands (<http://www.geoportail.fr/>) and elevation data from Google Earth for the few remaining islands. For those few islands, Google Earth was used to check that at least one point in elevation was higher than the considered sea level rise.

Assessing impacts of sea level rise on islands

Sea level rise scenarios

Islands are identified as submerged if their highest elevation is below the considered sea level rise projection. We used two different scenarios of sea level rise. First, we used a homogeneous scenario, where sea level rise is equal at all latitudes and longitudes. Then, we used a heterogeneous projection of sea level, where we considered spatial variability of the rates of sea level rise, which is mostly due to non-uniform changes in temperature and salinity, and related to changes in the ocean circulation. For the homogeneous scenario, we used an uniform increase of sea level by 1, 2 and 3 meters over the globe. For the heterogeneous scenario, we used the IPCC map that represents an ensemble mean of 16 Atmosphere-Ocean General Circulation Models, under the scenario A1B, which considered regional variability. Using ArcGIS, we determined the location of each island and we attributed the sea level value of increase by 2100 that varied from

0.05 m to 0.65 m for each island according to the projected local sea level rise. Because it is impossible to obtain island elevation data in decimeter units, we rounded off to the full next meter, always making a conservative estimate when doing so (e.g., 1.8 m to 2.7 m was considered as 2 m, see Fig. 2B for details). As mean sea level rise based on the IPCC scenarios (0.35 m) is now considered too conservative (Nicholls and Cazenave 2010), we have considered three different heterogeneous projections : a mean rise of 1.05 m, 2.10 m 3.15 m to match with the homogeneous scenarios of 1, 2 and 3 m. In the main text, these are notated as ~1 m, ~2 m and ~3 m, respectively. We assumed that all Mediterranean islands will be subject to an increase in sea level from 0.35 to 0.45 m (like the Atlantic zone) because data produced for 2021-50 mean projected an increase of sea level that ranges between +7 and +12 cm (Gualdi et al. 2013).

Number of island submerged

We used total island submersion as a metric because accurate digital elevation models (DEM) are not publicly available for all these islands, especially low-lying islands that are expected to be the most vulnerable to sea level rise. Additionally, assessing sea level rise impacts on low-lying islands is impossible without high resolution because most of the current satellite-based DEMs contain biases that greatly exceed the precision required for a study of low lying island submersion (Hinkel et al. 2010).

Case study of New

Caledonia Elevation data

In order to consider partial habitat losses, we used the Digital Elevation Model (DEM) from NASA's Shuttle Radar Topography Mission (SRTM) (Jarvis et al. 2008), we did not consider connectivity of cells or lateral erosion. We also calculated the sum of the number of pixels under the 3 different sea level rise projections by island and for the entire region using R.15 version.

Endemic plant species

We obtained endemic species area distribution polygons provided by the IUCN data- base for each of the 64 plants (IUCN 2012). Then, we calculated the species area distri-bution that will be submerged under an increase of sea level by 1, 2 and 3 meters for each endemic plant species within New Caledonia according to their spatial distribution.

Results

Potential island losses

We calculated the number of islands entirely submerged under three different scenarios of sea level rise (~1, ~2 and ~3 m) and two projections homogeneous and heteroge-neous. Our results indicated that about 5% of islands would be entirely submerged with a globally uniform sea level rise of 1 m (Figure 1). This corresponds potentially to 64 French islands that will be vulnerable to an increase of sea level by 1 meter. The uniform increase of sea level by 3 m increased this estimate to about 11% (*i.e.*, 145 is-lands). Using a spatially heterogeneous sea level rise scenario, we showed greater losses ranging from 6% to 12% of submerged islands for scenarios of ~1 and ~3 m, respectively (see Figure 1 and Material and methods). This last result corresponds potentially to 83 and 156 islands that will be at risk of submersion in the future. Globally, the number of islands potentially vulnerable to sea level rise was slightly more important for heterogeneous scenarios, whereas results using homogeneous scenarios were lower. However, for all projections considered, the regions with the most important number of islands potentially threatened were New Caledonia (>30% of the total islands en-tirely submerged were located in New Caledonia), French Polynesia (>30%) and the Mediterranean (10%), although many islands will also be submerged in other regions such as Caribbean islands, Madagascar and Guyana (Figure 2A and Figure 3).

Consequently, rising sea would potentially threaten a considerable part of French insular biodiversity, especially in New Caledonian region. Considering that at least 5% of the number of islands will be entirely submerged under an increase of sea level by 1 meter, many plants will be endangered by an increase of sea level as well as otherspecies located in these islands. In addition, other islands that are not under French jurisdiction but that are located in these regions could be highly vulnerable to sea levelrise, and the potential losses of insular habitat could be very similar at the world scale.

New Caledonia case study

Because our results showed that New Caledonia region is particularly sensitive to sea level rise, we decided to study the potential partial losses in this region. Overall, our results showed that between 1.7 and 2% of New Caledonian area will be permanently

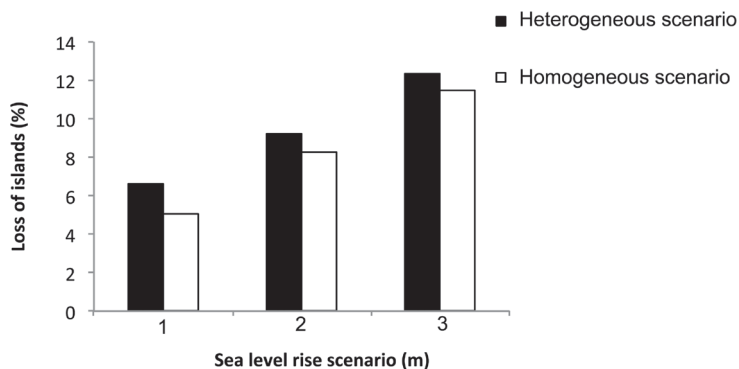


Figure 1. Percentage of islands entirely submerged under three scenarios (lower ≈ 1 m, middle ≈ 2 m and upper ≈ 3 meters) and two projections (homogeneous rise and heterogeneous rise).

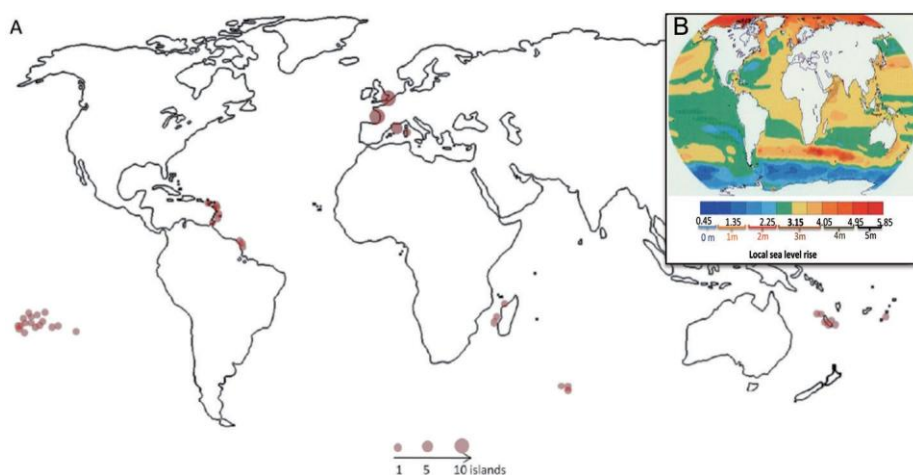


Figure 2. **A** Spatial distribution of submerged French islands following the pessimistic scenario (~ 3 m rise) **B** Local sea level change (m) due to ocean density and circulation change relative to the global average during the 21st century under SRES A1B scenario.

submerged under an increase of sea level rise by 1 to 3 meters, respectively (Figure 4AB). Taking into account partial losses of New Caledonian islands, we estimated that between 2.3% and 6.8% of islands will have more than half of their area entirely submerged. With an increase of sea level by 1 meter, 29.5% of New-Caledonian islands will have between 1 and 25% of their area inundated. Based on our results, more than 50% of islands will be safe from

permanent inundation because of their high elevation profile (Figure 4C) although we recognized that indirect effects of sea level rise such as lateral erosion could lead to significant effects for these islands.

Using the endemic plant species distribution, we estimated the species area distribution that will be submerged under an increase of sea level by 1, 2 and 3 meters. We then calcu-

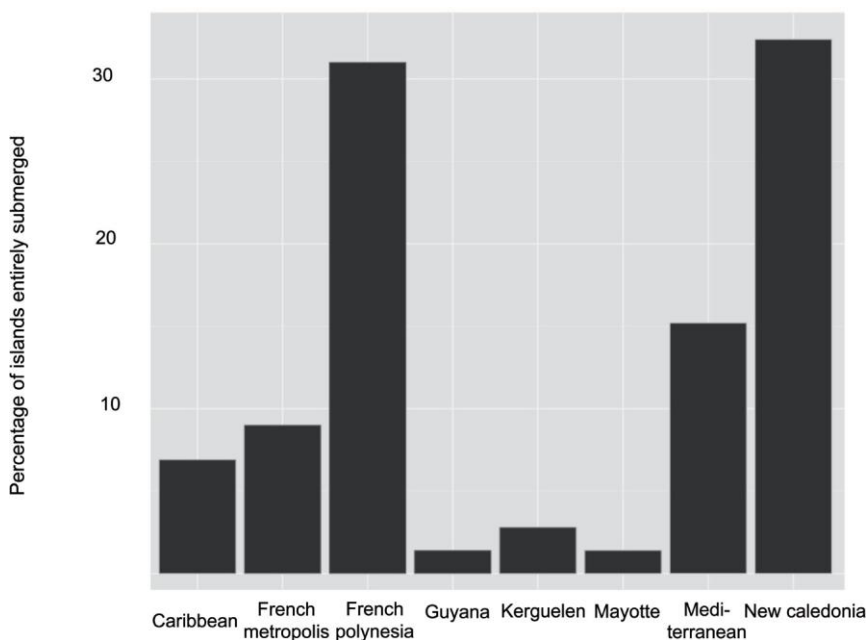


Figure 3. Spatial distribution of the entirely submerged islands for the different French regions under an increase of sea level by 3 meters.

lated the potential area losses for each endemic plant species under the different scenario of sea level rise and we averaged according to the IUCN status. Overall, our results showed that endemic plant species will lose between 1.25% and 3.98% of their area distribution under an increase of sea level by 1 and 3 meters, respectively (Figure 5). With an increase of sea level of 3 meters, the habitat loss of the species that are classified as “least concern” by the IUCN was 1.16%, while it reached 6.88% for the “critically endangered” plant species. These results highlighted that the vast majority of endemic plant species vulnerable to an increase of sea level, are already at a high risk of extinction. Consequently, species that already are at higher risk of extinction will lose the largest habitat following sea level rise.

Discussion

Over the next 60 years, sea level rise and higher storm frequency, together with natural and human-induced subsidence, population growth and urbanization, will cost roughly 9% of global GDP (Hanson et al. 2010). However, little attention has been paid to island vulnerability directly caused by sea level rise (Menon et al. 2010; Wetzel et al. 2012). It is clear that sea level rise will be the largest driver of habitat loss for insular habitats (Wetzel et al. 2012). Sea level rise is a particularly

critical consideration for preserving coastal biodiversity, yet many approaches for prioritizing conservation networks do not take this into account (Runting et al. 2013). Our results predicted that impacts of sea level rise on insular French

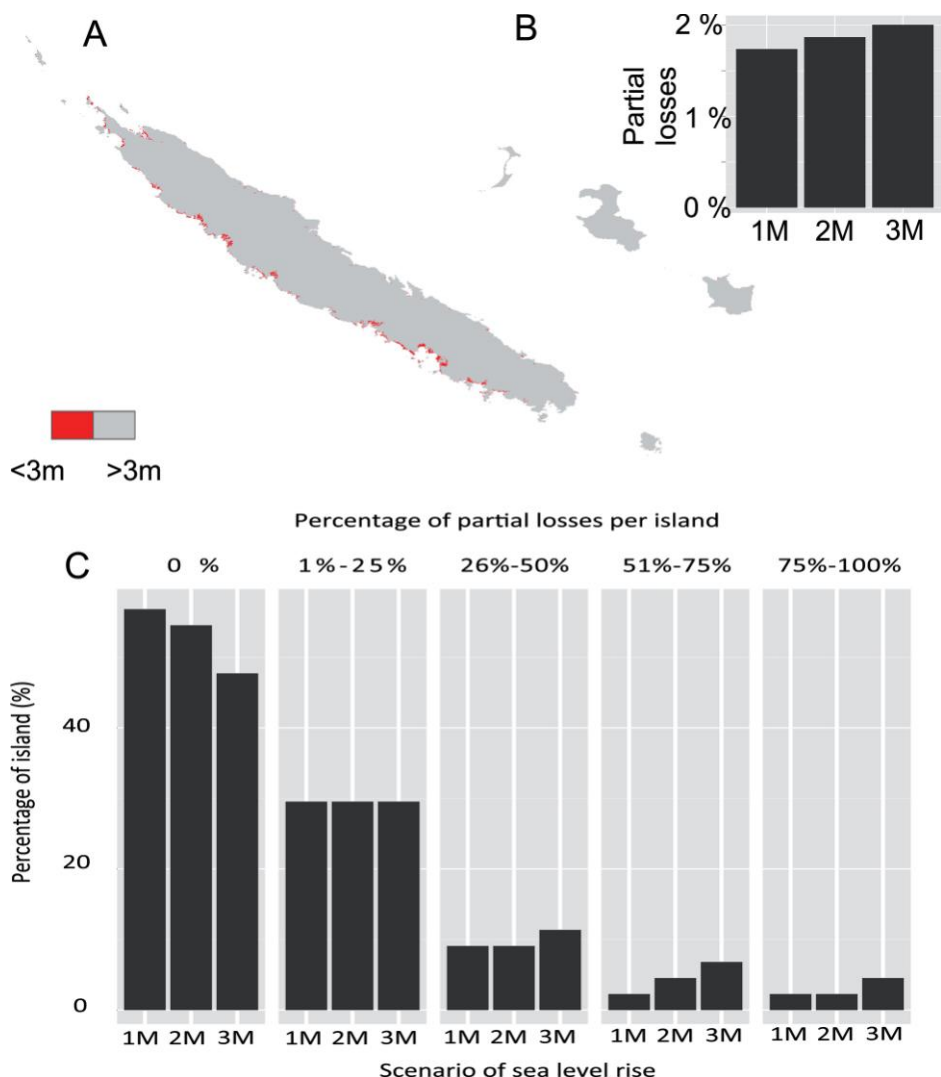


Figure 4. **A** Map representing the partial habitat losses of New Caledonia region with an increase of sea level by 3 meters **B** Percentage of areas partially submerged in New Caledonia region under an increase of sea level by 3 meters **C** Percentage of island that are partially submerged for different classes of submersion.

habitats are likely to be important, especially for two regions: New Caledonia and FrenchPolynesia. Under an increase of sea level by 1 m, at least 5% of islands will be potentially en- tirely submerged. Our pessimistic scenario projected a loss of up to 11% of French islands. Globally, we did not observe important differences between homogeneous and heteroge- neous projections results. Other studies

that attempted to study the potential impacts of sea level rise in terrestrial eco-regions (Menon et al. 2010) and on Indo-Malaysian islands (Wetzel et al. 2012) showed results of the same order of magnitude. We do regret our in-

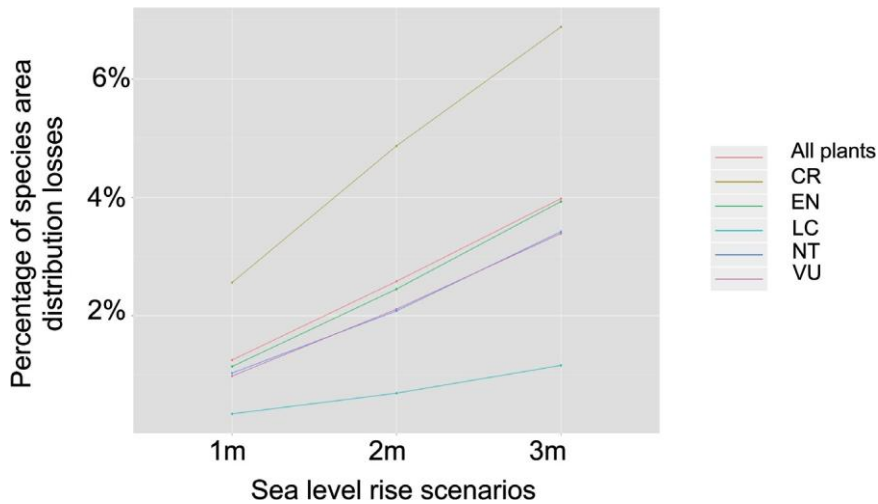


Figure 5. Percentage of species area distribution submerged under 3 different scenario of sea level rise for 64 endemic plants. We grouped the different species according to their IUCN status. CR : Critically endangered, EN : endangered, VU : vulnerable, NT : Near threatened and LC : least concern.

ability to work with a greater precision of elevation data and to take into account partial habitat losses due to marine intrusion for all the French islands. However taking into account partial losses of New Caledonia, we showed that this region will also suffer from significant partial losses of insular habitat. Therefore, neglecting partial loss of islands means that the impact of sea level rise will cause probably more dramatic land losses than projected by the study for the other regions. Actually, several factors may underestimate habitat loss estimations, especially: lateral erosion, tidal range, centennial tides or floods and increased salinity on new shorelines. For instance, beach erosion along the United States East Coast due to sea level rise was about two orders of magnitude greater than the rate of sea level rise (Zhang et al. 2004). This means that, for example, a 1 meter rise of sea level would create habitat loss of about 100 meters inland along the coasts due to lateral erosion. Therefore, results are conservative and they give evidence that sea level rise represents an important threat on insular biodiversity over the next decades. We did not either consider the indirect habitat losses following displacement of human population from inundated areas and the potential important ecological consequences if urban and intensive agricultural areas in the coastal zones of islands are relocated to the hinterland (Wetzel et al. 2012), though these effects have been shown to be sometimes greater than the losses directly due to sea level rise. Then, regarding endemic species distributions over New Caledonia, we showed that species that are already at risk of

extinction were the most vulnerable to sea level rise. This result is particularly important, because it means that endemic plants that are at risk of extinction are mainly located on the coastal areas. Although we focused on endemic plant species, rising seas will also flood other populations of different taxonomic groups including invertebrates and vertebrates. In addition, the two most important regions that are susceptible to be threatened by sea level rise are part of

biodiversity hotspots. For instance, French Polynesia contains 85 of the 425 atolls of the world that shelter nearly 19,000 vascular plant species including 3,450 endemicspecies. These species may also have to face many threats such as salinity intrusion, submersion, soil erosion and climate changes.

We attempt a first approximation of the potential impact of sea level rise on French biodiversity following marine intrusion. In our study, most of islands that showed important vulnerability to sea level rise were atolls. Their remoteness from mainland, &at topog- raphy and great susceptibility to natural disturbances (e.g., hurricanes) might lead to a low biodiversity present in these islands. Thus, the biodiversity on small islands and other low- lying coastal regions appeared to be highly vulnerable to sea level rise, but it is unclear how many species could be lost under existing sea level rise projections. To conclude, some pat- terns emerging from this study provided useful information for conservation planning. As our climate continues to change at a faster rate than previous century, sea level rise will cre- ate further challenges for the conservation of insular ecosystem in French territories, and in low lying areas worldwide. Given that French islands covers all latitudes in the Pacific, Indian and Atlantic oceans and in the Mediterranean, with the French maritime domain being ranked as the second largest in the world, our results suggested that the implications for the 180 000 world islands around the world should be considerable. Assuming that French islands are representative of worldwide islands, roughly 10,800 islands could be entirely lost with the 1 meter scenario. Consequently, new prioritizations programs for islands have to be established in order to mitigate the impacts of sea level rise. For example, in order to anticipate threats and prepare adequate conservation actions (e.g., local protec- tion, identification of refuges or translocation programs), conservation managers have to target specific islands that have high risk of being permanently inundated within the next decades. Our results suggested that the effects of sea level rise will be particularly danger- ous for New Caledonia, and French Polynesia. Considering their important contribution to global biodiversity and the threat of sea level rise for future biodiversity of some of these islands, there is an urgent need that islands feature prominently in global and regional conservation prioritization schemes. In addition, with accepted projections of sea level rise now exceeding one meter, the improvement of estimates of the associated loss of insular habitat and biodiversity becomes essential. In addition, it would be advantageous for deci- sion makers to have more certainty about future sea level rise, the nonlinearity of ice-sheet melt makes accurately predicting the change in sea level at a particular date unattainable at present (Hansen 2007). We hope that this study will provide a first valuable attempt for new research efforts in this direction.

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