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Trajectories of exposure and vulnerability of small islands to climate change

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Abstract

This paper advocates for a dynamic and comprehensive understanding of vulnerability to climate-related environmental changes in order to feed the design of adaptation future pathways. It uses the Trajectory of Exposure and Vulnerability (TEV) approach that it defines as 'storylines of driving factors and processes that have influenced past and present territorial system exposure and vulnerability to impacts associated with climate variability and change'. The study is based on the analysis of six peer-reviewed Pacific island case studies covering various geographical settings (high islands vs low-lying reef islands, urban vs rural) and hazards associated with climate variability and change; and that addressed the interactions between natural and anthropogenic driving factors; and adopted multi-decadal past-to-present approaches. The findings emphasize that most urban and rural reef and high islands have undergone increasing exposure and vulnerability as a result of major changes in settlement and demographic patterns, lifestyles and economies, natural resources availability and environmental conditions. The paper highlights three generic and successive periods of change in the studied islands' TEV: from geopolitical and political over the colonization-to-political independence period; to demographic, socio-economic and cultural from the 1960s to the 1980s; culminating in the dominance of demographic, socio-economic, cultural and environmental drivers since the 1980s. Based on these empirical insights, the paper emphasizes the existence of anthropogenic-driven path-dependency effects in TEV, thus arguing for the analysis of the temporal dimensions of exposure and vulnerability to be a pre-requisite for science to be able to inform policy- and decision-making processes towards robust adaptation pathways.

Introduction

It is widely acknowledged that tropical small islands are at risk of being severely affected by the current and anticipated impacts of climate variability and change, including both extreme events and gradual environmental changes [1]. Relevant extreme climate events include tropical and extra-tropical cyclones [1,2,3], and sea level extremes known in the equatorial Pacific Ocean as 'king tides' and resulting from the combination of spring tides (highest astronomical tides) with ENSO episodes [4,5]. Gradual climate-related changes mainly comprise accelerated sea level rise and ocean warming. In addition to ocean acidification these are expected to seriously affect island livelihoods

[1,6,7, 8, 9,10]. In some cases, the threats posed by climate-related hazards can be modulated by tectonic factors generating both sudden onset and rapid, and slow, vertical land motion [11]. The serious climate-related threats tropical small islands are already facing also result from both their biophysical characteristics (i.e., low elevation, small land areas, geographic isolation, fragile ecosystems and restricted natural resources) and human features (e.g., limited institutional, technical and financial capacities, and constrained development opportunities) [12,13,14]. Moreover, the impacts of sea-related events associated with climate variability and change (i.e., marine inundation and coastal erosion) are exacerbated by the fact that most inhabitants, infrastructures and activities are concentrated in coastal areas [1,15].

Furthermore, there is evidence that small islands' exposure and vulnerability to climate-related hazards have significantly increased over the past decades [1,16]. This increase in the exposure and vulnerability of island systems is commonly attributed to a complex combination of climate-related factors, especially accelerated sea level rise, and other anthropogenic factors [1,2,7,14,17]. The important contribution of these factors has recently been identified in several studies carried out in the Pacific region, highlighting in particular the implications of the settlement of low-lying hazard-prone areas as a result of limited alternatives; rapid population growth and poor planning; the transition from traditional to modern lifestyles based on a high dependence on imported food and other goods; widespread environmental degradation; and the failure of previous development and adaptation strategies supported by regional and international organizations which were incomplete, insensitive or totally inappropriate for the nature of existing problems [17,18,19,20,21,22,23,24,25,26]. Despite this recognition, two major knowledge gaps remain that relate to our limited understanding of the complexity of small island systems in terms of the spatial diversity and temporal dynamics in response to climate variability and change. This in turn limits the ability to develop and implement relevant place-specific risk management and adaptation policies [1,16,27].

The first gap refers to the diversity of island exposure and vulnerability profiles within both regions and archipelagos [1]. The driving factors and processes controlling the exposure and vulnerability of island systems vary widely across physical space (i.e., between mountainous and reef islands, urban and rural settings, independent countries and associated territories, etc.) as well as across socioeconomic and cultural contexts [28]. These differences need to be more systematically investigated [1] in order to avoid perpetuation of hasty generalizations that lead to false conclusions and inappropriate 'blue print' solutions being proposed [29]. This includes the common perception in international political arenas that all small island countries are equally highly vulnerable to climate change, as well as international development cooperation systematically promoting one-size-fits-all solutions such as hard coastal protection and urgent international migration, even though such initiatives generate adverse side effects because of lack of consideration of place-based specificities, such as cultural values and natural system dynamics. In the scientific arena also, hasty generalizations have led to premature conclusions about the physical fragility and potential disappearance of atoll countries as a result of rising sea levels [30,31].

The second knowledge gap this paper especially focuses on, relates to our understanding of the temporal dynamics of small islands' exposure and vulnerability [32]. While it is indeed usually assumed that the environmental and human features of an island are continually changing, the extent to which these influence the temporal evolution of the exposure and vulnerability of island systems remains under-researched. This “detection and attribution” issue limits the ability to accommodate the nature and magnitude of changes in human-nature interactions in development and adaptation planning on a given island system. It also limits the ability to predict the extent of the possible effects of these changes and proposed adaptations on the systems’ capacity to cope and proactively adapt to global environmental variability and change [18,31].

To help address this second gap, this paper advocates for the analysis of the temporal dimensions of exposure and vulnerability, which will in turn allow think future adaptation on empirical bases. We called this the “Trajectories of Exposure and Vulnerability” ('TEV) approach, which we define as ‘storylines of driving factors and processes that have influenced past-to-present island system exposure and vulnerability to impacts associated with climate variability and change. We consider an “island system” as composed of interacting environmental (coral reefs, sand beaches, etc.) and societal (population, infrastructures, institutions, economic and subsistence activities, cultural values, etc.) components. Exposure is ‘the presence of people, livelihoods, species or ecosystems, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected’ while vulnerability is ‘the propensity or predisposition to be adversely affected [and] encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt’ [33]. As noted above, the climate-related hazards considered in this paper include the sea-related gradual changes, i.e. sea level rise, as well as the rapid on-set climate extreme events.

MATERIALS AND METHODS

The analysis of six Pacific-island case studies presented in this paper was exclusively based on published literature in peer-reviewed journals (Table 1). Pacific islands are the focus of this paper because they offer a high diversity of physical characteristics (mountainous *vs.* reef islands, equatorial *vs.* tropical islands) and demographic patterns, socio-economic features and political status (independent countries *vs.* associated territories), and therefore experience many diverse factors driving their exposure and vulnerability.

Materials

The scientific literature (Table 1) provides an appropriate, though not exhaustive, coverage of the diversity of island situations. In this corpus, ‘high islands’ are represented by Simbo Island (Solomon Islands), Rarotonga (Cook Islands) and Loh and Tegua islands (Vanuatu), while low-lying reef islands are represented by Funafuti (Tuvalu), Tarawa (Kiribati) and Majuro (Marshall Islands) atolls. Stretching from 7°N to 21°S in the western and central Pacific Ocean, the studied islands experience various types of climate-related hazards, notably marine inundation, coastal erosion, and climate change-induced sea level rise. In the islands located in the western equatorial Pacific, marine inundation is also aggravated by sea-level extremes correlating with ENSO events. In one case (Vanuatu), sea level changes are modulated by tectonics. These case studies also allow for the examination of urban capital islands (e.g., Bairiki in Kiribati, Fongafale in Tuvalu, the Djarrit-Uliga-Delap district in the Marshall Islands, and Rarotonga in the Cook Islands) and rural islands (Simbo Island in the Solomon Islands, Loh and Tegua Islands in the Torres group in Vanuatu). All of the selected case studies represent timescales from multiple decades to one-century and therefore provide insights on the dynamics of exposure and vulnerability (i.e., "trajectories"). Finally, most of the studies consider both natural (i.e., climatic, oceanic, morphological and ecological processes) and anthropogenic (i.e., demographic, socioeconomic, political and cultural processes) drivers of change, making it possible to analyse the respective roles of these drivers over time.

Methods

The main methodology consisted, based on the qualitative expert judgement of the authors of the present paper, in building the storyline of change experienced by each island exclusively using the available peer-reviewed scientific literature mentioned above. It consisted of capturing the influences of the natural and anthropogenic factors and processes described in available papers on exposure and vulnerability for the timeframe reported in each study. This involved identifying the main categories of driving factors mentioned by the authors and understanding their interactions over time (i.e., the nature of these interactions and the resulting cumulative effects), and subsequently analysing the processes that generated changes in the exposure and vulnerability of each island. In other words, the method consisted in capturing in existing papers first, the major facts and drivers causing change in island organization and development (e.g., the fact is the installation of a military base, and the related driver is of geopolitical order) over time, the interrelations between drivers based on the authors' analyses, and the direction and magnitude of the induced change in exposure and vulnerability (based on the authors assumptions and on the conclusions that can be drawn from these case studies). The hypothesised storyline for each case study therefore comprised the direction (i.e., increase, stability, decrease) and magnitude of change in exposure and vulnerability over the time period considered. The contribution of some authors of the present paper to the completion of four case studies out of the 6 case studies on which the present paper is based on guarantees an adequate knowledge and understanding of the precise situation of the study islands.

The next step consisted in standardizing the results to ensure that a synthetic and consistent picture of each case study emerged, including the drivers, processes, nature, and the magnitude and rhythms of changes in exposure and vulnerability.

RESULTS: FROM STORYLINES TO TRAJECTORIES OF EXPOSURE AND VULNERABILITY

This section presents storylines of the changing exposure and vulnerability to climate variability and change of two broad categories of island types in the Pacific, small atoll reef islands with low elevation (< 4 m above mean sea level and < 1 km^2), and larger and higher islands that are less sensitive to climate-related hazards but where most human assets are exposed to climate hazards because of their location in low-lying coastal areas.

Low-lying reef islands of atolls

In atoll countries, the existing peer-reviewed scientific literature on exposure and vulnerability to climate-related hazards only deals with reef islands in urban areas, generally capitals. These islands fall into two distinct categories. The first involves extended urban districts including a chain of islets connected by causeways. Two such urban districts are well documented in the literature, the Djarrit-Uliga-Delap district (DUDD) on Majuro Atoll (9,7 km^2) in the Marshall Islands, and the South Tarawa Urban District (STUD, 15,6 km^2) on Tarawa Atoll in Kiribati. The second category includes single urban islands, such as Fongafale Islet in Funafuti Atoll, Tuvalu.

Djarrit-Uliga-Delap District, Marshall Islands

The DUDD extends some 20 km on the southern rim of Majuro Atoll. It can be considered as an "accident of history" [18] as its origin is the staggered construction of a military base on the uninhabited eastern islands of the atoll beginning in the 1940s. Up to that time settled islands were mainly on the sheltered western rim of the atoll, including the large island of Laura. These latter islands are relatively well protected from tropical cyclone impacts [18,34], therefore offering secure food and drinking water supplies. People on these islands have a rural lifestyle based on the sustainable use of natural resources. After the establishment of the military base, operation of the administrative centre and development of infrastructure by the US on eastern islands of the atoll rim created work opportunities, leading both to a shift of the main settlement from western rural Laura Island to eastern "modern" islands, and to the development and growth of housing on the eastern islands. Between 1947 and 1988 the population increased from 837 to 19,695 inhabitants, as a result of natural population growth and internal migration due to the relocation of the people from the atolls affected by nuclear testing and rural exodus. This population growth and the development of a cash society accelerated changes in lifestyles, which decreased access and use of natural resources and increased imports of goods. In November 1979 a major flood event severely affected the DUDD, highlighting the high exposure of its population to storm surges. This event led to the temporary relocation of 5,000 people to safer Laura Island. Despite this experience, housing expansion continued on the windward ocean shore, with land reclamation "pushing out the habitable area onto the reef platform" [18: 341] and thereby increasing population exposure to storm surges. Since then, the population reached about 28,000 inhabitants on Majuro in 2011 [35]. Although land reclamation has up to now contributed to a significant increase in land area on some islands [23], availability of reclamation materials will decrease in the long-term as a result of water pollution that increases coral mortality and decreases foraminifera production [36,37]. Moreover, land reclamation and seawall proliferation have disrupted coastal dynamics, accelerating coastal erosion that exacerbates population exposure to flooding at some locations [23]. In parallel, population vulnerability is increased as a result of more modern house styles favouring western designs that are less able to withstand tropical cyclones, as well as by the proliferation of sub-standard houses built by poor migrants. The current situation of Majuro Atoll illustrates the vicious cycles that can occur in overpopulated atoll capitals.

Faced with this critical situation, the Government is now attempting to raise funding for the construction of a massive seawall that would protect this urban district from storm waves all along its highly exposed ocean coast [23]. Such a measure however carries the risk of increasing the sensitivity of islands to flooding in the longer term, as it would prevent sediment deposition at the coast.

South Tarawa Urban District, Kiribati

On the whole, despite differences in chronology and colonial history, the TEV of the STUD is similar to that of the DUDD. The STUD stretches 35 km from west to east on the southern rim of Tarawa Atoll. It dates back to the development of key infrastructure by the British colonial administration in the first decades of the 20th century, including the harbour in the west and an airstrip in the east. People have been attracted from the outer atolls to these urban islands as a result of centralization of political power, concentration of administrative functions, key services (mainly education and health), work opportunities on the southern islands of this atoll (especially the three capital islands of Betio, Bairiki and Bikenibeu), and increasing connectivity of Tarawa Atoll to the rest of the world [38]. From the 1970s population growth due to the improvement of sanitary conditions and internal migration from rural atolls resulted in the population increasing from 6,101 inhabitants in 1963 to 50,181 inhabitants in 2010 [39]. Although the capital islands remained the most appealing of the atoll's southern islands, the linking of all islands by causeways that occurred in the 1990s encouraged the development of housing throughout the District. Even unstable coastal land was settled including recently formed sand spits and accreted areas, thus exacerbating population exposure to flooding at some locations [24]. Together, land shortage and the settlement of unstable land encouraged land reclamation and the construction of coastal defences that have adverse effects on the coastal environment (mainly through aggregate mining) and disrupted coastal dynamics [40,41]. As a result, the same vicious cycle effect as that observed in the DUD district can be identified: land shortage leads to the reclamation of upper beaches and inner reef flats, as well as to the construction of coastal defences. Both cause accelerated environmental degradation that exacerbates population exposure and vulnerability to current and future climate-related hazards. The most vulnerable families to these hazards are generally poor I-Kiribati migrants due to their limited access to cash revenues, health and education [24]. Lastly, due to inadequate waste and water management practices, rapid population growth has led to the contamination of groundwater resources, generating serious health problems also increasing population vulnerability [21,42].

Fongafale Islet, Tuvalu

Only one urban island is documented in the literature and considered in this study, namely Fongafale Islet, the capital of Tuvalu, located on Funafuti Atoll [20]. The British established the capital of the Gilbert and Ellice Islands colony (now the two nations of Kiribati and Tuvalu) on Tarawa Atoll. This partly explains why Tuvalu has no urban district. With the advantage of an airstrip that was constructed in 1942, Fongafale Islet was chosen as the capital at the time of independence (1978). This was despite its high sensitivity to flooding due to the presence in its central part of large swamps only separated from the ocean by a beach ridge. The vulnerability of this islet to flooding had been aggravated by the adverse environmental impacts of the construction of the airfield, which involved swampland reclamation, mangrove deforestation and aggregate mining that created numerous borrow pits [20]. Rapid population growth occurred as a result of the attraction of the capital encouraging continuous in-migration from outer atolls and abroad, including men returning from being employed in phosphate extraction on Nauru and Banaba islands. Thus, between the end of the 19th century and 2012 the population of Funafuti Atoll increased from 251 (7% of Tuvalu's population) to 6,194 people, or 62.7% of the total population [43]. As in the DUDD and the STUD, land shortages prompted people to settle in more hazard-prone areas, such as reclaimed parts of the inner swamp and on the ocean-side of the beach ridge. Settlement of these highly exposed areas, and the weakening of natural buffers, especially the ocean-side vegetated beach ridge, results in the flooding of inhabited areas when high sea levels occur [26]. Thus, the increasing exposure and vulnerability of the population of Fongafale Islet to climate-related hazards was triggered by geopolitical factors that have led to the concentration of a large population on a small flood-prone island. This has been subsequently exacerbated by unsustainable development practices.

To conclude, although the nature, magnitude and chronology of the processes driving change vary, the same effects are reported in all three urban districts and islands. While geopolitical (colonization and military strategies) and political (centralization of power and development of key infrastructures and services in one or several islands) factors have acted as triggers, demographic, socio-economic and cultural changes (attraction of the capital, changes in lifestyles and resource management, etc.) have rapidly become the key drivers of the TEV of these island systems. Since the 1960s-1970s they feed vicious cycles in which environmental degradation plays a central role in exacerbating short-term and long-term vulnerability to climate-related hazards.

High islands

Available studies of high islands highlight key differences between urban islands, including capital islands, and their rural counterparts. In addition, and similar to the findings of studies of atolls, they emphasize the major influence of demography, settlement and land use patterns and related lifestyles on both the nature of change and the TEV of islands, especially rural islands.

Urban islands: example from the Cook Islands

In an assessment of storm surge risk on Rarotonga, the capital island of the Cook Islands, de Scally [44] highlighted the key contribution of changes in settlement and land use patterns to increasing population exposure and vulnerability to climate-related hazards. As in many other mountainous islands of the Pacific, the population of Rarotonga moved from safe inland locations to flood-prone coastal areas, first under the influence of missionaries and then as a result of the concentration of critical infrastructures (harbours and airport) and job opportunities (mainly in administration and tourism). This led to the concentration of most of Rarotonga's inhabitants (10,572 inhabitants representing 70% of the country's total population) and the majority of the Cook Islands' government functions, economic activity and critical infrastructures in the coastal areas that are most exposed to tropical cyclones. Additionally, increased population pressure on coastal ecosystems has caused significant environmental degradation through the removal of the natural vegetation, blasting of channels through the reef flat and proliferation of coastal works, such as land reclamation and the construction of coastal protection. Environmental degradation has exacerbated both population exposure and the physical vulnerability of the island system to the impacts of sea-level rise, damaging ocean swells and tropical cyclones. Additionally, poor practices in urban planning, including establishment of cyclone safety centres in flood-prone areas, have increased the vulnerability of the population to climate-related hazards. The major relevance of this study compared to the rural ones below, is the high level of exposure and vulnerability of the entire country, as a result of centralization and the concentration of critical human and infrastructure assets in a small and vulnerable area on one of the country's 11 inhabited islands [45]. This case thus emphasizes two different but complementary processes that can co-exist and thereby increase exposure and vulnerability to climate-related hazards, i.e. the negative impacts of critical economic changes and the concentration of settlement in hazard-prone areas.

Rural islands: examples from the Solomon Islands and Vanuatu

Studies conducted in the Solomon and Vanuatu Islands enable the reconstruction of the TEV of rural communities living in high mountainous islands.

Simbo Island, Solomon Islands

In their study on Simbo Island, M. Lauer et al. [25] emphasize two key drivers of change that have influenced the TEV of the community to sea-related hazards. The first one refers to changes in settlement patterns: on Simbo island, as in many other Pacific islands [46], the shifting of settlements from inland village sites and high defensive coastal sites to low-lying coastal areas has generated exposure to sea-related hazards. Several factors successively caused people move to these highly exposed sites: firstly, the efforts made over the past two centuries by missionaries and government officials to gather people together in villages most of which are coastal, and later on the desire of Simbo Island's inhabitants to gain access to services and resources mainly located in coastal areas, such as health care, marine resources and the jobs provided by the copra-based plantation economy. The second key driver highlighted in this study is globalization, which is commonly considered to increase island communities' exposure and vulnerability to sea-related hazards. In Simbo, however, globalization does not necessarily undermine people's ability to cope with natural disasters and can even contribute to reduce vulnerability to them. Despite a dramatic boom in population numbers (from 376 inhabitants in 1930 to 1,782 people in 2009), the subsistence base has not been undermined due both to the high resilience[a] of marine ecosystems, thereby securing food supply, and to the persistence of traditional resource management practices. For example, maintenance of customary ownership practices supported the ability of this community to face a 12m tsunami in 2007 – the maintenance of land rights to inner garden plots enabled immediate relocation of villagers inland, providing them with an easy access to alternative land-based food resources. Although population growth increases stress on natural resources, these resources still adequately meet local household needs. In addition, globalization contributes to the decrease in population vulnerability to natural disasters through educational and professional opportunities supporting leadership building and access to external support that have also contributed to post-tsunami recovery. Globalization has also encouraged emigration, thus helping limit population growth and its pressure on ecosystems and natural resources. This study therefore brings new insights to the impacts of globalization on the TEV of rural communities to natural and more specifically climate- and sea-related hazards.

Loh and Tegua islands, Torres group, Vanuatu

The case study of Loh and Tegua islands brings original insights on the combination of two drivers, human and geophysical, in increasing population exposure on these islands [11]. As described above for Simbo Island, the western influence (missionaries and colonial power) has generated a shift of settlements from inner plateaux to coastal terraces, increasing people exposure to sea-related hazards from the end of the 19th century. Noteworthy, this increase in population exposure has occurred in a context of decrease in population numbers resulting from forced migrations organised by Westerners ("blackbirding"). In Loh and Tegua islands, a modulation in population exposure results from tectonic-induced environmental changes at different timescales and with different magnitudes. In 1997, a 50 cm relative sea level rise was indeed directly caused by the ground subsidence associated with a magnitude 7.8 earthquake. Afterwards, the relative sea level continued to increase until 2009 by almost 2 cm/yr^{-1} due to a combined effect of slow inter-seismic subsidence of the ground (estimated at 0.94 +/- 0.25 cm/yr^{-1} from 1998 to 2009) and absolute sea level rise (trend of 1.2 +/- 0.15 cm/yr^{-1} between 1997 and 2009). The combination of these different drivers has caused village flooding and the extension of marshy areas. This caused a rapid acceleration in population exposure. In 2009, another seismic event induced a 20 cm uplift of the islands, which resulted in a small and sudden decrease in population exposure. Additionally, population vulnerability has been exacerbated by the loss of environmental knowledge resulting from cultural change [46].

This case is distinctive as it emphasizes the key role that tectonic drivers can have on population exposure and vulnerability to sea-related hazards. In the Torres case, islands have been exposed both to slow and fast as well as up and down land movements. Although not detailed in the other cases presented in the paper, the tectonic driver is not specific to Vanuatu islands and can impact other places, such as the Solomon Islands where both up and down meter-scale vertical land movements were associated with the 2007 M8.1 earthquake [47]. This case again shows the key role of anthropogenic factors, i.e. changes in settlement patterns and cultural features, in TEVs.

DISCUSSION

This discussion touches upon the second knowledge gaps raised in the introduction, i.e. the factors and processes driving small islands' TEV.

Almost all of the TEVs we reported in this paper – except Simbo Island case – clearly highlight that both the exposure and vulnerability of island systems to climate-related coastal hazards have significantly increased over the past decades to century. However, the TEVs of small islands reveal key differences between atoll reef islands and high islands. At a general level, the TEVs reveal that populations on atoll reef islands are highly exposed and vulnerable as they are concentrated on flood-prone areas and in poor socio-economic and environmental conditions. In extreme cases such as Fongafale Islet, the intrinsic physical sensitivity of the island to marine inundation has been exacerbated by environmental degradation and unsustainable development practices which have undermined any natural resilience and irreversibly increased the vulnerability of the island system and population. The situation of capital towns in high islands, on the other hand, does not look to be as severe as the one of atoll urban islands.

Almost all the TEVs reveal change as continuous and gradual, suggesting the existence and prevalence of path–dependent processes. Exceptions do exist, however, as shown by the Vanuatu case (and any tectonically active region), where earthquakes have been responsible for slow and fast up and down land movements generating unpredictable and sometimes catastrophic changes in exposure. In all TEVs, the cultural values and natural resource management practices changed considerably throughout the timeline from colonization to the present. Although the direction and magnitude of changes relating to these two drivers varied significantly across case studies, changes generally led to an increase in island systems' vulnerability [22,42]. Finally, the TEV approach revealed the existence of periods where the relative prevalence and influence of particular drivers dominated other drivers, and this is particularly evident for atolls. Three generic periods arising from the panel of peer-reviewed literature we considered in this study, include: 1. Where geopolitical and political drivers dominated (i.e., from the colonization to political independence of island countries); 2. Where demographic, socio-economic and cultural drivers dominated (i.e., from the 1960s to the 1980s); and 3. Where environmental drivers dominated (i.e., from the 1980s to the present). These three periods of change, which are discussed below, occurred sequentially in the same order in all TEVs, with each subsequent period's predominant driver being the result of the previous period's predominant driver. Put simply, the political drivers in Period 1 changed the traditional cultural, land-use and socio-economic practices which then dominated Period 2, which in turn led to unsustainable resource-use practices and created the dominance of environmental drivers in Period 3 (Figure 1).

Geopolitical and political drivers have caused major and long-lasting changes in traditional settlement patterns and land-use practices that have affected both exposure and vulnerability [48,49]. Indeed, the European influence led to the concentration of scattered communities in coastal villages and thereafter, in coastal capitals that attract people from more distant locations. In high islands, this generally made settlements shift from safe inland locations to flood-prone coastal areas, resulting in people becoming more exposed to climate driven sea-related hazards. Such settlement shifts have also, in some cases, increased the sensitivity to new drivers- for example to vertical land motion in the Torres islands, illustrating the complex and changing interactions between various drivers. In atoll countries, uninhabited flood-prone islands were settled, significantly increasing population exposure. In addition, the centralization of power and emergence of island capitals caused profound lasting changes in the structure of island countries, leading to the growing concentration of the population on the capital atoll, which increased both exposure and vulnerability. And as the distribution of power and population was traditionally intimately correlated with natural resources management, changes in settlement patterns profoundly disturbed land tenure, resource use and livelihoods, and consequently decreased community long-term ability to cope with environmental stresses. Especially in atoll countries, World War II radically altered the environment through the construction of the first airfields and harbours and the maintenance of existing major infrastructure, which resulted in both a reduction in land access for the people living on capital islands where these infrastructures are located and heavy environmental degradation reducing natural resources availability. The emergence of urban areas and capitals in this period will have a long-lasting influence on the demographic, socio-economic and territorial dynamics of atoll countries, bringing about key changes in the vulnerability of their populations. These profound changes are not being challenged by the accession of these islands to political independence or autonomy. Given the profound path-dependencies that they have caused, geopolitical and political factors can therefore be considered as the main triggers of change in population exposure and vulnerability to climate driven sea-related hazards over the colonization-to-independence period. As such, they can be considered as 'root causes' [50] or 'systemic causes' [51] of vulnerability.

From the 1960s to early 1980s, the demographic and socio-economic impacts of centralization came to dominate, notably in urban areas and especially in capital islands, where they caused both significant changes in lifestyles and serious environmental degradation. From that moment on, population booms occurred in most island countries, notably as a result of the improvement in health conditions. The impacts of these population pressures and the extent of socio-economic changes have proved, however, to be radically different between urban and rural islands, supporting the need to recognise and identify differentiated TEVs. In urban areas, especially capitals, natural population growth combined with massive in-migrations from outer islands for access to better health, education and job opportunities [52] caused critical problems that to date, neither the public authorities nor development partners adequately planned for, nor have been able to subsequently manage or resolve. The growing disconnect between people and local natural resources has created a high dependency on cash to meet food requirements and has led to a dramatic increase in poverty and health problems due to limited work opportunities [21,26,53,54,55].

The third generic period in urban island TEVs is characterised by the prevalence of environmental degradation and natural resource extraction caused by growing pressures and disturbances due to growing populations and socio-economic activities such as reclamation works, aggregate mining, and infrastructure development. These environmental disruptions have both direct and indirect negative impacts on human well-being, including increasing scarcity of food resources, widespread ecosystem degradation and water pollution [36,54,56]. In fragile environments such as atolls, human-induced environmental degradation has even increased the geomorphic sensitivity of islands, exacerbating population exposure and vulnerability [20]. As a result, the vulnerability of reef island urban communities is increased by a cumulative loss of social (including cultural, and as a result of migration), economic (due to the failure in replacing natural resources by cash work) and natural capital that undermines community's response to disasters (see for example [26]).

Rural islands exhibit quite different TEVs compared to urban islands. Many remote rural islands have, so far, undergone limited socio-economic change relative to urbanized communities. In some cases (e.g. Simbo Island), traditional land use and resource management practices have persisted, which has usually preserved the social and natural capital supporting the ability of these island communities to face climate variability and change. This situation, however, is now rapidly changing as these islands increase their engagement with global markets in the form of cash cropping or migrating to urban centres for employment. This is particularly the case for rural islands close to urban centres. For example, on Simbo Island, nearby markets have contributed to diversification of island resources and remittances to local communities from relatives employed in urban centres and overseas have partially reduced the population's dependency on subsistence foodstuffs that may be destroyed in case of a natural disaster [57]. In such situations it is important to ensure subsistence foodstuffs are not entirely substituted by imported food products (which often have lower nutritional value too) as this makes people more dependent on cash and uncertain imports [55]. This notably highlights the importance of promoting the maintenance of food gardens to maintain or improve food security in rapidly urbanising islands [53]. In situations where rural islands are under the influence of urban centres, these islands exhibit major socio-economic changes (e.g., development of commercial agriculture, export of local food products) that generally increase the vulnerability of their populations by increasing their dependency on uncertain earnings (due to the high specialization of agriculture, limited diversification of outlets and price fluctuation of agricultural products on the global market) and accelerated environmental degradation [58]. Although these islands also benefit from the proximity of educational and professional opportunities they tend to lose local knowledge and ecological diversity over time, which undermines their adaptive capacities in the long-term [22,59] (see also [60] for an Indian Ocean case study). Thus, globalisation (i.e., access to markets and development) is a two-edged sword, which can increase or reduce exposure and vulnerability depending on how it is managed.

Lastly, reconstructing the TEV of small islands also provides insights on their future vulnerability. This is because the changes in exposure and vulnerability have proven to be generally unidirectional (except when unpredictable vertical land movements generate substantial changes in relative sea level as in the Torres Islands) and reinforcing due to the persistence and path-dependence of the societal and environmental processes controlling them. The future TEV of these islands will indeed, at least in the next decades, be consistent with recent societal-induced trends. This is all the more true where environmental change, degradation and losses are substantial, pervasive or irreversible (e.g., accelerating sea level rise and ocean acidification) and because the dependence of island populations on external cash revenues, imported food products, technical facilities, will undoubtedly continue to play a major role in the TEVs of islands in the next decades. This illustrates how climate change impacts are likely to exacerbate and accelerate existing environmental and socio-economic pressures increasing vulnerability. Additionally, future TEVs will also inevitably be influenced by changes in islands' societal characteristics, including factors such as community cohesion, leadership and individual support for collective action, and wider effects of internal and external migration and cultural change [22,42,52,59].

Conclusion

Using examples in Pacific small islands, this paper focuses on the temporal dimensions of exposure and vulnerability to climate-related environmental changes, based on the existing but still very limited peer-reviewed scientific literature. It firstly emphasizes that most urban and rural islands have undergone increasing exposure and vulnerability as a result of major changes in settlement and demographic patterns, lifestyles and economies, natural resources availability and environmental conditions. Overall, increases in exposure and vulnerability are greatest for urban districts and islands, and especially island capitals, and are intertwined socio-economic, cultural and environmental problems. Secondly, this study highlights three generic periods of change in the TEV of most islands, especially reef islands, as a result of successive shifts in the prevailing drivers: from geopolitical and political over the colonization-to-political independence period; to demographic, socio-economic and cultural from the 1960s to the 1980s; culminating in the dominance of demographic, socio-economic, cultural and environmental drivers since the 1980s. Such general similarities in the drivers and processes at work over time should however not obscure the differences seen on the field. Small islands indeed also exhibit a large diversity of situations, as both uncommon demographic changes, such as a decrease in population numbers, and specific drivers, such as the tectonic driver, may play as drivers in specific contexts and generate uncommon TEVs showing either opposite or chaotic trends compared to most island cases.

From a scientific perspective, the TEV approach facilitates highlighting latency phenomena that have long-lasting implications for the vulnerability of island communities [32]. Anthropogenic-driven path dependency effects indeed exist that make the understanding of the recent Past (i.e., TEV approach) relevant to reveal the key context-specific lock-in effects driving changes in the exposure and vulnerability of island systems, these lock-in effects having the potential to continue driving the changes in the next decades. The TEV lens thus seems useful to address the temporal dimensions of exposure and vulnerability, which is necessary to provide empirically-based answers to four key interrelated questions: (1) How have the exposure and vulnerability of an island system to climate-related hazards changed over time? (2) What factors and processes are driving these changes? (3) How do TEVs vary between and within small islands? (4) And to what extent do these TEVs provide insights to better project and plan for future changes in the exposure and vulnerability of island systems, and therefore aid in achievement of effective and desirable adaptation pathways? What we thus argue here is that due to its focus on the dynamic nature of the drivers of exposure and vulnerability, including their interactions and feedbacks, the TEV approach can inform policy- and decision-making processes by ensuring that decisions made at various points along the adaptation pathway are based on empirical, comprehensive and context-specific knowledge.

Regarding small islands in particular, we however call for more systematic and numerous case study analyses. Current knowledge is indeed still too limited to provide enough detailed material to in-depth understand the critical social, economic and governance drivers and their interactions over time. Such scientific advances would also help addressing the first gap mentioned in the introduction of this paper, i.e. highlighting the variability of situations within and across countries.

Notes

[a] Here we consider resilience as 'the capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation' (IPCC Fifth Assessment report glossary, see [33]).

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Tables (1 Table)

Table 1. Summary information and list of key references for informing the storylines and development of the 'trajectories of exposure and vulnerability' of Pacific islands

COUNTRY	Island group	Island and island type	Focus and timespans considered	Authors
KIRIBATI	**Tarawa Atoll** 1°30'N-173°E	- Reef islands of the South Tarawa Urban District + rural islands of North Tarawa	- Land area and shoreline changes, 1968-2007 + 1943-2007	[34]
		- Reef islands of the South Tarawa Urban District	- Coastal protection structures and shoreline modifications, 1968-2007	[35]
		- Reef islands of the South Tarawa Urban District	- Changes in population exposure to coastal erosion and marine inundation, 1968-2007/2008	[24]
TUVALU	**Funafuti Atoll** 8°31'S-179°12'E	- Reef island, urban island (Fongafale, capital)	- Vulnerability to marine inundation, end-19th-Present	[20]
MARSHALL ISLANDS	**Majuro Atoll** 7°07'N-171°13'E	- Reef islands, urban islands of the Djarrit-Uliga-Delap Urban District	- Changes in population exposure to storm surges, 1945 to Present - Coastal erosion, anthropogenic pressures, 1950-Present	[18,23,36]
SOLOMON ISLANDS	**Simbo Island** New Georgia Group 8°17'S-156°31'W	- Mountainous island, rural area	- Social-ecological system vulnerability to tsunamis, globalization	[25]
VANUATU	**Loh and Tegua Islands** Torres Group 13°S-166°32'E	- Mountainous islands, rural area	- Role of tectonic factors in population exposure, role of ancestral knowledge in vulnerability, past decades	[11,37]

COOK ISLANDS	Rarotonga Island 21°14’S-159°47’W	- Mountainous island, urban centre	- Evaluation of storm surge risk, 19th-Present	[38]