Climate change and Disaster Management

PACIFIC POSSIBLE BACKGROUND PAPER NO.6.

Pacific Possible

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Pacific Island countries face unique development challenges. They are far away from major markets, often with small populations spread across many islands and vast distances, and are at the forefront of climate change and its impacts. Because of this, much research has focused on the challenges and constraints faced by Pacific Island countries, and finding ways to respond to these.

This paper is one part of the Pacific Possible series, which takes a positive focus, looking at genuinely transformative opportunities that exist for Pacific Island countries over the next 25 years and identifies the region's biggest challenges that require urgent action.

Realizing these opportunities will often require collaboration not only between Pacific Island Governments, but also with neighbouring countries on the Pacific Rim. The findings presented in Pacific Possible will provide governments and policy-makers with specific insights into what each area could mean for the economy, for employment, for government income and spending.

To learn more, visit **www.worldbank.org/PacificPossible,** or join the conversation online with the hashtag #PacificPossible.

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Executive Summary

The Pacific region is known to be one of the most exposed to natural hazards and climate change in the world. Pacific Island Countries (PICs) are exposed to a wide variety of natural hazards, including cyclones, droughts, earthquakes, electrical storms, extreme winds, floods, landslides, storm surges, tsunami and volcanic eruptions. Some of these hazards will be exacerbated by climate change. Average ocean and land temperatures are increasing, and the seasonality and duration of rainfall is changing. Over the coming decades, tropical cyclones are expected to increase in intensity, though not necessarily in frequency, and to move closer to the equator. Because of higher ocean temperature and ice sheet melt, sea level is rising, thereby worsening coastal erosion and saline intrusion and increasing the severity of storm surges. All these impacts adversely affects agriculture, fisheries, coastal zones, water resources, health, and ecosystems and thus threaten entire communities and economies. The mere existence of low-lying atoll island nations like Kiribati, Tuvalu and RMI is threatened by sea level rise and storm surges, since they are only 1-3m above sea level.

People and economies in the Pacific are particularly vulnerable to hazard and climate change impacts because of geographical remoteness and isolation, dispersion across a large area in the Pacific Ocean, economic and social challenges and the degradation of natural resources. Vulnerability to extreme climate events is now increasing with population growth and migration (internal and external), poor coastal development and land use planning, unplanned urban growth, and water and ecosystem degradation including pollution of sub-surface and coastal waters. Vulnerability is exacerbated for the poorest populations (mostly in Kiribati, Vanuatu and FSM), who live in small communities on remote outer-islands, often on lands which are vulnerable to flooding and cyclones, and who rely on subsistence-farming and fishing for their livelihoods. These people have limited access to education and health facilities and lack the financial capacity (savings, insurance) to cope with the impacts of natural hazards and climate change. Women also suffer more from climate extremes than men, because they tend to depend more on natural resources for livelihood and subsistence, and are vulnerable to gender-based violence in the aftermath of disasters.

Despite a consensus that PICs will be disproportionately impacted by climate change, assessing the future cost of climate-change impacts in the Pacific Region is challenging. Firstly, there are deep uncertainties on the speed and sometimes direction of climate changes, especially at local scales. There are large differences on rainfall and storm surges changes between the projections of different climate models that do not seem to be diminishing with time. And given the small size of the PICs and the extensive ocean dominated areas where they are located, downscaling changes in climate and natural hazards at the country level gives an even wider range of potential changes. For instance, in Kiribati some models project an increase in extreme peak daily rainfall of 53% in 2050 while others predict an increase of 92%, for the same emissions scenarios. In addition, even if models were perfectly accurate, uncertainty would not disappear because future levels of greenhouse gas emissions, which by nature cannot be forecasted, largely determine future climate change. Secondly, climate change impacts will depend on the socio-economic choices made by countries for the next decades. It will be much more expensive to adapt to climate change in a society which heavily depends on agriculture production, with high poverty rates, inequalities, and poorly-managed infrastructure than in an inclusive society with safety nets and resilient infrastructure. Rapid and inclusive development can mitigate some climate change impacts by 2030, especially the impacts on the poorest (Hallegatte et al, 2016). Finally, the costs and benefits of adaptation will be determined by priorities of individual PICs. For instance, the best adaptation strategy will differ if the objective is economic efficiency, or if the objective is to remain below a defined level of risk.

Despite these challenges, it is possible to design resilient development strategies using new decision frameworks. Indeed, many decisions made now concerning development strategies and infrastructure investment in the PICs need to take into account climate change. Given the uncertainties around future climate change and associated impacts, infrastructure should be made resilient to possible changes in climate conditions. This aim implies that policy makers using climate information must change their practices and decision-making frameworks, for instance by adapting uncertainty-management methods. Five methods can be considered (Hallegatte, 2009):

(i) Selecting strategies that yield benefits even in absence of climate change, and therefore create no or little regret if the climate does not change as expected. Example of no-regret strategies include reducing leaks in water distribution systems, increasing the standards of new buildings, or increasing the frequency of road maintenance.

(ii) Favouring reversible and flexible options, like insurance, early-warning systems or easy-to-retrofit coastal defences.

(iii) Buying ‘‘safety margins’’ in new investments, with for instance restrictive land-use planning, higher coastal protection defences or bigger drainage capacity for urban infrastructure and roads.

(iv) Promoting strategies focused on institutions, policies and behaviour change, including the ‘‘institutionalization’’ of long-term investment planning, multi-criteria assessment and use of a range of policy and financial investment instruments.

(v) Reducing decision time horizons. For instance, in areas that could be flood-prone in the future, building cheaper houses with shorter lifetime that can be replaced quickly and at lower cost.

This report uses these generic methods to provide recommendations for climate resilient development in the PICs in the following sectors: coastal protection, flood management, water resources management, protection of infrastructure against changes in temperature and precipitations, protection of buildings against cyclone winds, and adaptation in the agriculture sector.

Improving Coastal Protection

The highest adaptation costs for PICs by 2040 will be coastal protection. In order to protect PICs from coastal erosion, sea and river flooding, and submergence, three “hard” options have been considered within this report including: (i) beach nourishment (particularly in areas with high tourism revenue); (ii) sea and river dike construction; and (iii) port upgrade. The level of protection required and the associated cost of these options varies largely between countries and the sea level rise scenarios, but the costs are always significant. In the best case, with a sea level rise of 40cm by 2100, costs in the 2040s vary between USD 3 million per year in Palau (1% of GDP assuming constant growth) to USD 97 million in the Solomon Islands (3% of GDP) and USD 17 million in Kiribati (4% of GDP). In the worst case, with a sea level rise of 126cm by 2100 and increased cyclones intensity, costs go up to USD 329 million per year in Fiji (3% of GDP) and USD 58 million in the Marshall Islands (13% of GDP). These figures far exceed the cost of coastal adaptation reported in other region – 0.8 % of the GDP for Sub Saharan Africa and less than 0.4% in other regions. Those high costs are primarily comprised of expenditure on the construction and maintenance of sea walls (more than 75% of the total in most countries). It is important to note that these costs assume that only the principal population centres will be protected, and not the outer islands and less densely populated coastal segments. This means that additional costs will be associated with internal migrations and densification of the population behind coastal protections.

Table 1 Range of adaptation costs for coastal protection by country (best case-worst case scenario) (million USD per year at 2012 international prices)

Country	**2020s**	**2040s**	**2040s as % of projected GDP (includes residual damages)**
Fiji	71-230	86-329	1-3%
Micronesia, Fed. Sts.	6-20	8-28	1-3%
Kiribati	13-42	17-54	4-11%
Marshall Islands	13-42	16-58	4-13%
Palau	2-9	3-11	1-2%
Solomon Islands	81-280	97-347	3-11%
Tonga	8-28	9-35	1-4%
Vanuatu	36-130	42-161	2-8%
Samoa	4-15	7-21	0-1%

Source: World Bank estimates

There is little prospect that the high costs of building sea walls could be financed by the countries themselves. Accordingly, the international community will have to assess the trade-off between large initial expenditures on construction that is designed to protect coastal communities for many years into the future versus expenditures and emergency relief and recovery programs when disasters occur. Some countries – e.g. the UK and France – have abandoned attempts to protect all of their coastlines from storm and wave damage; some of the Pacific Island countries may need to make a similar choice and set priorities in the geographical allocation of expenditures on coastal protection.

To manage the uncertainties around future climate change and shoreline behaviour, flexibility should be incorporated into the design of coastal protection interventions. In some situations, hard structural options could be combined with softer non-structural options (e.g: ecosystem based approaches, beach nourishment) to reduce the cost and mitigate the environmental and social impacts. Ensuring that future population growth is concentrated outside coastal zones and relocation of the existing population may be considered, although the implementation might be challenging due to land scarcity and tenure issues. Another option could be to raise buildings above coastal inundation levels to reduce the need for hard-infrastructure protection. In all cases, strengthening institutional capacity for integrated coastal management is an essential element of responding to climate change.

Managing floods and water resources

Many climate scenarios suggest that total annual precipitation will increase in most PICs as a result of climate change. This increase will be accompanied by greater variation in rainfall between wet and dry months, with more intense rainfall in the wettest periods of the year. For example, in Fiji while the 1 in 20 year peak rainfall event in 24 hours today is 245 mm, it would be about 300 mm in 2050 with climate change. There is also a potential for more severe droughts, especially for the Solomon Islands and Tuvalu and to a less extend Fiji, Palau and RMI. Hence, adaptation to climate change should involve measures to: (i) increase the capacity to store water that is accumulated in wetter months for use in the drier months; and (ii) manage the run-off caused by more intense periods of rain.

Table 2– Changes in high 1 in 20 year rainfall over 24 hour period by country for 2050
(mm of rain relative to recent climate)

Country	No Climate Change	Median Climate change	Extreme Climate Change
FJI	245	292	348
FSM	63	78	123
KIR	145	224	365
MHL	72	85	125
PLW	197	245	284
SLB	84	102	119
TON	57	68	82
TUV	83	102	127
VUT	189	230	281
SAM	79	97	116

Investment in increased water storage and rainwater harvesting, especially on islands with limited amounts of land suitable for reservoirs, will be critical. The alternative to investing in more water storage may be reliance upon desalination facilities or other alternative water resources, which (depending on scale) can result in a significant capital costs in addition to ongoing operational and maintenance costs.

A combination of initiatives will be required to minimize future flood risk. A key approach should be effective land-use planning for future urban development, as in general it is cheaper to keep economic assets out of flood prone areas than to build storm and flood defences to protect them. However, as for coastal protection, the implementation of such initiatives may be constrained by land scarcity and tenure issues. Alternatives include any combination of measures to provide protection to assets or accommodation to flood flows. One option for adapting to climate change would be to increase the existing design standards for flood defences, drainage infrastructure and buildings to a higher standard of protection, which would cater for any increases in risk due to higher rainfall, without resulting in a lower standard of protection over time due to climate change. Another strategy may be to ensure that the floor levels of all new buildings are raised so that their main thresholds are a metre or more above ground level. This would also benefit PICs who are vulnerable to coastal inundation and sea level rise.

A "one size fits all" approach to flood risk and drought management will not be appropriate for PICs. The selection of the best combination of interventions for each PIC will require a comprehensive investigation of the costs and benefits of each option, which will be specific to the needs of the beneficiaries. Limited investigations have been conducted in PICs to date, in part due to the lack of quality hydrological data upon which to base investigations.

Adapting infrastructure to changes in rainfall and temperature

Even if coastal protection is provided to protect infrastructure from seal level rise and storm surges, additional expenses will be required to protect power and telecommunication, water and sewers, urban, roads and other transport, hospitals, schools and housing infrastructure from changes in rainfall and temperature. The materials and designs used in building infrastructure, as well as the frequency of maintenance, would need to be altered to maintain the same quality of infrastructure services as in the absence of climate change. For example, in buildings it will be necessary to increase the capacity of ventilation systems in order to cope with more humidity and higher temperatures, and to strengthen the roofs to withstand higher levels of rain. In urban designs larger drainage and water storage systems will be required to cope with higher rainfall.

Assuming countries raise construction standards as they become richer (for example new urban drainage systems are built to withstand a 1 in 20 years event instead of 1 in 10, because the value of the assets that need protection is higher), the cost of protecting infrastructure against changes in rainfall and temperature due to average climate change in 2040 will vary from 2% to 20% of expenditures across the PICs. Fiji and Vanuatu will have lower adaptation costs, while atoll countries such as FSM and Kiribati will have higher costs. Roads account for more than 50% of the average costs of adaptation for most PICs and exceed 90% of the average costs in Solomon Islands and Samoa.

Table 3- Costs of protecting infrastructure relative to baseline expenditures
(Average cost of pre-emptive adaptation for all infrastructure assets by country for 2011-50; 20 year planning horizon; $ million per year at 2010 international prices with no discounting)

Country	Average cost	% of baseline expenditure
Fiji	20.2	3.0%
FSM	13.4	13%
Kiribati	18.9	21%
MHL	8.1	11%
Palau	4.5	6.3%
SLB	17.3	8.6%
Tonga	8.4	12%
Tuvalu	0.3	5.8%
Vanuatu	7.0	3.9%
Samoa	7.8	7.0%

For most type of infrastructure (e.g: health and schools infrastructure, housing, water supply and sewers) the lowest regret option is to adapt now to future climate changes. The lowest-regret strategy often entails planning ahead for only one or two decades. For example, for infrastructure that has generally a short life-span (such as houses), decision-makers and engineers should not be asked to design houses with a view to extend their lifetime beyond 20 years. It is cheaper to build infrastructure that can withstand the climate conditions of the next 10 to 20 years than building infrastructure that can withstand both current climate and the climate that will be experienced in 30 years. For many types of infrastructure the pre-emptive strategy is fully justified as the marginal cost is low (e.g: ICT, health and schools, water and sewers).

For roads, due to the the high costs of comprehensively protecting infrastructure against the worst case scenario and the high uncertainty surrounding future changes in rainfall, the optimum solution will be a combination of pre-emptive measures and strengthening preparedness. The lowest regret option for many PICs appears to be a mix of: (ii) relatively low cost adaptation measures (e.g. first and foremost proper maintenance but also increase the slope of pavement and/or the capacity of the drainage systems to reflect changes in future expected runoff or water flow) and (ii) be reactive to climate change impacts which would involve rebuilding those sections of the roads if and when they are damaged. However, this assumes that governments will have the financial and technical resources to react quickly in case of disasters and repair damaged roads promptly, whereas if those conditions are not met, the costs of being reactive may be largely underestimated. A possible cost-effective solution for managing future changes in climate and minimize the economic costs associated with a road failure could be to focus on non-engineering measures such as realignment, environmental management (increased vegetation land cover, preservation of mangroves…) and land-use planning, and on strengthening preparedness, and maintaining accessibility to essential infrastructure such as schools and hospitals following a disaster event by increasing the redundancy of the road network, thus making sure there are alternatives even if the main road is damaged.

The results provided within this report are indicative, but adaptation strategies need to be designed on a case by case basis. For instance in some places it may make sense to adapt roads to climate change by installing higher drainage capacity and elevating the road, while in other places increasing redundancy in the road network can be a more cost-effective solution. The best solution will depend on the local context, and in particular on the acceptable level of service failure.

Protecting buildings against cyclone winds

In addition to adapting buildings to withstand sea level rise, increased flooding and changes in temperature, it may also be necessary to protect them against stronger cyclone winds, as the intensity of tropical cyclones is likely to increase.

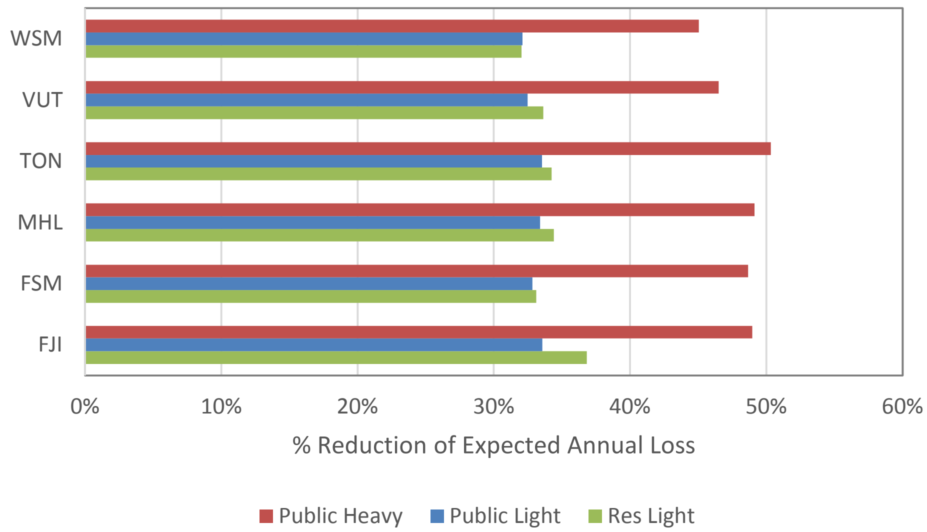
Ensuring that new buildings can withstand at least 1 in 50 year cyclone wind speeds should be a high priority for policymakers. The changes required to ensure that structures are more robust to cyclones will usually involve modest adjustments to designs when the buildings are constructed, and small additional costs. However, the successful implementation of higher building standards will require actions to improve compliance with the new code, including investment in training of engineers and contractors, strengthening of the design and construction permitting process, and provision of enforcement resources.

Reconstruction efforts should seek to ensure that buildings – especially, public buildings – should incorporate the code improvements necessary to ensure greater resilience to the current and future distribution of cyclone risks. The benefits of greater wind resistance will increase as a consequence of climate change over the life of the buildings that are either replaced or reconstructed during the recovery from these storms.

For existing buildings, cyclone wind retrofitting options can decrease expected losses by 35-50% (Figure 1). However, such investments are not always justified when the costs of heavy retrofitting to meet higher standards which would accommodate increased wind speeds are high relative to the benefits in terms of loss reduction. It is therefore necessary to prioritize the countries and the buildings for which retrofitting would be appropriate, in order to ensure cost-efficiency. For instance, retrofitting will be more cost-efficient in countries which face higher cyclone risks - notably Vanuatu, Fiji, RMI, Tonga and Samoa where retrofitting public buildings (e.g. schools, hospitals) appears to be economically justified.

The heavy retrofitting of public buildings becomes a viable policy option when factoring in their role as evacuation shelters during cyclones. Benefits including avoidance of potential loss of life or injuries and the loss of the services provided by buildings should be considered in future analyses. For housing stock, retrofitting is shown to be too expensive in many countries, and therefore early replacement of the buildings in combination with upgraded construction standards may be a better strategy.

Figure 1 - Loss reductions due to cyclone wind retrofitting options



Adapting the agriculture sector

As the climate changes, increased temperatures and higher risk of seasonal droughts are likely to decrease crop productivity and negatively affect livestock in PICs. For example, papaya is sensitive to temperature increase during flower production and higher temperatures result in lower productivity. Although increases in carbon dioxide concentrations could act as a "fertilizer" for some crops in the short-run (e.g. rice, sugarcane and sweet potato), the crop yields of cassava, maize, and taro is likely to decrease by 2050. Livestock may also be negatively impacted due to increased risk of heat stress.

Table 4: Relative Changes in Crop Yields (%) under Climate Change in 2050 Relative to 2000

Country	Cassava		Maize		Rice		Sugarcane		Sweet potato		Taro	
	Worst case	***Best case***	***Worst case***	***Best case***	***Worst case***	***Best case***	***Worst case***	***Best case***	***Worst case***	***Best case***	***Worst case***	***Best case***
Fiji	-36.5	-8.8	-7	1	-11	3.5	-8.3	2.8	-13.4	2	-17.5	1.1
Solomon Islands	-27.8	-17.9	-16.5	-0.3	-16.2	5.9	-12.9	0.9	-15	1.5	-18.6	-4.7

Source: Rosegrant et al. 2013, in ADB 2013

While the impact on GDP could be overall neutral for the Pacific region by 2050 (although some countries may experience negative impacts of 1-3 percent of GDP in this time period), by 2100 the impact could be strongly negative, equivalent to approximately 5 percent of Pacific GDP as all crop yields decrease. These impacts are likely to be underestimated given that they do not take into account interaction effects with other biophysical processes, such as salinity intrusion or the incidence of pests and diseases.

Adaptation to climate change in agriculture in PICs needs to be based on both low-cost no regret options and perhaps more expensive long-term solutions. Simple low-cost options that both improve productivity and increase resilience to climate change include mulching and multiple cropping, and improved farmer education. Longer term solutions should build agriculture systems that can be resilient to multiple changes, such as short periods of floods or droughts, saline intrusion, extremes of temperature, erosion, altered patterns of pests and diseases and changes in growing seasons. As agro-ecological conditions change, farmer re-education will be vital – preferably promoted through farmer-to-farmer exchanges. Other solutions are likely to incorporate more substantial and sustained investments, such as the development of new climate-smart crop varieties at regional or national level, higher design standards for agricultural assets (such as storage sheds and livestock shelters) to help reduce storm damage, or insurance mechanisms to address residual risks, which require considerable government involvement including consideration of premium subsidies and product development and loss assessment.

The Case of Atoll Islands

The atoll nations of Kiribati, Marshall Islands, and Tuvalu are particularly vulnerable to sea level rise and storm surges. As their highest point of elevation is only a few meters above sea level, in the absence of adaptation sea level rise will reduce the habitable surface over time and may lead to a dislocation of the island. For example, for Majuro Atoll in RMI, a 50cm rise in sea level may mean the disappearance of 80% of its land area (ADB, 2013). In Tuvalu's Fongafale Island (Funafuti), sea level rise by 2040 would lead to a more modest but still large loss of about 5.8-10% of Fongafale's land area and expose a further 10-11% of land area to occasional inundations.

The cost of managing the risk of sea level rise on atoll nations is likely to be significant. In Kiribati for example, the cost of coastal adaptation could be between US$ 17 to 54 million in the 2040s, which is about 4 to 11% of Kiribati's GDP. It is unlikely to be affordable for the Government of Kiribati to allocate such an amount in its annual budget to coastal protection for the next decades and significant financial support from the international community will be required. Ensuring decent living conditions on the atoll requires to arbitrate between hard protection options (i.e., through atoll raising, land reclamation, coastal protection) and softer ones (like rehabilitation or protection of mangroves and wetlands, early-warning systems, social protection or financial instruments) and to prioritize between investments in coastal protection, water desalinization, or other infrastructure in transport and energy. It also requires to carefully identify the trade-offs and synergies between multiple objectives in different sectors.

In the event that the international community will not allocate an estimated USD 10 to 50 million a year per atoll nation to protect them against sea level rise, or if the costs of adaption are much higher than expected, other long term options will need to be considered. Consideration should be given to the feasibility of a progressive relocation. Such an approach would need to be carefully planned and available resources would still need to be used to maintain acceptable living conditions on the atolls for the coming decades. There are political, social and economic sensitivities that would need to be carefully considered and addressed in the event that this option is adopted, as discussed in Wyett (2013). It is clear that a progressive and planned relocation of the population away from the most exposed areas would be less costly and preferable to a last-minute abandonment, which would require a significant level of emergency assistance.

Former President Anote Tong of Kiribati has spoken of the need to ensure "migration with dignity" for the country's population. While the Government of Tuvalu (2012) specifically mentions migration as a possible climate change outcome, survey data shows that the vast majority of Tuvaluans do not view this as a major reason for concern and are not, as yet, preparing to migrate due of climate change (Mortreux and Barnett, 2009). The decision to plan for a relocation of the population, or part of the population to another country is a difficult one to make, given the uncertainties surrounding the speed and strength of climate change and sea level rise. In addition, there is also uncertainty related to the availability of international aid, along with challenges linked to the social acceptability of a planned migration. However, it makes a lot of sense to start considering this option as a long-term solution to climate change impacts in atoll countries, using an integrated approach that involves all stakeholders and carefully examines the threats that climate change poses to life on the atoll nations. The costs of maintaining acceptable living conditions on the atoll nations for different time horizons should also be considered.

Conclusions

The findings and recommendations provided in this report should be used carefully and considered in accordance with the local contexts. Resilient development in PICs under tight budget constraints will require a compromise between hard protection options (such as sea walls, building retrofitting, and desalinisation plants, which are very expensive in Pacific Islands given the cost of importing materials and equipment) and softer options (such as rehabilitation or protection of mangroves and wetlands, early-warning systems, social protection and rainwater harvesting). It will also require prioritization between investments in coastal protection, flood protection, water supply, or resilient infrastructure.

The trade-offs and synergies between multiple objectives in different sectors will need to be identified. For instance, water desalinization requires a lot of energy (therefore opportunities for alternative energy sources such as solar energy should be sought), changes to climate-resistant crops can affect water demand by the agricultural sector, and land-use patterns can affect the exposure of the population to extreme events. Integrated design and assessment of adaptation across multiple sectors should be supported.

Introduction

Pacific Island Countries (PICs) are among the most exposed nations in the world to natural hazards (including floods, droughts, tropical cyclones, storm surges, earthquakes, volcanic eruptions, and tsunamis). They are also highly vulnerable to these hazards, which can result in disasters that affect their entire economies, human and physical capital, and impact their long-term development agendas. Since 1950, natural disasters have affected approximately 9.2 million people in the Pacific region, causing approximately 10,000 reported deaths. This has cost the PICs around US$3.2 billion (in nominal terms) in associated damage costs (EM-DAT, 2010[1]). The PICs are some of the most economically affected by disasters in the world, with, for instance, average annualized losses estimated to amount to 6.6% of the GDP for Vanuatu and 4.4% of the GDP for Tonga.

These losses may be compounded by the impacts of climate change. Sea level rise, increasing land temperatures, changes in the seasonality and duration of rainfall will affect infrastructure, coastal zones, water resources, agriculture, food security, and thus lives, livelihoods and economies.

Disasters, climate and weather extremes and projected changes in climate, are increasingly recognized as a major development challenge, as they adversely impact social and economic development and poverty reduction efforts. Accordingly, the Pacific Possible Strategic Report is being prepared, in order to take a long term view of the development challenges and opportunities faced by PICs and focus on activities that could have transformational impacts on countries in the region. Pacific Possible aims to identify and whenever possible quantify development gains that could be achieved if the right preconditions are in place. The long-term perspective adopted by Pacific Possible will consider major changes in the economic environment for PICs and their impact on the PICs development opportunities. Such changes will include climate change, with projected severe impacts on PICs, and in particular, atoll nations.

The Pacific Possible includes six thematic focus areas, one of which is "Managing increased stress on pacific livelihoods." This focus area will include consideration of natural disasters and the impacts of climate change on PICs, and this background paper has been prepared to support this process. This background paper will consider the following key issues regarding the changes in PICs by the year 2040:

1. The potential socio-economic impacts from natural hazards and climate change;
2. The cost of adaptation to minimise potential socio-economic impacts; and identification of the combination of investments and policies that are likely to have the highest impact in reducing the socio-economic impacts.

In order to develop effective adaptation strategies, it is essential to distinguish between the impacts of: (a) changes in the frequency and/or severity of extreme weather events; and (b) changes in "normal" climate conditions, such as higher mean temperatures, higher mean sea level the level and pattern of precipitation, ENSO cycles, etc.

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[1] EM-DAT: The OFDA/CRED International Disaster Database – www.emdat.be – Université Catholique de Louvain – Brussels – Belgium

For extreme weather events that underlie disaster risks, the starting point for PICs must be an assessment of whether current standards and practices offer an appropriate level of resilience in the context of current climate hazards. As countries develop they tend to invest in higher levels of resilience because the benefits of preventing losses outweighs the costs as the assets and incomes at risk grow. Today, the PICs invest less in disaster resilience than would be required to provide them with a high level of resilience. As such, it is possible that the additional costs of adapting to climate change-driven increases in extreme weather may be small relative to the costs of investing in greater resilience to current risks.

Adapting to changes in average climate conditions requires a gradual response. For example, this could be through changes in the design of infrastructure and other assets, investments in agricultural research & development, the management of water resources, or coastal adaptation. Given the uncertainties that exist around the future impacts of climate changes, (particularly future changes in rainfall patterns or impacts on extreme events), adapting will require flexible or low-regret options which perform well whatever the future brings. In some cases, the lowest regret option may be to wait and adapt reactively to climate change impacts, while in some sectors the lowest regret strategy will be to adapt pre-emptively.

This background paper considers adaptation for a range of sectors and situations, including infrastructure and buildings, coastal protection, the water sector, and agriculture. Special consideration is given to regional atoll islands due to their unique challenges, with many of them only 1-3m above sea level and sea levels predicted to rise by 25 cm by 2050 and 60 cm or more by 2100. It also considers the economic costs of adaptation and proposes some prioritised support for the 2040 timeframe of the Pacific possible.

1. Current Risks and Projected Climate Changes

1.1 Current Risk and Exposure in PICs

The Pacific region is known to be one of the most prone to natural disasters and climate change in the world. Key reasons are their high exposure to a wide variety of natural hazards (cyclones, droughts, earthquakes, electrical storms, extreme winds, floods, landslides, storm surges, tsunami and volcanic eruptions), geographical remoteness and isolation, and dispersion across a large area in the Pacific Ocean. The region is frequently hit by hazard events. Between 1950 and 2011, extreme weather-related events in the Pacific islands region affected approximately 9.2 million people in the Pacific region, approximately 10,000 reported deaths and damage costs of around US$3.2 billion. Recent estimates show that the expected losses due to natural disasters on an annualized basis in the Pacific far exceed those in almost all other countries in the world. The impact of natural disasters is equivalent to an annualised loss of 6.6 percent of GDP in Vanuatu, and 4.3 percent in Tonga.

Climate change is exacerbating the vulnerabilities of PICs. Tropical cyclones- a major cause of losses and damage for PICs -, are expected to increase in intensity, though not necessarily frequency, over the coming decades. In addition to changing extreme weather events, climate change is adding pressure on fragile island systems via increasing average ocean and land temperatures, changes in the seasonality and duration of rainfall, coastal erosion, saline intrusion and increasing sea level[2]. Climate Change may threaten the existence of entire low-lying atoll island nations, such as Kiribati, Tuvalu and RMI. These states are only 1-3m above sea level, and thus are threatened by projected sea level rises of around 60 cm or more by 2100. Climate change is already adversely affecting agriculture, fisheries, coastal zones, water resources, health, ecosystems and thus economies of countries and communities. If greenhouse gas emissions are not drastically reduced, continued changes in climate are likely to exacerbate these negatives effects[3].

In addition, the vulnerability of PICs is also increasing due to economic and social changes and the degradation of natural resources. Key drivers include population growth and migration (internal and external), poor coastal development and land use planning, unplanned urban growth, and water and ecosystem degradation including pollution of sub-surface and coastal waters.

Natural hazards and climate change affect countries differently as highlighted by the country risk profiles developed under the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI). Whereas atoll island nations outside the cyclone belt and seismic zones are more affected by slow-onset events, such as saline intrusions and coastal erosion, rapid onset disasters are frequent occurrences in the high-volcanic islands. Overall, hydro-meteorological disasters cause the majority of economic loss, whereas geo-hazards are by far the major cause of human loss.

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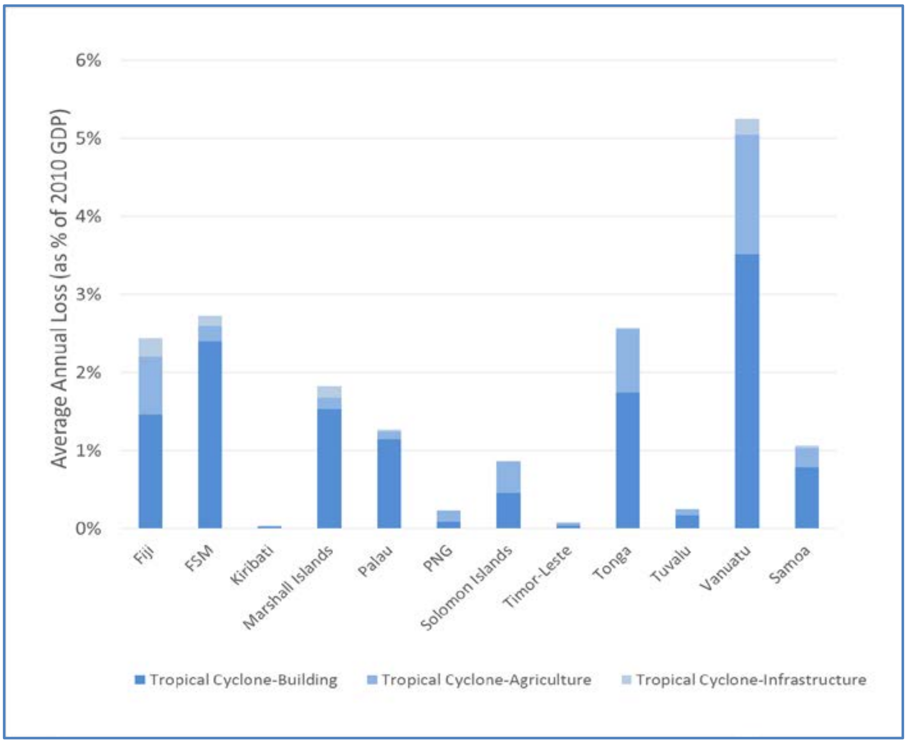
[2] IPCC, 2014 and Australian Bureau of Meteorology and CSIRO, 2011.

[3] World Bank, 2012b

1.1.1 Tropical cyclones

Tropical Cyclones have traditionally been the most serious climate hazard for PICs in terms of total damage and loss (Figure 2). Vanuatu is the most at risk from cyclone events, and is expected to lose on average 36.8million dollars annually.

Figure 2. Expected Average Annual Losses due to Cyclones in Pacific Island Countries



Source: PCRAFI Country Risk Profiles (World Bank, 2015)

From 1981 to 2016, there have been 27 Category 5 and 32 Category 4 cyclones which have had significant impacts on PICs. Being struck by a Category 5 cyclone has been a 1 in 10 year event for Fiji, Tonga and Samoa and a 1 in 5 year event for the Solomon Islands and Vanuatu. Samoa has been struck by seven Category 4 or Category 5 cyclones with peak wind speeds of greater than 58 metres per second (m/s). Tropical Cyclone Evan, which struck Samoa in December, 2012, caused total damage and losses of approximately US$210 million (30% of annual GDP), and Tropical Cyclone Ian, which struck Tonga in January 2014, resulted in total damage and losses of approximately US$50 million (11% of annual GDP). In March 2015, Tropical Cyclone (TC) Pam struck Vanuatu, Tuvalu and Kiribati. In Vanuatu, the cyclone killed 11 people and resulted in an estimated US$450 million damage and losses, equivalent to 64 percent of the GDP. More Recently, TC Winston struck Fiji as an extremely destructive Category 5 cyclone in February 2016, resulting in the death of at least 42 people and damage and loss that may exceed that seen following TC Pam.

The historical record suggests that the dramatic increase in impacts associated with tropical cyclones in the past several decades globally is largely due to increased exposure and vulnerability, rather than an increase in intensity or frequency of cyclone hazards. There is no consensus on changing frequencies or intensities of tropical cyclones on the global scale,[4] although there is emerging evidence of such changes in the Atlantic which has a record of longer-time series for these low probability events. For the Pacific, cyclones the time series is not sufficient to identify changes in their frequency and intensity.[5]

Cyclone season in the Pacific is influenced by the El Niño events. This was evident during one of the most active seasons in 2015/16.[i] For the first time since satellite observation started, three tropical cyclones of Category 4 (Saffir-Simpson scale) were observed simultaneously across the north-east Pacific - Kilo, Ignacio and Jimena - in September 2015. All three were over open water and thus did not cause damage to PICs.[ii]

1.1.2 Floods and droughts

Flood risk (from rainfall not associated with cyclones) is very significant in the region yet it is not consistently recorded. However, ad-hoc information for particular events suggests massive losses from floods. For example, Fiji experienced devastating floods in 2004, 2009, 2012 (twice) and 2014. The 2009 event caused damage and loss of 135 million USD (SOPAC, 2009).[6] More recently, flash flooding in the Solomon Islands in 2014 caused damage and loss estimated at US$108.9 million, equivalent to 9.2 percent of gross domestic product (GDP), and resulted in the death of 22 people and affecting approximately 52,000 people in total. The flooding caused damage to major infrastructure, fully destroying some 675 houses along with the food gardens that many people depend upon for their livelihood.

Droughts are increasingly affecting PICs. Only 52% of the populations in PICs currently have access to improved water supply.[7] Water sources are vulnerable to the effects of El Niño events, which have the potential for significant water-related impacts for many communities across the region. Both FSM and RMI have declared a state of emergency due to the 2015/16 El Niño induced drought, which has resulted in increased distance to water sources for many communities across the region. Previous examples of significant drought in the region include the drought that occurred in Tuvalu in 2011, which led to severe rationing of fresh water supplies in September/October of that year.

1.1.3 Coastal hazards

Coastal erosion, storm surges and king tides are majors hazards affecting the coasts of the PICs. There are up to 30,000 islands located within the Pacific Ocean with a total coastline of over 50,000 km. Most of the population, urban centres and critical infrastructure are located on the coast and

[4] See Weinkle et al., 2012 and Woodruff et al. 2013.

[5] Crompton et al. (2011), for example, argue that one would need to have 260 years of hurricane data to identify any trends in hurricane frequency associated with anthropomorphic climate change in the Atlantic Ocean. Since South Pacific cyclones are even less frequent than Atlantic ones, the time series necessary to identify historical trends there would be even longer. Complete Pacific cyclone data is only available from 1981, so clearly no trend can be deduced from observing this data. There is a somewhat longer time series available for the Atlantic, but even there the trends are uncertain.

[6] For Fiji, in EMDAT for example, there are zero damages recorded for the 2004 flood, 43 million USD for the 2009, 89 million USD for 2012 – but only one event is registered, and there is no record of the flood event in 2014.

[7] WHO & UNICEF Joint Monitoring Programme, 2013

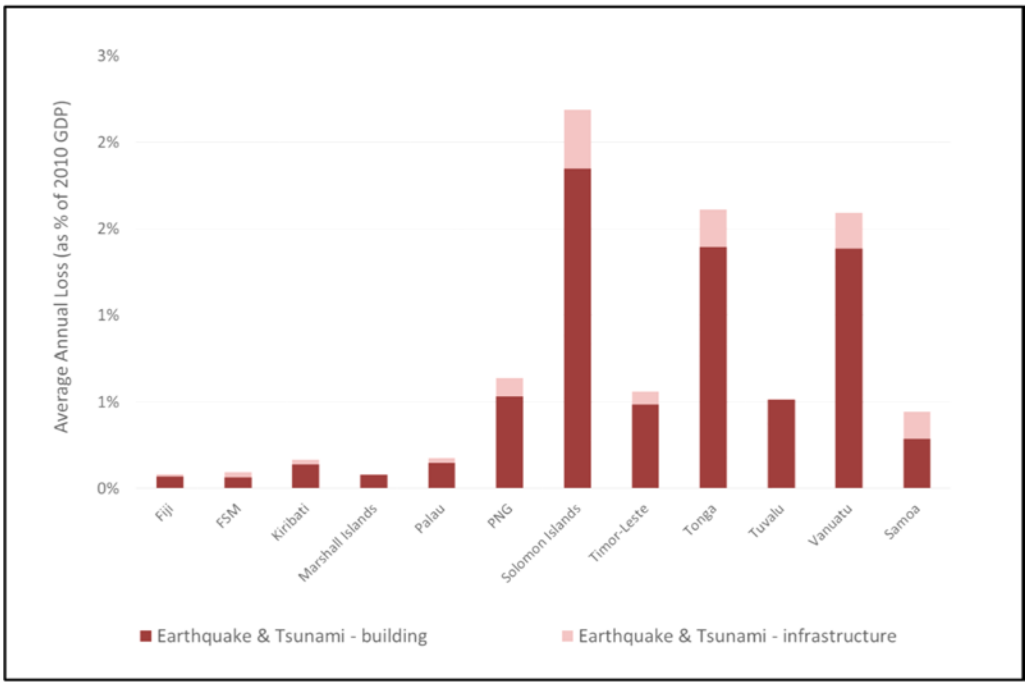
therefore exposed to coastal hazards. However as for floods only ad-hoc information is available on the economic impact of particular events. For example in November 1979, December 2008 and March 2014 large extratropical storms caused large swell and flooding throughout Majuro, RMI. The cost of property damaged during the 1979 event was estimated at USD26M and 110 homes were damaged during the March 2014 event (Hess et al., 2015). According to a recent study 57% of the assessed built infrastructure for the 12 Pacific island countries is located within 500 metres of their coastlines, amounting to a total replacement value of US$21.9 billion (Kumar and Taylor, 2015).

1.1.4 Tsunami and Earthquakes

Many PICs are situated within the Pacific “ring of fire” which aligns with the boundaries of the tectonic plates, making them extremely vulnerable to earthquakes and tsunamis. These tectonic plate boundaries are extremely active seismic zones, capable of generating large earthquakes and in some cases, major tsunamis that can travel great distances. Of all hazards that impact on PICs, tsunamis tend to result in the highest number of fatalities.

The potential impacts of earthquakes and tsunamis various significantly across PICs (Figure 3). Vanuatu is the most at risk to earthquakes and tsunamis of all PICs, and was affected by devastating earthquakes and tsunamis several times in the last few decades. For example, in 1999, a magnitude 7.5 earthquake caused extensive damage to Pentecost Island, leaving more than 10 dead, over 100 injured and millions of USD in losses. The earthquake generated a large tsunami including a six-meter wave. In 2002, a magnitude 7.3 earthquake struck near the national capital of Port Vila, causing millions of USD in damage to buildings and infrastructure. More recently, in 2009 a devastating tsunami struck Samoa following an 8.1 magnitude earthquake, resulting in waves of 14 meters which destroyed over 20 villages and led to 189 fatalities. In 2013, a tsunami struck the Solomon Islands, following an 8.0 magnitude earthquake, destroying homes and killing 9 people.

Figure 3. Expected Average Annual Losses due to Earthquakes and Tsunamis in Pacific Island Countries



Source: PCRAFI Country Risk Profiles (World Bank, 2015)

1.2 Climate Change and its Effect on PICs

1.2.1: Historical changes and their effects

For PICs, climate change manifests itself as changes in air and ocean temperatures, ocean chemistry, rainfall, wind strength and direction, sea-levels, wave actions, storm surges along with extremes such as tropical cyclones, drought and storm swell events. The effects of these changes depend on the biophysical nature of the island and its social, economic and political setting[8] .

Sea level rise, storm surge and swells particularly impact infrastructure. Rates of sea-level rise in the tropical Pacific, between 1993 and 2009 were about four times the global average (approximately 12 mm per year).[9] Swell events, particularly those that occur during strong El Niño events, lead to waves surging across low-lying islands causing severe damage to housing and infrastructure as well as natural

[8] Nurse et al., 2014

[9] Ibid. Global average over 1993-2011 are about 3.3mm yr-1. . Rates of sea-level rise are however not uniform across the globe and large regional differences have been detected including in the tropical Pacific, where reported rates have been approximately 12 mm yr -1 between 1993 and 2009; these are generally thought to describe transient rates associated with natural cyclic climate phenomena such as ENSO. Global sea level is likely to increase in the range of 0.17m (or 170mm) to 0.38m (or 38mm) by 2050 (IPCC fifth Assessment report, WG1, SPM).

resources, and affect thousands of people across the region. In many islands, changing patterns of human settlement affect the shoreline processes and cause shoreline erosion. Cyclones can cause shoreline erosion and damage, but depending on the location can also nourish and replenish a coast[10]. Human activity such as sand mining, pollution and settlement in the near-shore are currently major factors which have to be addressed to reduce the risk from climate change to shoreline, infrastructure and ecosystems.

Decreased rainfall threatens freshwater lenses, especially in islands with relatively low mean rainfall such as Tonga, Cook Islands and Niue, a 25% decrease in the replenishment of groundwater reduces the thickness of the freshwater lens by about 50%.[iii] Salt water intrusion from high sea levels/storm surges can take months or years to recover as freshwater lenses require recharge from significant rainfalls. Recovery from such shocks during the last El Niño in 1997 in the Cook Islands for example, took 3 years.[iv]

1.2.1 Projected changes in temperature and rainfall

Projecting climate change for small islands is challenging. Firstly, the size of the islands are much smaller than the grid squares of the global circulation models (GCM) that underpin the climate projections (which are between 200 and 600 km^2, depending on the model), resulting in inadequate resolution over the land areas of virtually all small islands. Secondly, there are limited regional socio-economic scenarios available at scales relevant to the small islands. Methodology has been developed to overcome these challenges for the Pacific at the regional level, and allows the determination of general trends rather than specific outcomes at the country level. Accordingly, although this paper presents projections for individual PICs, these results should be viewed with caution and as a general guide for projected changes in climate.

By 2050 mean temperatures in the Pacific Islands are expected to increase by 0.8 to 1.4°C relative to a baseline of 1980. The latest IPCC projections are between 1.5 °C and 3.7°C by 2100 with much variation in different seasons[11].

Mean annual precipitation by 2050 is likely to increase slightly in most PICs, with the exception of Kiribati, where it is likely to increase by 20-25% compared to the historical rainfall data (1948 to 2008) . However, there is considerable difference amongst the different climate models making it uncertain as to the extent of change that might occur in the populated areas of Tarawa. There is likely to be significant variation in the monthly precipitation – that is some months are likely to be dryer and some wetter – with the annual precipitation remaining about the same (see Annex 1).

[10] Etienne and Terry (2012) found that in Fiji, a category 4 cyclone nourished shorelines with fresh coralline sediments despite localized storm damage.

[11] Nurse et al, (2014).

1.2.2 Projections for tropical cyclones

There are likely to be more intense tropical cyclones and associated intense rainfall in the Pacific[12]. Modelling results indicate that it is unlikely that Cyclone Pam and Winston will remain unique, and more Pam-like storms of similar magnitude affecting the Pacific would be expected in the coming decades. Cyclones have a big impact on coastlines through storm surges that can be a long way from the main cyclone area. In March 2015, tidal surges associated with Cyclone Pam (estimated to be 3–5 m), swept across the low-lying islands of Tuvalu and caused more than US$ 10 million in damage, equivalent to 27% of the GDP. Impact of cyclones are likely to be exacerbated by increasing flooding as drainage will be hampered by sea-level rise, and the ongoing coastal erosion.

As the Pacific Ocean warms, the range of cyclones could move to the north and south of the current "typhoon/hurricane belt" and be more damaging. El Niño events are associated with equator-ward shift in cyclone tracks. Thus, if El Niño like events are to become more frequent or more intense – as suggested by some climate models - the long-term storm trajectory trends may be going both ways leading to a larger spread of cyclones outside of the historical cyclone belt (both closer to the equator, and pole-ward outside the current zone). This trend of changing trajectories is likely to end up being the most important shift for cyclones associated with climate change in the foreseeable future.

Experience shows that by far most of the mortality, morbidity and damage from cyclones is experienced in regions that are unaccustomed to them and therefore unprepared. However, most of the PICs are within the belt, but countries like Tuvalu that are close to the equator may experience more serious damage as they did in TC Pam and the damages can be severe in such low-lying atoll countries.

1.2.3 Projections for floods and droughts

Floods and seasonal droughts are likely to continue to increase. The intensity of rainfall is likely to increase, along with the possibility of urban floods and the associated damage to people and assets. In low-lying islands and coastal areas, these effects would be compounded by effects of storm surges which would affect infrastructure and freshwater lenses. The increased temperature and changes in the rainfall patterns also increase the likelihood of seasonal droughts. Given that much of the agriculture is rain fed and there is very little water storage, this would also in turn affect agriculture and water supply.

1.2.4 Projection for sea level rise and ocean acidification

Sea level rise for the Pacific is likely to be about higher than the global average, which is in the range of 0.17 m to 0.38 m by 2050, and influenced by El Niño–Southern Oscillation (ENSO) like events[13]. However, some recent global sea level rise estimates are considerably more alarming as more information on glacial melting and other feedback loops has been incorporated into climate models.

[12] IPCC 2014, Fifth Assessment Report, Work Group I, Technical Summary

[13] Ibid.

Sea level rise poses obvious difficulties for the atoll nations, but will also have an impact on low-lying areas elsewhere. Shorelines are particular vulnerable, as sea level rise will lead to continual increases in the damages caused by storm and wave surges and earthquake induced tsunamis. Wave overtopping and wash over events are likely to become more frequent with sea level rise and impact freshwater lenses dramatically. For example, on Pukapuka Atoll, Cook Islands storm surge over-wash in 2005 caused the fresh water lenses to become immediately brackish, taking around eleven months to recover. In very low-lying central areas of Fongafale Island, Tuvalu, during extreme high 'king' tides, large areas of the inner part of the island become inundated with brackish waters.

While some recent studies have observed increases in total land areas on some Pacific Islands over the past decades[14], they have generally occurred on mobile reef-top islands. Mobility of the shoreline is a natural process, and coasts have always been evolving, but constructions on the shoreline combined with sand beach mining and other disturbance in the sediment transport might significantly affect the normal process. Furthermore, the land area is not the only indicator to be considered. Other recent studies have pointed some modification of the morphology of the islands, with especially some reduction in the overall elevation of the islands, which might prove to be highly problematic for both fresh water resources and protection to coastal flooding.

These impacts will be compounded by ocean acidification and the consequent adverse effect on coral reefs. Coral reefs and mangrove forests serve as wave barriers and prevent the full force of storm surges from hitting coastal regions. Recent study shows that coral reefs decrease 97 percent of the storm-wave power and reduce wave height by 84 percent[15]. Their potential loss due to increased acidification and inability to grow can increase the effect of storm surge, wave actions and lead to increased erosion of coastal areas.

The combination of sea level rise and deterioration in coral reef and mangrove ecosystems and the increase concentration of population economic activity will make coastal areas more vulnerable to storms, regardless of whether storms will be more frequent and/or more intense. The increased vulnerability of coastal zones has been due to development decisions and is more recently being compounded by climate change.

1.3 Impact on Poverty and Gender

1.3.1 Poverty

Although there are pockets of extreme poverty throughout the Pacific Island countries, the majority of the poor can be found in just three countries, with around 90% of people in poverty in Kiribati, Vanuatu and FSM. There is no country where extreme poverty in urban areas is greater than 3

[14] Webb and Kench, 2010

[15] Ferrario et al., 2014

percent. However, it is much higher in the outer islands of some countries, particularly Kiribati. **Most of the poor in the Pacific live on outer islands, and here poverty is structural and persistent.**

The typical poor household in the Pacific lives in a small community on a remote outer-island far from the nation's capital and any other economic centres. They rely on garden-farming and fishing for their livelihoods, but many have poor soils where few crops grow. They lack basics like electricity, water supply and decent roads. Education and health facilities exist but are hard to get to, charge for service and are poor quality, so they are not used. The household is hit frequently by natural disasters like droughts, cyclones and earthquakes regularly and each time needs to appeal to extended family or wait for government assistance in order to go on with their life. Poorer populations tend to live on low value land, often close to flood prone waterways and in higher-risk coastal areas, making them more likely to be affected by adverse natural events.

While disasters impact whole societies, when they strike, the poor and vulnerable (including women, children and the elderly) are hit the hardest, exacerbating poverty. Poorer people in PICs may be disproportionately affected by disasters and climate for several reasons, for example: (i) the poor typically have inadequate financial means to deal with disaster events; (ii) poorer people have less access to insurance, cash reserves and alternative income sources that provide the mechanisms to recover quickly; (iii) in the face of more 'immediate' challenges, for example the threat of hunger, access to water or livelihood opportunities, poor people may be inclined to underestimate or ignore the risks incurred by living in hazard prone areas; (Iv) people who are at risk of falling into poverty and hardship –people just above the poverty line and vulnerable populations (i.e., children, women, elderly) – can be pushed into transient poverty when a disaster hits as their livelihoods become destroyed; (v) as poorer groups become affected by disasters and climate shocks repeatedly (for instance by low-intensity, high-probability shocks such as frequent storms, floods, or droughts), they have less chances of re-building their livelihoods and investing in human capital, thus becoming trapped in a cycle that sinks them further down into poverty. Insecurity and risk are closely associated with poverty in PICs, and people cite the impact of natural disasters as a contributing and frequently occurring trigger that pushes households into, or pushes them deeper, into poverty. In Fiji, a national level analysis of the relationship between poverty and disasters found that the level of poverty negatively affects the impacts of the disaster (SOPAC, 2009).

Climate and disaster risks strongly affect people's well-being in terms of health, environmental sustainability, gender equality, livelihoods and access to education. The poorest segments of the population in PICs are more likely to rely on subsistence farming, which makes them vulnerable to the impacts of disasters and climate change on crops, as was seen in Vanuatu following Tropical Cyclone Pam, where low-income individuals and those depending on subsistence livelihoods were disproportionally impacted due to reduced incomes and food sources. Increased hardship due to the impact of disasters on schools also has the potential to disproportionally impact poorer communities, with communities in rural areas already often having very restricted access to good quality education, and this can be compounded if a disaster event destroys school infrastructure, of if school buildings are used for emergency accommodation for an extended period following a disaster.

Disasters and climate change also threaten economic growth and poverty reduction in PICs, causing losses in lives and infrastructure, and these losses disproportionately affect the poor and most vulnerable. In addition, poverty can actually increase disaster risks due to potential linkages between poverty and the over-utilization of resources. For example cutting trees for firewood can increase erosion, impact the natural drainage basin, and thus increase the risk of flooding.

Given the extreme vulnerability of PICs to natural disasters, economic shocks, and climate change, adaptation measures to reduce exposure and vulnerability to risk lie at the heart of poverty reduction and shared prosperity. Reducing the exposure to risk will be crucial for improving living conditions in PICs, which is an important, non-monetary dimension of poverty reduction and shared prosperity. Approaches to reducing exposure are explored in Section 2 of this paper.

1.3.2 Gender

Women are disproportionately vulnerable to the impacts of natural disasters and climate change[16]. Globally, existing socio-economic inequalities, such as restricted education, decision-making and economic opportunities, increase women's vulnerability to natural hazards,[17] and there is a direct relationship between women's risk of being killed during disasters and their socio-economic status.[18]

Ingrained gender inequality and discrimination against women and girls can place them at higher risk to the effects of climate change and hazard events. Studies have shown that disaster fatality rates are much higher for women than for men, primarily due to gendered differences in capacity to cope with such events and insufficient access to information and early warnings[19,20]. For example, in 2007, when Bangladesh was hit by Tropical Cyclone Cidr, five times more women were killed than men. When Cyclone Nargis struck Myanmar in 2008, 61% of casualties were female.

Children are also particularly vulnerable to disasters and climate change, with more than 50% of all those affected by disasters worldwide being children[21]. Girl infants are at a particular risk. Recent research conducted by economists from the University of San Francisco and UC Berkeley on how typhoons in the past 25 years affected the Philippines shows that for up to 2 years after the disaster, post-typhoon mortality among baby girls is approximately 15 times higher than post-typhoon mortality among the general population, likely due to the indirect poverty-worsening effects of the

[16] World Bank, 2012a, World Development Report- Gender Equality and Development
[17] World Bank, 2013a. Improving Women's Odds in Disasters, available at:
[18] Neumayer and Pluemper, 2006. The Gendered Nature of Natural Disasters: The Impact of Catastrophic Events on the Gender Gap in Life Expectancy, 1981–2002, Annals of the Association of American Geographers, 97(3), 2007, pp. 551–566. Link. For further data on gendered impacts of disasters, see International Union for Conservation of Nature: http://cmsdata.iucn.org/downloads/disaster_and_gender_statistics.pdf. For further resources on gender and DRM, see Gender and Disaster Network: http://www.gdnonline.org/wot_papers.php.
[19] Peterson, 2007.
[20] Ikeda, 1995.
[21] UNISDR, 2010: http://www.unisdr.org/files/20108_mediabook.pdf.

storm.[22] Their chance of dying is even higher if they have siblings: it doubles if they have an older sister, and quadruples if they have an older brother. Contributing factors include reduction of health-related expenditure, including nutrition and medical visits, with infant inadvertently bearing the brunt of the economic devastation as families cut spending.[23] Baby boys show no increase in mortality rate.

The global trend of increased vulnerability for women and children during disaster and climate events is reflected in the Pacific region. In PICs, gendered asymmetry in vulnerability to disaster risk is primarily due to socio-economic, cultural, educational/informational and political power imbalances across all levels, as well as geographical and other factors. Socio-cultural norms may cause restrictions in movement to escape disasters (particularly water-related hazards), for example, where women have the primary role for caring for children and the elderly. In addition, women often have lower levels of access to economic resources, may be excluded from decision making in regards to disaster preparedness, and may have lower levels of literacy or access to information on natural hazards and climate risks, making it more difficult read and act upon disaster warnings.[24]

In terms of economic activity and employment opportunities, women in PICs have lower employment rates and are more likely to be unemployed, making them particularly vulnerable to external impacts such as disasters or climate change. The unemployment rate from Census data is over 70 percent for women in RMI, compared to 49 percent for men. In Kiribati, Vanuatu and FSM the difference is more marginal, while in Tuvalu women are slightly less likely to be unemployed. Less available income means that in case of a disaster, they might lack financial resources to restore their livelihoods and that of their families. Women are also more likely to report they are not active in the labor market because of home duties or caring responsibilities. These factors impact on the ability of women and female headed households to ensure they have the financial means required to recover from disaster events and adapt to climate change.

Women often live and work closely with the natural resources and geographical features that are most effected by disasters and shocks. For example, within the Pacific region, women's productive roles are often linked to natural resources, which mean that the physical impacts of rising sea levels, flooding and increased salt-water intrusion have the potential to jeopardize sustainable livelihood strategies, food security and family well-being. This was seen in Vanuatu following Cyclone Pam, the impact of which on subsistence farming resulted in decreases to women's resources to generate income and provide food for their families.[25]

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[22] Antilla Hughes &. Hsiang, 2013

[23] Ibid: 'The study found that in an average year, the income of Filipino households in typhoon-hit areas is depressed 6.6 percent due to typhoons that occurred the year before, leading to a 7.1 percent reduction in average household spending. However, when particularly strong storms strike, incomes may fall more than 15 percent the following year – compounding loss from damage to a family's home and belongings.'

[24] Aguilar, L. et al, 2009

[25]Government of Vanuatu, ' Vanuatu Post Disaster Needs Assessment – Tropical Cyclone Pam', March 2015.

In addition to the potential impacts on life and livelihoods, disasters and climate change have the potential to increase the exposure of women and children in PICs to sexual gender-based violence (SGBV). Women in PICs are already subject to high levels of sexual and gender-based violence, but violence has the potential to escalate following disasters and climate events. For example, after two tropical cyclones in Vanuatu in 2011, there was an increase of 300% in new domestic violence cases that were reported.[26]

Effective measures to adapt to climate and hazard risks in the future should recognize that roles and responsibilities are not uniform across PICs, and rather are influenced by culture and community, in addition to gender. Consideration of gendered divisions of labor and traditional knowledge can strengthen disaster and climate risk management in PICs. While PICs are not homogeneous, gender often dictates where women and men work and separates traditional knowledge into women's and men's knowledge. Traditional or local knowledge is therefore important for understanding gender roles and responsibilities in order to best manage climate and hazard risks.

While women have a higher vulnerability to natural hazards, they also play an important role in community level efforts to minimize the risks, including in community early warning and preparedness. For example, in Samoa, women tend to have higher secondary and tertiary education levels than do men (although this is not the case for all PICs) and as such, offer a well-educated human resource that can be utilized for risk mitigation initiatives, and mobilized as part of community awareness campaigns and disaster contingency planning. Separate consultations should be undertaken with women in regards to early warning and preparedness initiatives. For example, women's input should be sought in relation to evacuation shelter design, including how to make them more accessible and safe (in turn, reducing the threat of post-disaster SGBV), and also in regards to how early warning communication can be improved to ensure warning messages reach entire communities.

Opportunities to emphasise the agency, rather than vulnerability of women during the coming decades will be particularly forthcoming during recovery activities following disaster events. Practical actions to support gender equality can be readily integrated into recovery initiatives. Examples include the potential to issue deeds for newly constructed houses in both the woman's and man's names (subject to land ownership laws), building non-traditional skills through income-generation projects, utilising women for the distribution of humanitarian relief, and providing financing for women's groups to monitor disaster recovery projects.[27]

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[26] UNWomen, 2014

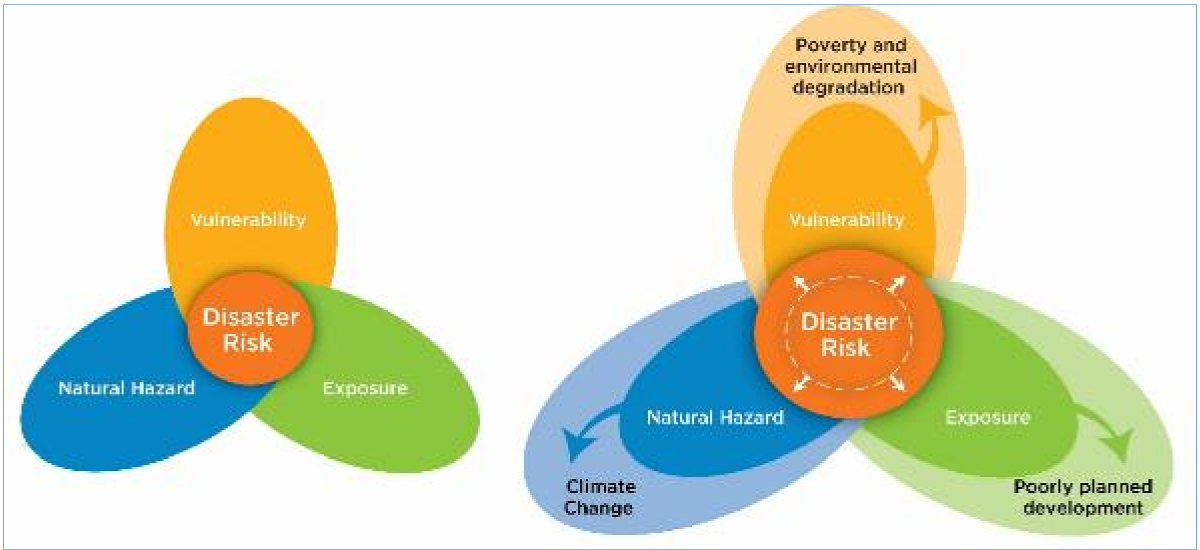
[27] Arnold, Margaret ,2012

2. Managing climate and Disaster Risks

This section describes some general principles on how to manage and reduce climate and disaster risks and strengthen resilience of Pacific islands Countries. The standard framework distinguishes between hazard, exposure, and vulnerability. In the short term, we have little control on the hazards themselves, and in the long term our main impact on hazard patterns is through our effect on the climate. But, policies can reduce exposure and/or vulnerability, and can also aim to reduce either damages or losses.

Climate change, poorly planned development, poverty and environmental degradation are all drivers that can increase the magnitude of this interaction, leading to larger disasters. The rising concentration of population and assets in naturally at-risk areas remains the most important driver of growing disaster risk[28]. This includes rapidly expanded settlements in low-lying coastal areas and floodplains, inadequate spatial planning and regulation enforcement, and lack of compliance or weak building standards. In addition, degradation of ecosystem (such as mangrove, coral reefs, sea grasses) lowers the capacity to buffer for the effects of climate extremes and provide for basic needs. Thus development choices, poverty, climate change are inter-connected and affect the risk and exposure of the people, economy and ecosystems. Weather-related hazards, exacerbated by climate change, can interact with local drivers of exposure (such as location of settlements in high-risk areas) and vulnerability (such as poverty or environmental degradation) to increase disaster risk.

Figure 4. Disaster Risk Assessment Framework - Source: Adapted from IPCC, 2012; World Bank 2013)



As a result, exposure, vulnerability and hazards have to be managed collectively to minimize disaster risk (Figure 4). Addressing climate and disaster risks without addressing the development deficit could be an ineffective response. It also requires global efforts to reduce greenhouse gas emissions so that magnitude of climate-related hazards do not increase.

[28] IPCC, 2012; World Bank, 2013b

2.1 Reducing Exposure

The most obvious of the menu of policies that reduce exposure is risk-based land-use planning, which can account for the risk profile of areas and the appropriate zoning laws and planning strategies that should accompany that risk profile. Environmental assessments of projected development does not always include an assessment of current and future risk profiles, nor an assessment of the resilience of the projected development to all identifiable and quantifiable risks. All too often, new settlements, especially within urban centers, are located in areas with high exposure to flood risks in particular.

Integrated coastal and watershed management plans are proving to be effective approaches for risk-based planning. Tools such as Simplecoast are participatory approaches being used in the Indian Ocean and West Atlantic islands for effective risk-based planning. Urban planners are increasingly using risk-based approaches to identify areas of high exposure but also factors that can increase vulnerability of the populations to flood risk, such as storm drains being blocked with solid waste, debris, branches, silt... Risk-based planning is also being used to ensure settlements and key-assets are not put into high exposure areas (e.g. in Samoa and Sao Tome) and the participatory approaches are providing means of getting consensus building to take action, such a relocation of a coastal roads.

Emphasizing irreversible risks in planning decisions irrespective of exposure can also be used. Using methods like 'rule-of-thumb' guidelines and emphasising irreversible risks to 'life and limb' can be used as a major aim for risk reduction in public policy. In practice, for example, this may mean a policy that reduces earthquake vulnerability of public buildings by some fixed amount (e.g., 50%) irrespective of the assumed exposure to hazards in each region or locality. Similar approaches can be used for hazards impacted by climate change, for which there is uncertainty on future probability distributions (e.g. floods, droughts, or cyclones).

Efficient and timely warning systems and impact forecasting is clearly the most efficient policy intervention to reduce mortality exposure. The major challenges is to develop an effective early warning system with last km connectivity and securing an effective response to the warnings that are supplied. The magnitude of benefits, in terms of life saved per dollar spent, are very large. An effective early-warning system for cyclones has been widely credited with reducing the likely death toll from Cyclone Pam in Vanuatu, which was one of the strongest cyclones to ever hit the South Pacific, and yet the mortality rate was relatively low.

2.2 Reducing vulnerability

Planners typically manage the vulnerability to extreme events by setting design standards capable of withstanding 1 in 50 or 100 year events – i.e. events with a probability of occurring in any year of either 2% or 1% - **without suffering significant damage**. The standards are set to balance the higher costs of building assets that are capable of withstanding more intense but less frequent storms against the potential benefits of lower damages. Residual risks can be covered by asset insurance mechanisms. If this trade-off is properly managed, the expected losses caused by the very infrequent events which do exceed the design standard will be quite small relative to the cost of building and maintaining the assets, especially if the damage is reduced by more resilient designs. Climate change will however alter this risk assessment.

An assessment of whether current standards offer an appropriate level of resilience in the context of current risks is important. Cyclones generally cause damage in PICs that is much smaller in absolute terms than in developed countries, but represent more than 5% of the GDP (see section 1.1.1) – this is rarely the case for richer countries. Two major aspects contribute to the differences. First, richer countries tend to invest in higher levels of resilience than poorer countries because benefits of preventing losses outweighs the costs as the assets and incomes at risk grow. Second, even if increasing resilience in the PICs was economically beneficial, they may not be investing as much in disaster resilience as might be warranted, given their income levels and the distribution of weather risks that they face. It seems likely that current design standards for buildings and infrastructure provide protection against storms with a return period of up to 10 year, but not against worse storms with a longer return period.

Even without climate change, it is not straightforward to assess the trade-off between the costs and benefits of investing in greater protection against storm damage caused by tropical cyclones in the Pacific. By definition, extreme events are outliers. Time series of 200+ years may be required to obtain reliable estimates of low probability events, whereas the data available covers less than 50 years. It is possible to combine statistical modelling with the experience of other regions to obtain an indication of the standards which may be reasonable, as was done with the PCRAFI assessment. These standards should be forward looking by taking account of the expected increase in the value of social and economic assets at risk as a consequence of economic growth over the next 20 or 30 years. Suppose that the design standards adopted would protect buildings and infrastructure against a 1 in 50 year storm. This means that the design standards are intended to ensure that there would less than a 2% chance of significant storm damage in any year. Two points or lines of enquiry would follow from this assessment of design standards.

- **First, all new projects should be required to comply with more protective design standards with more or less immediate effect.** The same principle should apply to the reconstruction and/or replacement of existing assets if they are affected by storms or other hazards.
- **Second, consideration should be given to upgrading or retrofitting existing assets so that they are brought into compliance with the new standards.** The net benefits of retrofitting buildings or infrastructure depend upon their residual life, since early replacement may be cheaper than a short term retrofit, and on the costs of modifying structures. An approach that is often adopted is to require that assets should be upgraded or replaced within a period of 10 or 15 years. This provides flexibility in implementing a strategy to upgrade and/or replace long-lived assets.

Vulnerability is closely aligned with poverty and inequality. Reducing poverty, increasing the access of the poor to resources (economic, political and social) and reducing unequal distributions of assets and incomes, will all contribute to enhance resilience and reduce vulnerability to disasters. As such, sustainable development goals, especially if they 'mainstream' disaster risk reduction, will contribute to reduce the impact of disasters under any future scenario. This will be especially important in reducing the indirect losses associated with disasters.

Vulnerability can be further reduced when disaster strikes through 'build back better' policies that enhance resilience and can potentially reduce both exposure and vulnerability. Disasters should thus be seen also as an opportunity to reconstruct infrastructure, and even institutions and social arrangements in ways that correct the vulnerabilities that were exposed by the event, and guarantees that a future hazard event will have less of an adverse impact on the exposed region. Often, these are missed opportunities, to implement equitable 'build back better' policies that can provide immense benefits to build long term resilience in exposed communities.

2.3 Adaptation and Development Deficit

Adaptation and development deficit have to be addressed before addressing future risks. Collectively reducing exposure, hazard and vulnerability as part of climate and disaster resilient development is proving to be good practice. However, it means that the current development needs have to be met. It is generally also true that a country with adequate resources and institutions is able to withstand the shocks of disasters better than the poorer countries with weak institutions. It is also clear that many countries, especially PICs, cannot manage the effects of current climate risks. Thus there is perceived "adaptation gap". Given the dynamic and interlinked nature of hazard, exposure and vulnerability, a long-term programmatic approach across multiple sectors is needed to address such gaps, ensure corrective action and financial and human resources for sustainable and resilient outcomes.

Achieving climate and disaster resilient development requires international community and national governments to promote approaches that progressively link climate and disaster resilience to broader development paths. There also has to be recognition that despite the best adaptation efforts, a residual risk of disasters must also be managed.

3. Adaptation to Climate Change and Disaster Risk for Key Sectors

3.1 Estimating Costs of Adaptation

Assessing the future cost of climate-change impacts in the Pacific Region is challenging for at least three reasons. First, there are deep uncertainties on the speed and intensity of climate change, especially at local scales. There are large differences between the projections of different climate models that do not seem to be diminishing with time. And given the small size of the PICs and the extensive ocean dominated areas where they are located, downscaling changes in climate and natural hazards at the country level gives an even wider range of potential changes. In addition, even if models were perfectly accurate, uncertainty would not disappear because future levels of greenhouse gas emissions, which by nature cannot be forecasted, largely determine future climate change. Second, climate change impacts will depend on the socio-economic choices made by countries for the next decades. It will be much costlier to adapt to climate change in a society which heavily depends on agriculture production, with high poverty rates, inequalities, and poorly-managed infrastructure than in an inclusive society with safety nets and resilient infrastructure. Finally, the costs and benefits of adaptation are determined by the framework that is used to assess them and the objectives that are set. For instance, the best adaptation strategy will be different in a cost-benefit analysis where the objective is economic efficiency than if the objective is a defined acceptable level of risk. These vary with context, country and stakeholders. In addition, estimates of the cost and benefit of adaptation are always incomplete as it is very difficult to model dynamic feedback between sectors, to model distributional impacts and to quantify social impacts.

Despite all these challenges, the Pacific Possible intends to give estimates of adaptation costs in the Pacific. Results use different methods for different sectors, and are based on previous studies[29], on models designed for the EACC[30], on the PCRAFI results modified to consider climate change impacts, and on the DIVA model. Importantly, this report proposes decision frameworks to account for the deep uncertainties on future climate change. Five methods can be considered:

(i) Selecting ''no-regret'' strategies that yield benefits even in absence of climate change. Example of no-regret strategies include reducing leaks in water distribution systems, increasing the standards of new buildings, or increasing the frequency of road maintenance.

(ii) Favouring reversible and flexible options, like insurance, early-warning systems or easy-to-retrofit coastal defences.

(iii) Buying ''safety margins'' in new investments, with for instance restrictive land-use planning, higher flood defences or bigger drainage capacity for urban infrastructure and roads.

(iv) Promoting soft adaptation strategies, including the ''institutionalization'' of long-term planning exercises and financial instruments.

(v) Reducing decision time horizons. In areas that could be flood-prone in the future, building cheaper houses with shorter lifetime can make sense.

The best adaptation strategies depend in the local context and are likely to be a mix of these options. The sections below only provide leads to orient decision-makers towards what can be done. Interactions between sectors call for integrated design and assessment of adaptation across multiple sectors, which are often developed by distinct communities.

3.2 Sea Level Rise and Coastal Protection

This section examines the implication of climate change on coastal zones focusing particularly on sea level rise, coastal erosion and inundation, as well as the cost of adaptation through approaches such as beach nourishment, sea and river dike construction as well as port upgrade.

[29] The Economics of Climate Change in the Pacific, ADB, 2013

[30] World Bank, 2010b

Methodology

The costs of adaptation are mainly derived from the DIVA model[31] , which provided an estimate of the average costs (capital and maintenance) per year for 3 decades (2020-29, 2930-39 & 2040-49). The model incorporates a simple cost-benefit test so that investment in coastal protection only occurs when either the density of population or the level of economic activity protected is high enough to justify the costs incurred. The analysis considers two main impact types---(1) coastal erosion; and (2) sea and river flooding, and submergence ---and three main adaptation approaches--- (1) beach nourishment (particularly in areas with high tourism revenue); (2) sea and river[32] dike construction; and (3) port upgrade due to climate change are considered (see Annex 2 for more details). Four different scenarios of global sea-level rise (SLR) were examined: (a) no SLR – the reference case to establish the baseline costs of coastal protection without climate change, (b) low SLR – a rise in average sea level of 40 cm above 1990 by 2100, (c) medium SLR – a rise of 87 cm, and (d) high SLR – a rise of 126 cm. Note that impacts due to salinization and wetland loss are not considered. Some modifications have been made to the original model and database, in order to better reflect the particular circumstances of the Pacific Island Countries (PICs). For this present study it has been assumed that only the principal population centres will be protected but not the outer islands and thinly populated coastal segments.

Results

There are large variations in costs across countries and SLR scenarios but overall the costs of protecting the pacific islands would be very high relative to the country's GDP. Table 5 shows the adaptation costs and residual damages over time by country for the medium SLR scenario (which does not include Tuvalu). Averaged over time and normalized by population in 2012 the coastal protection costs in the Medium SLR scenario range from about $50 per person per year for Samoa to $360 for the Solomon Islands and $620 for the Marshall Islands. Over 30 years the total cost of adaptation would be $1,500 per person for Samoa, but $11,000 for the Solomon Islands and $18,500 for the Marshall Islands. For Kiribati, the Marshall Islands, and Vanuatu the cumulative cost of adaptation per person would exceed 5 times the GDP per capita at PPP (Purchasing Power Parity).

[31] Hinkel et al., 2014

[32] This concerns the incremental costs of upgrading river dikes in coastal lowlands where sea-level rise will raise extreme water levels. Additional upgrade may be required if extreme river flows are increased, but this is not investigated here.

Table 5. Range of adaptation costs for coastal protection by country (best case-worst case scenario) (million USD per year at 2012 international prices)

Country	2020s	2040s	2040s as % of projected GDP (includes residual damages)
Fiji	71-230	86-329	1-3%
FSM	6-20	8-28	1-3%
Kiribati	13-42	17-54	4-11%
RMI	13-42	16-58	4-13%
Palau	2-9	3-11	1-2%
Solomon Islands	81-280	97-347	3-11%
Tonga	8-28	9-35	1-4%
Vanuatu	36-130	42-161	2-8%
Samoa	4-15	7-21	0-1%

Source: World Bank estimates

The main component of the costs of adaptation is expenditure on the construction and maintenance of sea walls – more than 75% of the total in most countries. The second component is beach nourishment as river dike costs are negligible in most pacific island countries. The main difference between these costs is that sea dikes must be built in advance of sea level rise and then maintained, whereas beach nourishment is a recurrent cost that can be adjusted as needs require. While the capital costs of sea dikes can be spread over time, the incidence of damage caused by permanent inundation and temporary flooding is likely to be much more uneven. In the absence of a long term strategy for the construction and maintenance of dikes the impact of sea level rise will be felt as intermittent but very large expenditures to deal with the aftermath of severe storm surges and exceptional tides.

The cost of coastal protection and residual damage exceed 5% of GDP in each decade for 4 countries – Marshall Islands, Kiribati, Solomon Islands and Vanuatu in the medium SLR rise scenario (Table 5). In addition, it may be assumed that the result would be the same or worse for Tuvalu. These figures far exceed the scale of adaptation costs relative to GDP reported in the EACC study by World Bank region – less than 0.8% of GDP for Sub Sahara Africa and less than 0.4% for the other regions.

The costs of adaptations vary significantly according to the SLR scenarios, with adaptations and residual damages estimated to be three times more costly in a high SLR scenario than in a low SLR one (see Annex 3 for more details).

Emerging policy message

There is little prospect that the high costs of building sea dikes could be financed by the countries themselves, so the international community will have to assess the trade-off between large initial expenditures on construction that is designed to protect coastal communities for many years into the future versus expenditures and emergency relief and recovery programs when disasters occur.

However, there is no consensus on how to respond to the potential impact of sea level rise. Some countries – e.g. the UK and France - have abandoned attempts to protect all of their coastlines from storm and wave damage. Though this is controversial, it is almost unavoidable in the face of steady and substantial land erosion.

A similar choice may have to be made by some of the Pacific Island countries which may need to set priorities in the geographical allocation of expenditures on coastal protection. For instance, coastal protection infrastructure could be prioritized in areas with high concentration of population (e.g: urban centres) and assets. In some situations, hard structural options can be combined with soft structural options (e.g: ecosystem based approaches, beach nourishment) in order to reduce the cost and mitigate the environmental and social impacts. Ensuring that future population growth is concentrated outside coastal zones and relocating the existing population may also be considered, although the implementation might be challenging due to the unavailability of land or land tenure issues. The development of any particular solution should be informed by a coastal hazard and vulnerability assessments, taking into account potential impacts of climate change. Uncertainties in the future climate change scenarios should not prevent the implementations of actions on coastal protections. Particular attentions should be provided as to provide enough flexibility in the design of these actions, in order to be able to adapt them when uncertainties on climate change scenarios and the way shorelines will respond.

Box 1: Coastal protection and Integrated Coastal Zone Management (ICZM)

There are three main types of adaptation response strategies that can be considered for reducing coastal risks, protection of human life and ecosystems – retreat, accommodate or protect. Options are also often grouped into three main categories: (i) Non-structural options which include development restrictions and relocation of people or assets away from high risk areas. However, these options are often difficult to implement in the pacific due to land unavailability or land tenure issues. Non-structural options also includes change in building codes such as elevation of floor levels, and reducing sand mining, (ii) Soft-structural (e.g. beach nourishment, ecosystem based approach such as mangroves plantation), and (iii) Hard-structural options (e.g. offshore structure, groynes, revetments and sea walls). In some cases, it may be appropriate to consider a combination of structural and non-structural options which can provide a balance between construction costs and the environmental and social impacts.

The selection of a particular solution should be informed by a coastal hazard and vulnerability assessment. Such assessment will allow to better understand the exposure to, and likely impact of, extreme events and ongoing climate change processes, enable targeted early warnings and assist in planning disaster response, prioritise capital works and inform design, and feed into building code and zoning requirements including floor levels and setbacks.

More broadly it is recommended that coastal protection become part of an Integrated Coastal Zone Management (ICZM) approach. It is “a comprehensive, multi-sectoral, integrated approach to the planning and sustainable development management of coastal areas”. This would allow to manage coast in an integrated way taking into account all aspects of development planning including the development of

Clearly, a wider range of adaptation options than considered in DIVA are available in practice and should be part of an integrated approach to coastal management. These include options which allow a planned retreat from the coast or which accommodate higher water levels by raising buildings above flood levels. These could lead to a reduced need for hard-infrastructure protection and may lead to successful adaptation at a lower cost than estimated here. Such measures are difficult to cost and require long-term strategies involving the integration of coastal planning and management. Few Pacific states have this capacity today. Strengthening institutional capacity for integrated coastal management is an essential element of responding to climate change.

3.3 Managing Water Resources and Flooding

The impacts of both flooding and drought may be exacerbated by future climate change and future increases in exposure due to increased population and poor land use planning. Many Pacific Islands have identified concerns about water supplies and their vulnerability to climate change as the primary environmental priority for many communities. In addition, there is a history of significant losses from floods within PICs, and there is the potential that these may increase with the onset of climate change. This section examines the implications of climate change for the management of water resources, focusing in particular on:

1. The problems of ensuring adequate resources for domestic and non-domestic water supply
2. Managing flooding caused by periods of intense rainfall.

Methodology

The potential impact of climate change on vulnerability to droughts and floods has been examined for several PICs based on the RCP4.5 climate scenarios. Statistics for historical rainfall data from records during the period 1948-2008 have been generated and then use as the baseline to investigate future rainfall changes. The model outputs from the RCP45 scenario have been used, and because of large inter-model spread in climate sensitivity and precipitation, the range of uncertainties (here, simulated precipitation) is considered wide enough to cover a range of plausible futures. A standard extreme value distribution known as the Gumbel distribution that has been used extensively to model extreme events such as floods and droughts has been created for the baseline and plausible futures. An example of this is presented in Annex 3.

For the drought analysis, a Gumbel distribution has been calculated for the Baseline period for low rainfall and the model outputs for each of the 19 RCP4.5 global climate models[33] (resulting in a total of 20 Gumbel distributions). For each of these distributions, the 1 in 20 year, and 1 in 50 year low rainfall has been calculated. Given that there are 20 Gumbel distributions that have been developed

[33] Model outputs for **drought** analysis include 19 **low** rainfall distributions – one for each of the 19 climate change scenarios included in RCP4.5 - plus one baseline minimum rainfall distribution, totaling 20 Gumbel distributions for the drought analysis

as part of this analysis, the results include 20 values of the 1 in 20 year drought, and 20 values for the 1 in 50 year drought for the year 2050. Low rainfall under low and medium plausible futures has been approximated for this analysis by respectively adopting the 10th and 50th percentile model outputs from the RCP4.5 climate scenarios. Drought results have been presented for the Baseline, compared to model outputs for extreme and medium climate change (Table 6).

For flooding, the analysis focuses on short term flooding, in which extreme amounts of rain in a period of 24 hours cause flooding within a relatively short distance of the original precipitation. The results should be taken as indicative of potential trends, as they are based on generic assumptions that should be refined with more specific information about actual conditions. Similar to the methodology used for droughts, the distributions of high 24 hour rainfall have been assumed to follow the Gumbel distribution, and the distributions have been estimated for the Baseline period for flooding and for the model outputs of the RCP4.5 climate change projections for 2050[34]. High rainfall under high and medium climate change has been approximated for this analysis by respectively adopting the 90th and 50th percentile results from the 19 Gumbel distributions that have been developed[35]. Flooding results have been presented for the Baseline, compared to the outputs for high and medium climate plausible futures.

Results

Drought

Under a medium climate change scenario, the risks of more severe drought in 2050 are small in most countries. Fiji, RMI, Palau, FSM, Vanuatu and Solomon Islands may experience a small reduction in some of the 1 in 50 year and 1 in 20 year low rainfall values, but the changes should not require major investment in additional water storage.

The results show the risks are likely to be much more significant should more extreme climate change take place, especially for the Solomon Islands and Tuvalu and to a lesser extent Fiji, Palau and RMI. There is a small but significant chance that changes in climate may lead to extended periods of little or no rain, particularly in Solomon Islands and Tuvalu, necessitating investment in either water storage or alternative sources of water (such as desalination) as a supplement to normal rainfall. Table 2 shows the changes in low rainfall that could be expected in 2050 under medium and extreme climate change for various 1 in 20 year and 1 in 50 year droughts, compared to the Baseline.

[34] Model outputs for **flood** analysis include 19 **high** rainfall distributions – one for each of the 19 climate change scenarios included in RCP4.5 - plus one baseline minimum rainfall distribution, totaling 20 Gumbel distributions for the flood analysis

[35] The differences between the high and medium model output results reflect the uncertainty concerning future climate projections (i.e., 19 models are included in RCP4.5, and there is significant variation between these models, due to factors such as varying future emissions levels etc.) rather than weather variability (such as dryer years or wetter years).

Table 6. Changes in low rainfall by country for 2050
(mm of rain relative to baseline)

Country	Change in 1 in 50 year minimum rainfall				Change in 1 in 20 year minimum rainfall			
	30 days	60 days	90 days	120 days	30 days	60 days	90 days	120 days
Model Outputs for Median Climate Change								
FJI	0	-5	-14	-6	-1	-6	-10	-5
FSM	0	-10	3	14	-2	-5	8	15
KIR	0	0	0	-17	0	0	-18	-5
MHL	0	-1	-7	-2	-1	-2	-4	0
PLW	0	-12	-6	2	-1	-10	3	8
SLB	-4	-17	-26	6	-4	-15	-23	10
TON	0	0	0	0	0	0	-0	-4
TUV	1	0	19	30	4	4	20	31
VUT	0	0	-3	-6	0	-0	-3	-10
WSM	0	0	0	0	0	0	2	4
Model Outputs for Extreme Climate Change								
FJI	-1	-22	-59	-67	-5	-36	-72	-84
FSM	-2	-27	-39	-36	-7	-30	-31	-35
KIR	0	0	0	-17	0	0	-19	-50
MHL	0	-13	-75	-71	-5	-33	-74	-75
PLW	0	-39	-51	-45	-5	-30	-47	-46
SLB	-65	-197	-332	-415	-65	-179	-299	-375
TON	0	0	0	0	0	0	-0	-5
TUV	-28	-102	-155	-230	-32	-98	-150	-221
VUT	0	0	-5	-10	0	-3	-13	-25
WSM	0	0	0	0	0	0	-16	-27

Source: World Bank estimates
Note: The differences between the medium and extreme model outputs reflect the uncertainty concerning future climate projections, rather than weather variability.

Surface water flooding

The results suggest that most of the PICs will experience an increased probability and severity of flooding, due to increased rainfall during high rainfall events[36]. Table 7 shows results for the peak 1 in 20 year rainfall over a 24 hour period for the No Climate Change Baseline compared to the medium and extreme model outputs for the RCP4.5 Climate Change model scenarios.

[36] Unfortunately, variations across the RCP4.5 climate scenarios point to increased flooding in a particular grid square for some scenarios and decreases for other scenarios, so that the level of uncertainty about the actual outcome is high.

Table 7. Changes in high 1 in 20 year rainfall over 24 hour period by country for 2050
(mm of rain relative to no climate change)

Country	Baseline (mm)	Model Outputs for Median Climate change		Model Outputs for Extreme Climate Change	
		Rainfall (mm)	Increase from Baseline (mm)	Rainfall (mm)	Increase from Baseline (mm)
FJI	245	292	47	348	103
FSM	63	78	15	123	60
KIR	145	224	79	365	220
MHL	72	85	13	125	53
PLW	197	245	48	284	87
SLB	84	102	18	119	35
TON	57	68	11	82	25
TUV	83	102	19	127	44
VUT	189	230	41	281	92
WSM	79	97	18	116	37

Source: World Bank estimates
Note: The differences between the medium and extreme model outputs reflect the uncertainty concerning future climate projections, rather than weather variability.

If it is assumed that the current standard is adequate (although recent flooding in PICs such as that which occurred in Solomon Islands in April 2014 and Fiji in April 2016 suggests that it is not), then consideration can be given to how best adapt to cater for increased rainfall due to future climate change. For example:

- Option 1 could be to enhance the defences to cater for future climate change, while maintaining the current standard of protection (i.e., to cater for 1 in 20 year events under future climate change conditions).
- Option 2 could be to increase the level of protection from the current standard for existing flooding to a higher standard of protection for existing flooding (i.e., move from a catering for a 1 in 20 year event under today's conditions, to a 1 in 50 year event under today's conditions. This option would not take future impacts of climate change into account).
- Option 3 could be to increase the level of protection from the current standard for existing flooding and also to cater for future climate change in 2050 (i.e., moving from a 1 in 20 year event under current climate conditions, to a 1 in 50 year event under future climate change conditions.

Catering for an increased standard of protection and increased rainfall due to climate change is likely to be prohibitively costly and may not be reasonable for PICS. Option 1 and Option 2 above are likely to provide realistic solutions for flood management in the future. Given that there is still a high degree of uncertainty surrounding the degree to which climate change may impact on future rainfalls, it may be that adopting a higher standard of protection for current standards could act as a proxy for catering for increased rainfall under future climate change scenarios.

For example, if it is assumed that PICs currently offer a standard of flood protection to cater for 1 in 20 year rainfall events, adopting a standard of protection to cater for a 1 in 50 year rainfall event under current conditions, could act as an approximation for catering for 1 in 20 year rainfall events in 2050 which are expected to increase due to climate change in some countries. This has been observed in several additional island countries such as Palau and Solomon Islands. This is illustrated in the figures below in Table 8. To use the example of Fiji, the 1 in 20 year peak rainfall for current conditions could be expected to be 245mm based on historical data. The 1 in 50 year peak rainfall based on historical data is 17% more than this. Looking at the RCP4.5 model outputs for median climate change, the 1 in 20 year peak daily rainfall would be expected to be only 2% higher than the current level. However, the 1 in 20 year peak daily rainfall resulting under the high climate change scenario would be an increase of 19% on current levels. This illustrates that adopting an increased standard of protection for flooding (i.e., for Fiji, moving from a 1 in 20 year standard to a 1 in 50 year standard) could serve to cater for increased rainfall even under the more extreme climate change scenarios, while maintaining the current minimum standard of protection over time. It would still be necessary to monitor the impacts of climate change, but this strategy would provide time to identify trends and respond appropriately in the future if needed once a more accurate understanding is obtained of the impacts of climate change on flooding in PICs.

Table 8. Comparison of baseline peak rainfall with peak rainfall in 2050 (by country and return period)

Country	Baseline		Model Outputs for Median Climate Change		Model Outputs for high Climate Change	
	1 in 20 year peak rainfall (mm)	% increase to 1 in 50 year peak rainfall	% increase in 1 in 20 year peak daily rainfall	% increase in 1 in 50 year peak daily rainfall	% increase in 1 in 20 year peak daily rainfall due to climate change	% increase in 1 in 50 year peak daily rainfall due to climate change
FJI	245	17%	2%	19%	19%	40%
FSM	63	12%	10%	23%	59%	82%
KIR	145	18%	31%	53%	63%	92%
MHL	72	14%	4%	19%	46%	69%
PLW	197	16%	7%	24%	16%	35%
SLB	84	14%	7%	22%	16%	31%
TON	57	14%	4%	19%	21%	40%
TUV	83	14%	8%	23%	24%	42%
VUT	189	16%	5%	22%	22%	42%
WSM	79	14%	8%	23%	19%	37%

Source: World Bank estimates

Note: The differences between the median and 10th percentile case reflect the uncertainty concerning future climate projections, rather than weather variability.

Table 8 illustrates that for some countries, adoption of a higher standard of protection plus adaptation to future climate change would necessitate an even larger investments in flood defences. For example, for FSM, Kiribati and the Marshall islands, moving from a 1 in 20 year standard of protection to a 1 in 50 year standard of protection while catering for extreme climate change would require the need to cope with around 70-90% increases in peak rainfall..

Rather than utilising flood defences, in some countries a better strategy may be to ensure that the floor levels of all new buildings are raised so that their main thresholds are a metre or more above ground level. This would also assist these countries to prepare for sea level rise. It may be prohibitively expensive to retrofit all existing buildings, but the design standards for new buildings – particularly, important public buildings – should set out to raise floor levels above future flood levels wherever possible and to encourage the implementation of other measures that would minimise the impact of flood damage. This could include raising power outlets and key services as well as avoiding the use of materials that are badly affected by flood water.

Changes in flood exposure and damage

Flood exposure and damage costs are high for many PICs under current climate conditions. Table 9 summarises the baseline flooding exposure (using historic data for 1981-2000) for four countries, showing the distribution of population and economic activity that are subject to various impacts (from no impact to very high impacts). It shows the current flooding risk exposure is high to very high in Fiji, and medium to high in Solomon Islands and Samoa. In Fiji 38% of the population and 19% of economic activity fall into the high or very high impact category. The hazards for these people are high to very high, not merely relative to other areas in Fiji but by comparison with flood exposure in all countries around the world. The proportion of the population subject to High and Very High impacts are much lower for the other countries, though 7-8% of economic activity in the Solomon Islands and Samoa is located in areas with high or very high flood impacts. Clearly, the areas at risk of flooding with high or very high impacts are candidates for additional investment in flood defences to raise the level of protection and reduce the flood losses which occur as a result of extreme weather under current climate conditions.

Table 9. Severity of flood impacts under current standard of protection and current climate conditions

	Exposure by impact				
Country	No impact	Low	Medium	High	Very High
Proportion of population					
Fiji	11%	14%	37%	32%	6%
Solomon Islands	59%	19%	19%	1%	1%
Vanuatu	63%	36%	1%	0%	0%
Samoa	62%	0%	36%	0%	1%
Proportion of economic activity					
Fiji	23%	17%	41%	16%	3%
Solomon Islands	68%	25%	1%	5%	2%
Vanuatu	92%	8%	0%	0%	0%
Samoa	76%	0%	16%	0%	8%

Source: World Bank estimates

The main impact of climate change will be a shift between the categories of medium to high and from high to very high impacts, with more people and economic activity falling into the category of a very high impact. Table 10 shows how the exposure under the current level of protection may change by 2050 due to the impacts of medium climate change. With no change in the level of protection, 26% of the population of Fiji and 7-8% of the economic activity of Fiji, Solomon Islands and Samoa will be at risk of Very High levels of flood damage. A strategy of raising the level of flood protection in these countries would provide immediate benefits as well as a substantial degree of insurance against all but the worst outcomes due to climate change.

Table 10. Severity of flood impacts under current standard of protection And medium 2050 climate conditions

	Exposure by rank of impact				
Country	No impact	Low	Medium	High	Very High
Proportion of population					
Fiji	11%	11%	10%	40%	26%
Solomon Islands	59%	59%	15%	23%	0%
Vanuatu	63%	63%	32%	5%	0%
Samoa	62%	62%	0%	1%	35%
Proportion of economic activity					
Fiji	23%	15%	42%	11%	8%
Solomon Islands	68%	25%	1%	0%	7%
Vanuatu	92%	6%	2%	0%	0%
Samoa	76%	0%	1%	15%	8%

Source: World Bank estimates
Note. The climate conditions considered in the above table relate to the medium model outputs.

Box 2 - Cost of flooding and adapting to flooding in Pacific Island Countries

Floods have caused millions of dollars of damage and loss to Pacific Island Country economies. In the case of Fiji, it is apparent that over the last 12 years, floods cost Government and communities some FJD$35 million a year. This figure would likely increase if the full range of potential floods and costs were accounted for (data is lacking) – the 100 year flood at Nadi alone is estimated to cost F$794M (NIWA, 2014). Only one study is known to have estimated the annual average damage from flooding, for the Vaisigano catchment in Apia, Samoa, at SAT 620,000/year (Woodruff, 2008). What is not readily detected by viewing raw damage figures is the effect of flooding on national economies – but as an example, flooding in and around Honiara in April 2014 had an economic impact equivalent to 9.2% of the Solomon Island's GDP.

Climate change and urbanisation are likely to increase the costs of flooding. Studies of two catchments in Fiji estimated that with 'moderate' climate change, annual flood losses would increase by 90%. With 'severe' climate change, annual flood losses could increase by nearly 275% (Brown et al., 2014).

The process of estimating the cost of adapting to flooding was outside the scope of this study, as it requires developing flood models on a catchment by catchment (or river by river) basis, and then establishing and costing the specific options that would be required to mitigate flooding for a particular situation. However, lessons can be learned from previous studies which have assessed the costs and benefits of interventions to reduce the risk of damage from flooding in specific PIC cities. For example, the cost of implementing the Navua River flood warning system in Fiji over 20 years was estimated at F$570K, yielding a benefit-cost ratio (BCR) of 3.7–7.3 (Holland, 2007). An assessment of management options for the Vaisigano floodplain in Apia, Samoa, found that house raising (BCR 8.0 for new wooden houses but still >1.0 for existing cement block houses) and improved flood forecasting systems (BCR 1.7–1.9) offered the best return (Woodruff, 2008).

Brown et al. (2014) compared the merits of various engineered solutions such as dredging rivers and riverbank reinforcement with ecosystem-based adaptation options for two catchments in Fiji. Under 'moderate' climate change, riparian buffers were judged to offer the best return (cost F$7M, BCR 2.3), followed by upland afforestation (but costing a prohibitive F$127M, BCR 1.1). Under 'severe' climate change, river dredging (cost $53M, BCR 1.3) and floodplain vegetation (cost F$22M, BCR 1.2) also had positive BCRs.

Emerging Policy Message

Even under existing climate conditions, several PICs experience flood and drought related challenges. There are significant economic impacts from river-based flooding, and significant water shortages due to drought, particularly during El Niño periods.

RCP4.5 Climate scenarios suggest that total annual precipitation will increase in most Pacific Island countries as a result of climate change. This increase will be accompanied by greater differences in rainfall between wet and dry months and more intense rainfall in the wettest periods of the year. Hence, adaptation to climate change will involve measures to: (i) increase the capacity to store water that is accumulated in wetter months for use in the drier months; and (ii) manage the run-off caused by more intense periods of rain.

Investment in increased water storage, especially on islands with limited amounts of land suitable for reservoirs will be critical. The alternative to investing in more water storage may be reliance upon desalination facilities or other alternative water resources, which (depending on scale) may result in significant capital costs in addition to ongoing operational and maintenance costs.

Due to the high level of uncertainty surrounding the degree to which climate change may impact on future rainfalls, it may be that adopting a higher standard of protection for current flooding conditions could act as a proxy for catering for increased rainfall under future climate change scenarios. One option could be to increase the design standard for flood defences from 1 in 20 year floods to a higher standard of protection, such as the 1 in 50 year standard.

An integrated mix of carefully evaluated flood risk management measures is likely to offer most benefit. Greater investment in and application of the flood risk management approach is required to increase public safety, to mitigate adverse impacts and to build communities resilient to current and future climates. The alternatives could include any combination of measures to provide protection to assets or accommodation to flood flows. Both protection and accommodation measures may involve substantial capital and ongoing maintenance costs.

3.4 Adapting Infrastructure to Changes in Rainfall and Temperature

This section provides an overview of different adaptation strategies and the cost of adapting infrastructure assets to changing climate. Infrastructure assets include power and telecommunication, water and sewers, urban, roads and other transport infrastructure, hospitals, schools and housing. Importantly, the analysis below only considers risks associated with temperature increase and precipitation changes, so it assumes that buildings can withstand stronger winds and that coastal adaptation is in place to protect the infrastructure against sea level rise and stronger storm surges. The cost of protecting buildings against tropical cyclones is discussed in Section 3.5 while the cost of protecting against sea level rise and storm surges is discussed in Section 3.2, so they are not considered here. The major findings are summarised below and details are provided in Annex 4.

Methodology

Costs of adaptation are highly dependent on future development pathways. To assess the cost of adaptation for infrastructure, a number of assumptions are made about future infrastructure investments as well as about the design standards that would have been applied to build these assets in the absence of climate change. This set of assumptions is referred to as reference scenario. The costs of adaptation are then assessed as the difference between expenditures in the reference scenario and expenditures in scenarios with climate change impacts, where the infrastructure is designed to withstand changes in temperature and precipitations. Accordingly, if the reference scenario assumes that resilience will increase over time in the absence of climate change, adaptation costs are much lower than if the reference scenario assumes there will be no frequent maintenance regimes in the next decades and new resilient standards are not used.

Here, in the reference scenario, it is assumed that there will be an improvement in the quality and maintenance of infrastructure services over the next decades. It is assumed that over time and development gains, a country will have a "normal" level of infrastructure defined as a function of GDP per capita, population, and a range of physical and climatic conditions with patterns similar to that of current high- and middle-income countries. The reference scenario also assumes that the quality, redundancy and maintenance levels of infrastructure increase over time, as a function of income growth, i.e. countries will invest in climate resilience infrastructure and will follow good practices in terms of maintenance to protect against current risk levels. Accordingly, PICs will not be protected against 1 in 1,000 or even 1 in 10,000 year floods like the Netherlands, because the opportunity cost of such defences – e.g. the sacrifice of expenditure on health or education – may not justify such high protection. But improving the resilience of current infrastructure can bring many economic benefits. Today infrastructure in the PICs is often badly damaged by cyclones. For example, Tropical Cyclone Pam (2015) caused losses to Vanuatu equivalent to 64% percent of GDP, of which 60% are related to infrastructure assets. Design standards often specify assets being able to withstand 1 in 50 or 100 year events – i.e. events with a probability of occurring in any year of either 2% or 1% - without suffering significant damage. Clearly these are not sufficient for the current conditions suggesting that changes in standards and codes and/or their enforcement are needed.

There are deep uncertainties on climate change impacts at local level in PICs, which makes it difficult to choose the best investment and the best adaptation strategy. For example, the construction of paved roads can include pavement surface that incorporate binders that are specified to perform to a particular level of pavement temperature – an indicator which depends upon maximum temperature and latitude. Designing for a higher level of the pavement temperature increases the initial cost of constructing the paved road but reduces the cost of maintenance due to avoided degradation of the pavement surface when/if the pavement temperature exceeds the design specification. Hence, the decision on adaptation strategy involves a trade-off between capital and maintenance costs which is affected by the probability that future climate conditions will exceed critical values for the pavement temperature.

Decision-makers face two major adaptation strategies: "wait, observe and then act" or "plan for a changed climate". In the former strategy, focus could end up on disaster risk management. The strategy would mean, for example for a road, binders or culverts are not changed compared to the reference scenario, but the road may have to be replaced before the end of its lifetime and there may also be service disruptions especially after heavy rainfall events. In the reference scenario, costs of the service disruption and/or increased maintenance due to climate change are not included. When decision-makers decide to plan ahead for a changed climate, the concepts of building back better and resilient reconstructions are incorporated. This strategy requires designing investment that will resist many different climate change impacts while being cost-effective and that could perform relatively well in a large number of possible scenarios. It may mean deciding, for example, to build flood defences today which are high enough to protect against a 1 in 100 year flood under the worst case climate scenarios for 2050, to construct paved roads and bridges capable of withstanding the high temperatures that are projected to occur in the next 30 years or to change the design standards for buildings so that they incorporate cooling and ventilation that can cope with projected temperatures and levels of humidity in 2030 or 2050. Upstream decisions may also be needed and should be informed by risk planning to help move assets out of high risk and exposure areas. The socio-economic costs and implications of such decisions are not included here.

The analysis presented in this section used 19 simulations run by 12 Global Climate Models (GCMs) runs using the RCP4.5 climate scenario (see Annex 1) for emissions of CO_2 and other greenhouse gases. It calculated the costs associated with the two major adaptation strategies in all those scenarios, always starting from the same reference scenario. However, the uncertainty on the reference scenario was not explored. Such an analysis produced a large number of possible outcomes.

Given the large number of outcomes, an approach based on criteria of "minimum maximum regret" is used to select the most appropriate strategy in each sector and each country. In this approach, the cost associated with every strategy is calculated and compared to the least-cost strategy, in each climate scenario. This is called the regret. From this the maximum regret associated with each strategy across all scenarios is calculated and the strategy with the lowest maximum regret is selected. For instance, investing in expensive planned adaptation option, when the climate change turns out to be the lowest possible might create a higher regret than waiting and reacting with adaptation options even if the world ends up with high climate change. If this is the case, the most appropriate strategy is to wait, observe and act. Results of such analysis and the trade-offs needed at the local level could be strengthened by considering several reference scenarios and taking into account the views of the local population and stakeholder, especially the level of disruption to the services that might be acceptable to them. Given the scale of the analysis – at best at a country level – such considerations are not included in the results presented.

Results

Using the 19 climate scenarios from RCP4.5, the average cost of adaptation where decision-makers plan for a climate changed future varies from 2% to 20% of baseline expenditures across the PICs (table 11). This result is across all 19 model outputs and for all infrastructure types. Fiji and Vanuatu are at the low end with very low adaptation costs while costs can reach more than 8% of baseline expenditure for FSM and Kiribati on average. The variation comes from different climate change impacts in different countries: for instance in all scenarios rainfall increases significantly in Kiribati while impacts are much smaller in Fiji, with sometimes a decrease in rainfall (see Annex 1).

Table 11. Costs of pre-emptive adaptation relative to baseline expenditures

(Average cost of pre-emptive adaptation for all infrastructure assets by country for 2011-50; 20 year planning horizon; $ million per year at 2010 international prices with no discounting)

Country	Average cost of pre-emptive adaptation over GCMs	% of reference scenario
Fiji	20.2	2.8%
FSM	13.4	13.4%
Kiribati	18.9	20.9%
MHL	8.1	11.5%
Palau	4.5	6.3%
SLB	17.3	8.6%
Tonga	8.4	11.7%
Tuvalu	0.3	5.8%
Vanuatu	7.0	3.9%
Samoa	7.8	7.0%

Roads account for more than 50% of the average costs of adaptation in all but two countries and exceed 90% of the average costs in Solomon Islands and Samoa (Table 12). Urban infrastructure and housing are important contributors to the average cost of adaptation in the Marshall Island, Palau and Tuvalu where there are limited road networks.

Table 12. Average cost of adaptation by infrastructure type over 20 year planning horizon across all 19 climate scenarios (costs as % of expenditures in reference scenario)

Country	Power & phones	Water & sewers	Roads	Other transport	Health & schools	Urban	Housing
Fiji	0.4%	0.1%	14.8%	0.3%	0.4%	0.6%	0.3%
FSM	0.9%	0.2%	40.1%	1.6%	1.0%	1.2%	1.5%
Kiribati	0.6%	0.6%	41.4%	1.7%	2.2%	2.8%	2.9%
MHL	1.4%	0.8%	29.9%	2.1%	4.1%	4.2%	5.7%
Palau	0.6%	0.0%	22.0%	2.6%	1.2%	1.4%	1.7%
Solomon	0.8%	0.1%	34.3%	0.4%	0.5%	0.8%	0.4%
Tonga	0.9%	0.7%	32.6%	1.0%	2.5%	2.7%	1.8%
Tuvalu	0.9%	0.0%	43.8%	0.0%	0.0%	2.1%	1.7%
Vanuatu	0.5%	0.1%	15.1%	0.4%	0.5%	0.9%	0.5%
Samoa	0.6%	0.1%	22.5%	0.6%	0.4%	0.6%	0.5%

The high cost of adaptation, especially for the road sector may be justified if the worst climate scenario occurs, but may not be justified in lower climate change scenarios. The criteria of "minimum maximum regret" to select the most appropriate strategy in each sector and each country is used here. Table 13 shows the results for each country and infrastructure in 2040, using a 5% discount rate for calculating adaptation costs and regrets.

Table 13. Lowest regret adaptation strategies for the 2040s by country and by infrastructure type (for * the lowest regret strategy may be reactive, while for others it is pre-emptive adaptation. The cost of the strategy in the worst case scenario as a % of expenditures in reference scenario.)

Note: a 5% discount rate was used to calculate the regrets

Country	Health & schools	Housing	Other transport	Power & telecoms	Roads	Urban	Water & sewers
FSM	(1.0%)	(3.0%)	(3.0%)	* (0.6%)	* (20.0%)	* (3.0%)	(0.3%)
Fiji	(0.5%)	(0.7%)	(0.7%)	* (0.1%)	* (3.0%)	* (0.5%)	(0.1%)
Kiribati	(2.0%)	(4.0%)	(3.0%)	(0.6%)	(20.0%)	(2.0%)	(0.4%)
MHL	(0.4%)	(1.0%)	(0.9%)	(0.5%)	* (10.0%)	(0.8%)	(0.09%)
Palau	(2.0%)	(3.0%)	(3.0%)	* (0.6%)	* (30.0%)	(2.0%)	(0.3%)
SLB	(0.4%)	(0.8%)	(0.8%)	* (0.1%)	* (4.0%)	* (0.5%)	(0.1%)
Samoa	(0.1%)	(0.2%)	(0.5%)	* (0.2%)	* (4.0%)	(0.2%)	(0.03%)
Tonga	(0.06%)	(0.0%)	(0.08%)	(0.3%)	* (2.0%)	(0.4%)	(0.02%)
Tuvalu	(0.8%)	(2.0%)	(1.0%)	* (0.5%)	* (20.0%)	(0.8%)	(0.2%)
Vanuatu	(0.6%)	(1.0%)	(1.0%)	* (0.4%)	* (10.0%)	(1.0%)	(0.1%)

For most type of infrastructure (e.g: health and schools infrastructure, housing, water supply and sewers) the lowest regret option is to adapt now to future climate changes. The lowest-regret strategy often entails planning ahead for only one or two decades. For example, for infrastructure that has generally a short life-span (such as houses), decision-makers and engineers should not be asked to design houses with a view to extend their lifetime beyond 20 years. It is cheaper to build infrastructure that can withstand the climate conditions of the next 10 to 20 years than building infrastructure that can withstand both current climate and the climate that will be experienced in 30 years. For many types of infrastructure the pre-emptive strategy is fully justified as the marginal cost is low (e.g: ICT, health and schools, water and sewers).

For roads, due to the the high costs of protecting infrastructure against the worst case scenario and the high uncertainty surrounding future changes in rainfall, decision has to be made case by case. The lowest regret option for many PICs appears to be reactive to climate change impacts which would involve rebuilding those sections of the roads if and when they are damaged. However, this assumes that governments will have the financial and technical resources to react quickly in case of disasters and repair damaged roads promptly, whereas if those conditions are not met, the costs of being reactive may be largely underestimated. In addition, in order to reduce the vulnerability of PICs, it is important to ensure vulnerable populations always have access to basic social services like schools and hospitals during disasters. A possible cost-effective solution for managing future changes in climate and minimize the economic costs associated with a road failure, could be to focus on strengthening preparedness (e.g: reducing the time needed to restore traffic, pre-selecting contractors, setting up an emergency fund, storing materials in advance to respond quickly) and maintaining accessibility to essential infrastructure such as schools and hospitals following a disaster event by increasing the redundancy of the road network, thus making sure there are alternatives even if the main road is damaged. More importantly the optimum solution will be a combination of relatively low cost adaptation measures (e.g. first and foremost proper maintenance but also increase the slope of pavement and/or the capacity of the drainage systems to reflect changes in future expected runoff or water flow) and strengthening preparedness.

Roads and urban infrastructure have relatively high costs of adaptation with the primary driver of adaptation costs being the increase in the amount and intensity of rainfall affecting maintenance as well as upgrading/reconstruction costs. This suggests investing in urban storm water drainage, especially in PICs where precipitations are projected to increase as in the Solomon Islands, FSM, Kiribati, and Marshall Islands. For roads, in some places like Kiribati it may be required to upgrade roads to higher standards to that they can withstand large increases in rainfall.

Emerging policy messages

Complying with the current construction standards and maintenance regimes should be a priority for all PICs. Current weather patterns affect the reliability of infrastructure especially road services and affect economies of many PICs. Given the present infrastructure is not able to withstand the current climate extremes, ensuring compliance, especially in the absence of new climate resilient standards together with maintenance based on good practices will decrease the damage to infrastructure and minimize service disruptions. Horizontal infrastructure such as water and electricity systems, transportation links (bridges, main roads), ports, are unique as their functioning have many impacts on other types of economic activities. Strengthening horizontal infrastructure therefore reduces both damages and the indirect losses associated with their failure to provide services during and after the emergency phase of a sudden-onset disaster event. Equally important as strengthening is inserting redundancies into crucial lifelines, so that a failure in one point does not lead to a collapse of the system. This is relevant not only for transportation, electricity and water systems, but also to other crucial lifelines like communication systems.

Assuming countries raise construction standards over time, the costs of adaptation for timeframe to 2050 is around 2-20% of baseline expenditures with the highest being more for countries where changes in precipitation particularly affect the road networks. But the actual costs may be higher in a more pessimistic reference scenario in which infrastructure would be closer to what it is like today. This is given that most of the infrastructure in PICs generally is not able to withstand the current climatic conditions.

The materials and designs used in building infrastructure, as well as the frequency of maintenance, would need to be altered to maintain the same quality of infrastructure services as in the absence of climate change. For example, in buildings it will be necessary to increase the capacity of ventilation systems in order to cope with more humidity, and to strengthen the roofs to withstand higher levels of rain. In urban designs larger drainage and water storage systems will be required to cope with higher rainfall.

Implementing adaptation options now for most infrastructure types would provide benefits irrespective of the severity of climate change in 2050s. For many types of infrastructure the pre-emptive strategy is also justified as the marginal cost is low.

For roads, the costs of raising standards to resist potential climate changes is high and the optimum solution will be a combination of pre-emptive measures and strengthening preparedness.

Adaptation strategies need to be designed on a case by case basis. For instance in some places it may make sense to adapt roads to climate change by installing higher drainage capacity and elevating the road, while in other places increasing redundancy in the network can be a more cost-effective solution. Many uncertainties other than climate were not considered in the analysis but are important in the decision-making process. Such factors include the acceptable level of service disruption that communities are willing to bare, the economic basis of the area (e.g. agriculture, tourism or others which are less affected by climatic factors) and the soft adaptation measures already in place (e.g. early-warning systems, social safety nets, insurances).

3.5 Improving the resilience of buildings to tropical cyclone winds

This section focuses on the options for reducing the damage from tropical cyclone winds[37] on housing and public building, both under current climate conditions and future climate scenarios up to 2050. The analysis focuses on national level options that can include combination of: i) retrofitting (upgrading) existing buildings to increase their wind resistance and ii) progressive replacement of the building stock using enhanced design standards that take account of increased wind speeds due to likely climate change conditions. Complementary analysis of progressive adjustment in design standards required to take account of changes in average temperatures, precipitation and humidity which affect the service life and habitability of buildings is presented in Section 3.5 and Annex 5.

Methodology

The PCRAFI modelling components have been combined with an analysis of the impacts of both climate change scenarios and strengthening measures for the building stock due to retrofitting and application of stringent building codes. The PCRAFI study developed a probabilistic risk model to estimate losses caused by tropical cyclones under historical climate conditions. Generally, the intensity of tropical cyclones is likely to increase by 3–5 percent per 1°C rise in sea surface temperature. This forms the basis of distributing changes in cyclone intensity[38] as measured by the projected 1 in100 years wind speed for 2050 under historical climate, low and high-emission scenarios (Table 14), further details of the climate models and assumptions can be found in Annex 1.

[37] Storm surge and flooding also damage buildings – however, the most effective protection options often require implementation of larger scale measures such as elevated dikes or changing land-use policies rather than measures that can be implemented at the individual building level. These topics are presented in Section 3.2 (Sea Level Rise and Coastal Protection) and Section 3.3 (Managing Water Resources and flooding) with further details in Annexes 5 and 6.

[38] Cyclone frequency is likely to decrease with climate change but this was not considered here as it is too difficult to model. The climate change impacts on cyclones used here should therefore be considered as upper bound impacts.

Table 14. Estimated increases in cyclone wind intensity up to 2050

Country	Likely wind speed with mean return period of 100 years (Kmph sustained over 1 min)		
	Historical climate	Low emission scenario	High emission scenario
Fiji	157	162	168
FSM	154	160	166
Marshall Islands	142	149	155
Tonga	152	158	165
Vanuatu	182	190	197
Samoa	152	158	165

Engineering-based functions from PCRAFI were used to analyse the possible reduction in cyclone wind damages due to improved building performance from retrofitting and code upgrading. For a given wind speed level, the amount of damage depends upon features of building design, materials and construction methods. Damage curves have been compiled reflecting current design and construction practices and for two retrofitting options: i) lower cost measure that are easily implemented (light retrofit), and ii) more extensive and costly improvements (heavy retrofit). It has been assumed that heavy retrofitting would be restricted to public buildings, including emergency shelters.

Benefit-Cost Ratios (BCRs) were calculated to assess the cost-efficiency of investing in retrofitting. The calculations used the PCRAFI inventory of buildings for each country combined with estimates of costs for the light and heavy retrofitting measures. The benefits of the reduction in cyclone damage due to the retrofitting measures were calculated for each building type as the present value of the reduction in the expected annual losses over a period of 30 years using discount rates from 2 to 5 percent. The BCR is the present value of discounted benefits divided by the initial cost of retrofitting. Three sets of benefit-cost ratio under three scenarios were calculated: no climate change, low-emission and high-emission[39].

The approach also evaluated the need to improve design standards to achieve a standard threshold of resilience to cyclone winds. This is important given that in many PICs, the existing building design practices offer limited resistance even to moderate 1 in 10 year or 1 in 20 year winds. A fairly low target design level resistance to the 1 in 50 year winds was used for this study. It means that over a 50 year service life, a building would still have a 60% chance of experiencing significant damage. This compares to design practices in some high income countries where building codes require resistance to the 1 – 500 year hazard, which offers a much lower (10%) chance of being exceeded in 50 years. The relative costs of implementing building codes that are resilient to projected climate change can be assessed by comparing the added cost to increase design thresholds to meet the 1 in 50 year wind intensity in 2050.

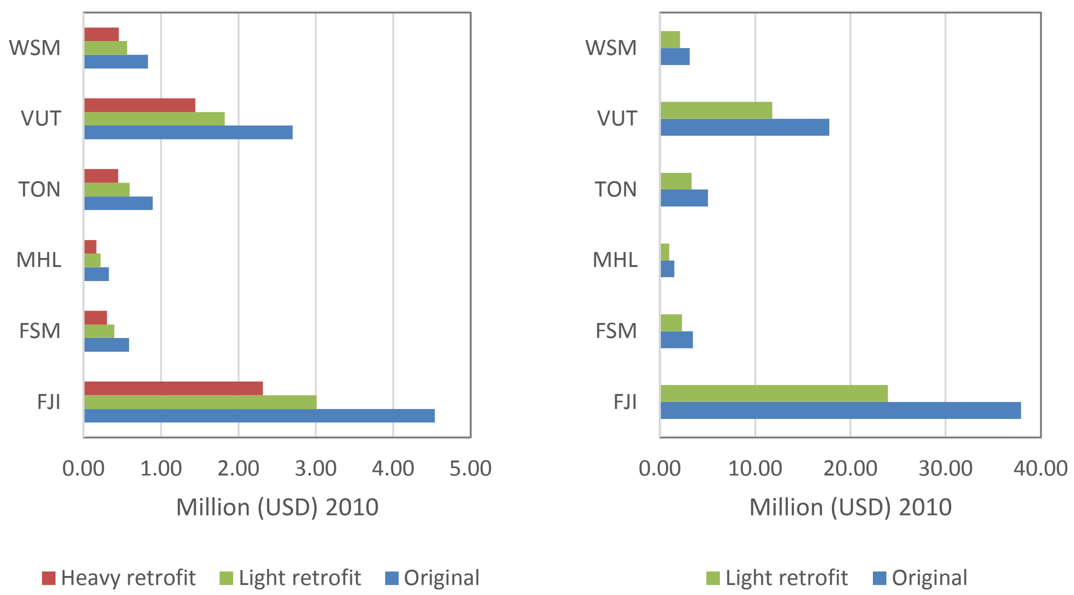
[39] The calculation of the benefits of retrofitting requires some specific assumptions when taking account of the impact of climate change. For this analysis a program to upgrade buildings that have an expected life of at least 30 years in 2020 has been considered. The benefits of retrofitting increase steadily from the no climate change value in 2020 to the 2050 Low/High value in 2050.

Results

There are significant decreases in expected annual losses as a result of light and heavy retrofitting measures (Figure 5**).** A strategy of implementing light retrofitting for public and residential building types of buildings is predicted to decrease average annual damages by about 35 percent for all six countries. Implementing heavy retrofitting for public buildings is expected to result in about 50 percent reduction in average annual damages. These are quite significant numbers, and suggest that retrofitting is an effective tool for reducing cyclone damages; however, the next results are equally important for considering the cost-efficiency of such investments.

Figure 5: Changes in expected annual damages due to retrofitting:

(a) public buildings **(b) residential buildings**



Favourable cost-efficiencies are possible in several PICs for light retrofitting of public buildings. Although heavy retrofitting offers significant loss reduction benefits, the much higher costs to implement such measures limits the efficiency of such measures. Table 15 shows the BCRs for the most prevalent construction types among public buildings, including timber frame and masonry structures. The highest BCRs are associated with the combination of a low 2% discount rate and the higher 2050 Climate Change scenario – under these assumptions 9 out of 12 country-material BCR results are greater than one. The majority of these results are robust when compared to the historical climate (NoCC) and low emission scenario (2050 Low). However, fewer country-material BCR results are favourable when analysed with a higher 5% discount rate. On average, timber structures have higher BCRs compared to masonry because they are more vulnerable to begin with, and therefore have a higher benefits of avoided losses when strengthened by retrofitting. The highest BCR are shown for countries with higher cyclone risk.

Table 15. Benefit-Cost Ratios for Light Retrofitting of Public Buildings (White: BCR<0.8, Blue: BCR>0.8 and <1, Green: BCR>1)

Country	Material	BCR @ 2% discount rate			BCR @ 5% discount rate		
		NoCC	2050 Low	2050 High	NoCC	2050 Low	2050 High
Fiji	Timber	1.03	1.11	1.20	0.71	0.75	0.80
	Masonry	1.04	1.13	1.23	0.72	0.76	0.82
FSM	Timber	1.57	1.70	1.85	1.08	1.15	1.23
	Masonry	0.49	0.53	0.58	0.34	0.36	0.39
Marshall Islands	Timber	0.97	1.04	1.13	0.66	0.71	0.76
	Masonry	0.30	0.32	0.35	0.20	0.22	0.24
Tonga	Timber	1.21	1.30	1.40	0.83	0.88	0.94
	Masonry	0.93	1.00	1.09	0.64	0.68	0.73
Vanuatu	Timber	1.79	1.92	2.08	1.23	1.30	1.39
	Masonry	1.67	1.81	1.97	1.14	1.22	1.32
Samoa	Timber	1.34	1.44	1.56	0.92	0.98	1.04
	Masonry	0.47	0.51	0.55	0.32	0.34	0.37

Cost-efficiencies are less favourable for light retrofitting of residential buildings due to higher relative retrofitting costs. For the most prevalent residential building types, the light retrofitting costs were originally estimated to range from 1-16% of replacement values. The results shown in Table 16 have capped the costs at 5% as an upper bound threshold given the uncertainty in estimating such costs. Even with the lower costs, there are limited combinations that yield favourable BCR results. Vanuatu is the only country for which the results are robust at both discount rates, and only for Timber and Traditional construction types.

Table 16. Benefit-Cost Ratios for Light Retrofitting of Residential Buildings (White: BCR<0.8, Blue: BCR>0.8 and <1, Green: BCR>1)[40]

Country	Material	BCR @ 2% discount rate			BCR @ 5% discount rate		
		NoCC	2050 Low	2050 High	NoCC	2050 Low	2050 High
Fiji	Timber	0.90	0.97	1.05	0.62	0.66	0.70
	Masonry	0.54	0.58	0.64	0.37	0.40	0.42
FSM	Timber	0.79	0.85	0.93	0.54	0.58	0.62
	Masonry	0.24	0.27	0.29	0.17	0.18	0.19
Tonga	Timber	0.74	0.80	0.86	0.51	0.54	0.58
	Masonry	0.26	0.28	0.31	0.18	0.19	0.20
Vanuatu	Timber	2.78	2.99	3.23	1.91	2.03	2.16
	Traditional	1.40	1.50	1.62	0.96	1.02	1.08
	Masonry	0.87	0.94	1.03	0.60	0.64	0.69
Samoa	Timber	0.73	0.78	0.85	0.50	0.53	0.57
	Open/Fale	0.27	0.29	0.31	0.18	0.19	0.21
	Masonry	0.24	0.25	0.28	0.16	0.17	0.18

A program of retrofitting and adaptation for implementation in the 2020s could combine retrofitting of existing buildings with the application of higher building standards for new buildings. The costs of the baseline investment program allow for the implementation of higher building standards to

[40] The BCRs for Marshall Islands left out of the Residential loss table considering they were significantly below one for all building types and discount rates.

ensure that new buildings are resilient to 1 in 50 year cyclones under current climate conditions. The results are summarised in Table 17 which shows the costs of early replacement, retrofitting and adaptation to climate change relative to baseline investment separately for public and residential buildings by country. The incremental cost of adaptation to climate change are less than 1% of the baseline investment program. The costs of early replacement and light retrofitting are 8-14 percent of baseline investment for public buildings in 5 countries and 17 to 27% in 4 countries. The heaviest costs arise for residential buildings in Vanuatu and all buildings in Samoa. In both countries the reason is the number of traditional and open structure buildings which could be replaced and/or upgraded in order to reduce the costs of building damage caused by cyclones. The analyses suggest that the benefits of early replacement and/or upgrades of vulnerable building types exceed the costs incurred, but such a program would represent a substantial commitment in these two countries.

Table 17. Cost of adaptation to higher cyclone winds for buildings by country

(USD million per year, 2020-29)

	Baseline capital cost		Extra for early replacement program		Extra for light retrofitting program		Extra for adaptation to 2050 High	
	Public (1)	Residential (2)	Public (3)	Residential (4)	Public (5)	Residential (6)	Public (7)	Residential (8)
Fiji	150.7	806.3	8.4	66.3	3.3	68.5	1.1	4.8
FSM	16.8	65.4	1.6	9.4	0.7	5.5	0.0	0.2
Marshall Islands	17.2	57.9	1.4	6.1	0.6	4.8	0.1	0.5
Tonga	25.0	82.1	1.8	8.7	0.7	13.4	0.0	0.3
Vanuatu	34.4	174.3	2.7	74.4	1.2	14.0	0.0	0.7
Samoa	21.4	55.0	4.6	44.5	1.0	4.1	0.0	0.3

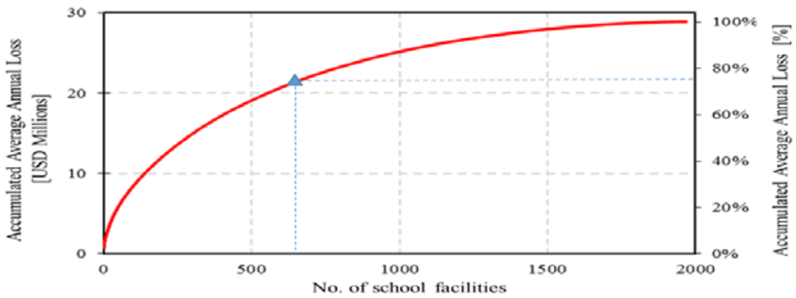
Source: World Bank estimates

Box 3 - Peru Safe School Program Case Study
Development of a seismic risk reduction strategy for school infrastructure in Lima

Project Context: Peru lies in the 'Pacific Ring of Fire', a highly seismic region where about 80 percent of all the world's earthquakes occur. In 2013, the Ministry of Education carried out the first nationwide public school infrastructure census of approximately 50,000 school facilities. With support from the World Bank/GFDRR the census results were analysed and a seismic risk assessment was conducted for the Lima Metropolitan area, which has a population of almost 10 million in a high seismic hazard zone.
Objective: The general aims of the structural retrofitting project are the following: i) reduction of the risk of death and injury, ii) reduction of the risk of damage and protection of the built environment, and, iii) reduction of the service disruption.
Technical Approach: The seismic risk assessment carried out for the 1,969 school facilities in Lima evaluated three components – hazard, exposure and vulnerability – and it provided an estimation of the expected losses taking into account the frequency of occurrence of various earthquake scenarios. Two main categories of intervention were recommended:

- *Category 1:* Demolition and replacement of school buildings with *High probability of collapse* according with the results of scenario analysis. The structural typologies under this category would face high costs and technical difficulties in order to retrofit.
- *Category 2*: Structural retrofitting of school buildings with *High probability of structural damage* according with the results of scenario analysis. Most of the school buildings under this category, which are viable at the technical and financial level, have a standard design and common seismic performance issues. The incremental retrofitting is the proposed approach for this category.

Prioritization: Given the number of school buildings in each category, the prioritization method became a critical tool for defining the investment plan. Three different parameters were used: Annual Average Loss (AAL) to define a risk rank of school facilities within the portfolio to know where the risk is concentrated, Cost Effective Analyses (CEA) for Category 1 to maximized the number of students to be covered in a specific investment plan, and Cost benefit analysis (CBA) for Category 2 to establish the order of retrofitting of school buildings in a specific investment plan.
The concentration of risk, analysed through the AAL, showed that by intervening in 35 percent of the most vulnerable schools in the portfolio, about 75 percent of the risk would be reduced.



Emerging policy messages

The results highlight the need for a selective approach in identifying opportunities to retrofit existing buildings to provide greater resilience to cyclone winds. Additional strategy for prioritizing retrofitting interventions should consider the following:

- Retrofitting is more cost-effective in countries which face higher cyclone risks - notably Vanuatu, Fiji, RMI, Tonga and Samoa. Following TC Pam and TC Winston, there were significant damages to the building stock. A preliminary analysis using the retrofitting schemes showed that losses could have been reduced by 25% with light retrofitting and over 35% with heavy retrofitting.
- Retrofitting public buildings appears to be economically justified in multiple countries. The result is based on analysis that has focused on the costs of repairing buildings in the event of cyclone damage. Including other losses, such as potential loss of life or injuries and the loss of the services

provided by buildings, would strengthen the case for retrofitting public buildings as they tend to have higher occupancy. In the case of seismically active countries, multi hazard retrofitting should be pursued to a standard that protects the life safety function of critical structures.

- The costs of heavy retrofitting are high relative to the benefits in terms of loss reduction. If large expenditures are required to bring buildings up to modern design specifications for wind resistance, early replacement may be a better strategy than retrofitting.
- Selective retrofitting could improve the efficiency of investing in both light and heavy retrofitting. A case study of schools in Lima, Peru (see Box 1) illustrates that focusing on the most vulnerable 35 percent of schools leads to a 75 percent reduction in risk.

Developing lower cost options for retrofitting, especially for housing, is critical. The low ratios of benefits to costs reflect the relatively high costs of upgrading housing. In Vanuatu, the average retrofit costs for residential buildings are often twice the average retrofit costs for public buildings when expressed as a proportion of average replacement values. Considering that it is not feasible to strengthen existing housing stock, it becomes critical to improve the safety of public buildings that can be used and evacuations shelters through retrofitting.

Reconstruction efforts should seek to ensure that buildings – especially, public buildings – should incorporate the code improvements necessary to ensure greater resilience to the current and future distribution of cyclone risks. The benefits of greater wind resistance will increase as a consequence of climate change over the life of the buildings that are either replaced or reconstructed during the recovery from these storms.

Additional cost of implementing higher design standards for new buildings that would ensure greater resilience to cyclone winds is small in relation to the total cost of construction. The changes required to ensure that structures are more robust to cyclones will usually involve modest adjustments to designs when the buildings are constructed. Lessons learned from New Zealand and USA, for example, indicate that new building codes offering greater seismic and cyclone resilience compared to the older code at the desired performance level are expected to add less than 5 percent to the cost of construction for new structure. On the other hand, it is often relatively expensive to retrofit existing buildings to meet higher design standards.

Moving ahead rapidly with the adoption and implementation of building codes to ensure that new buildings can withstand at least 1 in 50 year cyclone wind speeds should be a high priority for policymakers. However, the successful implementation would require actions to improve compliance with the new code including investment in training of engineers and contractors, and strengthening of the design and construction permitting process.

The results presented here provide a rough guide to assess the relative desirability of various retrofitting and code strategies. For any detailed analysis of retrofitting options, local circumstance including the specific costs of retrofitting, the age profile of the asset stock and the pattern of building usage must all be taken into account.

3.6 Adaptation in the Agricultural Sector

This section provides a summary of the likely impacts in the agricultural sector and associated costs from analysis of historical climate information and climate scenarios. Subsistence farming predominates in PICs, with most households selling small surpluses in the domestic market as a form of cash income. Traditional farming systems are predominantly based on root crops, tubers and coconuts; a wide variety of fruits and vegetables are also cultivated on most islands apart from the atolls. Livestock production (with the exception of Vanuatu which has a large beef industry) is almost entirely subsistence-oriented for household consumption or cultural obligations. Copra, coconut products, sugar, fruit and vegetables are also produced for export markets. Agriculture contributes to 20-30% of the GDP in the Solomon Islands, Vanuatu, Tonga, Kiribati and FSM.

Methodology

Some of the analysis uses the estimated costs of recent cyclones as well as crop modelling studies that use a range of climate scenarios and also include the effects of increased atmospheric carbon dioxide. The results from the ADB study on The Economics of Climate Change in the Pacific (2013) that looks at likely impacts in 2100 and using a range of low- and high-emission scenarios are also summarised. The ADB study looks mostly at the PICs as a whole, but some country-level results are also available.

Results

Historical information on cyclones and related flooding shows that the cost to agriculture in PICs can be high. Cyclones in particular can lead to 1-8% losses of the annual GDP as reflected in table 18 below. The costs are due to wide-spread destruction of crops, deaths of livestock, and the loss of fertile topsoil, while associated storm surges may inundate low-lying areas and cause a long-term increase in soil salinity – often killing crops or drastically reducing their productivity. Storm surges associated with cyclones may also contaminate freshwater aquifers that are used for supplemental irrigation. Waterlogging and flooding associated with heavy rainfall and tropical storms may also lead to crop damage. Cyclones may also damage key supporting infrastructure such as livestock shelters, water storage tanks, and irrigation equipment. These combined impacts from cyclones may result in substantial costs to the sector (Table 18).

Table 18. Estimated costs of selected extreme weather events on the agriculture sector

Country	Event	Year	Estimated cost to agriculture sector (US$ million)*	GDP that year (US$ million)*	Cost as % of GDP	Source
Fiji	Floods	2012	21.4	3,978	0.5%	National Disaster Management Office 2012
Samoa	Cyclone Evan	2012	28.5	804	3.5%	PDNA Govt of Samoa 2013
Vanuatu	Cyclone Pam	2015	57	449	8%	PDNA Govt of Vanuatu
Tuvalu	Cyclone Pam	2015	2.9	31	6.7%	WB internal DALA
Fiji	Cyclone Winston	2016	245	4530	5%	PDNA Govt of Fiji

** Apart from Tuvalu which is shown in Australian Dollars*

The quantification of the impact of climate change in 2050 on agriculture is challenging, but estimates indicate a decrease in the crop yields of cassava, maize, and taro, but potential increases for rice, sugarcane and sweet potato by 2050 (**Table 19**). The challenges of quantifying the impacts are due to the need to consider the interacting effects of salt water intrusion, flooding, effects on livestock and/or general ecosystem functioning. As climate changes, the increased temperatures and higher risk of seasonal droughts are likely to decrease crop productivity and negatively affect livestock. For example, papaya is sensitive to temperature increase during flower production and higher temperatures result in lower productivity. Although increases in carbon dioxide concentrations could act as a "fertilizer" for some crops, such benefits depend on the type of crop, water and nutrient availability, and the incidence of pest and diseases – which is likely to increase under climate change. Livestock may also be negatively impacted due to increased risk of heat stress.

Table 19. Relative Changes in Crop Yields (%) under Climate Change in 2050 Relative to 2000

Country	Cassava		Maize		Rice		Sugarcane		Sweet potato		Taro	
	Worst case	***Best case***	***Worst case***	***Best case***	***Worst case***	***Best case***	***Worst case***	***Best case***	***Worst case***	***Best case***	***Worst case***	***Best case***
Fiji	-36.5	-8.8	-7	1	-11	3.5	-8.3	2.8	-13.4	2	-17.5	1.1
Solomon Islands	-27.8	-17.9	-16.5	-0.3	-16.2	5.9	-12.9	0.9	-15	1.5	-18.6	-4.7

Source: Rosegrant et al. 2013, in ADB 2013

The impact of climate change on agriculture's contribution to GDP may be slightly positive up to 2050 and strongly negative thereafter. According to ADB (2013), the contribution to the total economic cost of climate change may be equivalent to approximately 5 percent of Pacific GDP by 2100 (Table 20). As the relative importance of agriculture to the Pacific economy is likely to decline over the coming years, due to the importance of other sectors increasing, it may be that the effect on GDP is lower than what might be expected. However, the impact is also likely to be underestimated given that the modelling shown below does not take into account interaction effects with other biophysical processes, e.g. salinity intrusion or the incidence of pests and diseases. Given the essential role of agriculture in many Pacific livelihoods and in ensuring domestic food security, it would be prudent and important to consider implementing adaptation options that would respond to the observed impacts such as those due to drought and salt water intrusion.

Table 20: Estimated impact of climate change on GDP by 2050 and 2100 of some countries due to effects on agriculture

Country	Impact of climate change on GDP		Of which % attributable to agriculture sector	
	2050	***2100***	***2050***	***2100***
Fiji	-2.75%	-4.0%	-1.25%	-1.5%
Samoa	-1.9%	-3.8%	0%	0%
Solomon Islands	-1.5%	-4.8%	0.0%	-1.6%
Vanuatu	-3.2%	-6.1%	-1.5%	-2.6%
PNG	-4.0%	-15.0%	+0.5%	-8.0%
Pacific Region*	-3.5%	-12.7%	0.0%	-5.4%

*Source: ADB 2013 * Including PNG and Timor-Leste*

Given the potential impacts and uncertainties it is important that adaptation strategies that are relatively low-cost are adopted now to minimise risk in the long-term. Adaptation may involve relatively simple and low-cost options that both improve productivity and increase resilience to climate change. Such solutions are increasingly being promoted within the framework of 'climate-smart agriculture' (see Box 4). Climate-smart agricultural practices can often be mainstreamed into the delivery of extension services, and generally require little or no additional inputs from farmers by promoting better agricultural practices such as mulching and multiple cropping (see Table 21). Others may require moderate or substantial and sustained investments such as developing new climate-smart crop varieties at regional or national level (such as the taro varieties developed by SPC), higher design standards for agricultural assets (such as storage sheds and livestock shelters) to help reduce storm damage, or insurance mechanisms to address residual risks (Table 22).

Box 2: Adaptation options integrated as part of climate-smart agriculture

Climate-smart agriculture (CSA) is an integrative approach to address the interlinked challenges of food security and climate change, that aims to (i) sustainably increase agricultural productivity, to support equitable increases in farm incomes, food security and development; (ii) adapt and build resilience of agricultural and food security systems to climate change at multiple levels; and (iii) reduce greenhouse gas emissions from agriculture where possible. Examples of climate-smart agricultural practices include:

Building resilience: crop insurance; seasonal forecasting; early warning systems; adopting irrigation and other innovations; using conservation agriculture techniques to improve soil health e.g. mulching to retain soil moisture; etc.

Climate proofing: adapting cropping systems to heat and water stress such as through improved varieties or changing the timing of planting; upgrading irrigation and drainage systems to allow for more intense precipitation; etc.

Transformational change: shift water-intensive agriculture away from areas threatened by climate change; transform agricultural systems from high-input to low-input

Source: FAO 2013, Climate-Smart Agriculture Sourcebook

The cost of many adaptation measures is low to moderate as reflected in the table below.

Table 21 Assessment of adaptation costs in agriculture

Adaptation measure	Expected cost	Quantification
Farmers adopt better agricultural practices such as mulching, multiple cropping, to improve resilience	Minimal	Could assume to be zero, if mainstreamed into existing extension services
Agricultural asset insurance	Moderate	1% of agriculture value-added*
Expansion of irrigation systems including supplemental irrigation using water-efficient/conservation systems.	Moderate	Unknown
Research and development to identify more resilient plant/livestock varieties	Substantial	Potential increase in costs of 25-30%*
Higher design standards for agricultural assets	Substantial	Unknown

** World Bank 2010, Economics of Adaptation to Climate Change*

Agriculture asset insurance requires a range of considerations. These include what sort of insurance might be appropriate (e.g. single crop or area-based – see Table 22). In all cases, the role of the government is critical. In many OECD countries, insurance in the agriculture sector has a heavy government involvement (Mahul & Stutley, 2010) including subsidies in premiums for crop insurance, development of likely premiums, support products, coverage and loss assessments.

Table 22 Potential categories of insurance in the agriculture sector

Type of insurance	Description
Single peril crop insurance, or damage based indemnity insurance	Insurance for a single hazard, for example fire, extreme rain. The claim payment is based on the percentage damage to a field of crops. This is the most common type of crop insurance
Multi-Peril Crop insurance (MPCI), or yield based crop insurance	Instead of directly insuring a crop, this provides insurance on the crop yield. Historical yield averages are established and the insurance pays out when yield drops below a percentage of the historical average (typically 50-70%)
Area yield index insurance (AYII)	Claims are paid out on the basis of a decrease in average yield in an area. Similar to MPCI but the historical yield is computed over an area greater than a single farm
Indirect index insurance (III)	Claims are paid on the basis of an index correlated with yield. Indices are typically calculated using rainfall or satellite data, but other data may be used. This may only be suitable for some PICs that have large scale production and data.
Calamity funds and ad hoc aid	In some countries, farmers may reasonably expect government aid in the event of large scale disasters

Source: *Adopted from Vivid Economic 2016. Building an evidence base on the role of insurance-based mechanisms in promoting climate resilience. Report prepared for the Climate Investment Funds; and Mahul & Stutley, 2010*

Given the impacts, adaptation to climate change in agriculture in PICs will require focus on agriculture systems that can be resilient to multiple changes, such as short periods of floods or droughts, saline intrusion, extremes of temperature, erosion, and altered patterns of pests and diseases and changes in growing seasons. Systems need to be simple, require little or no investment, and to be fail-safe for wide adoption, i.e. they must not increase the risk of a crop failure. Agro-ecological conditions will change so farmer education, and re-education, is vital – preferably promoted through farmer-to-farmer exchanges.

Emerging policy messages

The impact of climate change on agriculture will affect GDP, livelihoods and food security. While the impact is overall neutral for the Pacific region by 2050 (although some countries may experience negative impacts of 1-3 percent of GDP in this time period), by 2100 the impact is expected to be severe at around 5 percent of Pacific GDP.

Low-cost adaptation options can be adopted now and would benefit agricultural productivity and also improve food quality and security.

Some moderate cost options, if developed now, would provide resilience in the long-term. Research and development at the regional level can help overcome diseconomies of scale, but must be effectively disseminated to countries and to farmers in order to have an impact. Experience shows that the lead time for such work can be 3-5 years and should be started well in advance of any expected climatic change. In addition, it is also important to ensure that the new varieties are tested in a wide range of soil and climatic conditions prior to wider distribution.

Promotion of resilient approaches and technologies should focus on changes to agriculture systems and on the small-scale farmer who operates in a wide range of soil, terrain and rainfall conditions. This may be challenging if extension services are under-resourced. Insurance systems would require considerable government involvement including consideration of premium subsidies and product development and loss assessment. Such approaches can be integrated as part of the broader climate resilient systems for agriculture sector in PICs.

4. The Case of Atoll Islands

This section gives special consideration to Pacific Island atolls due to their unique challenges. Many atolls are only 1-3m above sea level, which makes them particularly vulnerable to sea level rise.

The atoll nations of Kiribati, Marshall Islands, and Tuvalu are particularly vulnerable to climate change. Their highest point of elevation is only a few meters above sea level, so in the absence of adaptation sea level rise will reduce the habitable surface by person over time in the long term, and will lead to a very severe dislocation of the island. For Majuro Atoll in RMI, for example, a 50cm rise in sea level (less than the average projection for sea level rise by 2080 for RMI under the worst RCP 8.5 scenario) may mean the disappearance of 80% of its land area (ADB, 2013). Our own calculations, predict more modest but still large loss of land in Tuvalu's Fongafale Island (Funafuti) associated with sea level rise by 2040. Based on a projected sea level rise of 62cm in 2090, the projected average estimate according to the ABN and CSIRO (2014) report, will permanently flood about 5.8-10% of Fongafale's land area. Holding constant the strength of storm surges and king tides, however, this will expose a further 10-11% of land area to these occasional inundations.[41] Overall, about 20% of the land area will be either permanently or temporarily flooded.

The more significant short-term risk, however, for the atoll nations, is the risk of storm surges. This risk is already very high, and with sea level rise and the deterioration of the ocean's ecology (coral reefs) this risk is becoming greater. Overall, for the atoll countries sea-level rise can result in 15-20% direct loss of habitable land in this century alone, thereby significantly increasing population density and reducing the amount of land available for cultivation and further concentrating the risk exposure from storm surges.

In addition, sea level rise and changes in rainfall patterns already stress their fresh water supply while ocean temperature increase and acidification threaten the marine ecosystems they depend on. There is wide agreement that the combination of sea level rise and deterioration in coral reef and mangrove ecosystems will make coastal areas considerably more vulnerable to storms. Climate change can also have negative impacts on agriculture revenues (see previous section).

Vulnerability is worsened by poor development planning and the countries' limited ability to respond and manage the risks. Kiribati, in particular, is one of the poorest of the Pacific Islands with 22 percent of the population living in extreme poverty in 2006 (the latest available survey) and as much as 66 percent of the population living at high risk of falling in poverty in case of external shock (climatic or economic). Although water consumption per person (around 60L per day[42]) is very low, water supply will soon become insufficient in the South Tarawa Island, because of high population growth and unsustainable levels of abstraction.

Former President Anote Tong of Kiribati spoke of the need to ensure "migration with dignity" for the country's population (about 110,000 people). At this point, we assume that Tuvalu and RMI do not have plans for migration that are viable and carefully planned. While the Government of Tuvalu (2012) specifically mentions migration as a possible climate change outcome, survey data show that the vast majority of Tuvaluans do not view this as a major reason for concern and are not, yet, preparing to migrate because of climate change[43]. The decision to plan for a relocation of the population, or part of the population, to another country, is a difficult one to make. It requires an integrated approach that carefully examines the threats climate change poses to life on the atoll and the costs of maintaining decent living conditions on the atoll at different time scales. It may be affordable to maintain access to land and fresh water for the next 40 years, but maybe not later. And

[41] These calculations are based solely on elevation maps of the island, using a 'bathtub fill' approach as in Shepard et al. (2012). Yamano et al. (2007) point out that Fongafale (Funafuti) includes significant land area that was reclaimed, and will likely flood given future events.

[42] White, 2010

[43] Mortreux and Barnett, 2009

planning for the next decades is very different whether the long-term perspective is to stay on the atoll or to leave.

Let's look at cost estimates for adaptation between now and 2050.

Mack (2015) estimates that the cost of desalination, to increase water supply by 1700kL a day in Kiribati, would be around 2.2 million USD per year between now and 2050. It would require investments in energy production (e.g. solar), which remain to be costed, but whose impact on the overall cost should remain limited.

The cost of coastal protection however competes in a different category. The DIVA model estimates that the cost of coastal protection in Kiribati (with dikes and beach nourishment) could be between 13 and 42 million USD per year in the 2020's and between 17 and 54 million USD per year in the 2040's, depending on sea level rise, and assuming that population and economic activities continue to settle and grow in the same areas as today – i.e. there is no active land use planning to relocate people and economic activities in safer zones. These costs can be put in perspective with the value of assets, such as buildings and infrastructure, estimated at US$ 1.2 billion (PCRAFI 2010). Taking into account residual risk, the cost of coastal adaptation could be between 4 and 11% of Kiribati's GDP in the 2040's.

It is pretty clear that the Government of Kiribati cannot allocate this amount on coastal protection in its annual budget for the next decades, even if all those investment are justified economically. The Government also needs to invest in transport and energy infrastructure, in education, health, social protection and many other sectors. And there is no point in protecting the island against storms if the basic living conditions are not insured.

We may assume that the international community is willing to finance coastal protection for Kiribati and pay between 10 and 50 million USD a year for the next 50 years. Adaptation on an atoll remains challenging and ensuring decent living conditions requires to arbitrate between hard protection options (i.e., through atoll raising, land reclamation, coastal protection) and softer ones (like rehabilitation or protection of mangroves and wetlands, early-warning systems, social protection or financial instruments) and to prioritize between investments in coastal protection, water desalinization, or other infrastructure in transport and energy. It also requires to carefully identify the trade-offs and synergies between multiple objectives in different sectors. For instance, water desalinization requires more energy (e.g. solar energy), changes to climate-resistant crops can affect water demand by the agricultural sector, land-use patterns affect agriculture production, water and energy demand, and the vulnerability of the population to extreme events. In addition, adaptation requires to invest in the education of the population, to ensure that there are qualified people able to maintain protection, install solar panels and operate desalination plants. It also requires to monitor fish populations and maintain fishing agreements to make sure their long-term income source – fishery licenses – remains sustainable.

If 10 to 50 million USD a year cannot be found externally, or if the costs of adaption are much higher than expected, other long term options will need to be considered. Consideration should be given to the feasibility of a progressive relocation. Such an approach would need to be carefully planned and available resources would need to be used to maintain acceptable living conditions on the atolls for the coming decades. There are political issues associated with this scenario, as discussed in Wyett (2013), but it is clear that this scenario is less costly and preferable to a last-minute abandonment with huge emergency assistance.

The World Bank in collaboration with other development partners is planning to help decision makers in Kiribati and maybe other atoll islands make these difficult decisions, given the uncertainties that exist on the speed and strength of climate change and sea level rise, and the uncertainties on the availability of international aid to finance coastal adaptation. **We will use methods called "Decision Making under Deep Uncertainty" (DMU), that offer a decision making framework** to help plan adaptation in an integrated way and prioritize resilient investments and adaptation strategies in spite of the deep uncertainties about future threats and budgets.

DMU methods help identify "no-regret" or "low-regret" solutions that have high utility no matter what the future brings. Thus, they can be robust even to deep uncertainties. For example, reducing leaks in water distribution systems or the conservation of natural costal inundation protection like mangroves or wetlands are always a good investment, regardless of how the climate, future demand, and other factors change. Similarly, shelters and early-warning systems are relatively low-cost options that would reduce disaster losses and save lives in the present climate. These examples suggest that finding a system's existing shortcomings may reveal no-regret or low-regret strategies: such strategies are beneficial over the short term (and thus easier to implement from a sociopolitical point of view) and may offer benefits under a wide range of future conditions.

DMU methods also favor options that are reversible and flexible and that enable decision-makers to adjust their decisions as new information becomes available. In this way, reversible and flexible decisions can help us reduce our regret. For example, insurance and early warning systems can be adjusted every year in response to new information on emerging risks.

Importantly, DMU methods recognize the importance of decision maker and stakeholder involvement in the (more quantitative) decision analysis. Consultations will therefore be conducted with decision makers, during all the steps of the analysis, in order to identify their preferences and objectives, and discuss available short-term and long-term solutions, including the option of leaving the atoll.

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Annex on detailed methodology (Volume II of the report):

Annex 1 - Climate change and Pacific Islands

Annex 2 - Sea Level Rise and Coastal Protection

Annex 3 - Managing Water Resources and Flooding

Annex 4 - Adaptation for Infrastructure

Annex 5 - Improving the Resilience of Buildings to Tropical Cyclones

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[i] https://www.humanitarianresponse.info/en/system/files/documents/files/el_Niño_infographic_20150609.pdf

[ii] http://erccportal.jrc.ec.europa.eu/getdailymap/docId/1286

[iii] http://www.unescap.org/resources/el-Niño-20142015-impact-outlook-and-policy-implications-pacific-islands-advisory-note

[iv] http://www.unescap.org/resources/el-Niño-20142015-impact-outlook-and-policy-implications-pacific-islands-advisory-note

Annex 1 – Climate change and Pacific Islands

This section discusses the current and future risk to Pacific Island countries from current and future climate risks. The projected changes in climate parameters are based on the approaches used by the latest Intergovernmental Panel on Climate Change (IPCC, 2014). The Pacific Possible study focuses on the 25 years up to 2040, but the main climate projections covering this period are centred on 2050 – using the average of model runs for either 2045 to 2054 or 2040 to 2059 relative to a baseline of the second half of the 20th century. The climate changes described here include changes in mean and extremes.

1. Climate Scenarios and Models

To project what climate change might look like in the future, computer simulation models have been created incorporating all known aspects and understanding of the atmosphere that may influence the climate and a variety of assumptions about the concentrations of greenhouse gases in the atmosphere (referred to as scenarios). The Intergovernmental Panel on Climate Change (IPCC) currently uses 26 different models, developed by various groups around the world. Climate models operate at a relatively coarse level of resolution – typically the grid cells cover 2.5-5° on the surface of the globe, so that it is necessary to downscale their results in order to generate projections that are useful for individual countries or regions. The models used in this study have been downscaled to 0.5° grid cells using a combination of interpolation and statistical methods (see Box 1.1). The process of downscaling may increase the variation across climate models. This arises because differences in assumptions about the way in which geophysical processes should be represented as well as in the parameterisation of key relationships. No single climate model or scenario is definitive. It is also important to bear in mind that climate models are global in scope, and this may related to an increased margin of error when downscaled to a 1 degree grid scale necessary to generate useful projections for the PICs.

The scientific community has recently produced future projections for four plausible new global Representative Concentration Pathways (RCPs) to help explore a range of global climate signals up to the year 2100 and beyond (e.g. Moss *et al.,* 2010). These were used extensively in the most recent IPCC assessments. The RCPs are named according to their global warming potential (e.g. RCP 4.5 corresponds to an increase in the greenhouse effect of 4.5 W/m^2 in 2100). The four RCPs are 2.6, 4.5, 6.0 and 8.5. The analysis presented in the paper focuses on population-weighted national average values[1] of the projections for annual precipitation, maximum monthly precipitation and minimum monthly precipitation. The variables are selected as they are influential in determining the impacts of climate change as well as the costs and options for climate resilient development. In total there are 48 scenarios – 19 for RCP4.5, 12 for RCP6.0 and 17 for RCP8.5.

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[1] To compute the national population weighted average value, the value of each climate parameter of each cell of the climate model grid is given a weight corresponding to the population living in the cell, following this equation:

$V = \frac{\sum_{i,j} P_{i,j} V_{i,j}}{\sum_{i,j} P_{i,j}}$, with $P_{i,j}$, the population of cell (i,j) and $V_{i,j}$ the value of the climate parameter of cell (i,j)

In general, there tends to be a substantial degree of agreement across models with respect to the path of average temperatures, but there is greater variability in projections of precipitation. Such differences increase as the unit of analysis – the grid square and time period – is reduced. Hence, projections of monthly rainfall for a small island would vary more amongst models than annual precipitation and/or projections for a large country. The variation amongst models is particularly large for the Pacific Islands because of the complexity of the interactions between the small land masses, the large areas of ocean and the atmosphere. In addition, all climate models incorporate elements of weather variability due to the inclusion of stochastic influences, either via parameter values or initial conditions. The projections used in this study smooth this inter-annual variability by constructing averages over two decades (2041-60) and by averaging over a number of model runs based on different initial conditions. The variation across projections is a measure of uncertainty across climate models but it should not be taken to reflect the variability in annual weather outcomes.

2. Historical and Projected Changes in Climate Parameters

2.1. Projected changes in temperature and precipitation

Regional studies show a temperature increase of +1.5 to 3.0 ºC by the year 2090 relative to a 20 year period centred on 1990. The Australian Bureau of Meteorology (BoM) and CSIRO for the 15 western tropical Pacific islands, using an ensemble of 15 global circulation models, project temperature increases of 1.5 to 3.0 °C by the year 2090 relative to a 20 year period centred on 1990 (Australian Bureau of Meteorology and CSIRO, 2014)

Average annual precipitation is likely to increase slightly (see Figure A1.1). The differences between the median values for the RCP4.5, RCP6.0 and RCP8.5 projections are relatively small. The scenarios show a small increase in annual precipitation in 2050 relative the average of 1950-2000 in most countries. The exception is Kiribati which is projected to receive 20-25% more precipitation in 2050 than in the past.

Box A1: Global Climate Models and Downscaling

To project what climate change might look like in the future, computer simulation models have been created incorporating all aspects of the atmosphere that may influence the climate. To do this, modelers break down the world into grid blocks, usually at a very coarse resolution of about 3-4 degrees (approximately 300-375 km) across the globe. The models are then run for the entire globe and values for each grid block, or cell, are returned. Global climate models simulated over many centuries are necessary to fully integrate the global climate system. Different models are used for different purposes. For example, models can be an atmospheric-only model (AGCM), an ocean-only model (OGCM) or a complex coupled atmosphere-ocean general circulation model (AOGCM). Global climate models typically have a resolution of a few hundred kilometers.

Downscaling is a method for obtaining high-resolution climate or climate change information from relatively coarse-resolution GCMs. Many impact models require information at scales of 50 km or less, so downscaling is used to estimate the smaller-scale information. In addition, many regional and local applications require this information over 3-5 decades, whereas global climate models are projections towards 2100. So modelers often construct regional climate models (RCMs) to provide useful climate change projections for limited areas, i.e. smaller land or sea areas, and run them for shorter time frames. Downscaling methods include statistical (or empirical) and dynamical downscaling. ***Dynamical*** downscaling uses a limited area, high resolution RCMs built by taking into account an area's regional landscape. Embedding, or "nesting," the RCM within the global climate model allows it to be driven by the boundary conditions of the global climate model, and enabling projections for climate change at a resolution of 25-50km. The advantage of this method is that it takes into account the possible statistical changes of the future climate. However, because it is so computationally intense, it is only possible to run the model for small areas of the globe at one time. **Statistical** downscaling derives statistical relationships between observed small-scale (often station level) variables and larger (GCM) scale variables, with the advantage of providing climate change information at a very high spatial or temporal resolution, which provides future data with the statistical properties of today's climate but incorporates climate change factors. Future values obtained from GCM projections are used to drive the statistical relationships and estimate smaller-scale details of the future climate. Statistical downscaling methods: are computationally inexpensive but limitations are that they assume climate statistics will remain unchanged in the future.

In this analysis, the projections have been downscaled to 10 arc-minute grid squares, equivalent to approximately 16 x 16 km on the equator, and then matched to population in 2000 for each grid square. The downscaled climate projections were obtained from WorldClim[2], while the population estimates are derived from the GRUMP database[3]

Outputs of models are represented as the differences (referred to as "**deltas**") between the climate projections for 2050s and the averages over the last half of the 20th century (1950-2000s) that are simulated by the models. The reason for doing this is that the simulated values of climate variables for a particular grid square for 1950-2000 will almost never correspond to the estimated or observed values for the same grid square. Hence, the projections are "calibrated or bias-corrected" by combining the observed values and the projected differences to generate projections for 2050. The consequence is that any statistical analysis of climate projections should focus on the deltas rather than on the calibrated value.

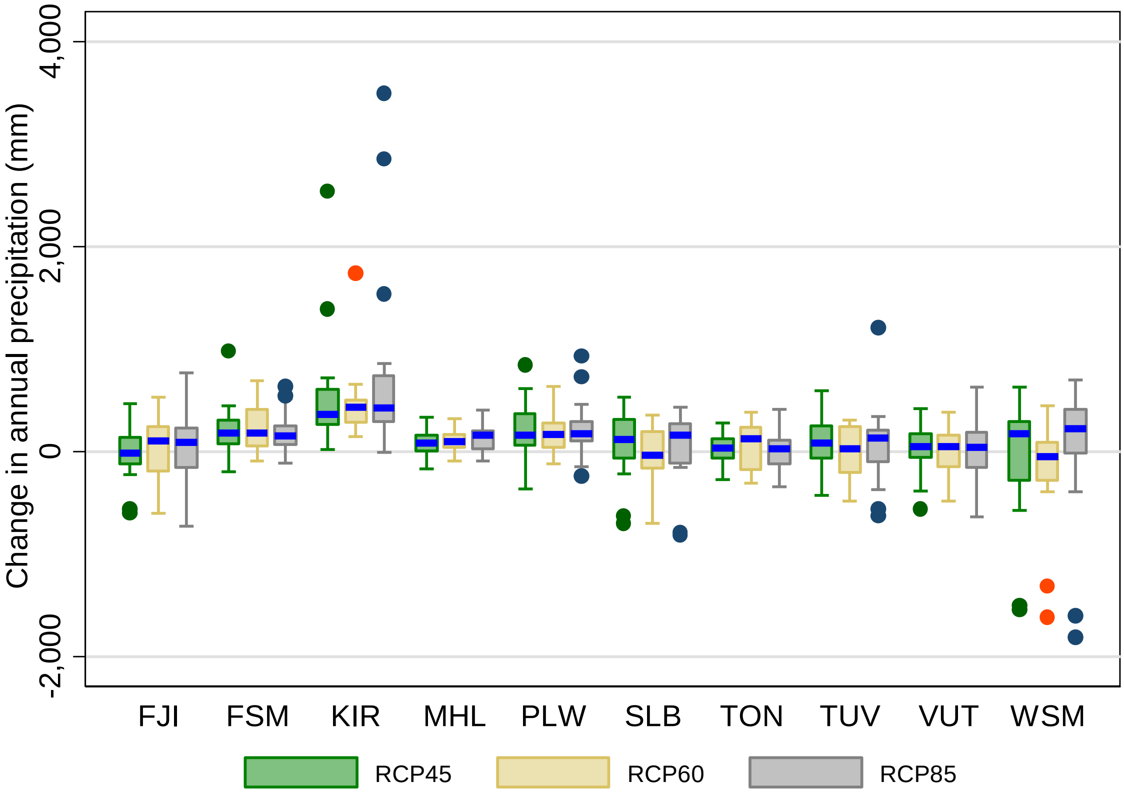
Monthly precipitation vary considerably between models for any island. Given the observed occurrences of seasonal droughts, analysis conducted included projections of monthly minimum and maximum precipitation. Since the models are constructed to simulate the mean outcomes of climate change, the differences between their projections for particular countries may simply reflect the uncertainties which arise in calibrating the parameters of complex models. Many combinations of parameters may yield similar global results, but they may differ markedly in how they represent the land-ocean interactions which determine climate outcomes for islands. Analysis from IPCC Fourth Assessment Report included three monthly temperature and precipitation for a range of scenarios. There was indication of decreased rainfall in the north Pacific for March-May and over September-November in south Pacific[4]. The current analysis shows the following: i) the differences between the projections from the different models up to 2050 are statistically not significant for mean annual precipitation or minimum and maximum; ii) the differences between the global circulation models (e.g. those developed by CSIRO, versus those by UK Met office) are substantial; iii) annual precipitation is likely to increase in FSM, Kiribati, Marshall Islands and Palau; iv) monthly variation in precipitation will increase significantly in all the PICs, but the effect on the total annual precipitation events out in the majority of the PICs. Some countries like Samoa and Kiribati show outliers which can indicate some problems with the models or could also indicate that there could be substantial increases (for Kiribati) or decreases (for Samoa) in annual precipitation.

[2] WorldClim is a set of global climate layers available only at www.**worldclim**.org

[3] GRUMP- Global Rural-Urban Mapping Project, available online at http://sedac.ciesin.columbia.edu/data/set/grump-v1-urban-extents. For more details, please refer to CIESIN et al. (2011)

[4] Nurse, McLean et et al. (2014), IPCC Fifth Assessment Report. Chapter 29, Small Islands

Figure A1.1: Distributions of projected annual precipitation for the Pacific Island countries compared to those modelled for 1950-2000. Please get the graphics people to change WSM to Samoa.



2.2. The role of the El Niño-Southern Oscillation (ENSO)

There is convincing evidence that ENSO indices are negatively correlated with monthly precipitation in some countries, i.e. strong El Nino episodes are followed by lower rainfall. Weather outcomes in the Pacific Islands are significantly affected by ENSO**.** There are two arguments that have been put forward about the impact of climate change on ENSO effects. First, it has been argued that climate change will be associated with stronger and more frequent El Nino like events. If correct, this will increase the inter-annual variability of rainfall. Second, it is suggested that the correlation between ENSO indices and rainfall may weaken or even reverse in some countries. A separate issue concerns a possible correlation between strong ENSO episodes and the occurrence of extreme weather, particularly in respect of the frequency of extreme rainfall events.

Overall, there is large uncertainty about the relationship between climate change and ENSO events. In the absence of clear evidence and agreement across climate scenarios it is not possible to reach any strong conclusions about the relationship between ENSO and the variability in annual precipitation in 2050 or beyond. However, based on the current understanding of the impact on ENSO events on PICs, it would be advisable to plan for the possibility that the inter-annual variability of rainfall will increase and that periods of drought - both within and across years – may become more frequent and severe. That will require either greater capacity for water storage or investment in other sources of water, such as desalination to manage variations in availability.

2.3. Effects of Climate Change on Tropical Cyclones

From 1981 to 2015, there have been 26 Category 5 and 32 Category 4 cyclones in the South Pacific. In round numbers, being struck by a Category 5 cyclone has been a 1 in 10 year event for Fiji, Tonga and Samoa and a 1 in 5 year event for the Solomon Islands and Vanuatu. Samoa has been struck by 7 Category 4 or Category 5 cyclones with peak wind speeds of greater than 58 metres per second (m/s) since 1981.

There is evidence of increased intensity of cyclonic activity since the mid-1970s.[5] ABM and CSIRO (2014) studies suggest a 2-11% increase in wind intensity by 2100. More recent work argues that there is an observed trade-off between intensity and frequency of cyclones.[6] This work identifies decreased frequency, but increased intensity of cyclones on a global scale.[7]

Globally the frequency of cyclones could decline by between 6% and 35%. On the other hand, the severity – measured by peak sustained wind speeds – of cyclones is expected to increase by between 4% and 11%. This is based on averages over a range of models and scenarios and studies conducted by the ABM and CSIRO (2014). The increase in wind speeds is a consequence of higher sea surface temperatures which provide the energy which determine wind speeds. This will increase the expected damage due to cyclones under current standards by 9% in the South Pacific and 21% in the North Pacific up to 2040. For instance, the best estimate of a 1 in 50 year 10-min sustained wind speed over land for current climate conditions is about 42 m/s. As a result of climate change, this may increase to 46 to 51 m/s by the end of 21st century. As a point of comparison, the wind speeds for Cyclone Pam were close to their peak of 69 m/s when it hit Vanuatu in March 2015, causing extreme damage. While the cyclone was not the most intense storm recorded in the South Pacific, it was at the top of the probability distribution of wind speeds for Vanuatu.

A warming Pacific Ocean could mean changes to the typhoon/hurricane belt, moving it to the north and south of the current area.[8] El Niño events (ENSO) are associated with equator-ward shift in cyclone tracks.[9] Thus, if El Niño like events are to become more frequent or more intense, the long-term storm-trajectory trends may be going both ways leading to a larger spread of cyclones outside of the historical cyclone belt (both closer to the equator, and pole-ward outside the current zone). This trend of changing trajectories is likely to end up being the most important shift for cyclones associated with climate change in the foreseeable future. Experience shows that by far most of the

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[5] Emanuel (2005).

[6] Kang and Elsner (2015).

[7] Mei et al. (2015) find evidence of increasing cyclone intensity in the North-Western Pacific (affecting FSM and RMI). Bender et al. (2010) similarly conclude there is no evidence of increased frequency of 'weaker' cyclones but there is of an increase in 'intense' storms (category 4-5 on the Saffir-Simpson scale).

[8] Ramsay (2014) and Kossin et al. (2014) recently provided evidence to support this conjecture, arguing that in the past several decades the 'peak intensity' region for cyclones has drifted toward the poles.

[9] See Ramsay (2014). La Niña events are associated with pole-ward shifts. Li et al. (2010) investigate the change in trajectories of tropical cyclones in the North Pacific, and find that their model suggests storm activity shifting from the West to the Central Pacific potentially affecting both FSM and RMI more frequently.

mortality, morbidity and damage from cyclones is experienced in regions that are unaccustomed and therefore unprepared for them.[10]

2.4. Effects of climate change on sea level rise and ocean acidification

As more information on glacial melting and other feedback loops has become available and incorporated into climate models, sea level are projected to rise more than the current IPCC assessments imply. As sea-level rise, coast line will be eroded and will become more vulnerable, with expected continual increases in the damages caused by storm wave surges and earthquake induced tsunamis.[11] Cyclones are particularly likely to have a bigger impact on coastlines, impact that will be exacerbated by increasing flooding as drainage will be hampered by sea-level rises, and the ongoing coastal erosion.

Ocean acidifications and the consequent potential destruction of coral reefs and mangrove forests is likely. Coral reefs and mangrove forests both serve as wave barriers and prevent the full force of storm surges from hitting coastal regions. According to a recent meta-estimate, coral reefs could attenuate 97 percent of the storm-wave power and reduce wave height by 84 percent.[12] Without live reefs that can re-generate and continue protecting the coasts, many areas may end up becoming much more exposed to storm surges (and any other strong wave action). There are no available estimates of the impact of the deteriorations of these ecosystems on the Pacific Islands.

There is wide agreement that the combination of sea-level rise and deterioration in coral reef and mangrove ecosystems will make coastal areas considerably more vulnerable to storms, regardless of whether storms will indeed be more frequent or more intense (or both). This process of increased vulnerability of coastal zones began years ago, both because of anthropomorphic climate change, and other changes wrought on the environment by modern population growth and changing living patterns.

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[10] The typhoon Nargis in Myanmar in 2008 killed more than 100,000 people (EMDAT estimates 138,000). A year earlier, a stronger storm hit Bangladesh, which is much more accustomed and therefore prepared for these events. In Bangladesh, mortality was around 3,500.

[11] Woodruff et al. (2013).

[12] Ferrario et al. (2013).

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Annex 2 – Adaptation to current Extreme Weather Events and Natural Hazards

Integrating adaptation with development

Plans for adaptation to climate change must be integrated with the development and implementation of policies to address existing weather risks. In the immediate future the reduction of expected storm damage under current climate conditions is likely to be the primary determinant of how the Pacific Islands should allocate funds to managing these hazards.

At the systemic level, prioritizing risk-informed economic growth and development planning and mainstreaming disaster risk reduction into all planning decisions should in itself lead to reductions in risk. The wisdom of integrating disaster risk management and adaptation to climate and development planning is acknowledged widely and reflected in the UN climate change convention, the Sendai Framework on Disaster Risk Reduction and the Sustainable Development Goals.

The standard framework for risk assessments used to inform DRR is one that distinguishes between hazard, exposure, and vulnerability, and between damages and losses. In the short term, we have little control on the hazards themselves, and in the long term our main impact on hazard patterns is through our effect on the climate. But, policies can reduce exposure and/or vulnerability, and can also aim to reduce either damages or losses. In the long term, climate change mitigation policies like changes in carbon emissions may also change the hazards, but more tangible outcomes in the next couple of decades for the region may result from a focus on exposure and vulnerability, and on reducing both direct and indirect impacts of adverse events. The reduction of exposure and vulnerability are discussed below.

Estimating costs of Adaptation

There have been a number of studies to estimate the cost of adaptation. The main ones of relevance to the PICs are the World Bank's Economic of Adaptation and the others are ADB and PICRA studies (see Box A2.1)**.**

Box A2.1: summary of recent studies highlighting impacts, and associated costs of adaptation

The studies conducted by ADB (2013), PICRA (Keener et al., 2012) and in Tarawa, Kirbati (World Bank, 2000) provide qualitative and quantitative estimate. PICRA highlights the negative impacts on tourism, water resources. The Kiribati and Tarawa specific study focuses on the impacts of sea level rise which is likely to be most severe in the low islands of the Pacific. In Tarawa, though the impact of coastal erosion is expected to be modest (3–4 percent of the land by 2100), inundation could lead to annual average damages of US$6.6 to US$12.4 million by 2050. Periodic storm surges could result in the inundation of up to 55 to 80 percent of land areas in North Tarawa, and 25 to 54 percent of areas in South Tarawa by 2050. For Tarawa and perhaps many low-lying atoll islands in the Pacific, such trends would impact the vital groundwater resources. With the projected rainfall increase of 7–10 percent, the sea level rises by 0.4 meters, the islands' width would be reduced through inundation, resulting in decline of main groundwater supply by 19–38 percent by 2050. The resulting economic losses could average US$0.7–$2.7 million a year, and require the development of alternative groundwater sources, desalination, or rainfall collection. The study highlights the vulnerability of agriculture crops through saltwater intrusion affecting te babai (giant taro) production in particular – and loss of coastal land to inundation could affect the production of copra, breadfruit and pandanus. Tarawa alone could face average annual damages from climate change of US$8-$16 million, as compared to a GDP of US$47 million.

The ADB study is extensive and uses climate projections for 2041–2060 and 2061-208 with a baseline of 1981-2000 and a range of low, medium and high scenarios (A2, A1B, B1, B2), combined with 20 global circulation models and a regional model. It provides qualitative and quantitative estimates of costs of adaptation for the region as a whole. It covers Cook Islands, Fiji, Kiribati, RMI, FSM, Nauru, Palau, PNG, Samoa, Solomon Islands, Timor-Leste, Tonga, Tuvalu, and Vanuatu. The impacts and adaptation options and costs are as follows:

- **Infrastructure**: Airports and seaports, road infrastructure, and local communities, all of which are highly concentrated on coastal areas, could sustain significant damage from the expected sea-level rise. These risks are considered as early as possible in the project design stage. It is important to contain the risks posed by extreme weather events and by potential future climate risks within manageable levels. Although climate proofing could increase the upfront costs of the infrastructure projects, such higher costs could be economically justified by the long lifetime of many infrastructures and by the high probability of climate-related damage in the Pacific.
- **Buildings**: Although better elevation data are needed for more reliable projections of inundation risk, the impact of sea-level rise would put large coastal areas at risk of inundation. Under the A1B scenario, high range rise, ranging from 1.2 meters in the Cook Islands to 1.7 meters in Solomon Islands by 2100; low-range estimates suggest that sea-level rise to range from 0.5 meter to 1.1 meters for those two islands, respectively.
- **Coastal areas**: Economic impacts in the coastal areas would also be significant. The impacts in the coastal areas would consist of three components: dryland loss, wetlands loss, and forced migration. The total impact in the coastal areas, through all three channels, is projected at $469 million or 1.3% of the region’s annual GDP equivalent by 2100.
- **Energy**: A warmer climate would put pressure on the rapidly rising energy demand for space cooling in households and buildings around the Pacific. When income and population growth in the urban areas are considered, the cost of cooling is estimated to reach $1,017 million or 2.8% of the region’s annual GDP equivalent by 2100.
- **Water sector**: Sea-level rise combined with changes in precipitation will impact water supply and groundwater from well fields near the coastal regions (Rasmussen et al. 2013). There is risk that the already limited freshwater resources in the region may be severely impacted by increasing salinization.
- **Agriculture**: The negative effect on agriculture contributes the most to the total economic cost of climate change in the Pacific—approximately half of total economic cost amounting to 5.4% of GDP in 2100 under a high emissions scenario [A2]. Overall, global warming is expected to negatively impact crop productivity in the Pacific. The largest yield losses are projected for sweet potato in PNG and the Solomon Islands, with losses in excess of 50% of yield for the former by 2050 under the medium emissions scenario [A1B]. For sugarcane, losses would be relatively small in B2050, but would rise in Fiji by 2070 to a more substantial 7% to 21%. Maize would have moderate losses of 6% to 14 % in Timor-Leste and Vanuatu by 2050, with a rise to 14% to 17% by 2070 in the former. Results also show cassava and taro would be significantly impacted. Rainfed agriculture appears to be particularly vulnerable to the impacts of climate change
- **Tourism**: Climate change would likely also impact tourism, which is another key economic sector of the region. As the world warms up, the Pacific region as a whole would become a less attractive tourism attraction and total tourism revenues are projected to fall. By the end of the century, tourist numbers are projected to be approximately one-third lower than in a business-as-usual scenario. Under all climate scenarios, the impact of climate change would be to reduce tourism revenues by 27% to 34% for the Pacific region as a whole.

Economic damages from Tropical Cyclones

Most cyclones attain their peak wind speeds over the open sea and wind speeds decay rapidly once they make landfall. In a statistical analysis of cyclones in the NW Pacific Emmanuel (2000) separates cyclones whose maximum intensity was limited by landfall and those whose maximum intensity was limited by other factors.[13] The average peak wind speed of cyclones hitting land in the NW Pacific was 34 m/s with a standard deviation 15 m/s[14]. The 90th percentile of the distribution corresponds to a peak wind speed of 169 km/h. The average rate of decay of peak wind speed over land was 63 km/h per day, so that even the most intense cyclones lose most of their potential to cause damage within 24-36 hours.

Storm damage tends to increase exponentially with the difference between the peak wind speed and the design standard for buildings and other structures. In Japan, design standards for specific locations are based on estimates of storms with a 100 year return period – i.e. a 1% chance of occurring in any year. The peak wind speeds incorporated in building standards range from 50 m/s in the extreme south to 30 m/s for mountainous areas of northern Honshu and Hokkaido.

The calculations presented here assume that wind damage is zero or minimal for storms with peak wind speeds up to 30 m/s or 108 km/h. Above that level the amount of damage is assumed to be proportional to $(w - 108)^{2.5}$ where w is peak wind speed measured in km/h. This corresponds to the damage relationship used by analysts for post-1980 buildings built to a design standard of 30 m/s.

Climate change is expected to shift the distribution of cyclones by peak wind speed, but only gradually. Scientists who model cyclones estimate that the intensity of cyclones will increase by 3-5% per 1°C rise in average sea surface temperatures. However, the long run dynamics of the relationship between increases in mean surface temperatures over land and in open oceans are far from simple. The historical data shows that there is a 5% chance that the maximum sustained wind speed in a particular year will be 165 km/h or greater. This means that the total area under the curve to the right of 165 km/h is equal to 0.05. An alternative way of expressing the same idea is that a maximum wind speed of 165 km/h or greater is a 1 in 20 year event or has a return period of 20 years denoted as R20. Climate change is expected to shift the whole distribution to the right as illustrated by the dashed line. (Figure A2.1) This implies that the probability of maximum wind speed of 165 km/h or greater is now 16% rather than 5%. The same shift may be expressed by observing that the maximum wind speed with a return period of 20 years is now 171 km/h rather than 165 km/h. Thus, references to a change in the frequency and severity of extreme events are a way of describing the shift in the overall probability distribution of the maximum wind speeds of cyclones which make landfall within a year.

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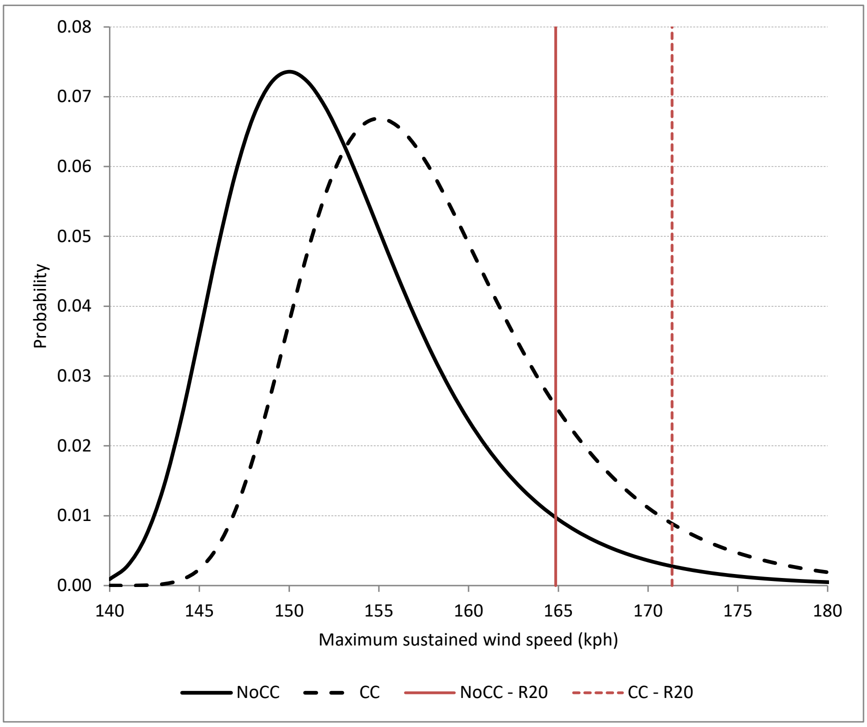
[13] As a result of the resolution of the analysis "landfall" did not include hitting (relatively) small islands and peninsulas such as Hainan and Taiwan.

[14] Different practices in reporting peak wind speeds meant that Emmanuel standardised his data to produce estimates of maximum wind speeds averaged over 1 minute – the usual practice in reporting hurricanes in the US. As a broad guide, peak wind speeds averaged over 1 minute are 12-14% greater than peak wind speeds averaged over 10 minutes. Gust speeds, measured over a period of 5 seconds, may be up to 25% higher than peak wind speeds averaged over 10 minutes.

Figure A2.1: Current probability distribution of wind speeds and how it could change with climate change



Under such assumption, the expected annual losses for PICs due to storm damage can be calculated using the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI) model under current levels of protection (2013) and adjusted for the increase in risks to 2040 due to climate change (2040). The current estimates for average annual damages for these five countries (which ones) is $85 million with another $53 million associated with indirect losses. The projected increase in expected annual damage by 2040 for these five island countries is $10 million at 2013 prices without adaptation. At the extreme end of the distribution of risks, the total damages associated with 1-in-100 year storms for each island will increase by $142 million for the five islands together due to the shifting of the risk profile caused by climate change up to 2040 without adaptation. These assessments exclude the impact of sea level rise and correspond only to the impacts of the wind.

Estimate of changes in the potential magnitude of cyclone losses are based on historical information about the severity of cyclones by 2.5 arc-min grid square compiled by the Center for Hazards and Risk Research (CHRR) at Columbia University for the World Bank – CHRR (2005)[15]. Average wind speeds for each of the CHRR historical deciles were calculated using Emmanuel's statistical distributions. The change in peak wind speeds due to climate change were computed for each GCM using (a) 50% of the increase in mean temperature for the months July-October (the main cyclone season), and (b) a sensitivity of a 5% increase in cyclone intensity per 1°C increase in temperature. The results were linked to separate GIS estimates of the distribution of urban and rural population by grid square.

[15] Database available on line at : http://sedac.ciesin.columbia.edu/data/set/ndh-cyclone-hazard-frequency-distribution (last access April 18, 2016)

The level of economic losses caused by major cyclones – an average of $1.3 billion per year in the period 1994-2005 globally – suggests that an economic case can be made for adopting design standards for buildings and other structures which provide more protection against wind damage than current standards. A 1 in 50 year design standard means that the infrastructure can withstand peak wind speed over land of 185 km/h (Carpenter, 2006). It would be appropriate to adopt design standards to ensure that buildings and other structures can withstand peak wind speeds of at least 200 km/h. For structures with an economic life of more than 60 years, it might be appropriate to adopt a design standard of at least 215 km/h to take account of both climate change and the desirability of adopting more stringent standards as the value of assets at risk increases.

The costs of adopting these design standards might increase the typical cost of constructing urban houses and commercial buildings by 4-5%.[16] About 80% of the additional cost is driven by the adoption of building codes designed to withstand the peak wind speeds associated with a 1 in 50 year storm rather than the considerably lower performance of current buildings. The remaining 20% of the additional cost represents the cost of ensuring that structures built up to 2050 are capable of coping with the higher peak wind speeds associated with more intense typhoons as a consequence of further climate change.

Reference:

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Carpenter, G. (2006). Typhoon Saomai: Impact and historical comparison. London: Guy Carpenter and Company

CHRR (2005) Global Cyclone Hazard Frequency and Distribution – Version 1.0. CIESIN, Columbia University. New York, USA

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Keener, V. W., Marra, J. J., Finucane, M. L., Spooner, D., & Smith, M. H. (Eds.). (2012). Climate Change and Pacific Islands: Indicators and Impacts. Report for The 2012 Pacific Islands Regional Climate Assessment. Washington (PICRA), DC: Island Press.

Rasmussen, P., Sonnenborg, T. O., Goncear, G., & Hinsby, K. (2013). Assessing impacts of climate change, sea level rise, and drainage canals on saltwater intrusion to coastal aquifer. *Hydrology and Earth System Sciences*, *17*(1), 421-443.

World Bank (2000). Cities, Seas, and Storms: Managing Change in Pacific Island Economies, Volume IV Adapting to Climate Change, *International Bank for Reconstruction and Development/The World Bank*, Washington, DC, USA, 135 pp.

[16] This estimate is based on the assumption that current building standards will cope with wind speeds equivalent to those of a Category 1 hurricane in US terms. [For reference Hurricane Katrina was a Category 5 hurricane in its most intense phase over the Gulf of Mexico but it had subsided to a Category 3 hurricane by the time it made landfall and struck New Orleans.] Updates of building codes in South Florida implemented in 1994, 2002 & 2007 to withstand stronger hurricanes have progressed in steps of approximately 16-20 kph in the peak wind speed for which buildings are designed. The most recent code update should enable buildings to withstand peak wind speeds up to 195 km/h averaged over 10 minutes, equivalent to the middle of the wind speeds associated with a Category 4 hurricane. Using the methodology described in Appendix to the World Bank's paper on adaptation for climate change for infrastructure, the adoption of a 1 in 50 year design standard of 195 km/h would involve costs equivalent to 5 code updates @ 0.8% of base costs for each update. Adaptation to climate change up to 2050 would imply an additional code update if the design standard in 2050 is based on a peak wind speed of 215 km/h.

Annex 3 - Adaptation for Infrastructure

This annex provides an overview of different adaptation strategies and the cost of adapting infrastructure assets to changing climate. Infrastructure assets include power and telecommunication, water and sewers, urban, roads and other transport infrastructure, hospitals, schools and housing. Importantly, the analysis below only considers risks associated with temperature increase and precipitation changes. The cost of protecting buildings against tropical cyclones is discussed in Annex 2 (and chapter 3.5 of the main report) while the cost of protecting against sea level rise and storm surges is discussed in Annex 5 and chapter 3.2, so they are not considered here.

1. Methods

1.1 General approach

To assess the cost of adaptation for infrastructure, a number of assumptions are made about future infrastructure investments as well as about the design standards that would have been applied to build these assets in the absence of climate change. This set of assumptions is referred to as reference scenario. The costs of adaptation are then assessed as the difference between expenditures in the reference scenario and expenditures in scenarios with climate change impacts, where the infrastructure is designed to withstand changes in temperature and precipitations. Accordingly, if the reference scenario assumes that resilience will increase over time in the absence of climate change, adaptation costs are much lower than if the reference scenario assumes there will be no frequent maintenance regimes in the next decades and new resilient standards are not used.

The basic approach used in this study is described thereafter. For any country j and date t (t = 2015, 2020, …) it is assumed that there is some "normal" level of provision of infrastructure of type i, which will be denoted by Q_{ijt}. The "normal" level of infrastructure reflects the decisions made in middle or high income countries around the world about the amount of infrastructure which they require given GDP per person, population plus a range of physical and climatic conditions. This baseline relies on the idea that there are common elements in the ways in which countries have developed over time but with adjustments to take account of (a) the specific physical characteristics of different countries, and (b) differences in the initial distribution of infrastructure across countries.

In the period from t to t+1, for example from 2020 to 2025, the country will have to invest in order to meet the normal level of infrastructure in t+1 and to replace infrastructure in situ at date t which reaches the end of its useful life during the period. Thus, the total value of capital investment in infrastructure of type i in country j and period t in the baseline with no climate change is

$$K_{ijt} = C_{ijt}[Q_{ijt+1} - Q_{ijt} + R_{ijt}] \quad (1)$$

where C_{ijt} is the unit cost of investment and R_{ijt} is the quantity of existing infrastructure of type i that has to be replaced during the period. The change in the total cost of infrastructure investment may be expressed in terms of the total differential of (1) with respect to the relevant climate variables that affect either unit costs or efficient levels of provision for infrastructure of type i:

$$\Delta^C K_{ijt} = \Delta^C C_{ijt}[Q_{ijt+1} - Q_{ijt} + R_{ijt}] + (C_{ijt} + \Delta^C C_{ijt})[\Delta^C Q_{ijt+1} - \Delta^C Q_{ijt} + \Delta^C R_{ijt}] \quad (2)$$

In this formulation the Δ^C operator refers to the difference between the values of investment, costs, etc for the climate change scenario and their values under the baseline with no climate change (NoCC).

An equivalent equation may be derived for the costs of operating and maintaining infrastructure. In the discussion that follows, the first part of the right hand side of equation (2) is referred to as the Delta-C (cost) component of the cost of adaptation, while the second part is referred as the Delta-Q (quantity) component. These components themselves cover a number of ways in which climate change may cause changes in the costs or quantities of providing infrastructure services.

(a) ***Delta-C***. The main impact of climate change on the ***cost*** of providing infrastructure services arises because the materials and designs used in building infrastructure must be altered so as to maintain the quality of infrastructure services provided by a unit of infrastructure – e.g. a kilometre of paved road or a fixed telephone connection.[17] For example, different – and more expensive – binders have to be used in the pavement layer of roads if they are exposed to higher temperatures. More culverts may have to be installed to minimise the risk of flooding and damage caused by standing water, while changes in the number and duration of freeze-thaw cycles may require changes to the depth of sub-surface layers and surface materials. Hence, it is common to refer to "climate proofing" investments or ensuring "climate resilience".

    The study is predicated on the assumption that adaptation takes the form of adjustments to materials, structural designs, and equipment that are required to deliver the same level of performance as would have applied if climate change had not occurred. Thus, if roads or buildings are currently constructed to withstand a 1 in 50 or 1 in 100 year flood or wind storm, then the same design standard should apply but under the circumstances of a changed frequency or severity of those events. The changes in the unit costs - ΔC_{ijt} - represent the costs of building infrastructure that delivers the same level of performance in the face of different climatic stresses. The derivation of the cost changes, expressed as dose-response relationships for a basic set of climate stressors, are summarized in Box 3.1.

    The dose-response functions are applied to estimates the average values of climate variables under a scenario of a stable climate and alternative scenarios for climate change by country.[18] The method generates a series of cost increases – expressed in terms of constant 2010 prices - by type of infrastructure, country, and time period. When applied to the baseline projection of infrastructure demand, the difference between the cost of the baseline investment program for a stable climate and for a changing climate is referred to as the Delta-C cost of adaptation. This is the first term on the right hand side of equation (2) – i.e. $\Delta^C C_{ijt}[Q_{ijt+1} - Q_{ijt} + R_{ijt}]$. A similar exercise may be carried out for operating, maintenance and replacement costs in order to calculate the increment in annualised infrastructure costs as a consequence of climate change.

[17] See Canadian Standards Association (2006) for discussion of this issue.

[18] For this study, the climate projections are the population-weighted national averages discussed in Annex 1. Thus, references to climate variables by country in this paper should be construed as referring to the population-weighted averages of, say, precipitation for the various grid squares that cover the country.

Box A3.1 – Baseline projections of infrastructure

The baseline projections used in the analysis rely upon a combination of assumptions about population and economic growth with a set of econometric equations that capture how the demand for infrastructure changes as countries develop.

Socio-economic projections. The demographic assumptions which underpin the analysis are based upon the Medium Fertility scenario in the 2010 Revision of the UN Population Division's population projections, which provides projections of population by age group up to 2100 together with associated estimates of fertility and mortality rates. The Medium Fertility scenario is usually regarded as a central projection that reflects historical experience of changes in fertility rates as countries develop, so it has been used in this study. Projections of the proportion of the population living in urban areas are taken from the UN's World Urbanisation Prospects 2009 (UN-DESA, 2010).

The projections of GDP per person for the countries covered by the study were generated by updating the country projections used in the Economics of Adaptation to Climate Change (EACC) study, so that they are based on estimates of actual values for 2010 together with the projection 5-year growth rates for 2011-15, etc.

Patterns of economic development. The econometric equations are estimated using data from the 2011 version of World Development Indicators (WDI) database published in 2011 by the World Bank. This information was supplemented with data on infrastructure availability from a wide variety of sources including other international organisations (FAO, ITU, WHO, UNICEF, UPU, etc), official country data (especially Census data), and various systematic surveys such as Demographic and Health Surveys (DHS), Living Standards Measurement Surveys (LSMS) that are broadly consistent across countries. The final dataset consists of unbalanced panels with missing data, especially for earlier periods. Thus, it is not possible to make use of econometric specifications involving autoregressive or similar errors over time.

The base specification for infrastructure indicators is log-linear with a wide range of regressors including population (by age group in the case of health and educational infrastructure), GDP per person at 2005 real international prices (PPP), urbanization, physical country characteristics (such as size, % steep land, % arid or semi-arid), controls for historical endowments, and climate variables which are treated as fixed effects in the baseline projections. A logit transformation was used for indicators such as the proportion of roads that are paved and the proportions of urban or rural households connected to electricity, water or sewer networks. This ensures that projections are constrained between 0 and 1.

Alternative specifications including the quadratic and interaction terms in GDP per person, urbanization and country size were investigated. For example, municipal water use per person rises up to a level of GDP per person of about $15,000 and falls thereafter. It was essential to retain a quadratic specification for both municipal and industrial water consumption per person. The set of climate variables tested in the models included average temperature, annual precipitation, seasonal patterns of temperature and precipitation measured by the ranges between the maximum and minimum monthly values, and their extreme values measured by their 1^{st} and 99^{th} percentiles.

Since it is almost certain that the errors are correlated across countries and over time it was essential to use estimation methods that are robust to a wide range of error structures. Many panel data estimators are prone to yield biased estimates of either coefficients or their standard errors if the parametric assumptions incorporated in the model are violated. For this reason most of the models were estimated using pooled OLS with random effects and Driscoll-Kraay standard errors. In the case of proportions that are very close to 1 for most middle or high income countries – e.g. the proportion of urban and rural households with electricity or water connections – the estimation was carried out using a panel tobit specification with random effects.

The projections generated by the econometric equations for each country have been calibrated to match estimates of the actual values of the infrastructure variables in 2010. This is equivalent to introducing a set of country dummy variables constructed to ensure that the residuals for 2010 are zero.

(b) ***Delta-Q***, the ***quantities*** of infrastructure assets required (holding income, population and other socio-economic variables constant) may change as a consequence of different climatic conditions. Again, this has two dimensions. The first is that climate change may change the level or composition of demand for energy, transport and water at given levels of income, so it is necessary calculate the net impact of these changes in terms of capital and operating costs. The second is that climate change will mean that countries have to invest in specific additional assets in order to maintain specific standards of protection for non-infrastructure activities – e.g. higher flood defences or greater capacity to handle storm water drainage.

The Delta-C dimension of the study is uncontroversial in principle, though more or less difficult to assess in practice. Various organisations have made broad brush estimates of the cost of "climate proofing" existing investment programs in developing countries such as UNFCCC (2007), WRI (2008). Typically, the analysis starts from a baseline program of investment in infrastructure by time period. Then, an estimate is made of the percentage increase in unit costs required to ensure that investments are resilient to climate change.

One problem with the "climate proofing" approach concerns the investment program to which the cost of climate proofing should be applied. In few cases, it is possible to start from a detailed inventory of infrastructure assets and then to ask what investments will be required to meet future demand for infrastructure services. The best example of this approach is a study of the costs of adaptation to climate change in Alaska (Larsen et al, 2008). However, such an exercise requires an inventory of infrastructure assets and it does not take account of future investment in infrastructure.

While the principle that climate change may affect the demand for infrastructure seems straightforward, the task of estimating the Delta-Q costs of adaptation is much more difficult for two general reasons.

(a) Many of the impacts of climate on demand for infrastructure are long term in nature. This may not be true for electricity or water, but any influence of climate on the demand for roads will operate via the path of economic development over a period of one, two or many decades. There are two consequences. First, the Delta-Q component of the cost of adaptation will not arise on a regular schedule every five years. The calculation merely identifies additions to and subtractions from a liability (or asset) that will materialise in future as economic activity adjusts to the changes in climate that are taking place. Second, when planning for future infrastructure development, governments need to consider how climate change may affect the amount and type of infrastructure that would be required if it would influence future patterns of economic activity.

(b) In practice there is no way of quantifying the impact of climate on the demand for infrastructure other than through some forms of panel data analysis - pooling data for countries, regions, states or other geographical units over time. Inevitably, climate is a cross-sectional variable (since year to year variations are weather) which may easily be confounded with other cross-section fixed effects. The results of the econometric analysis that has been undertaken tend to be stronger and more convincing for sectors like energy, water and road transport.

For these reasons, the Delta-Q component of the cost of adaptation has only been included in this study for a small number of adjustments that cannot be easily classified as either cost or quantity changes. The most important of these are modifications to the capacity of drainage systems for roads and urban areas to handle greater volumes of storm water due to more intense precipitation and greater vulnerability to flooding. In the case of buildings, the analysis covers enhancements to heating, cooling and ventilation systems required to cope with higher levels of humidity.

Note that here, in the reference scenario, it is assumed that there will be an improvement in the quality and maintenance of infrastructure services over the next decades. It is assumed that over time and development gains, a country will have a "normal" level of infrastructure defined as a function of GDP per capita, population, and a range of physical and climatic conditions with patterns similar to that of current high- and middle-income countries. The reference scenario also assumes that the quality, redundancy and maintenance levels of infrastructure increase over time, as a function of income growth, i.e. countries will invest in climate resilience infrastructure and will follow good practices in terms of maintenance to protect against current risk levels. Accordingly, PICs will not be protected against 1 in 1,000 or even 1 in 10,000 year floods like the Netherlands, because the opportunity cost of such defences – e.g. the sacrifice of expenditure on health or education – may not justify such high protection. But improving the resilience of current infrastructure can bring many economic benefits. Today infrastructure in the PICs is often badly damaged by cyclones. Box 3.1 gives more details about the way the reference scenario was calculated.

1.2 The deep uncertainties on future climate and associated costs

Different climate models incorporate different representations of the physical processes that determine the response of the global climate to the accumulation of CO_2 and other Green House Gases in the atmosphere and to other factors that influence the future evolution of climate conditions at the regional or sub-regional level. In this sense, each climate scenario can be regarded as reflecting a distinct structural representation of climate interactions. Since various climate scenarios are based on structural models that are conceptually different, each projection could be treated as being equally likely. It would be wrong to rely on probability-weighted combinations of the different projections or to only consider the average of all the projections. There is no "correct" future climate projection. Therefore, it is important to consider a wide range of climate projections.

Additionally, while projections of temperature up to 2100 tend to be similar across these models, there are substantial differences between climate models in their projections of precipitation, both in total and its distribution over the year. Such differences are critically important for adaptation analysis for infrastructure because the largest component of adaptation costs are driven by factors linked to the amount and pattern of precipitation. These differences between the projections generated by different climate scenarios therefore require explicit consideration and analysis.

The work carried out in preparing this chapter examined 19 climate scenarios up to 2050 that are based on separate Global Circulation Models (GCMs) runs using the RCP45 scenario for emissions of CO_2 and other greenhouse gases (see Annex 1). The projections for the key climate variables – monthly values of precipitation, minimum and maximum temperatures – for each GCM are constructed by calculating average differences for 2041-60 (2050) for 1° grid squares with respect to the average of runs for the same GCM over the period 1950-2000. The projections were extended to 2090 to also consider planning horizons. These differences were added to the mean values of historical climate variables, obtained from the Princeton daily climate dataset discussed in Annex 1 for the same time period. The values were then interpolated to generate projections for each time period.

Since the costs of adaptation is affected by changes in average as well as extreme values (represented by the 99th percentile) of humidity, temperature and precipitation, statistical models calibrated upon historical data have been used to estimate the changes in weather variables that are not given directly by the GCMs.

This step in the analysis goes beyond the use of standard climate variables that are generated by climate models. It requires specification of indicators that reflects the sensitivity of different types of infrastructure – such as pavement temperature or humidity-based measures – that are functions of either daily weather conditions or extreme values. A variety of statistical models have been used to derive projections of such variables using the outputs from climate models. These statistical models are based upon detailed data on daily weather conditions by 1° grid square for 1948-2008 that has been compiled by a group at Princeton. The climate stresses included in the analysis for each category of infrastructure are summarized in Tables A3.1 (capital costs) and A3.2 (Operations & Maintenance costs). One feature of the approach is to identify a set of common components – paved and unpaved surfaces, different types of buildings, etc. – that are found in several categories and which can be treated similarly in addition to the elements that are specific to each category. Box 2 provides more detail on the nature and definition of climate stresses and the associated dose-response relationships.

For each infrastructure component and category a set of dose-response relationships between the relevant climate stresses and (a) the costs of initial construction, and (b) ongoing operating and maintenance costs have been specified using detailed evidence collected by engineers from experience around the world. These dose-response relationships capture the change in costs as materials and designs used in building infrastructure are modified to maintain the quality of the infrastructure services in the face of climate change. For example, more expensive binders have to be used in the pavement layer of roads if they are exposed to higher temperatures. More culverts may have to be installed to minimize the risk of flooding and the damage caused by standing water. Dose-response curves are typically step functions and specific how the costs of constructing and maintaining infrastructure assets are altered by changes in climate stresses that they are designed to withstand. This evidence is routinely incorporated in design and building codes that take account of the performance of different specifications. Such standards are not set in an arbitrary manner; they are based on systematic procedures for assessing and updating the trade-off between the costs of implementing more stringent specifications and the benefits in terms of either lower O&M costs and/or the reduction in the risks of damage and failure caused by weather stresses including extreme events. Thus, the dose-response relationships used in this study reflect the economic and engineering choices made by a wide pool of experts based upon their collective knowledge as well as the development of materials and construction methods.

Box A2 – Dose-response relationships for climate impacts

The development of dose-response relationships for different components of infrastructure has been described in detail in reports produced for the EACC study – see World Bank (2010), Hughes et al (2010) – and subsequent papers – e.g. Chinowsky et al (2009, 2011). A crucial feature of the analysis is that each type of infrastructure is treated as a combination of building components which may be affected by various climate stresses. These components are: bridges, paved surfaces, unpaved surfaces, utility poles, rail track, large commercial buildings, small commercial buildings, housing, and other items. The climate stresses for large commercial buildings are applied in the same way for the similar component of electricity generating plants, water and wastewater treatment works, etc so that the total impact of the climate stresses for a particular asset is an average of the stresses for each component weighted by its share in the total cost of the asset.

Additional adjustments are made for specific types of infrastructure as a result of particular climate stresses. These adjustments are primarily linked to (a) operating & maintenance costs (O&M), and (b) reductions in the economic life of assets. For example, the efficiency of electricity generating plants and water or wastewater treatment processes is affected by an increase in ambient temperature, while exposure to higher levels of relative humidity will accelerate deterioration – and thus reduce the economic life of buildings with wood cladding.

A final point to note is that many climate stresses involve some kind of step function (i.e. with threshold effects). Existing design parameters might be appropriate for a particular component as long as the climate stress does not change by more than x units, so the cost of adaptation is only incurred when the projected change in climate conditions exceeds this threshold and then the cost of adaptation remains constant until a second threshold at 2x units is surpassed. Hence, the calculation of the costs of adaptation involves a series of thresholds for each climate stress. Table xx summarises the key elements of the dose-response relationships by infrastructure component, asset type and type of impact.

Paved and unpaved roads. The pavement layer of paved roads will deteriorate rapidly with use if the surface temperatures which they are exposed to exceed the design specification of pavement binders by more than even a few degrees C. The consequence is an increase in annual maintenance costs to repair surface damage, potholes, etc and a reduction in the operating life of the pavement. The stress is not simply a matter of the maximum air temperature that the pavement is exposed to in the course of a year because the temperature of the pavement layer does not respond immediately to changes in air temperature. Instead, it increases gradually in response to an extended period of high air temperatures.

With daily temperature data it is possible to calculate the pavement high and low temperature equations used to specify appropriate grades of pavement binders developed to meet the requirements of the Federal Highway Works Administration's Superpave model (Mohseni, 1998). The pavement high temperature, which is critical in this context, is a function of the maximum value of daily maximum air temperatures averaged over 7 days over the life of the pavement with an adjustment for latitude to take account of the period of direct exposure to sunlight. Superpave specifies a series of pavement high temperature thresholds starting at 36° C separated by increments of 6° C which require different grades of pavement binder with an average increase of 7% in the capital cost of constructing a paved road for each step increase in binder specification. The cost of annual maintenance is assumed to increase pro rata with the capital cost of constructing the road.

Existing roads that are exposed to higher temperatures than they were designed for will require more maintenance and may have to be replaced earlier than planned. The additional costs due to higher maintenance and reduced lifespan will depend upon age, highway maintenance practices, usage patterns and other stresses, so it is difficult to specify general rules for estimating the costs that will be incurred. The model assumes that if future pavement temperatures exceed the threshold, and so the pavement binder requiring a higher grade, then all paved roads will gradually be replaced over a period of 20 years. Higher maintenance and vehicle operating costs on roads that have not been replaced translates into an annual cost equal to about 8% of capital costs.

A second extension concerns the damage caused by flooding events that require almost complete reconstruction of sections of highway. The dose-response relationship relies upon a piecewise linear relationship between the return period of flooding events of different degrees of severity and the proportion of highway length that requires reconstruction. This varies from 0% for 1 in 2 year floods to about 15% for 1 in 100 year floods. The expected value of the loss in any year can be calculated by summing the products of the damage caused by floods and the probability of floods of the associated severity. Hence, if we suppose that a 1 in 100 year flooding event based on historical experience (NoCC) translates into an average flood depth of 1 metre. If some episodes of heavy rainfall become more frequent as a result of climate change, then the probability of a 1 metre flood in any year may increase from 1% to, say, 1.25% and the expected value of flood damage in any year will increase with the shift in the probability distribution of flood severities. To calculate the increase in the value of expected flood damage, a Gumbel distribution is estimated using historical data on the maximum 3-day precipitation for the grid cell observed. The increase or decrease in maximum 3-day precipitation under each climate scenario is estimated using a statistical model. Allowing for the shift in the distribution of all flood events by a 10% increase in maximum 3-day precipitation leads to an increase of approximately 40% in the total flood damage. An elasticity of 4 of flood damage with respect to changes in maximum 3-day precipitation is high and would, in the longer term, warrant changes in the design of new roads. Hence, it has been assumed that this additional cost applies to existing roads while new roads are designed to maintain current expected levels of damage due to flooding.

Buildings and housing. The potential damage to buildings and housing caused by climate is associated with the deterioration of exposed wood structures and the need to increase ventilation and/or cooling capacity to cope with higher levels of humidity. Since it is impossible to obtain reasonable estimates of the proportion of buildings that are primarily constructed with exposed wood, we have adopted the simple assumption that all rural housing constructed with durable materials consists of wooden buildings. This is certainly an over-estimate but it provides a worst case estimate of the impact of climate change on rural housing. The requirements for ventilation and/or cooling are assumed to apply to all other buildings that are constructed of durable materials: this includes most urban housing, schools, health facilities, offices, etc.

Models of the decay of wood structures link to climate conditions – initially in North America but now more widely around the world - are usually based on the use of the Scheffer Index which was proposed as the basis for explaining empirical data in 1971 (Scheffer, 1971). This index is based upon the product of monthly average temperature and the average number of days in the month with significant precipitation (> 0.25 mm) summed over all months and normalised to give values in the range 0 to 100 for locations in North America. Higher values of the Scheffer index (SI) are associated with shorter expected lives for wood structures constructed with untreated timber. For our analysis we have converted the Scheffer index to a measure of time to failure, i.e. when the structure must be replaced or undergo substantial maintenance, in years using an empirical relationship. Since small changes in climate may not have a significant practical effect on the economic life of buildings, the analysis has been restricted to cases in which the change in time to failure exceeds 5 years.

Since there is no simple way of designing or modifying wood structures to offset this loss of life, the cost of adaptation is identical to the impact of climate change and is equal to the loss of life multiplied by the average cost of constructing new houses. Of course, as implied by the assumption that the minimum life of a wood building is 15 years, there is always the possibility of using durable materials other than wood – bricks, concrete blocks, walls with cement rendering, etc. Such options will usually increase building costs by a large margin though the quality of housing services provided by the building may change substantially as well.

In the late 1990s the National Research Council of Canada sponsored a large research project (the MEWS project) to study the impact of climate stresses on buildings. The study concluded that the impact of climate on external cladding made of non-wooden material should be minimal. Hence, the study went on to examine the effects of climate on the specification of heating, ventilation and cooling (HVAC) systems. This led to the development of the MEWS methodology and of a moisture index, referred to as the MEWS index, which can be used to define climate zones with respect to the potential severity of moisture problems (Cornick & Dalgleish, 2003). The MEWS index concentrates on the effects of changes in humidity due to changes in temperature and/or precipitation. Higher index values imply that ventilation and cooling systems must be upgraded in order to protect buildings and the health of their occupants. The MEWS index is defined in terms of a wetting index, which is a function of precipitation, and a drying index, which depends upon relative humidity. It is constructed to measure the amount of moisture that a building will be subjected to under different climate conditions. In principle, the index may be calculated using hourly or daily averages, but the investigators propose a robust approximation that can be estimated using monthly averages for precipitation, temperature and relative humidity. This approximation was used to generate estimates of the MEWS index from 2010 to 2090 by climate scenario and grid cell.

The normalisation of the MEWS index yields values that typically fall in a range from 0 to 1.5. The MEWS methodology suggests that the severity of moisture stresses on buildings may be classified as follows:

Moisture stress	***Range of MEWS index***
Low	< 0.7
Limited	0.7 – 0.8
Moderate	0.8 – 0.9
High	0.9 – 1.0
Severe	> 1.0

We have assumed that each step from a lower to a higher category of moisture stress requires an upgrade in ventilation and cooling systems of buildings in order to maintain the design standard of building performance and comfort. The average cost of an upgrade is estimated to be 4.5% of construction costs, which corresponds to the components of HVAC systems that would need to be replaced. There is an equivalent increase in annual maintenance costs for the building.

Table A3.1: Climate stresses increase capital cost for different infrastructure asset categories

	Temperature	Precipitation	Other
Bridges		Maximum	
Paved surfaces	Maximum	Total	
Unpaved surfaces		Total	
Utility poles			Maximum wind speed
Railways			
Large commercial buildings	Mean	Total	
Small commercial buildings	Mean	Total	
Housing		Total	
Electricity generation	Maximum		
Water treatment			
Wastewater treatment			
Storm water drainage		Maximum	
Wood buildings			Temperature & precipitation Scheffer index
Brick/concrete buildings			Relative humidity – MEWS index

Table A3.2: Climate stresses increase O&M cost for different infrastructure asset categories

	Temperature	Precipitation	Other
Bridges			
Paved surfaces	Maximum	Total	Flooding
Unpaved surfaces		Maximum	Flooding
Utility poles			
Railways	Maximum		
Large commercial buildings	Mean	Total	
Small commercial buildings	Mean	Total	
Housing		Total	
Electricity generation	Mean		
Water treatment	Mean	Maximum	
Wastewater treatment	Mean	Maximum	
Storm water drainage		Maximum	
Wood buildings			Temperature & precipitation Scheffer index
Brick/concrete buildings			Relative humidity – MEWS index

1.3 Choice between possible adaptation options

The deep uncertainties on future climate change impacts on infrastructure in PICs makes it is difficult to choose the best investment and the best adaptation strategy. For example, the construction of paved roads can include pavement surface that incorporate binders that are specified to perform to a particular level of pavement temperature – an indicator which depends upon maximum temperature and latitude. Designing for a higher level of the pavement temperature increases the initial cost of constructing the paved road but reduces the cost of maintenance due to degradation of the pavement surface when/if the pavement temperature exceeds the initial design specification. Hence, the decision on adaptation strategy involves a trade-off between capital and operation and maintenance costs. This optimal choice is affected by the probability that future climate conditions will exceed critical values for the pavement temperature.

Decision-makers face two major adaptation strategies: "wait, observe and then act" or "plan for a changed climate". In the former strategy, focus could end up in preparation to post-disaster responses. The strategy would mean that, for example for a road, binders or culverts are not changed compared to the reference scenario, but the road may have to be replaced before the end of its lifetime and there may also be more service disruptions during its operating period especially after heavy rainfall events. In the reference scenario, costs of the service disruption and/or increased maintenance due to climate change are not included. When decision-makers decide to plan ahead for a changed climate, the concepts of building back better and resilient reconstructions are incorporated. This strategy requires designing investment that will resist many different climate change impacts while being cost-effective and being able to perform relatively well in a large number of possible scenarios. It may mean deciding, for example, to build flood defences today which are high enough to protect against a 1 in 100 year flood under the worst case climate scenarios for 2050, to construct paved roads and bridges capable of withstanding the maximum temperatures that are projected to occur in the next 30 years or to change the design standards for buildings so that they incorporate cooling and ventilation that can cope with projected temperatures and levels of humidity in 2030 or 2050. Upstream decisions may also be needed and should be informed by risk planning to help move assets out of high risk and exposure areas. The socio-economic costs and implications of such decisions are not included here.

One element of the trade-off between pre-emptive and reactive adaptation is how far ahead to look, i.e. the choice of a planning horizon. The extreme version of climate proofing considers the worst climate conditions that an asset is expected to experience over its life – perhaps 40 years ahead. However, it could be worth to compare that option with an alternative of considering the climate change observed during the first 20 years of the asset's life. In the extreme case, no additional maintenance or adaptation costs should be required over the 40 year period but the initial capital costs may be relatively high. The alternative will involve lower initial costs but the prospect of higher maintenance or replacement costs in years 21 to 40 if climate change turns out as expected. If there is uncertainty about future climate conditions, the trade-off is subject to the probability that the climate stresses leading to additional maintenance costs will occur. There is no single "right" choice in such cases. The best strategy depends upon the discount rate, the relative costs of pre-emptive investment vs reactive maintenance and retrofitting, the distribution of climate uncertainty and attitudes to risk.

There is a further consideration which policymakers may wish to take into account. Pre-emptive adaptation implies a degree of commitment that does not exist when reactive adaptation is chosen. Rebuilding roads with stronger pavement binders after 30 years may be the outcome of an efficient strategy, but that does not ensure that it will be implemented when the time comes. Any assessment of the costs and benefits of action at the time when the climate threshold has been passed will confirm that either an upgrade or a replacement is justified, but there will always be the risk that the necessary funds will not be available when they would be required.

The commitment implied by pre-emptive adaptation may be regarded as underpinning a robust decision in a context in which there is substantial uncertainty about both climate change and the availability of the resources when they would be required. However, this does not mean that the trade-off between the costs of pre-emptive adaptation and later actions based upon better information can be ignored. Since the resources available for the initial capital spending are limited, a greater emphasis on pre-emptive adaptation comes at the expense of lower investment in other types of infrastructure or productive assets.

To help choose amongst strategies, and given the large number of potential climate outcomes, an approach based on criteria of "minimum maximum regret" is used to select the most appropriate strategy in each sector and each country. In this approach, the cost associated with every strategy is calculated and compared to the least-cost strategy, in each climate scenario. This difference is called the regret. The maximum regret associated with each strategy across all scenarios is then calculated and the strategy with the lowest maximum regret is selected. For instance, investing in expensive planned adaptation option, when the climate change turns out to be the lowest possible, might create a higher regret than waiting and reacting with adaptation options even if the world ends up with a high climate change. If this is the case, the most appropriate strategy is to wait, observe and act. Results of such analysis and the trade-offs needed at the local level could be strengthened by considering several reference scenarios and taking into account the views of the local population and stakeholder, especially the level of disruption to the services that might be acceptable to them. Given the scale of the analysis – at best at a country level – such considerations are not included in the results presented.

2. Results

2.1 Estimating the cost of pre-emptive and reactive adaptation strategies for each climate scenario

Estimations of the costs of pre-emptive adaptation require that the policymakers decide how far to look forward. Is it the worst outcome that might occur over the life of road that matters, even though this would result in over-designing the road for the majority of its life? Should the planning horizon be the same for all climate scenarios?

The maximum economic life of the assets considered in the study is 60 years for water and sewer networks and similar items. Building assets that are capable of withstanding weather stresses that they may only encounter at the very end of their life is likely to be an unnecessarily expensive strategy. For pragmatic reasons, therefore, the maximum planning horizon examined in this study is 40 years, assuming that assets built in 2045 should be capable of withstanding the weather stresses to which they may be exposed up to 2085. At the other end of the scale, the minimum planning horizon is 0 year, which defines a mixed strategy consisting of the combination of reactive and pre-emptive adaptation based on the best evidence of current climate conditions. In between these two extremes the analysis examines planning horizons of 10, 20 and 30 years in order to assess whether the most economic planning horizon varies across the different types of infrastructure or over time.

Table A3.3 – Assumed economic life or renovation period requirement of infrastructure assets

Life (years)	Infrastructure assets
10	Unpaved roads
20	Airports
40	Generating plants, fixed telephone lines, ports, water & wastewater treatment, electricity networks, water networks, health, education & social infrastructure
50	Paved roads, railway track
60	Sewer networks, housing

The asset lives shown in Table A3.3 reflect the economic lives of the assets that are likely to be affected by climate change or which require renovation at regular intervals – e.g. in the case of airports these are the runways and buildings. The assumptions are consistent with either standard engineering practice or with the typical economic lives used by regulators. Where a range of asset lives could be justified, the values adopted fall towards the bottom end of the range to provide adequate safety margins. The assumptions are broadly consistent with the lower end of the time scales listed in Table 1 of Hallegatte et al (2012) because adopting longer asset lives reduces options for responding to climate change in a flexible manner as more information is collected.

Costs of pre-emptive adaptation are then defined as the sum of the ***base cost of the project***, that is, the cost of the project that would have been implemented if the planner were certain that future climate conditions will be identical to the historic climate, ***incremental capital costs*** of adaptation due to the prospect of climate change, and ***O&M costs*** that must be incurred annually. Both the incremental capital costs and the O&M costs will depend on the choice of the planning horizon and will vary by climate scenario. In addition, the O&M costs will depend on the actual climate outcome.

On the other hand, when estimating the cost of reactive adaptation, the policymaker must decide whether or not to upgrade the project or to replace the asset prior to the completion of its economic life. Upgrading the asset so that it can withstand future climate stresses will save from having to incur continually higher O&M cost and will make economic sense if the change in climate patterns is significant. For simplicity the analysis only accounts for upgrades and early replacement for a small number of infrastructure assets that have a relatively short expected life. The primary categories are unpaved roads that can be upgraded to paved roads and heating and air conditioning systems in buildings. Also for simplicity it is assumed that the decision is made halfway through the expected life of the asset.

Costs of reactive adaptation are defined as the sum of the ***base cost of the project, O&M cost***, and ***costs of upgrade or early replacement of the asset.*** O&M costs under reactive adaptation will be higher than O&M costs under pre-emptive adaptation for the same climate event. O&M costs and the costs of upgrade or early replacement will vary by climate scenario and depend on actual climate outcomes.

The costs of pre-emptive adaptation

The costs of pre-emptive adaptation must be measured by reference to an assumption about what would happen if there was no adaptation – the Reference scenario. There are two reasonable variants of a Reference scenario which can be used to answer different questions.

The first variant of the Reference scenario is relevant when comparing pre-emptive and reactive adaptation. Reactive adaptation does not assume that climate change is and will be ignored when planning new investments. The point is that that **reactive adaptation focuses on what has happened in the past rather than attempting to project what will happen in future.** A scenario which is consistent with this approach and with standard engineering practice would be one under which plans are based on actual weather/climate conditions over a window of 30, 40, 50 years immediately preceding the period in which the investment is made. A window of 40 years has been used in this study so that the Reference scenario for comparing pre-emptive and reactive adaptation in the period 2031-35 is constructed by using the average of weather/climate conditions for 1990-2030. This variant of the Reference scenario is referred to below as the Base scenario as it represents a plausible description of what would happen if countries do not implement policies that explicitly promote pre-emptive adaptation.

The second variant assumes that the Reference scenario is identical to No Climate Change (NoCC). This variant answers the question: "What does Fiji or the Solomon Islands have to spend on pre-emptive adaptation relative to a future in which there was no climate change?" The question is purely hypothetical but it underpins discussions under UNFCCC for monetary transfers to developing countries to cover some or all of the costs of adaptation to climate change.

Table A3.4: Costs of pre-emptive adaptation relative to baseline expenditures

(Average cost of pre-emptive adaptation for all infrastructure assets by country for 2011-50; with a 20 year planning horizon; in $ million per year at 2010 international prices with no discounting, over the range of the 19 different GCMs, with a RCP 45 scenario)

Country	Adaptation costs relative to Base scenario			Adaptation costs relative to NoCC scenario		
	Average over GCMs (in M $US)	Average as % of baseline	Median as % of baseline	Average over GCMs (in M $US)	Average as % of baseline	Median as % of baseline
Fiji	13.9	1.9%	1.5%	20.2	2.8%	2.0%
FSM	8.7	8.7%	7.0%	13.4	13.4%	10.1%
Kiribati	8.7	9.6%	8.9%	18.9	20.9%	20.6%
MHL	4.6	6.5%	7.1%	8.1	11.5%	11.3%
Palau	1.9	2.6%	1.2%	4.5	6.3%	3.5%
SLB	14.6	7.3%	6.9%	17.3	8.6%	7.8%
Tonga	3.2	4.5%	4.2%	8.4	11.7%	10.9%
Tuvalu	0.1	3.0%	3.0%	0.3	5.8%	5.5%
Vanuatu	2.1	2.1%	1.5%	7.0	3.9%	1.8%
Samoa	1.7	4.8%	4.3%	7.8	7.0%	5.5%

The average costs of pre-emptive adaptation over all climate scenarios relative to the Base and NoCC scenarios are shown in Table A3.4. These costs are calculated using a planning horizon of 20 years which may be regarded as a compromise between making no allowance for future climate change and incurring significant capital cost to protect against conditions 40 years into the future. By construction the costs of pre-emptive adaptation relative to the NoCC scenario are higher, in some countries 2-3 times higher, than the costs relative to the Base scenario. In many of the countries, a significant portion of the costs of adapting to climate change will be absorbed, almost automatically, into regular expenditures on investment and O&M following standard engineering practice.

The average cost of pre-emptive adaptation for all infrastructure types across all climate scenarios varies from 2% to 10% of baseline expenditures across the Pacific Island countries. Fiji and Vanuatu are at the low end with adaptation costs of about baseline expenditures versus more than 8% for FSM and Kiribati. Under the worst case scenario the costs of pre-emptive adaptation are 24% and 18% of baseline expenditures. Table A3.5 shows that roads account for more than 50% of the average costs of pre-emptive adaptation in all but two countries and exceed 90% of the average costs in Solomon Islands and Samoa. Urban infrastructure and housing are important contributors to the average cost of adaptation in the Marshall Island, Palau and Tuvalu. These are relatively small countries with limited road networks.

Table A3.5: Roads account for the largest share of the costs of pre-emptive adaptation

(% composition of the average cost of pre-emptive adaptation by country for 2011-50, compared with the Base scenario;20 year planning horizon; no discounting, average over 19 GCM, with RCP 45 scenarios)

Country	Power & phones	Water & sewers	Roads	Other transport	Health & schools	Urban	Housing
Fiji	2.9%	0.4%	81.9%	0.2%	0.9%	7.0%	6.8%
FSM	0.9%	0.1%	88.0%	0.1%	0.7%	1.7%	8.4%
Kiribati	0.3%	0.3%	79.0%	0.1%	2.1%	6.8%	11.2%
MHL	1.5%	0.4%	35.4%	0.2%	4.1%	21.1%	37.2%
Palau	2.1%	0.0%	48.1%	0.5%	2.1%	18.5%	28.0%

SLB	0.6%	0.4%	95.3%	0.1%	0.4%	1.2%	1.9%
Tonga	3.1%	0.9%	64.5%	0.3%	5.9%	6.2%	19.1%
Tuvalu	7.1%	0.0%	50.0%	0.0%	0.0%	21.4%	14.3%
Vanuatu	1.9%	0.5%	77.5%	0.5%	2.2%	4.9%	12.5%
Samoa	1.1%	0.2%	91.8%	0.2%	0.7%	1.3%	4.6%

Table A3.6 shows the time profile of the average costs of pre-emptive adaptation over all climate scenarios expressed as shares of baseline infrastructure expenditures by decade. The relative cost of adaptation tends to decrease time in most of the countries though the costs follow an inverted-U in Kiribati and the Marshall Islands. The declines in relative costs are more marked for Fiji, FSM, Palau, Tuvalu and Samoa.

Table A3.6: The time profile of pre-emptive adaptation costs varies greatly across countries

(Average of the over-cost of pre-emptive adaptation for all infrastructure assets by country for 2011-50; compared with the Base scenario, 20 year planning horizon; costs as % of baseline expenditures)

Country	2011-20	2021-30	2031-40	2041-50
Fiji	2.6%	2.1%	1.8%	1.4%
FSM	11.4%	9.6%	8.4%	6.6%
Kiribati	8.9%	10.1%	10.6%	8.8%
MHL	6.9%	7.5%	6.2%	5.8%
Palau	3.4%	3.2%	2.5%	1.8%
SLB	7.6%	7.3%	7.5%	6.9%
Tonga	5.8%	4.4%	4.1%	4.3%
Tuvalu	4.4%	3.6%	2.7%	1.8%
Vanuatu	2.6%	2.4%	2.1%	1.7%
Samoa	6.3%	5.2%	4.7%	3.8%

The average cost of pre-emptive adaptation increases as the length of the planning horizon is increased. This is not inevitable. Looking further ahead increases the capital cost of building infrastructure, but unless the planning horizon is equal to the expected life of infrastructure the higher initial cost may be offset by lower O&M costs in future. In practice, the difference between the average costs of pre-emptive adaptation using a planning horizon of 10 years and using one of 40 years varies from 4% for Tonga to 21% for Fiji and Palau. These calculations assume that the correct GHG emission scenario is known, so the choice of a planning horizon is more a matter of risk management than simple cost.

Pre-emptive adaptation costs vary greatly by sector. As shown in Table A3.7, the average cost of pre-emptive adaptation in Fiji ranges from 15% of baseline expenditures for roads to less than 1% for all other sectors. In three countries – FSM, Kiribati and Tuvalu – the average cost of adaptation for roads in more than 40% of baseline expenditures. The median shares across all 10 countries are less than 1% of baseline expenditures for power & phones, water & sewers, other transport and social infrastructure. The medians are between 1% and 2% for urban infrastructure and housing and over 30% for roads. For roads, the major elements in the cost of adaptation are (i) the cost of resurfacing paved roads and of using more expensive pavement binders to cope with higher pavement temperatures, and (ii) the additional cost of building and maintaining unpaved roads due to changes in the level and monthly pattern of precipitation. These costs will also affect other transport – railways, ports and airports - as well.

Table A3.7: Average costs of pre-emptive adaptation vary considerably by sector
(Average cost of pre-emptive adaptation by sector over all climate scenarios;
20 year planning horizon; % of baseline expenditures)

Country	Power & phones	Water & sewers	Roads	Other transport	Health & schools	Urban	Housing
Fiji	0.4%	0.1%	14.8%	0.3%	0.4%	0.6%	0.3%
FSM	0.9%	0.2%	40.1%	1.6%	1.0%	1.2%	1.5%
Kiribati	0.6%	0.6%	41.4%	1.7%	2.2%	2.8%	2.9%
MHL	1.4%	0.8%	29.9%	2.1%	4.1%	4.2%	5.7%
Palau	0.6%	0.0%	22.0%	2.6%	1.2%	1.4%	1.7%
SLB	0.8%	0.1%	34.3%	0.4%	0.5%	0.8%	0.4%
Tonga	0.9%	0.7%	32.6%	1.0%	2.5%	2.7%	1.8%
Tuvalu	0.9%	0.0%	43.8%	0.0%	0.0%	2.1%	1.7%
Vanuatu	0.5%	0.1%	15.1%	0.4%	0.5%	0.9%	0.5%
Samoa	0.6%	0.1%	22.5%	0.6%	0.4%	0.6%	0.5%

2.2 Choosing robust strategies for adaptation

We use the criteria of minimum maximum regret to select the most appropriate strategy in each sector and each country. We calculate the cost associated to every strategy, compared to the least-cost strategy, in each climate scenario. This is called the regret. We then calculate the maximum regret associated with each strategy across all scenarios, and select the strategy with the lowest maximum regret. For instance, investing in expensive pre-emptive adaptation and then seeing low climate change impacts might create a higher regret than observing and doing reactive adaptation even in high climate change impacts scenarios. If this is the case, the most appropriate strategy is to be reactive. Table A3.8 shows the results for each country and infrastructure in 2040, using a 5% discount rate for calculating adaptation costs and regrets.

Table A3.8 – Lowest regret adaptation strategies for the 2040s by country and by infrastructure (P=proactive, in green and R=reactive), and cost of the strategy in the worst case scenario as a % of baseline expenditures.

Note: a 5% discount rate was used to calculate the regrets

Country	Health & schools	Housing	Other transport	Power & telecoms	Roads	Urban	Water & sewers
FSM	P (1.0%)	P (3.0%)	P (3.0%)	R (0.6%)	R (20.0%)	R (3.0%)	P (0.3%)
Fiji	P (0.5%)	P (0.7%)	P (0.7%)	R (0.1%)	R (3.0%)	R (0.5%)	P (0.1%)
Kiribati	P (2.0%)	P (4.0%)	P (3.0%)	P (0.6%)	P (20.0%)	P (2.0%)	P (0.4%)
MHL	P (0.4%)	P (1.0%)	P (0.9%)	P (0.5%)	R (10.0%)	P (0.8%)	P (0.09%)
Palau	P (2.0%)	P (3.0%)	P (3.0%)	R (0.6%)	R (30.0%)	P (2.0%)	P (0.3%)
SLB	P (0.4%)	P (0.8%)	P (0.8%)	R (0.1%)	R (4.0%)	R (0.5%)	P (0.1%)
Samoa	P (0.1%)	P (0.2%)	P (0.5%)	R (0.2%)	R (4.0%)	P (0.2%)	P (0.03%)
Tonga	P (0.06%)	P (0.0%)	P (0.08%)	P (0.3%)	R (2.0%)	P (0.4%)	P (0.02%)
Tuvalu	P (0.8%)	P (2.0%)	P (1.0%)	R (0.5%)	R (20.0%)	P (0.8%)	P (0.2%)
Vanuatu	P (0.6%)	P (1.0%)	P (1.0%)	R (0.4%)	R (10.0%)	P (1.0%)	P (0.1%)

We find that pre-emptive adaptation is always the best strategy for health and schools infrastructure, housing, other transports and water and sewers. It is also the best strategy for urban in all countries but Fiji, FSM and SLB. However for power and telecoms and for roads, the best strategy is often being reactive to climate change. Indeed, the cost of reactive adaptation is sometimes very low in this analysis, even in the worst case scenarios. This low cost of reactive adaptation is due to the assumption that governments can react very quickly in case of disasters and repair damaged infrastructure within a few days. Under those optimistic assumptions on the resources available for interventions in case of disruption, reactive adaptation might make economic sense. However, if those conditions are not met the costs of reactive adaptation may be largely underestimated. For instance if a bridge collapses, the costs of reactive adaptation might increase very fast. And if there is uncertainty about the future availability of funds to react to disasters, it might be safer to commit to more resistant infrastructure today.

Note also that roads have a much higher adaptation cost than other infrastructure. This comes from two major assumptions: first, protecting against temperature extremes is very expensive if temperature does not increase as fast as it was planned for, so even though it makes economic sense to protect roads against future floods by increasing drainage systems for instance, it does not often make economic sense to protect pre-emptively against high temperatures. Second, same as for other infrastructure it is assumed that maintenance is frequent for roads and that interventions can be very fast to rehabilitate the roads after a disruption. If these assumptions do not hold, the cost of being reactive might increase exponentially if the roads remain unusable for more than a few days.

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Annex 4 – Improving the Resilience of Buildings to Tropical Cyclones

Damage to housing and public buildings is a large component of the total losses caused by tropical storms in the PICs. Damage to the housing stock has a direct impact on the well-being of the population, while public buildings are critical for maintaining public services and are widely used as temporary shelters during extreme weather events. The experience of cyclone damage over the last three decades shows that much of the existing stock of buildings has limited resistance to wind speeds, even associated with moderate 1 in 10 year or 1 in 20 year. Any increase in storm intensity due to climate change will substantially magnify damages.

This annex focuses on the options for reducing the damage to buildings caused by cyclone winds, both under current climate conditions and under future climate scenarios up to 2050. The effects of flooding and storm surges are discussed in Annexes 5 and 6. National level strategies to building resilience to tropical cyclone damages may involve some combination of retrofitting (upgrading) existing buildings to increase their wind resistance, and progressive replacement of the building stock using enhanced design standards that take account climate change conditions expected over the life of the building.

The distributions of extreme wind speeds

The PCRAFI study developed a probabilistic model to estimate tropical cyclone hazard for each of the PICs under historical climate conditions. For the purpose of this exercise, threshold values associated with the 50 to 250 year return period were used to calibrate a simplified extreme value distribution – the Gumbel distribution - of the maximum wind speed in each year for each country.[19] The PCRAFI model provides more detail on the geographical pattern of cyclone risks in each country but the limitations of data and resources mean that this study has focused on conditions typical of the main urban centres in each country.

There is no consensus on how the distribution of extreme wind speeds for a particular location or country will shift as a consequence of climate change (WMO 2007). Both Emanuel (2005) and Knutson et al. (2010) emphasize the link between sea surface temperatures and cyclone intensity, with higher ocean temperatures being associated with both higher sustained wind speeds and higher rainfall. Generally, changes in sea surface temperatures follow changes in average land temperatures but with a considerable lag. For this analysis, changes in average land temperatures are used as the basis for distributing changes in cyclone intensity up to 2050. The statement prepared by a WMO expert group (WMO, 2007) states that both theory and observation support a conclusion that the intensity of tropical cyclones will increase by 3–5 percent per 1°C rise in sea surface temperature. Emanuel (2005) uses a figure of 5 percent in considering changes in his power dissipation index for tropical cyclones.

[19] The Gumbel distribution is a probability distribution which is widely used to describe extreme weather and related events such as the maximum wind speed, river flow, flood level, etc in any year. It is a two parameter distribution with one parameter defining the mode of the distribution and the other defining the scale or variance of the distribution. It is convenient because the percentage points of the cumulative distribution – used for return periods – can be easily calculated once the parameters of the distribution have been estimated. The Appendix provides further details on the use of the Gumbel distribution.

The average of the RCP45 climate scenarios for 2050 suggests that the maximum monthly average of maximum daily temperatures will increase in a range from 1.2°C for Tonga to 1.4°C for Kiribati.[20] To set a low estimate of the increase in the distribution of cyclone wind speed these estimates are combined with an assumption that cyclone intensity will increase by 3 percent per 1°C rise in sea surface temperature (the bottom end of the IWTC range).[21] A high estimate was obtained by combining the RCP85 climate scenarios with the assumption that cyclone intensity will increase by 5 percent per 1°C rise in sea surface temperature (the top end of the IWTC range). Table A4.1 summarises the increases in cyclone intensity for each country that have been used to examine the benefits of upgrading buildings to provide greater resilience against damage caused by cyclones.

Table A4.1 – Assumed increases in cyclone intensity up to 2050 by country

	Increase in maximum monthly average of daily maximum temperatures (°C)		Wind speed with mean return period of 100 years (mph sustained over 1 min)		
Countries	**RCP45**	**RCP85**	**NoCC**	**2050 Low**	**2050 High**
Fiji	1.26	1.57	106	110	114
FSM	1.33	1.68	94	97	102
Marshall Islands	1.33	1.70	79	82	86
Tonga	1.20	1.53	93	96	100
Vanuatu	1.27	1.59	111	115	119
Samoa	1.22	1.56	105	109	113

Building damage due to cyclone winds

Damage functions that estimate average damage caused by cyclone winds have been prepared by civil engineers. Damage is expressed as a percentage of the replacement cost of the structure related to the peak sustained wind speed of the cyclone. The amount of damage depends upon features of building design, materials and construction methods, and cover the following building types: (a) timber single storey, (b) timber multi-storey, (c) traditional, (d) open-walled (pole) structures, (e) masonry, (f) reinforced concrete, (g) steel, and (h) steel + concrete. For each building type, damage curves have been compiled for unimproved buildings reflecting current design and construction practices and for buildings that have been improved using lower cost measure that are easily implemented (light retrofit). Damage curves have also been prepared for a subset of building types – timber single storey, timber multi-storey, and masonry - after the implementation of more expensive and intrusive improvements (heavy retrofit). These building types are the most common in the region but it has been assumed that heavy retrofitting would be restricted to public buildings.

[20] Monthly averages for the daily maximum temperature have been used because they provide an upper limit on sea surface temperatures that are consistent with a seasonal equilibrium between land temperatures and sea surface temperatures in ocean areas close to land which will determine the intensity of cyclones as they make landfall.

[21] The analysis applies the assumed increase in the cyclone wind intensity to both the mode and scale parameters of the Gumbel distribution. This means that the mode of the distribution shifts upwards while the variance of distribution increases.

Figure A4-1 – Damage curves for timber buildings exposed to cyclone winds

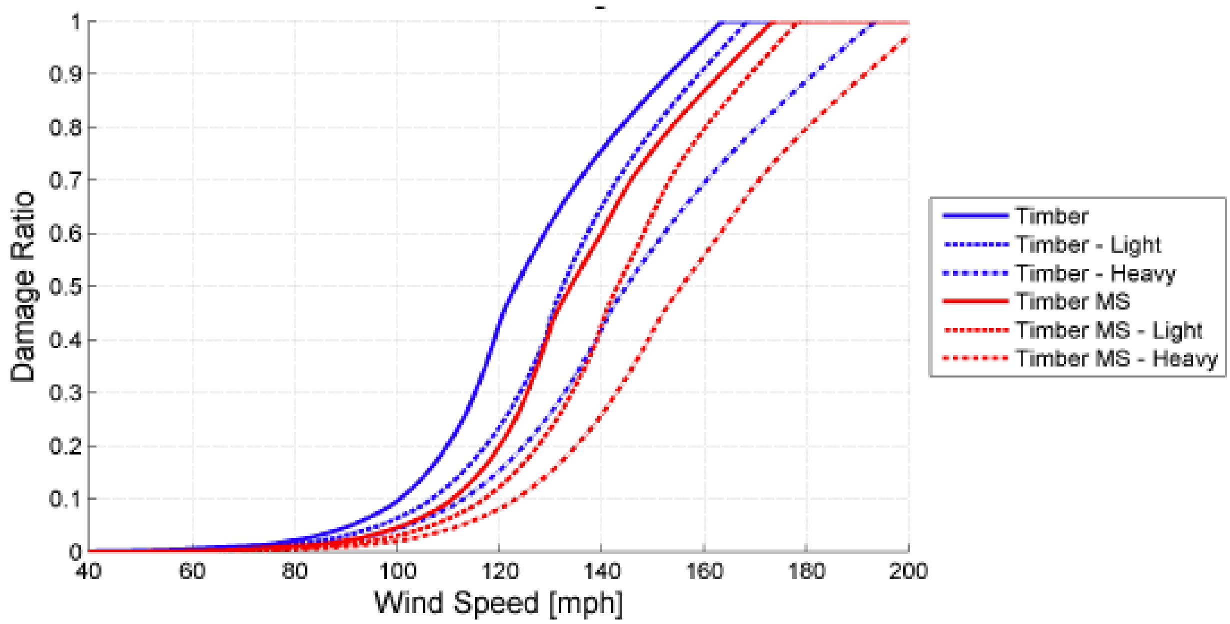

Figure A4-1 illustrates the damage curves for single and multi-storey timber buildings. The damage is approximately 5 percent of replacement value for a sustained wind speed of 88 mph rising to 10 percent at 100 mph, 30 percent at 115 mph, and complete loss at 162 mph. With a light retrofit those thresholds are increased to 94 mph, 106 mph, 123 mph and 168 mph respectively. While the increases in the thresholds may seem small, the probabilities of sustained peak wind speeds above 100 mph are very low. So retrofitting may have a significant impact on the average level of cyclone losses over a period of years.

The damage curves are interpolated from point estimates at 5, 10, 20, … mph and used as the functions D(S) in the calculation over the full distribution of cyclone wind speeds. The PCRAFI country inventories of buildings and average replacement values were used to compile an asset database covering six countries.

Table A4.2 provides estimates of the expected annual losses due to cyclone winds for the current stock of buildings, summing by main building type over both residential and public buildings. The expected losses under historical climate conditions (NoCC) are particularly large for Fiji – over $5,8760 per building averaged over all buildings or $7,350 per building for timber buildings. At the other end of the scale, the expected losses for FSM and the Marshall Islands are about one-fifth of those for Fiji at $1,000-1,100 per building averaged over all buildings

Table A4.2 – Estimates of expected cyclone losses for current building stock

Country	Building category	Number of buildings	Expected values of losses ($ million per year)			Loss per building	% increase relative to NoCC scenario	
			NoCC	2050 Low	2050 High	$ NoCC	2050 Low	2050 High
FJI	Timber	87,839	64.59	81.97	103.48	7,354	27%	60%
	Masonry	67,634	35.97	51.51	73.35	5,318	43%	104%
	Trad/Open	20,883	4.37	5.62	7.19	2,093	29%	65%
	Other	3,984	0.81	1.15	1.62	2,037	42%	99%
	Total	180,340	105.74	140.25	185.64	5,863	33%	76%
FSM	Timber	13,078	1.75	2.15	2.66	1,335	23%	52%
	Masonry	13,003	1.11	1.43	1.84	857	28%	65%
	Trad/Open	2,890	0.13	0.16	0.20	463	23%	51%
	Other	187	0.01	0.01	0.01	474	29%	66%
	Total	29,158	3.00	3.75	4.72	1,030	25%	57%
Marshall Islands	Timber	5,111	0.48	0.60	0.76	940	25%	59%
	Masonry	4,298	0.31	0.41	0.55	729	31%	74%
	Trad/Open	1,281	0.01	0.02	0.02	94	27%	62%
	Other	1,325	0.03	0.04	0.05	235	31%	73%
	Total	12,015	0.84	1.07	1.38	697	28%	65%
Tonga	Timber	18,160	3.53	4.47	5.74	1,945	27%	62%
	Masonry	9,972	0.90	1.22	1.66	907	35%	84%
	Trad/Open	2,343	0.06	0.08	0.10	253	28%	66%
	Other	1,275	0.10	0.13	0.17	746	33%	79%
	Total	31,750	4.59	5.89	7.67	1,446	28%	67%
Vanuatu	Timber	20,252	8.01	10.12	12.81	3,958	26%	60%
	Masonry	26,328	5.94	8.24	11.47	2,257	39%	93%
	Trad/Open	37,667	4.62	5.85	7.44	1,225	27%	61%
	Other	2,474	0.22	0.30	0.41	888	37%	87%
	Total	86,721	18.79	24.51	32.14	2,167	30%	71%
Samoa	Timber	14,004	3.25	4.03	5.03	2,319	24%	55%
	Masonry	8,283	1.63	2.12	2.79	1,964	30%	71%
	Trad/Open	20,110	1.49	1.87	2.39	739	26%	61%
	Other	1,283	0.11	0.14	0.18	856	29%	68%
	Total	43,680	6.47	8.16	10.39	1,481	26%	61%

The table also shows the increases in expected losses under the Low and High scenarios for 2050, holding the number and composition of buildings constant. The increases are 26-33 percent for the country totals in the 2050 Low scenario and 57-76 percent for the country totals in the 2050 High scenario. Fiji and Vanuatu, which have high current losses due to cyclone winds, are worst affected by climate change with an increases of 76 percent and 71 percent under the 2050 High scenario. Measures to increase the resilience of buildings to cyclone winds are most likely to pay off in these countries. Among the different building materials, it is masonry buildings which are likely to experience the largest increases in expected cyclone losses.

Retrofitting existing buildings

The costs of retrofitting were calculated using the PCRAFI inventory of buildings for each country combined with estimates of costs for the light and heavy retrofitting measures. These preliminary estimates were based on reconstruction and repair costs from the recent cyclones in Tonga and Vanuatu, which were used to estimate unit costs for anchoring and bracing walls, nailing or strapping roof elements, strengthening roof ties, installing shutters for windows and other openings, and similar measures.

As a preliminary filter, the undiscounted sums of the reduction in annual losses were calculated in order to identify the combinations of country and building type for which the benefits of light retrofitting are less than the costs incurred under the most favourable assumptions of no discounting and the 2050 High climate scenario. These are:

Micronesia – all buildings

Marshall Islands – all buildings

These countries were excluded from further analysis. For the remaining four countries, the benefits of the reduction in cyclone damage due to the retrofitting measures were calculated for each building type as the present value of the reduction in the expected annual losses over a period of 30 years using discount rates from 2 to 5 percent. The benefit-cost ratio is the present value of discounted benefits divided by the initial cost of retrofitting.

There are no combinations in which the additional benefits of heavy retrofitting (relative to light retrofitting) under the most favourable assumptions exceed the additional costs incurred.

Table A4.3 shows the ratios of the present values of benefits and costs for public and residential buildings in the cases for which light retrofitting might be economically justified using these discount rates.[22] Combinations for which the benefit-cost ratio is at least 1 are shaded. What stands out is that light retrofits for public buildings constructed from timber or traditional materials in Fiji, Vanuatu and Samoa are economically justified for a range of assumptions and discount rates. In addition, it would be worth undertaking light retrofits for public buildings constructed of masonry for both climate change scenarios at the low discount rate in Fiji and Vanuatu.

The benefits of retrofitting housing built with traditional materials or open pole structures would exceed the costs in Fiji and Vanuatu, except for the combination of the NoCC scenario and the higher discount rate. Otherwise, even for the countries that are most at risk of severe cyclone damage – Fiji, Vanuatu and Samoa – retrofitting timber houses is rarely justified, even for a low discount rate, if the cost of a light retrofit exceeds 5% of replacement value.

[22] The calculation of the benefits of retrofitting requires some specific assumptions when taking account of the impact of climate change. For this analysis we consider a program to upgrade buildings that have an expected life of at least 30 years in 2020. The benefits of retrofitting increase steadily from the NoCC value in 2020 to the 2050 Low/High value in 2050.

Table A4.3 – Ratios of benefits to costs for light retrofitting by country

Country	Material	Benefit-cost ratios @ 2% discount rate			Benefit-cost ratios @ 5% discount rate		
		NoCC	2050 Low	2050 High	NoCC	2050 Low	2050 High
A. Public buildings							
Fiji	Timber	2.39	2.72	3.11	1.64	1.83	2.04
	Masonry	1.17	1.40	1.69	0.80	0.93	1.09
	Trad/Open	5.41	6.31	7.43	3.71	4.22	4.83
	Other	0.49	0.60	0.77	0.33	0.40	0.49
Tonga	Timber	0.76	0.86	0.98	0.52	0.58	0.64
	Masonry	0.37	0.42	0.50	0.25	0.28	0.33
	Trad/Open	1.10	1.25	1.46	0.75	0.84	0.95
	Other	0.09	0.10	0.12	0.06	0.07	0.08
Vanuatu	Timber	1.57	1.77	2.02	1.08	1.19	1.33
	Masonry	0.89	1.04	1.24	0.61	0.70	0.81
Samoa	Timber	1.75	1.94	2.17	1.20	1.31	1.44
	Masonry	0.50	0.57	0.65	0.35	0.38	0.43
	Trad/Open	1.48	1.64	1.83	1.02	1.11	1.21
	Other	0.09	0.10	0.12	0.06	0.07	0.08
B. Residential buildings							
Fiji	Timber	0.71	0.81	0.92	0.49	0.54	0.61
	Masonry	0.63	0.75	0.91	0.43	0.50	0.59
	Trad/Open	3.66	4.16	4.76	2.51	2.79	3.12
	Other	0.11	0.13	0.16	0.07	0.09	0.10
Tonga	Timber	0.18	0.20	0.23	0.12	0.14	0.15
	Masonry	0.09	0.10	0.12	0.06	0.07	0.08
	Trad/Open	0.33	0.37	0.42	0.23	0.25	0.28
	Other	0.04	0.05	0.06	0.03	0.03	0.04
Vanuatu	Timber	0.84	0.95	1.08	0.58	0.64	0.71
	Masonry	0.27	0.31	0.37	0.18	0.21	0.24
	Trad/Open	1.38	1.55	1.76	0.94	1.04	1.16
	Other	0.06	0.08	0.09	0.04	0.05	0.06
Samoa	Timber	0.94	1.04	1.16	0.64	0.70	0.77
	Masonry	0.25	0.29	0.33	0.17	0.19	0.21
	Trad/Open	0.51	0.57	0.64	0.35	0.38	0.42
	Other	0.06	0.07	0.08	0.04	0.05	0.05

The results highlight the need for a selective approach in identifying opportunities to retrofit existing buildings to provide greater resilience to cyclone winds. A case study of schools in Lima, Peru (see Box A4.1) illustrates that focusing on the most vulnerable 35 percent of schools leads to a 75 percent reduction in risk. In particular:

- Retrofitting is more cost-effective in countries which face higher cyclone risks - notably Fiji, Vanuatu and Samoa. The case for retrofitting in Fiji has been reinforced by the damage caused by Cyclone Winston in February 2016.
- The analysis has focused on the costs of repairing building in the event of cyclone damage. Including other losses such as potential loss of life or injuries and the loss of the services provided by buildings in the analysis would strengthen the case for retrofitting public buildings. These tend to have higher occupancy so that the wider impacts of cyclone damage may justify expenditures on light retrofitting that might not be justified on a narrow benefit-cost assessment. This is particularly likely to be the case for timber public buildings whose benefit-cost ratios tend to be significantly higher than those for masonry and concrete buildings.
- The benefit-cost ratios for public buildings constructed of traditional materials or with open wall structures are high or very high because such buildings are extremely vulnerable to damage. However, since the number of buildings involved is relatively small, a better long run strategy might be to replace them with more resilient structures built with materials and design standards that will resist much higher sustained wind speeds.
- The costs of heavy retrofitting are high and the benefits in terms of loss reduction are modest. If large expenditures are required to bring buildings up to modern design specifications for wind resistance, early replacement may be a better strategy than retrofitting.

Developing lower cost options for retrofitting, especially for housing, is critical. The low ratios of benefits to costs reflect the relatively high costs of upgrading housing. In Vanuatu, the average retrofit costs for residential buildings are often twice the average retrofit costs for public buildings when expressed as a proportion of average replacement values.

These results provide a rough guide to assess the relative desirability of various retrofitting strategies. The limitations of the data and modelling mean that the margins of error in the estimates give rise to significant confidence bands around the ratios of benefits to costs. For any detailed analysis of retrofitting options, local circumstance including the specific costs of retrofitting, the age profile of the asset stock and the pattern of building usage must all be taken into account.

Changes in design standards for new buildings

Changes in the weather stresses on buildings due to climate change will require modifications to the design standards which are incorporated in building codes that apply to new buildings. There are two forms of adaptation that have been examined in this study. The first covers the progressive adjustment in design standards required to take account of changes in temperatures, precipitation and humidity which affect the life and habitability of buildings. These changes affect the specification of heating, ventilation and air-conditioning (HVAC) systems, which must be upgraded to cope with more moisture. In addition, higher precipitation puts more stress on the exterior cladding, roofs and windows of timber structures, especially if they will require more maintenance or more frequent replacement in future. The costs of this type of progressive adaptation are included in the analysis detailed in Annex 3 which covers both housing and public buildings used for the provision of infrastructure services, health and education, and urban services. The distinction between public and commercial buildings is rarely sharp and varies across countries. Hence, the costs associated with the adaptation of public buildings are not reported separately but are included in the costs for each type of infrastructure. The costs of progressive adaptation for housing are reported separately in Annex 3.

The second type of adaptation for new buildings covers the costs of implementing more stringent building codes designed to reduce the damage caused by the peak sustained wind speeds that occur during cyclones. The question is: what will it cost to increase design standards in order to achieve a standard threshold of resilience to cyclone winds for (a) the historical climate, and (b) the projected climate for 2050? The answer to part (a) of the question gives a measure of the adaptation deficit – i.e. the cost of achieving a desired level of security under current conditions – while the difference between (b) and (a) tells us about the extra cost of adapting to climate change up to 2050.

The calculations are illustrated in Table A4.4. The starting point is a wind speed threshold for each type of building representing the maximum wind speed at which the expected damage may be regarded as minimal. In this case the thresholds, shown in the first row, are the wind speeds for which expected damage is less than 1 percent of replacement value, based on the PCRAFI damage functions. These range from 65 mph for traditional buildings to 85 mph for masonry buildings and 105 mph for steel buildings. The next block shows the mean return periods (in years) for these minimum damage thresholds in each country. In Fiji this varies from 2 years for timber and traditional buildings to 90 years for steel buildings. The third block shows how much the wind resistance of each building type would have to be increased to incur minimum damage under a cyclone with a mean return period of 50 years under current climate conditions. For Fiji the required increase in wind resistance is 32-35 mph for timber and traditional buildings but nil for steel buildings. Finally, the fourth block shows an equivalent increase calculated using the projected distribution of cyclone intensities under the 2050 High scenario. In this case the required increase in wind resistance is 39-42 mph for timber and traditional buildings in Fiji and 2 mph for steel buildings.

Table A4.4 – Determinants of adaptation costs for new buildings

	Timber 1S	Timber MS	Traditional	Open structure	Masonry	Concrete	Concrete/Steel	Steel
Maximum wind speed for "minimum damage"								
	66	68	65	76	85	89	85	105
Existing MRPs (years)								
Fiji	2	2	2	4	11	16	11	90
FSM	21	23	20	36	61	76	61	100
Marshall Islands	43	49	40	81	100	100	100	100
Tonga	10	12	9	23	50	70	50	100
Vanuatu	2	2	2	4	9	13	9	59
Samoa	7	8	7	13	25	33	25	100
Increase in wind resistance for MRP=50 years for NoCC (mph)								
Fiji	34	32	35	24	15	11	15	0
FSM	16	14	17	6	0	0	0	0
Marshall Islands	2	0	3	0	0	0	0	0
Tonga	19	17	20	9	0	0	0	0
Vanuatu	37	35	38	27	18	14	18	0
Samoa	29	27	30	19	10	6	10	0
Increase in wind resistance for MRP=50 years for 2050 High (mph)								
Fiji	41	39	42	31	22	18	22	2
FSM	22	20	23	12	3	0	3	0
Marshall Islands	8	6	9	0	0	0	0	0
Tonga	26	24	27	16	7	3	7	0
Vanuatu	45	43	46	35	26	22	26	6
Samoa	36	34	37	26	17	13	17	0

Estimates of the cost of implementing more stringent building codes designed to ensure that buildings can withstand higher wind speeds have been derived from the experience of changes to building codes in South Florida that were implemented in 1994, 2002 and 2007. These step changes adjusted the hurricane damage threshold from Category 1 before 1994 to Category 4 after 2007.[23] The increase in design wind speeds occurred in step of 10-12 mph and the 2007 code update was intended to enable buildings to withstand 1-min sustained wind speeds up to 140 mph.

Using the methodology described in Appendix to the World Bank's paper on adaptation for climate change for infrastructure, each code update costs an average of 0.8 percent of base capital costs and it is assumed that each update increases building resilience by 10 mph. Thus, moving to a 50 year mean return period (100 mph) in Fiji under the historical climate involves the equivalent of 4 code updates (3.2 percent) for timber buildings and 2 code updates (1.6 percent) for masonry, concrete and

[23] Note that the thresholds apply to wind speed when the storm makes landfall. This is usually significantly lower than the peak wind speed over the ocean. As an example, Hurricane Katrina was a Category 5 hurricane in its most intense phase over the Gulf of Mexico but it had subsided to a Category 3 hurricane by the time it made landfall and struck New Orleans.

concrete/steel buildings. Taking account of climate change up to 2050 using the 2050 High scenario would add the equivalent of 1 code update (0.8 percent) for all of the building types.

The percentage costs of adapting to any climate scenario must be applied to a baseline level of investment in new buildings. The principal determinants of the baseline investment are:

- Replacement of existing buildings at the end of their life.
- Meeting increased demand for space due to population and economic growth.
- Upgrading the resilience of the asset stock by replacing vulnerable building types with less vulnerable structures.

In the case of public buildings the baseline level of investment has been estimated on the assumptions that (i) buildings are replaced after 50 years; (ii) growth in demand for space is equal to growth in population plus growth income per head based on the socio-economic projections which are used for the analysis of infrastructure in Annex 3 and (iii) all public buildings are constructed of masonry or concrete or concrete & steel by 2050. In the case of residential buildings, the first two assumptions are the same while the third is that the total number of timber single and multi-storey buildings remains the same while all traditional and open structure buildings are replaced by masonry or concrete buildings.[24]

The results of the analysis are summarised in Table A4.5 which shows the baseline levels of investment in new public and residential buildings by country and the associated costs of adapting to the 2050 High cyclone scenario.[25] The equivalent estimates for the 2050 Low scenario are either zero or very small. For new buildings overall, the cost of adaptation even in the 2050 High scenario is significantly less than 1% of the baseline investment.

[24] This does not imply direct replacement of traditional houses by masonry houses but a shift in the overall composition of the housing stock that gradually reduces the number of traditional houses to nearly zero. Since the average costs of masonry and concrete houses are 2 to 5 times those of tradition and open structure houses, the change in the composition of the housing stock accounts for a large share of the baseline investment in Vanuatu and Samoa where traditional and open structure buildings account for about 45 percent of the total housing stock.

[25] The total capital cost in the table refers to the annual cost of constructing new and replacement buildings to which the more stringent design standards would be applied averaged over the period 2015-35.

Table 4A.5 – Cost of adaptation to higher cyclone winds for new buildings by country
(million $ per year, 2015-50)

	Total capital cost		Adaptation to 2050 High	
	Public	Residential	Public	Residential
Fiji	129.1	889.5	1.0	6.8
Micronesia	11.6	51.2	0.1	0.4
Marshall Islands	13.4	55.5	0.0	0.0
Tonga	20.5	75.7	0.2	0.6
Vanuatu	22.5	176.7	0.2	1.4
Samoa	17.7	84.9	0.0	0.1

Source: World Bank estimates

Conclusion

The primary conclusion from the study is that the additional cost of implementing changes in design standards for new buildings that would ensure greater resilience to cyclone winds is very small in relation to the total cost of construction. The changes required to ensure that structures are more robust to cyclones will usually involve modest adjustments to designs when the buildings are constructed. In New Zealand, for example, increasing the resilience of buildings to 100% of the new building code (from a previous 33% found in the older code) was expected to add about 5 percent to the cost of construction. On the other hand, it is often relatively expensive to retrofit existing buildings to meet higher design standards. Moving ahead rapidly with the adoption and implementation of building codes to ensure that new buildings can withstand 1 in 50 or even 1 in 100 year cyclone wind speeds should be a high priority for policymakers.

A policy of gradual replacement of buildings is feasible with a more strict building code and efficient enforcement of this code. One relatively easy way to achieve better compliance is to hold builders liable to damages should a hazard materialize within a pre-specified limited period of time, if the construction was found to be non-compliant. This, of course, will not be sufficient without other consenting and enforcement mechanisms, and functioning legal processes.

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Box A4.1- Storm return periods and economic damages

This box focuses on the impact of and adaptation to changes in the distribution of tropical storms that strike the country as a consequence of climate change. Since the modelling relies upon concepts such as the "return period" of storms with different impacts, this appendix is intended as a very brief introduction to the basic analysis of extreme events. It focuses on the probability distribution for cyclones characterized by their peak wind speeds sustained over land for a period of either 1 minute or 10 minutes.[26] Peak wind speeds are closely correlated with structural and economic damage caused by high winds, storm surges, intense rainfall, and flooding.

In any year (t), a country – for example, Samoa - is struck by a series of more or less severe storms (n=1, … N_t) with peak wind speed for each storm denoted by S_{tn}. The maximum peak wind speed in year t is S_t^* = max (S_{tn}) for given t. The analysis focuses on the characteristics of the distribution of S_t^* over many years. It is standard to use some variant of the generalized extreme value (GEV) distribution to describe the distribution of extreme values of natural events such as floods, storm surges, wind speeds, earthquakes, etc. (Evans, Hastings, and Peacock 2000). In this case, the two parameter version of the GEV distribution, also known as the Gumbel distribution, will be used because of the limited data that is available. The two parameters are location α (the mode of the distribution) and scale β > 0.[27] The probability of a storm with a peak wind speed of S* ≥ S is:

$$prob(S^* \geq S) = 1 - \exp\left\{ -\exp(\frac{-(S-\alpha)}{\beta}) \right\}. \quad (0.3)$$

The return period of a storm with peak wind speed of S is the reciprocal of prob (S* ≥ S). Thus, the peak wind speed for a storm with a return period of N years is:

$$S(N) = \alpha - \beta \ln[\ln(N) - \ln(N-1)] \quad (0.4)$$

The expected value of the economic damage caused by storms in any year is

$$E(D) = \int_{S_D}^{S_M} p(S) D(S) dS \quad (0.5)$$

where p(S) is the probability density function for peak wind speed S, D(S) is the damage function for wind speed S, S_D is the minimum wind speed for which significant damage is observed, and S_M is the maximum wind speed used for the calculation. A discrete approximation is used in place of the continuous integral with steps of 0.1 mph. The value of S_M corresponds to the peak wind speed with a return period of 250 years since there is insufficient data to calibrate either the probability distribution or the damage function beyond this level.

The impact of a shift in the probability distribution of storms on the expected value of storm damage can be largely offset by changing the design standards that are applied when building new assets

Three points should be noted:

[26] In the USA, it is standard practice to report peak wind speed measured sustained over a period of 1 minute, whereas most other meteorological agencies follow the international standard of reporting peak wind speeds sustained over a period of 10 minutes. A widely-used rule of thumb is that 10 minute sustained peak wind speeds are 14% lower than 1 minute sustained peak wind speeds. The AIR Worldwide report for PCRAFI followed US practice in estimating the return periods for peak cyclone wind speeds. Media reports of cyclones tend to focus on gust wind speeds that are not sustained over any defined period, but there is no standard way of measuring and/or reporting gusts so that such reports cannot be used to calibrate a distribution of extreme wind speeds.

[27] In the three-parameter variant of the GEV distribution, the inner exponential is replaced by a power function using a shape parameter γ. The two-parameter variant is a special case of the three-parameter specification with γ=0.

- These calculations only apply to damage that can be prevented by implementation of appropriate design standards. The potential damage to agricultural assets such as coconut plantations will increase if peak wind speeds with a 10- or 50-year return period increase

- Existing assets have been built to older design standards and will suffer more damage than new assets. In some cases their remaining economic life may be relatively short, so that the increased risk of storm damage may be relatively small. A trade-off has to be made between the options of accelerated depreciation (early replacement) of long-lived assets that do not meet the new design standards and incurring higher costs of maintenance and repairs as a consequence of more serious storm damage

- In some cases, the best strategy is to ensure that buildings and infrastructure assets are located out of harm's way. This is particularly true for vulnerability to storm surges and flooding caused by intense rainfall. Thus, when thinking about design standards it is important not just to focus on resistance to wind damage but also to ensure that planning and development policies take proper account of the impact of changes in the severity and frequency of storms in future.

Annex 5 - Sea Level Rise and Coastal Protection

Analysis using the DIVA model

This study draws upon the results of an analysis of the costs of coastal protection that was undertaken as part of the World Bank's Economics of Adaptation to Climate Change (EACC) (World Bank, 2010) study with some adjustments to reflect the particular circumstances of the Pacific Island Countries (PICs). The main features of the analysis are as follows: (a) average costs per year are reported for 3 decades (2020-29, 2930-39 & 2040-49); (b) the costs of protection against more intense storm surges are included in the analysis; (c) the estimates cover both capital and maintenance costs; and (d) the model incorporates a simple cost-benefit test so that investment in coastal protection only occurs when either the density of population or the level of economic activity protected is high enough to justify the costs incurred.

The EACC analysis applied country-wide population densities for many of the coastal segments in the PICs. The consequence was that the cost-benefit test applied a uniform level of protection to most segments in each country, even though this might involve very high costs per person for small islands. For this study it has been assumed that the principal population centres will be protected but not outlying islands and thinly populated coastal segments. For example, for Kiribati Tarawa, Marakei and Kiritimati are protected but not the other atolls. In Vanuatu protection is concentrated on the islands of Espiritu Santo, Efate, Malakula and Tanna. Following a selective strategy reduces the costs of adaptation by 45-50% for Kiribati and Vanuatu and by 25-35% for Fiji, FSM, the Marshall Islands and the Solomon Islands. There is limited scope for reducing costs in Palau and Samoa in this way. However, reducing the level of protection will increase the extent of residual damage caused by sea level rise – inundation of land, forced migration of people and economic activity, temporary flooding. The costs of these residual impacts are estimated and reported along with the costs of protection.

The analysis considers two main impact types---(1) coastal erosion; and (2) sea and river flooding, and submergence ---and three main adaptation approaches--- (1) beach nourishment (particularly in areas with high tourism revenue); (2) sea and river[28] dike construction; and (3) port upgrades due to climate change--are considered (see Box 5.1 for more details). It should be noted that impacts due to salinization of fresh water and land, as well as wetland loss are not considered.

[28] This concerns the incremental costs of upgrading river dikes in coastal lowlands where sea-level rise will raise extreme water levels. Additional upgrade may be required if extreme river flows are increased, but this is not investigated here.

Box 5.1 – Estimating the costs of coastal protection, the DIVA model

The costs are mainly derived from the DIVA model which conducts global assessments based on 12,148 coastal segments that collectively make up the world's coast, except for Antarctica, and a linked database and set of interacting algorithms (McFadden et al., 2007; Vafeidis et al., 2008). The sea-level rise scenarios due to global warming are downscaled with an estimate of the vertical land movement in each segment. The coastal erosion analysis only considers sandy coasts and takes account of the direct 'Bruun' effect and indirect effects of sea-level rise, and beach nourishment where this occurs. The indirect effect occurs at major estuaries and lagoons which are identified in the DIVA global database The flooding analysis determines the flood areas for different return periods and extreme water levels, including the effects of dikes.

Since there is no empirical data on actual dike heights available at a global level, "optimum" dikes heights were estimated for the base year of 1995 using a demand for safety function[29]. Dike heights are then upgraded with sea-level rise to 2050, if appropriate, including anticipating changes up to 50 years into the future. Increased flooding due to sea-level rise along the coastal-influenced reaches of major global rivers (which are identified in the DIVA global database) is also considered. Damages are evaluated in terms of physical, social and economic indicators such as: (1) 'land loss' – the land lost due to erosion or submergence; (2) 'people actually flooded' -- the expected number of people subject to annual flooding; (3) 'forced migration' -- the number of people that have to migrate due to land loss (due to erosion and submergence); and (4) 'forced migration costs' – the costs of this migration.

DIVA implements the different adaptation options according to various complementary adaptation strategies. For beach nourishment, a cost-benefit adaptation (CBA) strategy is implemented that balances costs and benefits (in terms of avoided damages) of adaptation, including the tourist value of beaches. For dike building, the demand function for safety is applied through time, subject to population density: no dikes are built at low population densities (<1 person/sq. km.), while 98% of the dike height is built for a population of 1,000 persons/ sq. km. The unit cost of dikes, beach nourishment and port upgrade were derived from the global experience of Delft Hydraulics (now Deltares). Note that in this analysis, DIVA has been extended to include a sensitivity analysis of more intense tropical storms. In terms of adaptation costs, this only influences dike costs. The maintenance costs of the sea and river dikes and the upgrade of existing port areas globally are also computed outside DIVA. Port costs are based on a strategy of continuously raising the existing port areas[30] as sea levels increase. Throughout the analysis, only the incremental costs of climate change are considered, assuming the current situation being optimal, and therefore the costs

Four different scenarios of global sea-level rise (SLR) were examined: (a) no SLR – the reference case to establish the baseline costs of coastal protection without climate change, (b) low SLR – a rise in average sea level of 40 cm above 1990 by 2100, (c) medium SLR – a rise of 87 cm, and (d) high SLR – a rise of 126 cm. These scenarios were selected to represent a range of interesting, useful, and plausible scenarios to reflect the uncertainty in climate projections. They are, however, not specifically linked

[29] This demand for safety function increases with per capita income and population density and decreases with the costs of dike building -- this is posited as the solution to a cost-benefit analysis (Tol et al., 2006).

[30] It is assumed that all new port areas will include sea-level rise to 2050 in their design, so upgrade costs will be effectively zero.

to temperature rise (due to uncertainties in the timing of deglaciation) and the rise of sea-level is assumed linear between 1990 and 2100. Intensification of storms in areas currently subject to such storms is also considered by assuming an arbitrary 10% increase in flood heights with the high sea-level rise scenario in these areas by 2100, but with assumptions of no change in their frequencies. The adaptation costs for the low, medium and high SLR scenarios are calculated as the difference between the estimated total costs for the scenario minus the cost under the no SLR scenario.

Uniform population growth, so that coastal populations do not grow relative to other areas, is imposed on the projections of population and GDP growth. However, a scenario of no population growth is also considered such that all future growth happens in areas that will not be affected by sea-level rise. Following best engineering practice, for sea and river dikes sea-level rise is anticipated in terms of additional height for 50 years into the future (i.e., expected extreme sea levels in 2100 determine the dyke heights in 2050). For other adaptation measures, there is no anticipation of future conditions, again reflecting best engineering practice[31]. Adaptation methods are applied in a standard way around all coasts using criteria that select optimum or quasi-optimum adaptation strategies.

Results

The DIVA analysis covered 9 out the 10 Pacific Island members of the World Bank Group. The country excluded was Tuvalu for which it was not possible to make reasonable estimates of the costs of coastal protection. The costs of protecting the 9 atoll and reef islands that comprise Tuvalu would be very high relative to the country's GDP, even in the low SLR scenario, and there is no consensus on how to respond to the potential impact of sea level rise. It may be necessary to consider relocation of populations from some of the islands.

Table A5-1 shows the adaptation costs over time by country and SLR scenario. The medium scenario for each country is highlighted as a central estimate. The costs under the worst scenario – high SLR with worse cyclones – are 50-75% higher than the medium SLR scenario. This means that there is a large degree of initial uncertainty about the magnitude of the adaptation costs that will be incurred up to 2050. Since sea level rise is a gradual process this uncertainty should be reduced over time as it becomes clearer how sea level is responding to climate change.

Averaged over time and normalized by population in 2012 the coastal protection costs range from about $50 per person per year for Samoa in the Medium SLR scenario to about $360 for the Solomon Islands and Vanuatu and $620 for the Marshall Islands. Over 30 years the total cost of adaptation would be $1,500 per person for Samoa but $11,000 for the Solomon Islands and $18,500 for the Marshall Islands. For Kiribati, the Marshall Islands, and Vanuatu the cumulative cost of adaptation per person would exceed 5 times GDP per person at PPP (Purchasing Power Parity).

[31] Beach nourishment being a regular process (every 2-5 years), the design of the beach profile will therefore continuously be adapted to the current situation.

Table A5-1 – Adaptation costs for coastal protection by country, decade and SLR scenario

(million USD per year at 2012 international prices)

Country	Code	Scenario	Adjusted adaptation costs		
			2020s	2030s	2040s
Fiji	FJI	Low	71	78	86
		Medium	156	174	193
		High	230	257	290
		High cyclones	261	293	329
Micronesia, Fed. Sts.	FSM	Low	6	7	8
		Medium	13	15	16
		High	19	22	26
		High cyclones	20	23	28
Kiribati	KIR	Low	13	15	17
		Medium	29	32	36
		High	42	47	54
		High cyclones	42	47	54
Marshall Islands	MHL	Low	13	14	16
		Medium	28	32	37
		High	41	48	56
		High cyclones	42	49	58
Palau	PLW	Low	2	3	3
		Medium	5	6	6
		High	8	9	9
		High cyclones	9	10	11
Solomon Islands	SLB	Low	81	89	97
		Medium	181	201	222
		High	269	298	332
		High cyclones	280	311	347
Tonga	TON	Low	8	8	9
		Medium	17	19	21
		High	25	28	31
		High cyclones	28	31	35
Vanuatu	VUT	Low	36	39	42
		Medium	80	88	96
		High	117	129	143
		High cyclones	130	144	161
Samoa	WSM	Low	4	5	7
		Medium	8	9	11
		High	13	16	19
		High cyclones	15	18	21

Source: World Bank estimates

The main component of the costs of adaptation is expenditure on the construction and maintenance of sea dikes – more than 75% of the total in most countries. The second component is beach nourishment as river dike costs are negligible in most countries. The difference between these costs is that sea dikes must be built in advance of sea level rise and then maintained, whereas beach nourishment is a recurrent cost that can be adjusted as needs require. While the capital costs of sea dikes can be spread over time, the incidence of damage caused by permanent inundation and temporary flooding is likely to be much more uneven. In the absence of a long term strategy for the construction and maintenance of dikes the impact of sea level rise will be felt as intermittent but with very large expenditures to deal with the aftermath of severe storm surges and exceptional tides.

There is little prospect that the high costs of building sea dikes could be financed by the countries themselves, so the international community will have to assess the trade-off between large initial expenditures on construction that is designed to protect coastal communities for many years into the future versus expenditures on emergency relief and recovery programs when disasters occur. Some countries – e.g. the UK - have abandoned attempts to protect all of their coastlines from storm and wave damage. Though this is controversial it is almost unavoidable in the face of steady and substantial land erosion. A similar choice may have to be made by some of the Pacific Island countries which may need to set priorities in the geographical allocation of expenditures on coastal protection.

Table A5-2 shows the residual physical damage that would be expected if the coastal protection measures costed in the previous table were implemented. The residual loss of land to erosion and submergence is relatively small under all scenarios in all countries other than the Solomon Islands. The main residual impact concerns people at risk of intermittent flooding in Kiribati, the Solomon Islands and Vanuatu. These live in areas where the analysis indicates that the costs of protection may exceed the benefits of reductions in risk.

Finally Table A5-3 shows the combined cost of coastal protection and residual damage as a % of projected GDP at PPP for the middle of each decade. Since projected economic growth outstrips the increase in the cost of protection the shares decline over time. Even so, for the High SLR scenario they exceed 10% of GDP in each decade for Kiribati, the Marshall Islands and the Solomon Islands and it is only slightly lower for Vanuatu. In each case the figures would be higher but for the assumption that a strategy of selective protection is adopted. In addition, it may be assumed that the result would be the same or worse for Tuvalu. These figures far exceed the scale of adaptation costs relative to GDP reported in the EACC study by World Bank region – less than 0.8% of GDP for Sub Southern Asia and less than 0.4% for the other regions.

Table A5-2 – Average residual physical damage by country and SLR scenario for 2020-49, with "optimal" protection level

Country	Code	Scenario	Residual damage (average 2020-49)		
			Land loss (sq. km/yr)		People flooded
			Erosion	Submergence	000s/yr
Fiji	FJI	Low	0.11	0.02	0.05
		Medium	0.22	0.03	0.06
		High	0.43	0.06	0.10
		High cyclones	0.49	0.07	0.11
Micronesia, Fed. Sts.	FSM	Low	0.02	0.00	0.08
		Medium	0.04	0.00	0.13
		High	0.16	0.00	0.04
		High cyclones	0.18	0.00	0.05
Kiribati	KIR	Low	0.15	0.01	0.14
		Medium	0.30	0.03	0.14
		High	0.57	0.06	0.14
		High cyclones	0.66	0.07	0.16
Marshall Islands	MHL	Low	0.09	0.00	0.01
		Medium	0.18	0.00	0.03
		High	0.33	0.00	0.05
		High cyclones	0.38	0.00	0.05
Palau	PLW	Low	0.00	0.00	0.00
		Medium	0.00	0.00	0.00
		High	0.00	0.00	0.03
		High cyclones	0.00	0.00	0.03
Solomon Islands	SLB	Low	0.19	4.10	0.57
		Medium	0.39	8.46	0.56
		High	0.75	14.48	0.55
		High cyclones	0.86	16.66	0.64
Tonga	TON	Low	0.01	0.00	0.07
		Medium	0.02	0.00	0.09
		High	0.04	0.01	0.46
		High cyclones	0.05	0.01	0.53
Vanuatu	VUT	Low	0.09	0.09	0.12
		Medium	0.19	0.18	0.17
		High	0.37	0.36	0.17
		High cyclones	0.43	0.41	0.20
Samoa	WSM	Low	0.04	0.00	0.04
		Medium	0.09	0.00	0.04
		High	0.07	0.00	0.13
		High cyclones	0.08	0.00	0.14

Source: World Bank estimates

Table A5-3 – Costs of coastal protection and residual damage as % of projected GDP

Country	Code	SLR scenario	Adaptation & residual damage costs as % of GDP at PPP		
			Based on projected mid-decade GDP		
			2020s	2030s	2040s
Fiji	FJI	Low	1%	1%	1%
		Medium	2%	1%	1%
		High	3%	2%	2%
		High cyclones	3%	2%	2%
Micronesia, Fed. Sts.	FSM	Low	1%	1%	1%
		Medium	3%	2%	2%
		High	4%	3%	3%
		High cyclones	4%	4%	3%
Kiribati	KIR	Low	5%	4%	4%
		Medium	11%	9%	8%
		High	16%	13%	11%
		High cyclones	16%	13%	11%
Marshall Islands	MHL	Low	5%	4%	4%
		Medium	10%	9%	8%
		High	15%	13%	13%
		High cyclones	15%	14%	13%
Palau	PLW	Low	1%	1%	1%
		Medium	1%	1%	1%
		High	2%	2%	2%
		High cyclones	3%	2%	2%
Solomon Islands	SLB	Low	5%	4%	3%
		Medium	10%	8%	7%
		High	15%	12%	10%
		High cyclones	16%	13%	11%
Tonga	TON	Low	1%	1%	1%
		Medium	3%	2%	2%
		High	4%	3%	3%
		High cyclones	4%	4%	4%
Vanuatu	VUT	Low	3%	3%	2%
		Medium	7%	6%	5%
		High	10%	8%	7%
		High cyclones	11%	9%	8%
Samoa	WSM	Low	0%	0%	0%
		Medium	1%	1%	1%
		High	1%	1%	1%
		High cyclones	1%	1%	1%

Source: World Bank estimates

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Annex 6 - Adaptation in the Water Sector

1. Introduction

This annex examines the implications of climate change for the management of water resources, focusing in particular on:

1. the problems of ensuring adequate resources for domestic and non-domestic water supply
2. Managing surface water flooding caused by periods of intense rainfall.

Consultation exercises in many Pacific Islands have identified concerns about water supplies and their vulnerability to climate change as the primary environmental priority for many communities. This is highlighted by the drought that occurred in Tuvalu in 2011 which led to severe rationing of fresh water supplies in September/October of that year and emergency assistance from various countries. As a country comprised of small reef and atoll islands whose weather is strongly affected by La Nina and El Nino episodes, Tuvalu is extremely susceptible to deviations in monthly rainfall that must be offset either by drawing upon stored water or by reliance upon relatively expensive desalination. More recently, both RMI and FSM have declared a state of emergency in 2016 due to ongoing drought linked to the 2015/16 El Nino event.

There is a history of significant losses from floods within PICs, and there is the potential that these may increase with the onset of climate change. For example, Fiji experienced devastating floods in 2004, 2007, 2009, 2012 (twice) and 2014. The 2009 event is reported to have caused damage and loss of 135 million USD (SOPAC, 2009).[32] More recently, flash floods in the Solomon Islands in 2014 caused damage and loss estimated at 109 million USD, equivalent to 9.2 percent of gross domestic product (GDP), resulted in the death of 22 people, and affected approximately 52,000 people in total. Flooding has the potential to cause damage to major infrastructure, destroy homes, impact agriculture and lead to loss of life.

2. Methodology

The potential impact of climate change on vulnerability to droughts and floods has been examined for several PICs based on the RCP4.5 climate scenarios. Actual historic rainfall data from records for the period 1948-2008 has informed the analysis and been used as the basis for “No Climate Change Baselines” for minimum and maximum rainfall. A standard extreme value distribution known as the Gumbel distribution (conventionally used to model floods and droughts caused by extreme periods of rainfall) has been created for the “No Climate Change Baselines” and for and for each of the RCP4.5 climate scenarios (19 in total) for maximum and minimum rainfall.

[32] The recording of the losses caused extreme events affecting the Pacific Islands countries is very erratic and does not follow standardized methods. For Fiji, the SOPAC event database reports losses of less than 1 million USD (at 2009 constant prices) for the 2004 flood, 59 million USD for floods in 2005, 85 million USD for floods in 2007, 43 million USD for the flood in 2009, zero for the floods in 2012, and the entry for the flood in 2014 is only a placeholder.

Droughts and water supply

For the drought analysis, the impact of climate change on droughts was estimated for 2030 and 2050. The analysis focuses on 2050 since the results for 2030 are broadly consistent. A Gumbel distribution has been calculated for the No Climate Change Baseline and each of the RCP4.5 global climate models (i.e., 19 climate change distributions in total, plus one baseline distribution, totalling 20 Gumbel distributions for the drought analysis). For each of these distributions, the 1 in 20 year, 1 in 50 year and 1 in 100 year drought has been calculated. Given that there are 20 Gumbel distributions that are being used, this means that the analysis results in 20 values of the 1 in 20 year drought, 20 values for the 1 in 50 year drought and 20 values for the 1 in 100 year drought for the year 2050. Results have been presented for the No Climate Change Baseline, compared to the 10th percentile and median case (i.e., rainfall determined by the 10th and 50th percentiles of the 19 RCP4.5 distributions for minimum rainfall).

Surface Water Flooding

For flooding, the analysis focuses on short term flooding, in which extreme amounts of rain in a period of 24 hours cause flooding within a relatively short distance of the original precipitation. This includes flash floods, floods caused by storms, and riverine floods in areas with rapid run-off as is characteristic of volcanic islands. Using changes in the distribution of maximum 24 hour rainfall with an assumption about the existing or future level of flood protection, it is possible to estimate changes in flood exposure for specific locations and climate scenarios. The results must be treated as providing an indication of the nature of the changes that may occur, since they are based upon generic assumptions that should be refined with more specific information about actual conditions. The impact of climate change on the distribution of the maximum amount of rainfall within a 24 hour period in any year is used as the indicator which determines changes in the probability and severity of flooding.[33] This is a necessary simplification which takes no account of potential changes in hydrology and other factors (i.e., such as increased development within the floodplain) that may alter the relationship between peak rainfall and flooding.

Similar to the methodology used for droughts, the distributions of maximum 24 hour rainfall have been assumed to follow the Gumbel distribution, and the distributions have been estimated for the No Climate Change Baseline for flooding and the RCP45 projections for 2050. Results have been presented as a comparison of the maximum rainfall for the No Climate Change Baseline with the median and 90th percentile case (i.e., maximum rainfall determined by the 50th and 90th percentiles based on the 19 RCP4.5 distributions). The distributions for each climate scenario are estimated from the RCP45 projections for 2050, based on combining the historical weather variability with the shifts in the mean values and variances of precipitation generated by each climate model. The key idea underpinning the analysis is illustrated in Figure A6-1.

The solid curve shows the distribution of the maximum 24 hour rainfall in a year without climate change for a particular location or grid square. It is assumed that people and assets are protected

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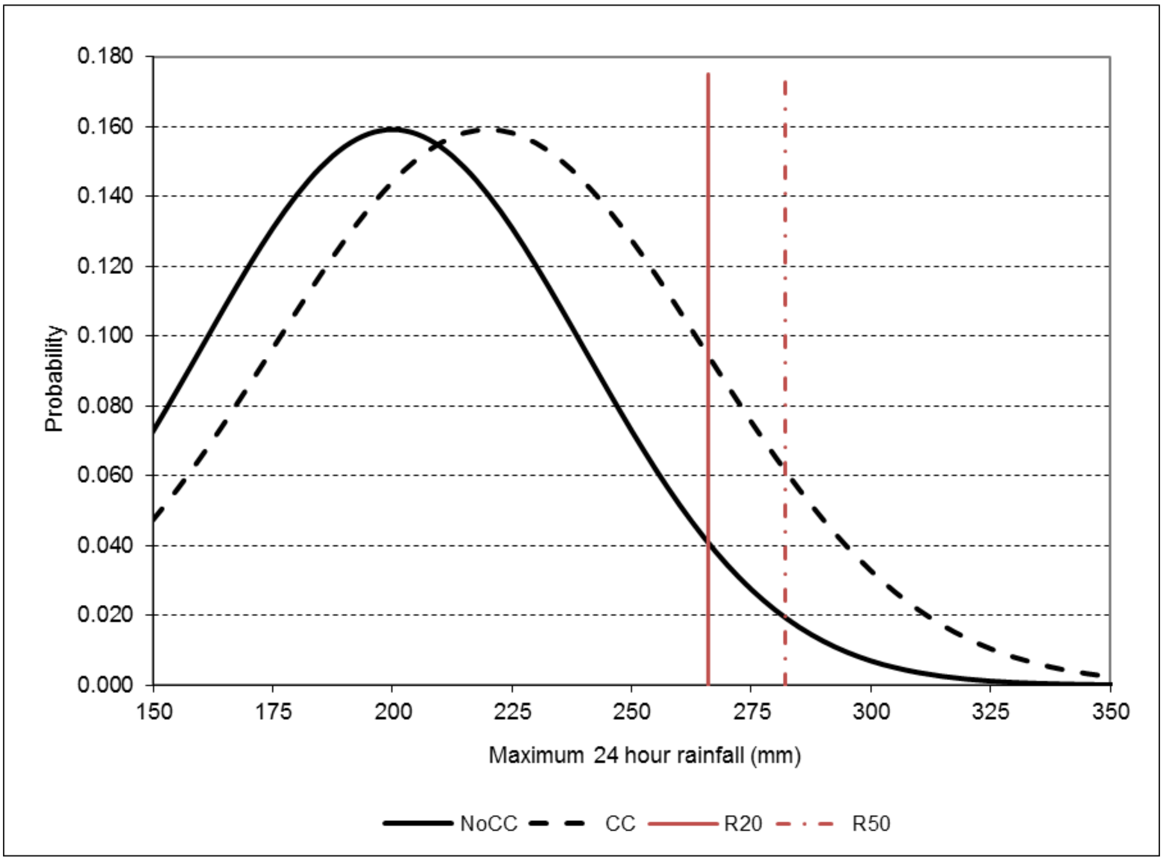
[33] A similar analysis was carried out using data on maximum 72 hour rainfall. The results are very similar to those from the analysis of maximum 24 hour rainfall, so they are not reported here.

against flooding by measures that are effective up to a 1 in 20 year flood as measured by the rainfall level R_{20}. This means that there is a 5% chance in any year that floods will occur. The average severity of the floods that do occur may be computed from the mean of the distribution that lies to the right of R_{20}. Now, suppose that the distribution of maximum 24 hour rainfall shifts to the right – the dashed curve – as a consequence of climate change. If no additional investment is made in flood prevention, the probability that there will be flooding will be higher than 5% and the average severity of the floods that do occur will also increase. Of course, if the distribution of maximum monthly rainfall had shifted to the left, both the probability of floods and their average severity would decrease.

Figure A6-1 – Distribution of extreme rainfall events and flood prevention



NoCC denotes maximum 24 hour rainfall without climate change
CC denotes maximum 24 hour rainfall with climate change
R20 denotes rainfall level for 1 in 20 year flood
R50 denotes rainfall level for 1 in 50 year flood

Flood impacts

This section describes the methodology used to examine the impact of changes in the probability distribution of floods. As noted above, the coverage of the raw data is erratic and various efforts have been made to produce consistent datasets that can be analysed using GIS tools. This study has relied upon datasets on flood hazards for 2.5 arc-minute grid squares (roughly 5 x 4 km) compiled for the World Bank by the Center for Hazards and Risk Research - CHRR (2005) - at Columbia University using data for the period 1981-2000 standardised to the year 2000 as the base year for population and economic activity. The datasets reflect the risks of mortality and economic losses due to flooding averaged over a period of two or more decades. Grid squares for which the risk is very small or cannot be assessed are given zero values, while grid squares for which a hazard (defined by the probability of an event multiplied by the magnitude of the impact) is assigned are ranked by decile with 1 corresponding to the lowest decile and 10 the highest decile. The deciles are based on the global distribution of non-zero hazards. There is one grid square in the Solomon Islands with a mortality hazard of 10 meaning that it is among the top 10% of grid squares in the world with the highest expected number of deaths per year caused by flooding. Similarly, there are 10 grid squares in Fiji which have a mortality hazard of 9, placing them between the 80^{th} and 90^{th} percentiles in terms of the expected number of deaths per year caused by flooding.

There are some limitations to the CHRR data. For example, the CHRR data records negligible or missing hazards for flood impacts in 6 of the PICs – FSM, Kiribati, Marshall Islands, Palau, Tonga and Tuvalu. This is consistent with the SOPAC risk database, but does not necessarily mean that these countries are free of flood hazards. In addition, the CHRR data on economic losses is either missing or assigned to a national average category for Fiji, the Solomon Islands and Samoa, reflecting an absence of disaggregated data. Hence, the mortality hazard has been used as a generic indicator of the relative severity of flood impacts across grid squares. Based on the global distributions, the decile bands for mortality hazards are spread as roughly geometric series with a ratio of the upper to the lower threshold for deciles 2, … , 9 equal to 1.5. The values for each grid square have been aggregated using weights based on: (a) total population in 2000; and (b) the mean value of night-time lights in 2013 as an indicator of economic activity.[34] The population-weighted hazards reflect the potential impact of flooding on the population of the region or country affected, while the lights-weighted hazards reflect the potential impact on economic activity.

Significant mortality or economic losses will only occur if the severity of the storm or floods surpasses a threshold set by existing levels of storm or flood protection. For example, the calculation of the average economic loss involves two elements: (a) the probability p(S) that an event of severity S which is greater than the no damage threshold S_N will occur; and (b) the economic loss L(S) that will occur if an event of severity S occurs. Hence,

$$Average\ loss = \frac{\sum_{S>S_N} p(S)L(S)}{GDP} \qquad (6)$$

There is very little general evidence about the relationship L(S) between the magnitude of floods and the amount of damage which they cause, because this depends greatly upon local conditions – topography, the type of assets which are affected, etc. As an illustration, consider a 1 in 100 year

[34] The first dataset of night-time lights covering most of the world extracted from images from the Defence Meteorological Satellite Program – Optical Line Scanner (DSMP-OLS) was compiled for 1994-95. Annual updates are prepared and made available by NOAA's National Geophysical Data Center. Doll (2008) and Addison & Stewart (2015) describe how the data is compiled and may be interpreted. The intensity of night-time lights is strongly correlated with economic activity in geographical cross-sections but changes in lights do not provide a reliable guide to changes in economic activity over time.

event with 24 hour rainfall of R_{NoCC} under the no climate change baseline and R_{CC} in 2050 after climate change with $R_{CC} > R_{NoCC}$. The proportional increase in the volume of flood water exceeding the standard 1 in 20 year no damage threshold for this event can be calculated from $(R_{CC} - R_{20}) / (R_{NoCC} - R_{20})$. However, the additional volume of water in the flood may either lead to the same assets (buildings, factories, land, etc) being flooded but to a greater depth and/or to a large set of assets being affected. Since flood plains will be affected first, it is likely that the outcome will be some combination of greater depth and greater extent.

The evidence on damage as a function of inundation depth is mixed. One UK study proposed a square root damage function (i.e., HR Wallingford, (2007)) – whereas studies based on Dutch work have tended to use linear damage functions (i.e., Bouwer et al, (2010), Genovese, (2006), and Kok, (2001)). The damage caused by an extension of flood area will depend upon the nature of the assets at risk. Since there are no general grounds for preferring any one approach, a linear damage function based on the proportional increase in the volume of flood water has been used here.

3. Key Findings

Drought

For the median case (i.e., the 50th percentile case based on the 19 RCP4.5 distributions), the risks of more severe drought are small in most countries. Table A6-1 shows the changes in low rainfall in 2050 for 1 in 20 year and 1 in 50 year droughts for periods from 30 to 120 days for RCP4.5 climate scenarios. Fiji, RMI, Palau, FSM, Vanuatu and Solomon Islands may experience a small reduction in some of the 1 in 50 year and 1 in 20 year low rainfall values, but the changes should not require major investment in additional water storage. Table A6-1 also shows the 10th percentile of the distribution of changes, which highlights a worse case than the median situation.

The risks are much more significant for the case which presents the lowest 10% of rainfall (i.e., the 10th percentile case based on the 19 RCP4.5 distributions), especially for the Solomon Islands and Tuvalu and to a less extend Fiji, Palau and RMI. It must be emphasised that the differences between the median and 10th percentile case reflect the uncertainty concerning future climate projections rather than weather variability. Still, while this uncertainty remains, there is a small but significant chance that changes in climate may lead to extended periods of little or no rain, particularly in Solomon Islands and Tuvalu. For Tuvalu this would imply a repetition of the problems that occurred in 2011 and the need to invest either in water storage or in alternative sources of water such as desalination as a supplement to normal rainfall. The Solomon Islands is much larger and more diverse than Tuvalu, but the manner in which the estimates are constructed imply that such droughts are likely to affect the main population centre of Honiara and the province of Guadalcanal. Heavy investment in either water storage or alternative sources of water would be required in the worst of the RCP4.5 climate scenarios examined for Solomon Islands. Smaller investments in water storage may be required in Fiji, the Marshall Islands and Palau.

Table A6-1 – Changes in severity of potential drought by country for 2050
(mm of rain relative to no climate change)

Country	Change in 1 in 50 year low rainfall				Change in 1 in 20 year low rainfall			
	30 days	60 days	90 days	120 days	30 days	60 days	90 days	120 days
Median climate scenario (i.e., 50th percentile based on Grumbel distributions for each of the 19 RCP4.5 Scenarios)								
FJI	0	-5	-14	-6	-1	-6	-10	-5
FSM	-0	-10	3	14	-2	-5	8	15
KIR	0	0	0	-17	0	0	-18	-5
MHL	0	-1	-7	-2	-1	-2	-4	0
PLW	0	-12	-6	2	-1	-10	3	8
SLB	-4	-17	-26	6	-4	-15	-23	10
TON	0	0	0	0	0	0	-0	-4
TUV	1	0	19	30	4	4	20	31
VUT	0	0	-3	-6	0	-0	-3	-10
WSM	0	0	0	0	0	0	2	4
10th percentile scenario (i.e., 10th percentile based on Grumbel distributions for each of the 19 RCP4.5 Scenarios)								
FJI	-1	-22	-59	-67	-5	-36	-72	-84
FSM	-2	-27	-39	-36	-7	-30	-31	-35
KIR	0	0	0	-17	0	0	-19	-50
MHL	0	-13	-75	-71	-5	-33	-74	-75
PLW	0	-39	-51	-45	-5	-30	-47	-46
SLB	-65	-197	-332	-415	-65	-179	-299	-375
TON	0	0	0	0	0	0	-0	-5
TUV	-28	-102	-155	-230	-32	-98	-150	-221
VUT	0	0	-5	-10	0	-3	-13	-25
WSM	0	0	0	0	0	0	-16	-27

Source: World Bank estimates
Note: The differences between the median and 10th percentile case reflect the uncertainty concerning future climate projections, rather than weather variability.

Surface water flooding

The RCP4.5 climate scenarios considered suggest that most of the PICs will experience an increased probability and severity of flooding. Unfortunately, variations across climate scenarios point to increased flooding in a particular grid square for some scenarios and decreases for other scenarios, so that the level of uncertainty about the actual outcome is high.

Table A6-2 provides a comparison of the estimated values of 1-day extreme rainfall levels for 1 in 20 year events under the No Climate Change Baseline as well as for the median and 90th percentile cases (based on 50th and 90th percentiles of the the 19 RCP4.5 distributions) for the year 2050. For example, in Fiji the 1 in 20 year rainfall event for the No Climate Change Baseline was 245 mm while the 1 in 20 year event would be 292 mm in 2050 under the 90th percentile case (increase of 19%). The columns with percentage increases show: (a) the effect for moving from a 1 in 20 year standard to a 1 in 50 year threshold; (b) the effect moving from a 1 in 20 year standard to a 1 in 20 year standard which caters for climate change in 2050; and (c) the effect moving from a 1 in 20 year standard to a 1 in 50 year standard which caters for climate change in 2050. For Palau, the No Climate Change Baseline 1 in 20 year rainfall is 197 mm, and increases by 7% to 210 mm for the 1 in 20 year standard when the climate change in 2050 is considered (for the median case). Moving to the 1 in 50 year standard today would increase the threshold by 16% (229mm). Moving to the 1 in 50 year standard which would cater for the impacts of climate change in 2050 (for the median case) would result in an increase of 24% (244mm).

Table A6-2 – Changes in peak rainfall by country and return period

Country	Baseline with no Climate Change		% increase in 1 in 20 year peak daily rainfall due to climate change		% increase in 1 in 50 year peak daily rainfall due to climate change	
	1 in 20 year peak rainfall (mm)	% increase to 1 in 50 year peak rainfall	In 2050 for median climate case	In 2050 for 90th percentile climate case	In 2050 for median climate case	In 2050 for 90th percentile climate case
FJI	245	17%	2%	19%	19%	40%
FSM	63	12%	10%	59%	23%	82%
KIR	145	18%	31%	63%	53%	92%
MHL	72	14%	4%	46%	19%	69%
PLW	197	16%	7%	16%	24%	35%
SLB	84	14%	7%	16%	22%	31%
TON	57	14%	4%	21%	19%	40%
TUV	83	14%	8%	24%	23%	42%
VUT	189	16%	5%	22%	22%	42%
WSM	79	14%	8%	19%	23%	37%

Source: World Bank estimates
Note: The differences between the median and 10th percentile case reflect the uncertainty concerning future climate projections, rather than weather variability.

It is helpful to consider the options available to policymakers in considering how much to invest in flood protection. Assume that the existing flood defences protect against 1 in 20 years floods under historical (NoCC) climate conditions – i.e. 197 mm in 24 hours for Palau. Since climate change requires some adaptation, there are various options that could be considered:

- Option 1: Enhance the defences to cater for future climate change, while maintaining the 1 in 20 year standard. This would require defences for the example case of Palau that can cope with 24-hour rain of 210 mm in 2050 (7% more) under the median climate change case or 229 mm in 2050 (16% more) under the 90th percentile climate change case.
- Option 2: Increase the level of protection from the 1 in 20 year standard for current flooding to the 1 in 50 year standard for current flooding. This option would not take future impacts of climate change into account. Note that the increase due to the adoption of the higher standard of protection is larger than the increase due to the impact of climate change under the median case for Palau. However, ignoring the effect of climate change would not be advisable.

- Option 3: Increase the level of protection from the 1 in 20 year standard for current flooding to the 1 in 50 year standard that would be required to cater for climate change in 2050. In the case of Palau, for example, the planning threshold would be a level of 24-hour rainfall of 244 mm in the median climate case – an increase of 24%.[35]

For all countries other than Kiribati the increase in the level of flood defences required to adapt to climate change up to 2050 under the median case is smaller than the increase implied by moving from a 1 in 20 year standard of protection to a 1 in 50 year standard. Kiribati is the outlier, as moving from a 1 in 20 year standard of protection with no consideration of climate change to a 1 in 50 year standard with no consideration of climate change would require an increase of 18%, whereas keeping the standard of protection at the 1 in 20 year level, but adopting consideration of the median climate case would require an increase of 31% in 2050. The results emphasise the large variations in precipitation between different RCP4.5 climate scenarios with increases in the 90th percentile rainfall under the 1 in 20 year standard of 16-24% in 7 countries and more than 45% in FSM, Kiribati and the Marshall Islands.

For some countries, adoption of Option 3 – higher protection plus adaptation to future climate change – would necessitate very large investments in flood defences. For example, for FSM, Kiribati and the Marshall islands, moving from a 1 in 20 year standard of protection to a 1 in 50 year standard of protection under the 90th percentile climate case would require the need to cope with 70 to 90% increases in peak rainfall. However, this presents a dilemma for the design of flood defences in such countries, which consist of atoll islands with limited differences in elevation and extremely rapid run-off of storm water. The worst episodes of intense precipitation are linked to cyclones when storm surge is a major threat. Reliance upon dykes to protect the coastline against storm surges will tend to slow the run-off of rain water and encourage the accumulation of flood water behind the dykes. As a consequence, a better strategy may be to ensure that the floor levels of all new buildings are raised so that their main thresholds are a metre or more above ground level. It may be prohibitively expensive to modify all existing buildings, but the design standards for new buildings – especially, important public buildings – should set out to raise floor levels wherever possible and to encourage the implementation of other measures that would minimise the impact of flood damage. Such measures would include raising power outlets and key services as well as avoiding the use of materials that are badly affected by flood water.

Changes in flood exposure and damage

Flood exposure and damage costs are high for many PICs under current climate conditions. Table A6-3 summarises the baseline flooding exposure (using historic data for 1981-2000) for four countries, showing the distribution of population and economic activity that are subject to various impacts (from no impact to very high impacts). It shows the current flooding risk exposure is high to very high in Fiji, and medium to high in Solomon Islands and Samoa. In Fiji 38% of the population and 19% of economic activity fall into the high or very high impact category. The hazards for these people are high to very high, not merely relative to other areas in Fiji but by comparison with flood exposure in all countries

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[35] The increases are multiplicative, so 1 + 24% = (1 + 7%) x (1 + 16%) after rounding.

around the world. The proportion of the population subject to High and Very High impacts are much lower for the other countries, though 7-8% of economic activity in the Solomon Islands and Samoa is located in areas with high or very high flood impacts. Clearly, the areas at risk of the flooding with high or very high impacts are candidates for additional investment in flood defences to raise the level of protection and reduce the flood losses which occur as a result of extreme weather under current climate conditions.

Table A6-3 – Severity of flood impacts under current standard of protection and current climate conditions

Country	Exposure by rank of impact				
	No impact	Low	Medium	High	Very High
A. Proportion of population					
Fiji	11%	14%	37%	32%	6%
Solomon Islands	59%	19%	19%	1%	1%
Vanuatu	63%	36%	1%	0%	0%
Samoa	62%	0%	36%	0%	1%
B. Proportion of economic activity					
Fiji	23%	17%	41%	16%	3%
Solomon Islands	68%	25%	1%	5%	2%
Vanuatu	92%	8%	0%	0%	0%
Samoa	76%	0%	16%	0%	8%

Source: World Bank estimates

The results indicate that the main impact of climate change will be a shift between the categories of medium to high and from high to very high impacts, with more people and economic activity falling into the category of a very high impact. Table A6-4 shows how the exposure under the current level of protection may change by 2050 due to the impacts of climate change (applying the median case, based on the 19 RCP4.5 distributions)**.** With no change in the level of protection, 26% of the population of Fiji and 7-8% of the economic activity of Fiji, Solomon Islands and Samoa will be at risk of Very High levels of flood damage.

Table A6-4 – Severity of flood impacts under current standard of protection and 2050 climate conditions (median case)

Country	Exposure by rank of impact				
	No impact	Low	Medium	High	Very High
A. Proportion of population					
Fiji	11%	11%	10%	40%	26%
Solomon Islands	59%	59%	15%	23%	0%
Vanuatu	63%	63%	32%	5%	0%
Samoa	62%	62%	0%	1%	35%
B. Proportion of economic activity					
Fiji	23%	15%	42%	11%	8%
Solomon Islands	68%	25%	1%	0%	7%
Vanuatu	92%	6%	2%	0%	0%
Samoa	76%	0%	1%	15%	8%

Source: World Bank estimates
Note. The climate conditions considered in the above table relate to the median case, based on the 19 RCP4.5 distributions.

Table A6.5 shows the same analysis for 2050 but under the 90th percentile case. In this case there is a more general upward shift in the level of exposure to flood damage. In Fiji, 76% of the population (up from 38% under the No Climate Change Baseline) and 60% of economic activity (up from 19% under the No Climate Change Baseline) are located in grid squares that would be exposed to High or Very High flood damage under the 90th percentile case. There is a similar large increase in exposure from Medium to High flood impacts in Samoa.

Table A6-5 – Severity of flood impacts under current standard of protection and 2050 climate conditions (90th percentile case)

Country	Exposure by rank of impact				
	No impact	**Low**	**Medium**	**High**	**Very High**
A. Proportion of population					
Fiji	1%	10%	14%	37%	39%
Solomon Islands	25%	41%	20%	12%	2%
Vanuatu	10%	54%	31%	5%	0%
Samoa	27%	35%	0%	36%	1%
B. Proportion of economic activity					
Fiji	1%	24%	15%	41%	19%
Solomon Islands	62%	7%	24%	1%	7%
Vanuatu	2%	90%	6%	2%	0%
Samoa	10%	67%	0%	16%	8%

Source: World Bank estimates

Note. The climate conditions considered in the above table relate to the median case, based on the 19 RCP4.5 distributions

Table A6.6 presents the same results in a different way by assigning decile values to create an index of the severity of flood damage for each grid square and then aggregating over all grid squares in each country using either population or economic activity weights. The index is scaled so that the lowest significant impact – i.e. the bottom of the first global decile - has the value 1, while the bottom of the top decile has the value 38.443 (= 1.5^9). The index suggests that the 2050 median climate case would lead to an increase in the expected level of flood damage of about 20% in Fiji and Vanuatu but of about 40% in the Solomon Islands and Samoa. For this case, the differences between the impacts on population and economic activity are small. Under the 2050 90th percentile case the expected level of flood damage approximately doubles for Fiji and the Solomon Islands, In this case, the increases are even larger for Vanuatu and Samoa, reaching almost 160% for economic activity in Vanuatu, albeit from a rather low base.

Table A6-6 – National indices of flood damage by climate scenario for current protection

Country	Index of overall flood impacts		
	No climate Change	Median Climate Change (i.e., 50th percentile based on Grumbel distributions for each of the 19 RCP4.5 Scenarios) in 2050	90th percentile Climate Change (i.e., 90th percentile based on Grumbel distributions for each of the 19 RCP4.5 Scenarios) in 2050
A. Population weights			
Fiji	11.0	13.2	22.8
Solomon Islands	2.9	4.0	5.7
Vanuatu	1.7	2.1	4.0
Samoa	4.0	5.7	8.9
B. Economic activity weights			
Fiji	7.6	9.2	15.7
Solomon Islands	2.9	4.0	5.5
Vanuatu	0.8	1.0	2.0
Samoa	4.2	6.0	9.4

Source: World Bank estimates

The effects of increasing the level of protection provided by flood defences are shown in Table A6-7. Increasing the level of protection to the current 1 in 50 year peak rainfall (Option 2, as discussed above) would substantially reduce the damage caused by flooding in the No Climate Change Baseline and in the 2050 median climate case. However, it would still leave all countries with higher levels of flood damage under the 2050 90th percentile case. Going further by adopting the 2050 1 in 50 year level of protection (Option 3 above) would reduce the amount of flood damage even more in all countries under the 2050 median climate case but would still not prevent a deterioration under the 2050 90th percentile case.

Table A6-7 – National indices of flood damage under enhanced protection by climate scenario

Country	Index of overall flood impacts					
	1 in 20 year protection			1 in 50 year protection		
	No Climate Change	Median Climate Change in 2050	90th percentile Climate change in 2050	No Climate Change	Median Climate Change in 2050	90th percentile Climate change in 2050
A. Population weights						
Fiji	4.7	7.0	16.5	2.7	4.9	14.5
Solomon Islands	1.2	2.4	4.1	0.2	1.3	3.0
Vanuatu	0.7	1.1	3.0	0.4	0.8	2.6
Samoa	1.7	3.4	6.6	0.2	1.9	5.1
B. Economic activity weights						
Fiji	3.2	4.9	11.3	1.8	3.4	9.9
Solomon Islands	1.2	2.4	3.8	0.2	1.3	2.8
Vanuatu	0.3	0.5	1.5	0.2	0.3	1.4
Samoa	1.8	3.6	7.0	0.2	2.0	5.4

Source: World Bank estimates
Median Climate Change denotes 50^{th} percentile based on Grumbel distributions for each of the 19 RCP4.5 Scenarios in 2050
90^{th} Percentile Climate Change denotes 90^{th} percentile based on Grumbel distributions for each of the 19 RCP4.5 Scenarios in 2050

Conclusions

Climate change is, of course, only one factor that will determine changes in flood hazards over the next 3 decades. Migration of people and economic activity to flood plains and other areas that are prone to flooding will exacerbate the changes in overall levels of flood damage. Further, changes in patterns of land use – especially, deforestation, changes in cultivation practices, and the expansion of urban or semi-urban settlements - will accelerate the rate of run-off from upland areas and reduce the capacity of land to absorb excess water temporarily. Equally, the impact of changes that may be expected to accompany economic development will be multiplied by the impact of climate change on the volumes of water that must be handled during periods of intense rainfall.

The results suggest that a strategy of raising the level of flood protection in these countries would provide immediate benefits as well as a substantial degree of insurance against all but the worst outcomes due to climate change. It would still be necessary to monitor the impacts of climate change but this strategy would provide time to identify trends and respond appropriately 20 years from now.

The probabilities of suffering major economic losses due to floods are very unevenly distributed across different localities – cities, districts, counties, etc. The population density in flood-prone areas is much higher than in low risk areas. People are much more at risk of flooding if they live in the flood plain of a major river. This analysis only captures a part of the impact of extreme weather events. Future vulnerability to extreme weather events will depend on how countries address future climate risks in planning the location of economic and urban development. It is much cheaper to keep infrastructure, housing and economic assets out of harm's way than to build ever-larger storm and flood defences. On the other hand, the pressures to develop areas at risk of infrequent but major damage are difficult to resist. While better planning can reduce exposure in future, existing patterns of development have magnified flood risks and this will only change slowly – if at all – in future.

4. Emerging Policy Message

The following emerging policy messages relate to drought and flood management in the Pacific.

1. **Even under existing climate conditions, several Pacific Island Countries experience flood and drought related challenges.** There are significant economic impacts from river-based flooding, and significant water shortages due to drought, particularly during El Nino periods.
2. **Climate scenarios suggest that total annual precipitation will increase in most Pacific Island countries as a result of climate change.** This increase will be accompanied by greater differences in rainfall between wet and dry months in the year and more intense rainfall in the wettest periods of the year. Hence, adaptation to climate change will involve measures to: (i) increase the capacity to store water that is accumulated in wetter months for use in the drier months; and (ii) manage the run-off caused by more intense periods of rain.

3. **Investment in water storage, especially on islands with limited amounts of land suitable for reservoirs.** The alternative to investing in more water storage may be reliance upon desalination facilities or other alternative water resources, which (depending on scale) can result in a significant capital costs in addition to ongoing operational and maintenance costs.
4. **In the case of flood, greater investment in and application of the flood risk management approach is required to increase public safety, to mitigate adverse impacts and to build communities resilient to current and future climates.** The alternatives could include any combination of measures to: (i) modify the level and path of flood waters to protect assets, for example, through the use of flood retention infrastructure; (ii) strengthen assets (such as infrastructure or homes) to enable them to cope with and accommodate flood waters; or (iii) flood warning systems to alert affected communities and response organisations to the impending risk of flooding. Both protection and accommodation measures may involve substantial capital and ongoing maintenance costs. One option for adapting to climate change would be to increase the design standard for flood defences from 1 in 20 year floods to a higher standard of protection (such as the 1 in 50 year standard). Depending upon the distribution of flood events and of the damage which they cause, this could substantially reduce the economic loss associated with more frequent and/or severe flooding as a result of climate change.
5. **The probabilities of suffering major economic losses due to floods are very unevenly distributed across different localities – cities, districts, counties, etc.** The population density in flood-prone areas is much higher than in low risk areas. People are much more at risk of flooding if they live in the flood plain of a major river. Future vulnerability to extreme weather events will depend on how countries address future climate risks in planning the location of economic and urban development. It is much cheaper to keep infrastructure, housing and economic assets out of harm's way than to build ever-larger storm and flood defences.
6. **Best practice teaches that an integrated mix of carefully evaluated flood risk management measures is likely to offer most benefit.** This first requires a comprehensive investigation of the advantages and disadvantages of various options for the location of interest. But few such investigations have been conducted in Pacific Island Countries. One difficulty is a lack of quality hydrological data upon which to base investigation. Another need is for consistent approaches to cost-benefit assessment, including standard guidance in relation to damages, discount rates and time horizons.[36] Governments may need training in the skill of multi-criteria assessment. In the past, expensive structural measures have been implemented without proper assessment. Regulation of land use and application of building codes have been relatively weak. Considerable attention has been invested in flood warning systems, though for many Pacific Islands, the short and steep catchments mean that only short warning times are available.

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