‘NextGen’ Projections for the Western Tropical Pacific:

Climate hazard-based impacts on **coffee production in Papua New Guinea**

Case Study

January 2022

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This report has been prepared for the Australia-Pacific Climate Partnership (APCP) as part of the APCP-funded project entitled NextGen Climate Projections for the Western Tropical Pacific. The report is based on a sectoral use case led by CSIRO and SPREP, and the authors and contributors to the report are as follows:

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Contents

Summary

This study is one of several case studies selected to represent various sectors across several different Pacific Island countries. These case studies serve to assist stakeholders in terms of understanding and visualising climate change projections and putting them in relevant context for sectoral applications as part of the *Next Generation Climate Projections for the Western Tropical Pacific*, referred to here as ‘NextGen’. The methodological framework used in this assessment can be found in recent reporting by CSIRO and SPREP (2017), with updated guidance by CSIRO and SPREP (2022).

This report is for governments, the PNG National Weather Service and sector stakeholders to use for general communications and policy related questions. The principles and datasets used in this case study can also inform sector impact assessments. **Rather than providing a comprehensive analysis of sectoral impacts, we aim to demonstrate the application of climate projections in a case study. The results are to be used as a guide to inform more detailed assessments.**

Coffee growing in PNG © Mr Rodney Sinaune (Niugini Digitial Films) and Coffee Industry Corporation (CIC).

Key Results

This NextGen case study investigates the impacts of current and future climate change on coffee production in Papua New Guinea (PNG). Coffee is grown in the Highlands region of PNG, both on larger commercial estates (20 – 400 ha) and as an important crop for smallholder farmers in village coffee gardens. It is the second most important export crop in PNG, providing a significant national economic benefit, and the industry is a major employer with one third of the country's population being smallholder coffee farmers (AECOM 2018).

Through recent and ongoing consultation with PNG coffee producers and relevant industry bodies, using their knowledge and experience of what has been occurring under current climate settings, several climate related impacts were identified.

Ongoing increases in greenhouse gas emissions will cause further global warming and regional climate change (Table 1). Following a low emissions pathway (RCP2.6) would be consistent with achieving the Paris Agreement target of keeping global warming below 2°C and minimising impacts on PNG, while following a high emissions pathways (RCP8.5) would lead to a global warming of 4.4°C with significant impacts on PNG.

Table 1 Projected changes in PNG (mainland) annual temperature and rainfall. Median changes are given, with the 10-90 percentile uncertainty range in brackets. Changes are for 20-year periods centred on 2030, 2050 and 2070, relative to 1986-2005, for low emissions (RCP2.6: green) and high emissions (RCP8.5: red). In 2030, changes are similar for low and high emissions. Source: CSIRO and SPREP (2021)

	2030	2050	2070	1.5°C global warming	2°C global warming	3°C global warming	4°C global warming
Temperature from 1986-2005 (°C)	0.7 (0.5 to 1.1)	🟩 0.8 (0.6 to 1.2) 🟥 1.4 (1.0 to 2.0)	🟩 0.8 (0.5 to 1.3) 🟥 2.2 (1.6 to 3.2)	0.8 (0.5 to 1.0)	1.2 (0.9 to 1.4)	2.1 (1.7 to 2.4)	2.9 (2.4 to 3.4)
Annual rainfall from 1986-2005 (%)	4 (-1 to 9)	🟩 4 (0 to 9) 🟥 7 (-1 to 15)	🟩 5 (-1 to 9) 🟥 10 (-1 to 20)	3 (-3 to 6)	6 (0 to 12)	8 (-2 to 18)	13 (-1 to 26)

The potential impacts of projected climate conditions are assessed in this study:

Climate related conditions to be assessed	Coffee production under future conditions
Average daily temperature optimum of 18 – 24°C may be exceeded in future	Within the defined coffee growing regions, sites with optimum temperatures for coffee production may shift uphill, with a decrease in areas too cool, and an increase in areas too warm. The net effect is a slight increase in suitable areas by 2050 and a slight decrease in suitable areas by 2090, especially under a high emissions pathway.
Coffee Leaf Rust disease pressure increases with higher minimum temperatures	Projected warming will increase the range of this fungal disease affecting more coffee growing regions.
Elevation suitability for growing coffee	With increasing temperatures, current understanding of altitudinal limits for coffee growing will need to be redefined.
Mean rainfall changes may affect production	Average annual rainfall is projected to increase in most areas of PNG. Under some, not all, future scenarios, parts of PNG Highlands may become less suitable by being too wet for optimal coffee production.
Extreme rainfall affects drainage, access and disease pressure	Extreme rainfall events are projected to increase in frequency and intensity, increasing the potential for water logging and erosion, reducing accessibility to some farms, and increasing fungal disease pressure.
Coffee production is adversely affected by drought	Reduction in drought frequency and duration is projected for PNG thereby reducing exposure of coffee production to drought conditions, though when drought occurs in future, it may be more extreme.

The combination of all these impacts is likely to cause some ongoing, and in some cases increasing or decreasing, challenges to the industry due to future climate change in the period beyond 2030, and especially after 2050 if the world continues to follow a socio-economic pathway with high greenhouse gas emissions. While not reported on here, there will also be indirect or secondary impacts to the industry from a changing climate, including changes to transport and supply chains, national and international markets and so on.

1 Introduction

1.1 Reason for conducting this case study

Coffee has been identified by the PNG Coffee Industry Corporation Ltd (CIC), PNG Department of Agriculture (regional offices, e.g. Goroka, East Highlands Province), coffee producers, and the PNG National Weather Service as a product with potential for economic development for the country and smallholder farmers. In relation to potential impacts from climate change, the CIC have expressed significant interest in improving their understanding of the future climate in their region along with the impacts this may have on their crops, products and lifestyles.

Given this interest, as part of an Australian Government's Australian Pacific Climate Partnership (APCP), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), working with the Secretariat of the Pacific Regional Environment Programme (SPREP) have undertaken this case study with the support of the PNG National Weather Service (NWS). Collaboration between local farmers and producers, scientists and associated sectoral decision-makers was critical in development of this report (see Section 3.1).

The case study has three goals:

- **Awareness raising** – the results presented here can be used to start discussions and raise awareness of the current and future climate change impacts on coffee farming for stakeholders in PNG. Training manuals have recently been produced in other countries, e.g. Climate-Smart Agriculture in Cocoa training manual (Dohmen et al. 2018), to help with raising awareness.
- **Climate change impacts** – potential impacts documented here can be used as input to more detailed climate change impact assessments and inform associated analysis of adaptation options and action planning.
- **Provide incentive for the global community to mitigate greenhouse-gas emissions** – in order to demonstrate the benefit of global emissions reductions, this report illustrates impacts for 'worst case' and 'best case' scenarios which consider high and low global emission pathways. These scope the potential range of projected climate outcomes for the Pacific Island Countries, while also incorporating any beneficial outcomes gained through the global community achieving the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement targets.

1.2 Case studies in the context of NextGen climate projections

The case study presents information from several sources to address the climate related impacts identified for coffee in PNG. For consistency, these are derived from the same set of underlying CMIP5 climate model experiments (Taylor et al. 2012):

- Some new research developed for this report, also demonstrating climate model selection techniques.
- Some new ways for interpreting projected risks from climate change (also see NextGen country report for PNG – CSIRO and SPREP 2021), adding more sectoral context and detail. These concepts can be found in the green break-out boxes throughout the report.
- To aid more comprehensive reporting, and where relevant to sector stakeholders, we also included results from previous reports (e.g. Pacific-Australia Climate Change Science and Adaptation Planning (PACCSAP) CSIRO, Bureau of Meteorology and SPREP, 2014) to guide the user to the broader range of material currently available to assist in the impact assessment. Refer to the yellow break-out boxes for information derived from other sources throughout the report.

2 Coffee in Papua New Guinea

2.1 Socio-economic context

Arabica coffee (*Coffea arabica* L.) is the second most important agricultural export in Papua New Guinea (PNG), after palm oil (Bourke and Harwood 2009), with PNG being the major coffee producing centre in the Oceania region (FAO 2019). While Robusta (*Coffea canephora*) is also produced in PNG, we will not be assessing this variety in this case study.

PNG produces, on average, about 0.8 % of the total global production by tonne (1961 – 2017) (FAO 2019). Coffee production employs about 2.5 million people (out of around 8 million total population in 2016) in PNG (Sengere 2016), involving around 50 % of rural households (Taylor et al. 2016). Since the 1960s, both production (kg) and land area (ha) devoted to coffee have been increasing, with yields (hg/ha) being fairly consistent since 1990 (Figure 1) (FAO 2019).

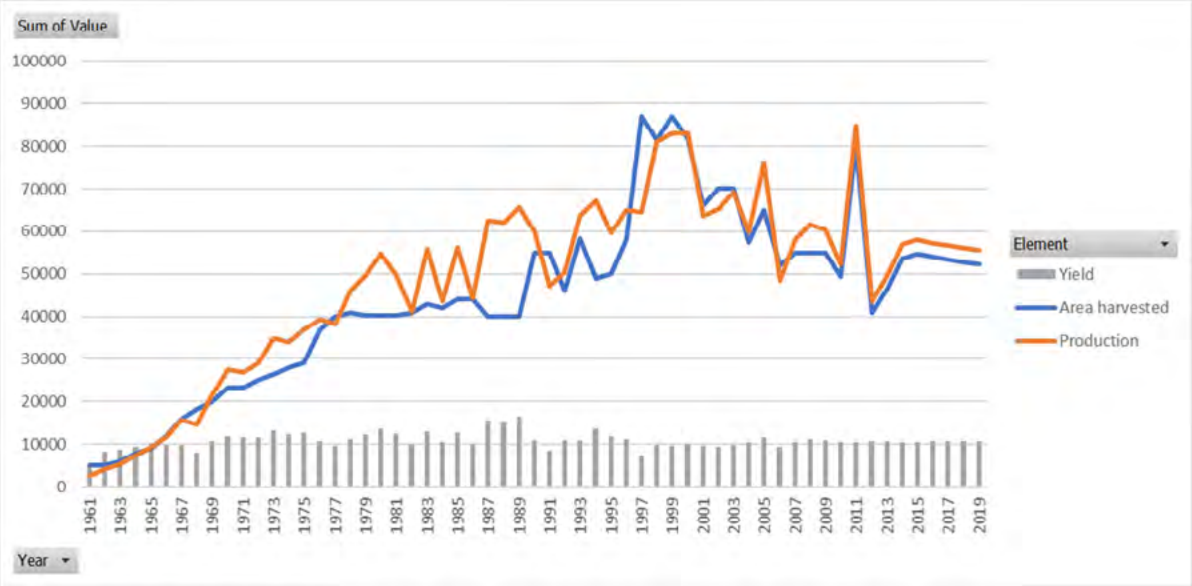


Figure 1 Papua New Guinea coffee production (kg; orange), area harvested (ha; blue), and yield (hg/ha; grey bars) (1961-2019) (FAO 2019)

Coffee was first introduced into PNG in 1873 by French missionaries (Harding et al. 1986; Bourke and Harwood 2009). The PNG Arabica coffee industry expanded rapidly from small beginnings in the 1950s to become a thriving industry in the 1960s and 1970s. As of 2017, an estimated 54,000 hectares was under cultivation in PNG (FAO 2019) with 90 % grown in the Highlands (Sengere 2016). In 2015, 58% of the Highlands coffee production was from the Eastern Highlands Province (EHP), the fertile Waghi Valley spanning Western Highlands Province (WHP) (9 %) and Jiwaka Province (14 %) (CIC data) (Figure 2).

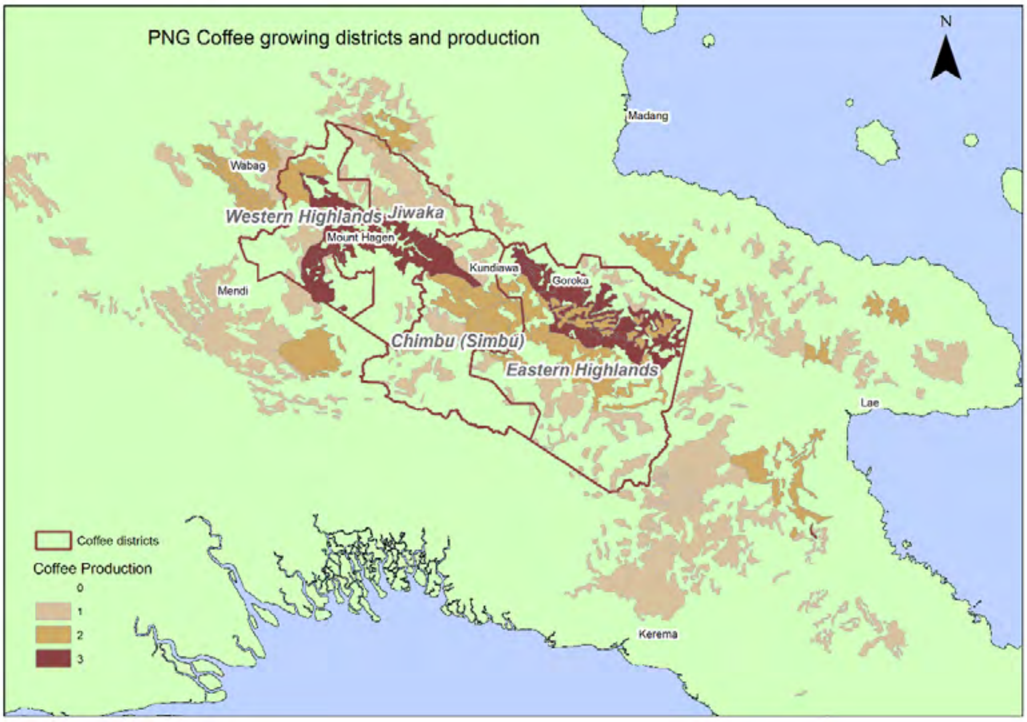


Figure 2 Map of PNG districts (italics outlined in brown), with levels of inputs and outputs for village coffee production in PNG indicating none (green O), minor or insignificant (light brown 1), Significant (brown 2) and very significant (dark brown 3) (Bourke et al. 1993)

2.2 Biophysical context

2.2.1 Climate

The Highland province's annual rainfall ranges around 2000-3000 mm, with rainfall in the eastern provinces having more annual variability than in the west (Bourke and Harwood 2009). Current annual average temperatures are around 18–21°C, or up to 24°C, where coffee is grown.

2.2.2 Altitude

Altitude has the greatest influence on temperature in PNG. Above 500 m, temperature falls at a regular rate of 0.5°C for every 100 m increase in altitude, or 5°C for every 1000 m. This decline in temperature with altitude is known as the 'lapse rate'. The lapse rate causes differences in maximum and minimum temperatures of up to 16°C over the range of occupied land in PNG, from sea level to 2800 m (Bourke and Harwood 2009).

Altitude is a metric used in describing areas suitable for coffee production. Favourable conditions for the growth of Arabica coffee in equatorial areas is approximately between 1,000 and 2,000 m above sea level (Teketay 1999). However, the optimum altitude for the growth of coffee differs from country to country due to differing latitude-based temperature regimes. For instance, the optimum altitude on Mt Kilimanjaro in Tanzania is 1370 to 1680 m while it is 1590-1770 m in Kenya and 920 m in Mexico. For PNG, the optimal elevation for Arabica coffee is between 700 m and 2050 m altitude, while Robusta coffee (a less important export for PNG, not assessed in this case study) is usually grown between sea level and 550 m (Bourke and Harwood 2009).

2.2.3 Coffee pests and diseases

A major concern with coffee production is coffee berry borer *(Hypothenemus hampei)* (CBB), which has caused yield losses as high as 50 % in coffee regions in Indonesia, South America and Southeast Asia (Figure 3). While PNG was reported as one of the few remaining major coffee growing areas where CBB was not present in 2014 (CABI 2014), confirmation of this pest has subsequently been reported (Personal communication, PNG workshop). Problems with the pest are exacerbated by warming. Jaramillo et al. (2009) analysed data from Colombia, Kenya, Tanzania and Ethiopia, estimating that for every 1°C rise in average temperature there would be an 8.5 % increase in the pest (Taylor et al. 2016).

Coffee leaf rust *(Hemileia vastatrix)* (CLR) is a fungal disease that has had a major impact on coffee production globally over the past 200 years, with greater impact in warmer locations. It was introduced into the PNG highlands in 1986, causing loss of production at lower elevations (800–1400 m), but is not, as of 2009, a serious pathogen in the main producing zone at 1600–1800 m elevation (Bourke and Harwood 2009). Bourke (2009) also notes that future increases in temperature and rainfall, even if small, will increase the risk that coffee leaf rust will become more severe in the main PNG coffee-producing areas. Given the difficulty of controlling CLR, greater incidence of the disease would likely reduce yields in the main producing zone.

Figure 3 Coffee borer beetle entering and exiting a coffee cherry Attribution: Michael C. Wright, CC BY-SA 4.0 via Wikimedia Commons (top). A coffee leaf infected by coffee leaf rust, photographed in NW Rwanda in July 2011. (bottom)

Pests such as coffee leaf miner and nematodes (Meloidogyne incognita) have not been reported as a problem in PNG, but a study in Brazil indicated that the incidence was likely to increase by up to 4, 32 and 61% under temperatures projected for 2020, 2050 and 2080 respectively, due to a greater number of generations per month than occurred under climate conditions experienced between 1961 and 1990 (Taylor et al. 2016).

3 Climate influences on coffee under current conditions

3.1 Stakeholder perspective

A workshop in PNG in November 2020 acknowledged that this case study has included relevant metrics for assessing climate change risk for coffee production in PNG.

The workshop, attended by CIC, NWS, and other relevant parties (see Appendix), had the following objectives:

1. Present information about historical relationships between climate and coffee production, current climate change science, and potential future impacts for coffee and cocoa farming from climate change in PNG.
2. Discuss mechanisms and opportunities to communicate this climate change information to stakeholders for decision-making and planning.


Coffee cherries © Mr Rodney Sinaune (Niugini Digital Films) and Coffee Industry Corporation (CIC).

3.2 Review of Literature

A literature review and engagements with key stakeholders identified the following key climatic influences on coffee production:

- For the purposes of this study, an upper temperature threshold of 24°C is assumed (Harding et al. 1986, Teketay 1999, Davis et al. 2012, Taylor et al. 2016) given the stated optimum mean annual temperature range for Arabica is 18–21°C, or up to 24°C. At temperatures above 23°C, development and ripening of fruits are accelerated, often leading to the loss of beverage quality, although in some locations higher temperatures (24–25°C) can still produce satisfactory yields of beans, such as in northeast Brazil (Davis et al. 2012). In regions with a mean annual temperature below 17–18°C growth is depressed (Davis et al. 2012), with 17°C used as the lower temperature threshold in determining production suitability for this assessment.
- Continuous exposure to temperatures as high as 30°C leads to stress, which manifests as depressed growth and abnormalities, such as the yellowing of leaves and growth of tumours on the stem (Taylor et al. 2016).
- For PNG, coffee leaf rust (*Hemileia vastatrix*) incidence reaches a peak in May, June and July and can result in yield losses, however, if the average January minimum temperature is less than 15°C, epidemic development (5 months later) will not reach levels which require chemical control (Brown et al. 1995). Germination and infection processes of CLR are adversely affected where night-time temperatures are below the range 13 - 15.5°C (Nutman et al. 1963, Kushalappa et al. 1983, De Jong et al. 1987).

- PNG highland locations in the elevation range of 1600–1800 m offer ideal conditions for the production of Arabica coffee (Taylor et al. 2016). The higher minimum night-time temperatures that occur in the regions below 1400 m can lead to CLR development (Brown et al. 1995).
- Coffee grows best in high rainfall areas, but there are different estimates of the optimum range of annual rainfall, including 1700-5000 mm (Bourke and Harwood 2009) and 1500-3000 mm with 2000-3000 mm as the optimum range (Taylor et al. 2016). Harding et al. (1986) suggests > 4000 mm as low suitability.
- In relation to drought, the pattern of wetter and drier periods is also important for coffee growth, budding and flowering. Insufficient moisture can cause biennial bearing; wet conditions can delay ripening; small rainfall events can initiate flowering (Taylor et al. 2016) though there is agreement in the literature that a 2-month dry spell is important.
- Drainage is a critical component for selection of suitable sites for coffee farms (Harding et al. 1986). Extreme or heavy rainfall is a factor that is related to waterlogging, increasing the importance of drainage.

This case study examined these climate factors as contributing to the potential vulnerability of the coffee industry in PNG. However, there are many other climate and non-climate related issues that need to be assessed before the overall climate change risk to the coffee industry can be understood. These include:

- Other climatological factors include preference for some cloud cover, and higher humidity reducing sunlight intensity, with high wind-speed being detrimental (Teketay 1999).
- Farm management practices and the coffee supply chain (processing, storage, transport, etc.)
- Access for farmers by the transport network. Low prices in recent years and deteriorating market access from flood affected roads have probably been greater contributing factors to loss of production than crop disease (Taylor et al. 2016).
- Worker productivity and a range of other relevant socio-economic factors impacting on the practices, lifestyles, and well-being of smallholder coffee production.
- The relative advantage or disadvantage of the PNG coffee industry compared to production in other developing countries (Latin America and the Caribbean, with African countries' production also contributing a significant proportion).

Working with coffee © Mr Rodney Sinaune (Niugini Digital Films) and Coffee Industry Corporation (CIC).

4 Projected climate hazard-based impacts on coffee in Papua New Guinea

Stakeholder workshop interaction (via Zoom, November, 2020) and scientific literature reviews informed our approach when assessing the potential impacts of projected climate changes, leading to the identification of the following questions about future coffee production in the PNG Highlands:

1. Will projected temperatures affect production suitability?
2. How do different greenhouse gas emission scenarios impact PNG's climate, in turn impacting coffee production?
3. How may extreme temperatures change in future?
4. Will changes in minimum temperature conditions affect pest and disease pressure?
5. What might the altitude profile for coffee production look like in the future?
6. How will projected rainfall conditions change, affecting coffee production?
7. Are drought conditions projected to change?

Methods outline

Spatial interpretation of current and future coffee production conditions are explored here using a GIS mapping platform. Current climate conditions for a 30-year period centred on 1995 (1981-2010) are shown, contrasting with a range of future climate scenarios that illustrate both best case (or least change) and worst case (or most change) for a 30-year period centred on 2050 (2036-2065). These future climate scenarios were presented to indicate the range of potential climate hazard-based impacts to which coffee production may be exposed. (See Methods details and data section at the end of this report).

Where relevant in explaining the analysis and assessment of the above questions, NextGen information 'Boxes' are included throughout the report (See NextGen country report – CSIRO and SPREP 2021).

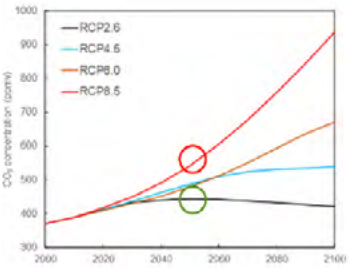
NextGen Climate Projection Information Boxes:

Box 1	'Worst case' and 'best case' scenarios
Box 2	Projected change: near term, medium term and long term
Box 3	Near-term variability and change

Box 1: ‘Worst case’ and ‘best case’ scenarios

The various scenarios of possible future climates are affected by

- global greenhouse gas and aerosol emissions pathways
- regional climate responses to each emissions pathway
- ongoing natural climate variability.



- ***High case*** - the world is following a high emissions pathway (RCP8.5) on track for 3.3-5.7°C global warming by 2100 (or even more), under a ‘fossil-fuelled development’ socio-economic pathway.
- ***Low case*** - the world is following a pathway to decarbonise the economy (net zero emissions) by 2070 (RCP2.6), giving a two-thirds chance of staying below 2°C global warming by 2100.

The ‘emissions’ component, often referred to as Representative Concentration Pathways (RCPs) (Van Vuuren, et al. 2011), must be framed as possible scenarios of human development and actions.

The ‘response’ component needs an analysis of various lines of evidence including how the climate responds to those emissions according to Global Climate Model simulations. For each emissions pathway, the main two dimensions of the broader climate response are the amount of global warming in response to the emissions (measured globally as ‘climate sensitivity’), and the change to regional circulation and weather systems (the ‘dynamical’ change). Simulations from different climate models can be used to assess the range of change in each of these parts of the story.

The table below shows projected changes in PNG annual temperature and rainfall. Median changes are given, with the 10-90 percentile uncertainty range in brackets. Changes are for 20-year periods centred on 2030, 2050 and 2070, relative to 1986-2005, for low emissions (RCP2.6: green) and high emissions (RCP8.5: red). In 2030, changes are similar for low and high emissions.

	2030	2050	2070	1.5°C global warming	2°C global warming	3°C global warming	4°C global warming
Temperature from 1986-2005 (°C)	0.7 (0.5 to 1.1)	🟩 0.8 (0.6 to 1.2) 🟥 1.4 (1.0 to 2.0)	🟩 0.8 (0.5 to 1.3) 🟥 2.2 (1.6 to 3.2)	0.8 (0.5 to 1.0)	1.2 (0.9 to 1.4)	2.1 (1.7 to 2.4)	2.9 (2.4 to 3.4)
Annual rainfall from 1986-2005 (%)	4 (-1 to 9)	🟩 4 (0 to 9) 🟥 7 (-1 to 15)	🟩 5 (-1 to 9) 🟥 10 (-1 to 20)	3 (-3 to 6)	6 (0 to 12)	8 (-2 to 18)	13 (-1 to 26)

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When planning to inform adaptation strategies for the future it is strongly recommended to consider a *range of plausible future climate outcomes* with regard to the influence of climate:

- ***Best case scenario*** – representative climate model CNRM-CM5 with a low emission pathway RCP2.6. This gives a lower warming over PNG with little change in rainfall (Figure 4, left).
- ***Worst case scenario*** – representative climate model GFDL-CM3 with a high emission pathway RCP8.5. This gives a higher warming over PNG with a wetter climate (Figure 4, right).

The temperature and rainfall changes simulated by all available climate models between the baseline and future period can be plotted as a 2D shape that describes the range of change for both the Low Case and High Case emission pathways. The two different scenarios – hot/wet and warm/little rainfall appear in diagonally opposite corners of each shape:

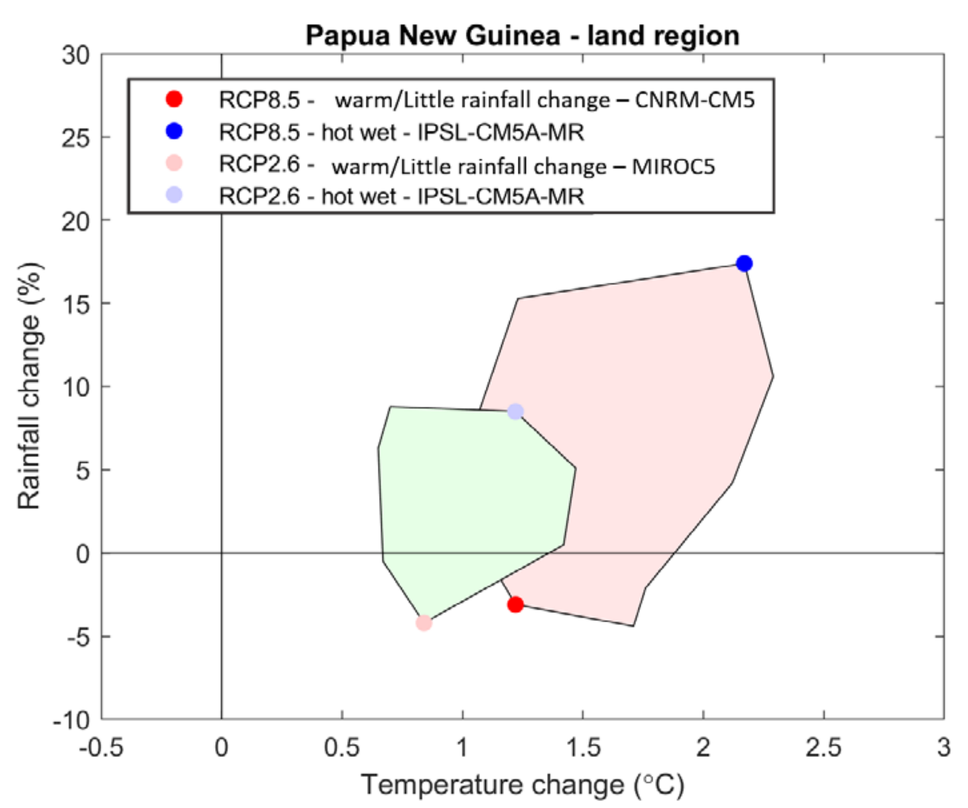


Figure 4 Simulated change in annual temperature and rainfall in the PNG region between 1986-2005 and 2040-2059 from CMIP5 models (coloured shapes), showing the selected climate models that are representative of a warm/little rainfall change future or ***best case scenario*** (CNRM-CM5) and a hot/wet future or ***worst case scenario*** (GFDL-CM3). Source: https://www.pacificclimatefutures.net/en/climate-futures/future-climate/.

4.1 Will projected warming affect suitability for coffee production?

In accordance with reviews of the literature and feedback from stakeholder engagement, this NextGen assessment defines the suitable areas for growing coffee under a current climate as where annual average temperatures are between 17°C and 24°C. In Figure 5, average temperatures above 24°C have been shaded red, while suitable areas, with temperatures between 17°C and 24°C, are shaded yellow, and lower than 17°C is shaded blue, with hatched shading showing locations of coffee plantations in 1993 (Bourke et al. 1993).

To estimate the suitability for growing coffee by 2050 (2036-2065), it is prudent to consider the potential range of projected temperatures. A 'best case scenario' (Figure 5; mid panel) and a 'worst case scenario' (Figure 5; lower panel) are therefore illustrated (BOX 1 describes how 'best case' and 'worst case' scenarios were selected).

By 2050 (2036-2065), the 'best case scenario' (a low emissions pathway and least change in temperature and rainfall) indicates a few areas that are currently suitable (yellow) may become too warm, i.e. more red shading (Figure 5; middle) but most areas may not be adversely impacted.

By 2050 (2036-2065), under the 'worst case scenario' (a high emissions pathway and most change to temperature and rainfall), some areas that are currently suitable (yellow) will become too warm as indicated by the increase in the red area compared to the current climate (Figure 5, bottom panel). Some areas currently too cool may become more suitable (reduction in blue area).

By 2050 (2036-2065), the area suitable for coffee growing increases from 71% currently to 76% for the best case scenario and 75% for the worst case scenario by 2050 due to an increase in the area that is too warm and a decrease in the area that is too cool (Table 2).

Table 2 Suitability for coffee growing by 2050 (2036-2065) (Percent of PNG Coffee districts see Figure 2). These calculations are drawn from the best case scenario (CNRM CM5, RCP2.6) and worst case scenario (GFDL-CM3, RCP8.5) (BOX 1) with emissions pathways and time periods as indicated.

Percent of PNG coffee district	Current (1981-2010)	Best case 2050 (2036-2065) (CNRM CM5, RCP2.6)	Worst case 2050 (2036-2065) (GFDL-CM3, RCP8.5)
Too cool (< 17°C)	29	23	15
Suitable (17°C – 24°C)	71	76	75
Too warm (>24°C)	0	1	10

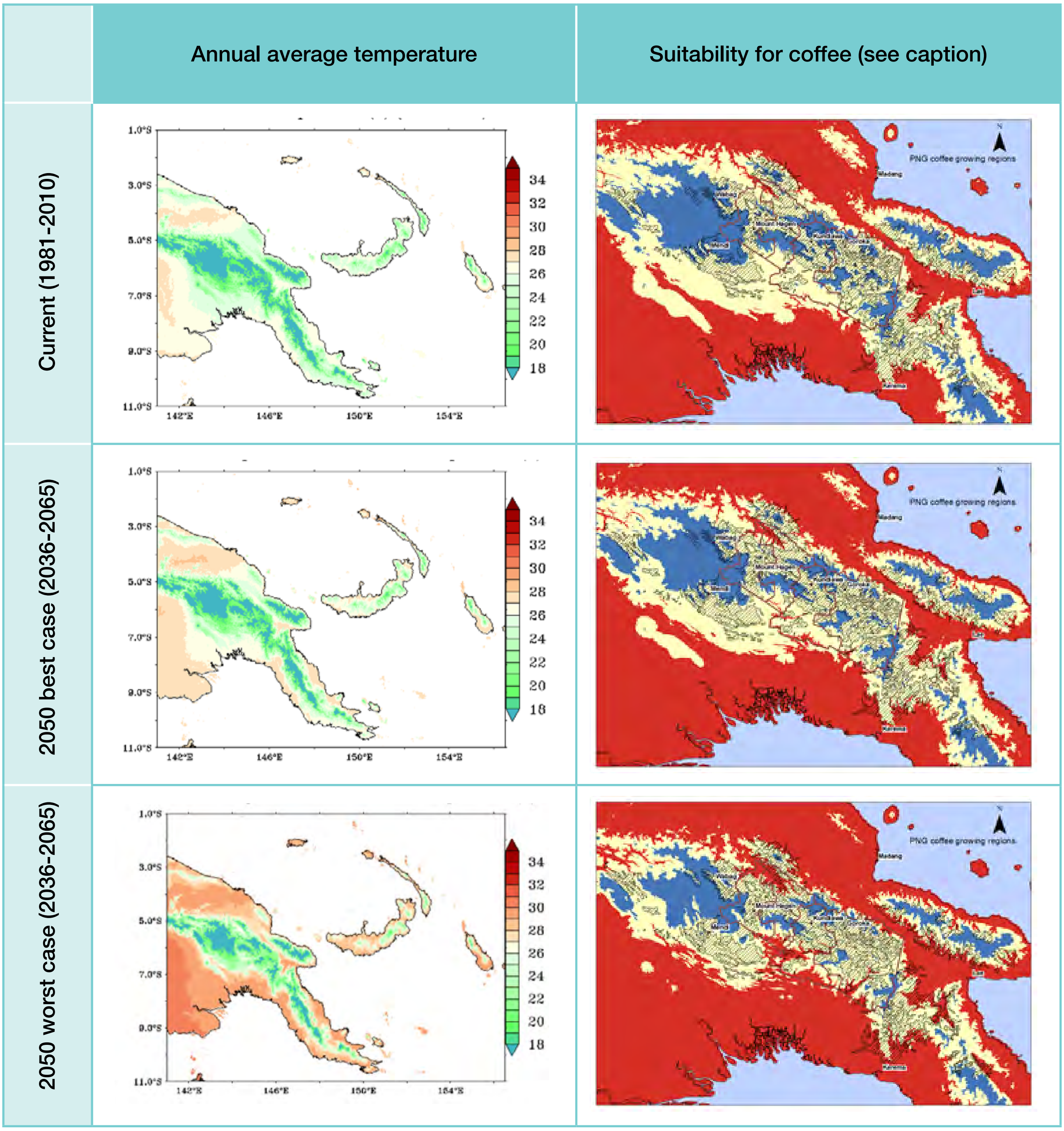
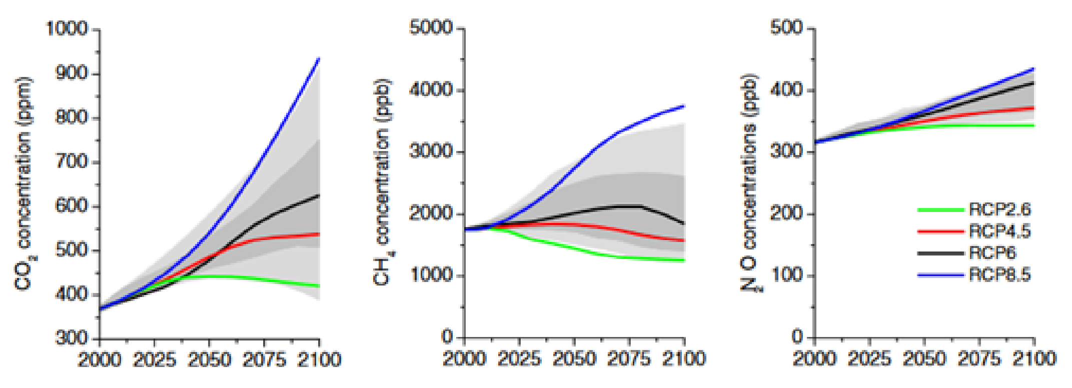


Figure 5 PNG annual average temperature (° C) (1981-2010) (top left) (Source: Adjusted WorldClim, see Methods details). Projected annual average temperature (°C) for 2050 (2036-2065) under best case (lower warming and low emissions; CNRM CM5, RCP2.6) (middle left) and worst case (higher warming and high emissions; GFDL-CM3, RCP8.5) (bottom left) climate scenarios. Coffee suitability maps (right) with coffee districts (brown lines) and coffee production areas (hatch) corresponding to different scenarios: optimal 17 - 24°C = yellow; warmer than optimal > 24°C = red; cooler than optimal < 17°C = blue.

4.2 How does the level of global greenhouse gas emissions impact Papua New Guinea's climate, in turn impacting coffee production?

Box 2: Projected change: near term, medium term and long term

Greenhouse gases (GHG) trap heat in the atmosphere. The main greenhouse gases are water vapour, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Human activities such as burning fossil fuels, agriculture and land-use change (e.g. deforestation) have increased GHG concentrations in the atmosphere. GHGs have a long lifetime in the atmosphere, so GHGs emitted today remain in the atmosphere for decades to come and it is not until a few decades have passed that differences in atmospheric concentrations will become apparent as seen in the graph below (Van Vuuren et al. 2011).



Projected temperature changes evolve in a similar way for PNG: under the high emissions pathway in the pink shaded band (RCP8.5), and a low emissions pathway in green (RCP2.6), with the model averages shown as thick lines (Figure 6). In the near term (2020-2039) the range of projected temperature change is similar for both emissions pathways, but in the medium term (2040-2059) the pathways begin to separate, and by the long term (2060-2079) the pathways give very different outcomes. By 2080, there is almost no overlap. Given the long lifetime of greenhouse gases in the atmosphere, early actions taken to reduce emissions by the global community can slow the rate of climate changes experienced. (NB these changes are relative to the pre-industrial 1850-1900 period, different to the PACCSAP baseline of 1986-2005) (CSIRO and SPREP, 2021)

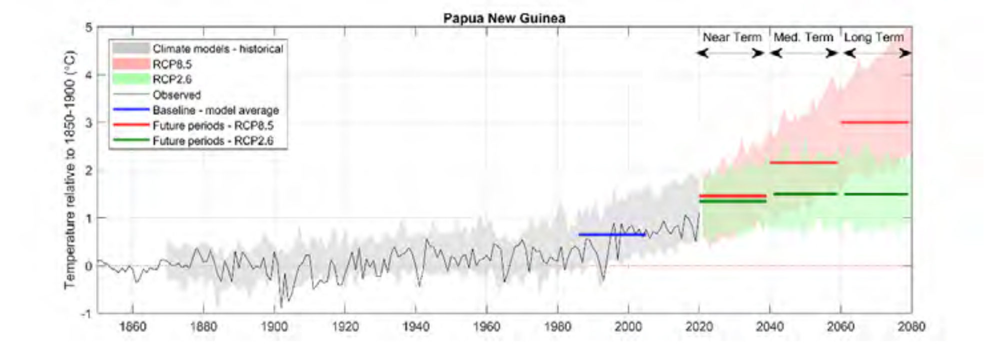


Figure 6 Climate model representation of historical and projected temperature time-series anomaly (cf. 1850-1900) for PNG (Mainland region). The top panel shows the observed temperature time-series anomaly (black line) superimposed on the 40-CMIP5 model representation of past climate (grey band) and projected temperatures to 2080 and under RCP8.5 (pink shading) and RCP2.6 (green shading). Red and green bars indicate the 40-model mean for 20-year periods, showing the growing difference in the projections into the future as described under the different RCPs, and also the remaining overlap of model range between the two (CSIRO and SPREP, 2021).

Relating different emissions pathways to the suitability for coffee production is illustrated by comparing the left- and right-hand columns of Figure 7. Here, there is negligible difference in suitable area (yellow) by 2030 under lower and higher emissions pathways. By 2050, however, the differences in suitability are more noticeable, with higher emissions causing a more negative impact. This difference gets larger through the century. By 2090, under a high emissions pathway, the effect on suitability is much greater than if a low emissions pathway is followed.

Coffee cherries at various developmental stages © Mr Rodney Sinaune (Niugini Digital Films) and Coffee Industry Corporation (CIC).

Coffee beans: unroasted (left) and roasted (right) © Mr Rodney Sinaune (Niugini Digital Films) and Coffee Industry Corporation (CIC).

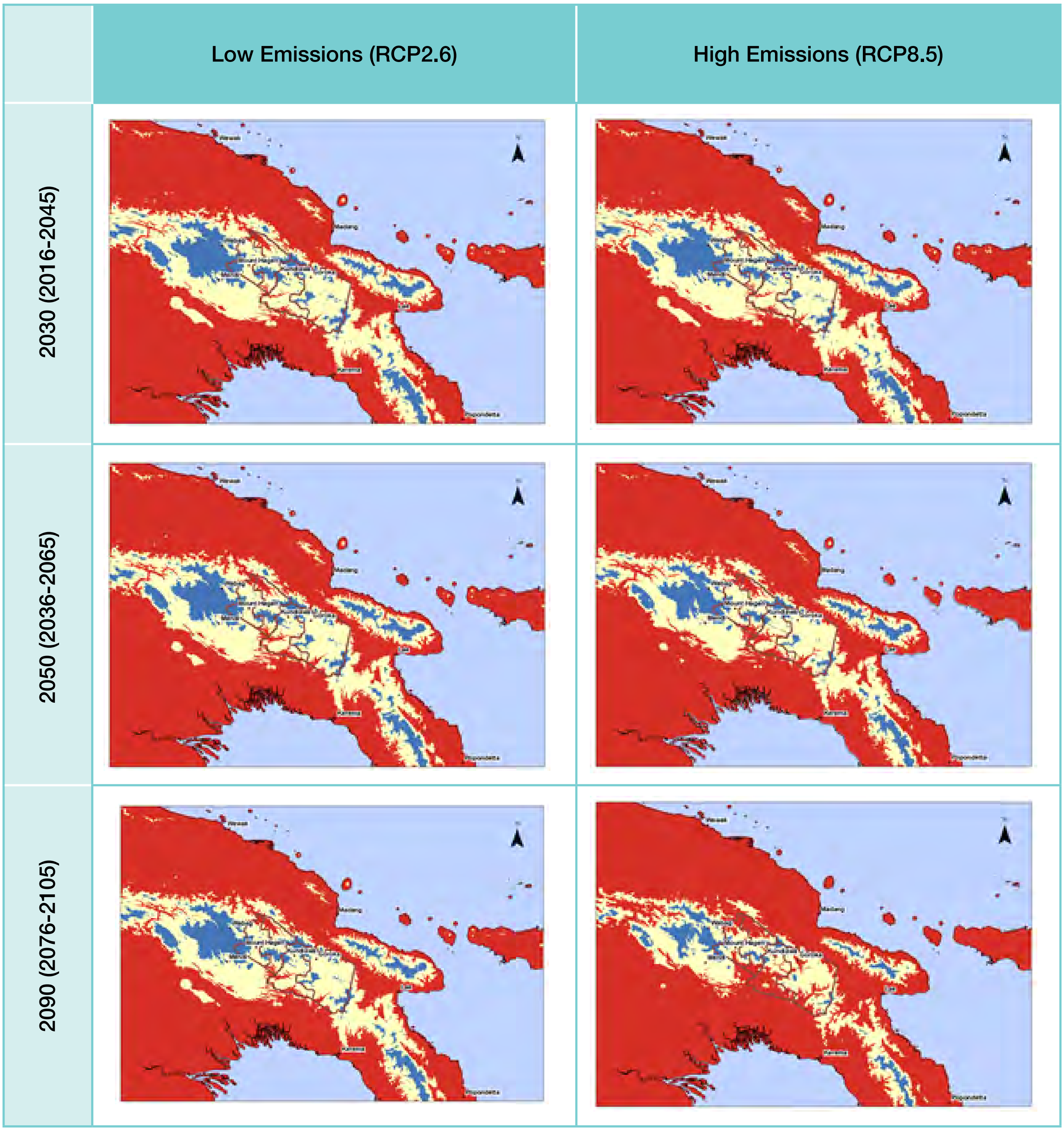


Figure 7 PNG annual average temperature (° C) with coffee districts (brown lines). Coffee suitability[1] maps: optimal 17 - 24°C = yellow; warmer than optimal > 24°C= red; cooler than optimal < 17°C = blue (GFDL-CM3, RCP2.6; left) and (GFDL-CM3, RCP8.5; right), for 20-year periods centred on 2030, 2050 and 2090 indicated from top to bottom. The maps for 2050 RCP2.6 and RCP8.5 are the same as those in Figure 4 for 2050 best case and 2050 worst case.

Under lower emissions the changes in suitability for growing coffee are minimal - around 77 % suitable in the current coffee growing districts (Figure 8), even toward the end of the century. However, under high emissions by 2090, the suitability is reduced to 68% with almost a quarter of the coffee growing district becoming too warm.

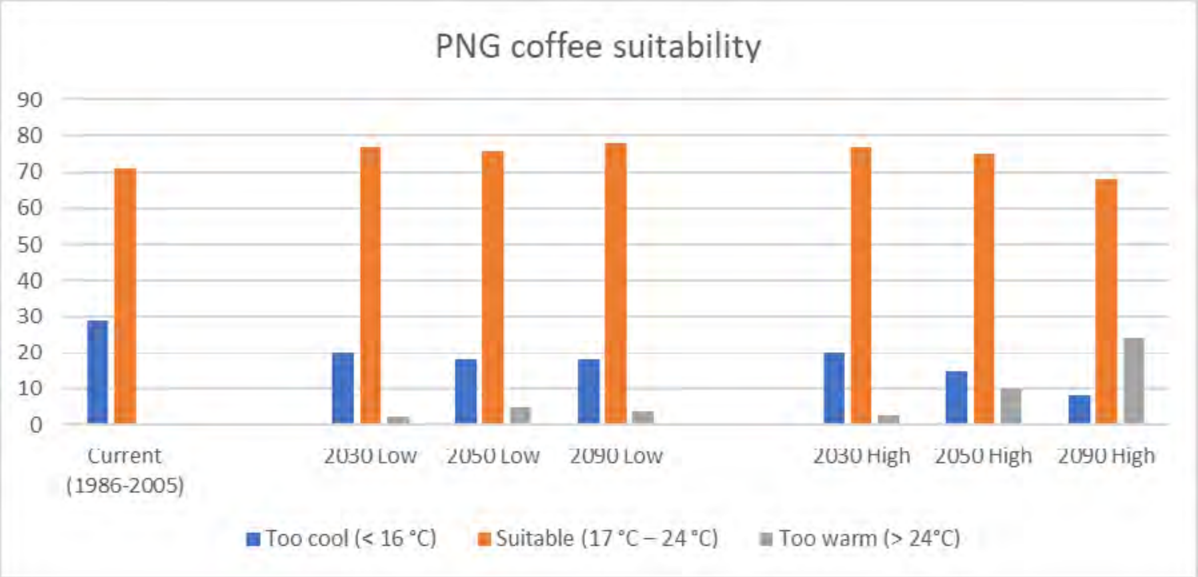


Figure 8 Suitability for coffee growing by 2050 (2036-2065) (Percent of PNG Coffee districts see Figure 2). These calculations are drawn from the best case scenario (CNRM CM5, RCP2.6) and worst case scenario (GFDL-CM3, RCP8.5) with emissions pathways and time periods as indicated.

The Paris Agreement target of keeping global warming to well below 2°C above pre-industrial levels is consistent with the best case scenario for PNG.

Continuous exposure to more extreme temperatures as high as 30°C leads to stress in coffee plants, which is manifest as depressed growth and abnormalities, such as the yellowing of leaves and growth of tumours on the stem (Taylor et al. 2016).

It has been reported that amplified warming is projected for elevated areas in PNG (Australian Bureau of Meteorology and CSIRO 2011), consistent with other regions of the world, and our physical theories of climate warming (Pepin et al. 2015).

In the PNG Highlands area, projected temperature changes could become an important limiting factor to coffee growing in some regions by 2050, and certainly by 2090 under if a high emissions pathway (***High case;*** RCP8.5) is followed. Conversely, this modelling indicates that under a low emissions pathway (***Low case;*** RCP2.6) suitability is not affected as much.

4.3 Will changes in minimum temperatures affect coffee leaf rust disease pressure?

Many of the current coffee growing areas in PNG may experience minimum temperatures which are sub-optimal for coffee production in the medium term (to approximately 2050), with the likelihood that pests and diseases will be a more prominent problem (Taylor et al. 2016).

Cooler conditions are currently experienced in the more elevated areas (Figure 9; top left). To determine the potential risk of CLR for PNG coffee production, regions with average January minimum temperatures above 15°C were defined as having a higher risk of fungal spread. (Please note, temperature is the only climate variable considered in this high-level assessment on CLR risk). In Figure 9 (top right), higher risk of fungal spread is shown in pink (26 % of coffee district) while lower risk of fungal spread is shown in blue (74 % of coffee district).

Under projected warming scenarios (see BOX 1), areas more suitable for fungal spread (pink shading) increase slightly under the 'best case' scenario (40 %; Figure 9; bottom left), and to a larger extent under the 'worst case' scenario (58 %; Figure 9; bottom right).

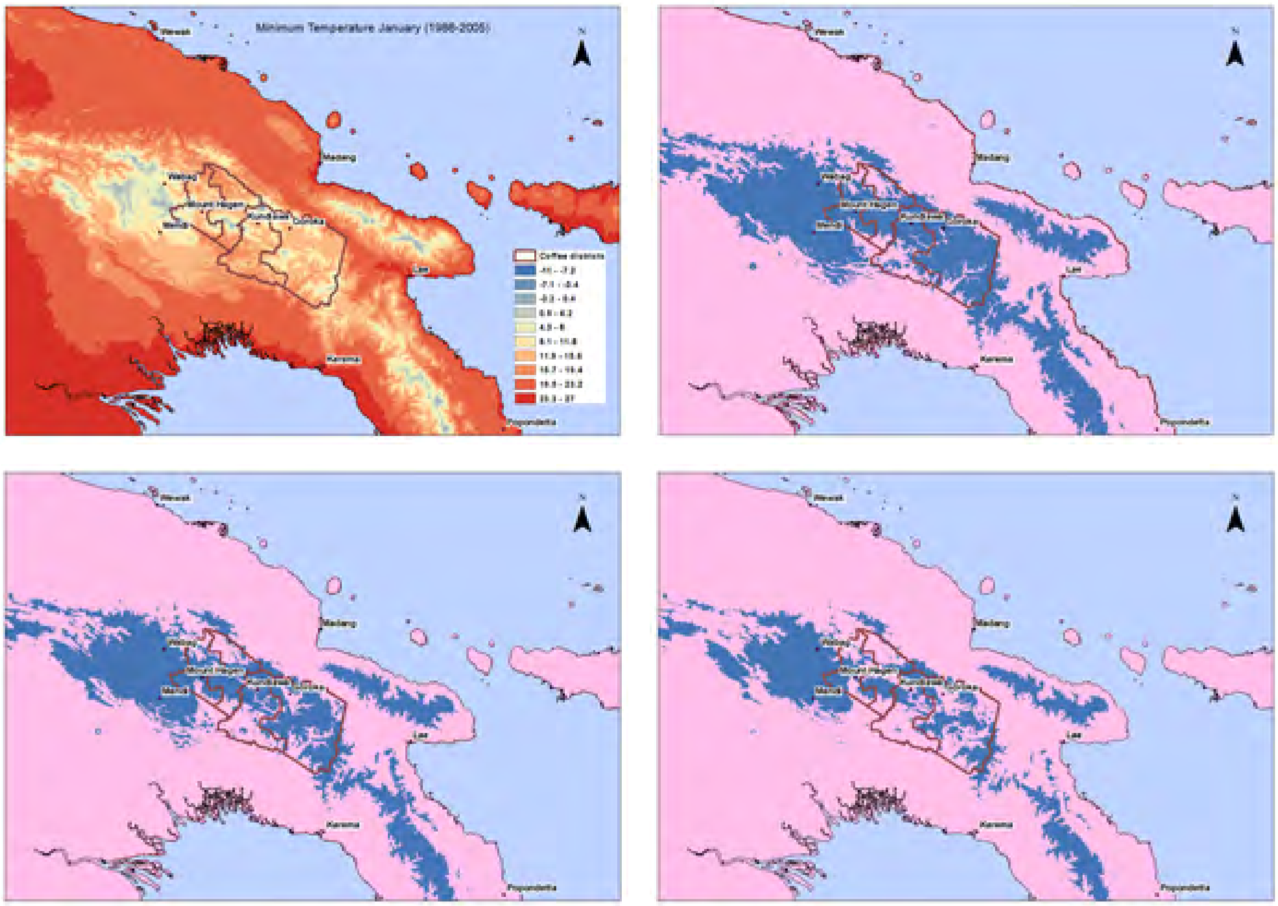


Figure 9 PNG minimum January temperature (°C) (1986-2005) (top left) (Source: Adjusted WorldClim, see Methods) with higher risk for CLR spread (top right; Higher risk: >= 15°C pink, Lower risk: < 15°C blue) under current climate (top right), for 2050 (2036-2065) under 'best case scenario' (model CNRM CM5, RCP2.6) (bottom left) and 'worst case scenario' (higher warming model GFDL-CM3, RCP8.5) (see BOX1) (bottom left).

This case study raises awareness that there is increasing risk of exposure to CLR in PNG. The 'best case' scenario results in less change to disease pressure, compared to the 'worst case' scenario, indicating a benefit from mitigation of emissions. This preferred outcome would be achieved by following the Paris Agreement aspirations, indicated by the 'best case' scenario.

4.4 What might the altitude profile for coffee production look like in the future?

The 1400 m elevation level corresponds well with the minimum January temperature boundary of 15°C under current climate conditions, because the lower risk CLR area (blue) occurs in these areas (Figure 10, top). By 2050, NextGen analysis showed that the area with higher risk of fungal spread is encroaching above 1400 m above sea level ('worst case scenario'; Figure 10, bottom).

It could be expected that, increasingly, areas currently classified as optimum (> 1400 m) for the production of Arabica coffee, could become more marginal.

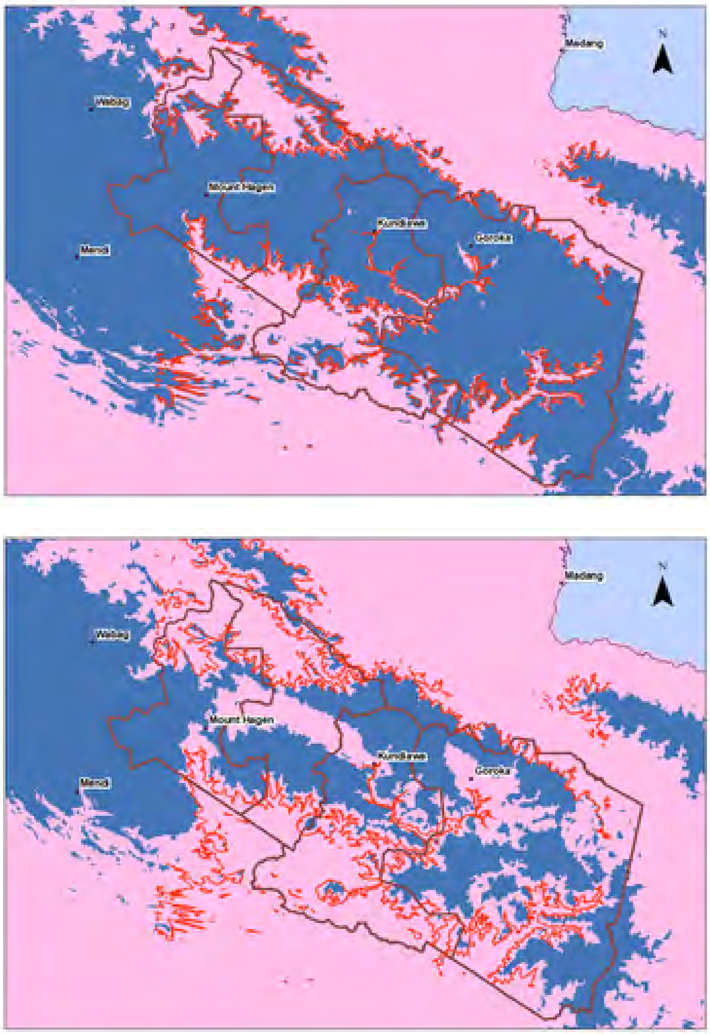


Figure 10 PNG minimum January temperature (° C) (1986-2005) (top) (Source: Adjusted WorldClim, see Methods) and 2050 (2036-2065) 'best case scenario' (lower warming model CNRM CM5, RCP2.6) (bottom left) and 'worst case scenario' (higher warming model GFDL-CM3, RCP8.5) (see BOX1) with risk for CLR spread indicated (Higher risk: >= 15°C pink, Lower risk: < 15°C blue). Elevation of 1400 m above sea level (red line) (Source: https://earthexplorer.usgs.gov/ see Methods)

Further to this argument, Jaramillo et al. (2011) predict that for every 1°C rise in average temperature, coffee will have to be grown about 150 m higher to avoid CBB damage, an emerging pest in PNG. In East Africa, the CBB is already present at altitudes of 1800 m and reports from Tanzania indicate that the insect has spread 300 m higher during the last 10 years.

4.5 How will projected rainfall conditions affect coffee production?

4.5.1 Changes to mean rainfall

For coffee growing, rainfall of 1250–3000 mm per annum, preferably between 1500–2000 mm, has been reported (Wood and Lass 2008), where Hanson et al. (1998) suggests annual rainfall of 1800-2600 mm, while Bourke and Harwood (2009) indicate coffee is grown where annual rainfall is 1800-5000 mm.

Overall, average rainfall changes under the 'best case scenario' indicate little change, however 'worst case scenarios' indicate that many areas may become too wet for optimal production (defined for this study as above 3000 mm) of coffee in PNG (modelling not shown). It is worth noting that the year-to-year rainfall variability over PNG is much larger than the projected change, except in the upper range of models in the highest emissions scenario by 2090 (Figure 11). Furthermore, it must be acknowledged that rainfall projections have lower confidence compared to temperature projections, so changes outside the projected range are possible.

It is important to note that there will still be wet years (increased fungal pressure or drainage issues) and dry years (reduced crop growth), and natural decadal variability. Any effect of climate change on average rainfall may not be obvious in the short or medium term due to this large natural variability. It can be noted however, that in future this rainfall variability will continue, with some periods showing wetting trends and other periods showing drying trends (Figure 12). This means that adaptation strategies require flexibility to deal with this rainfall variability, together with ongoing monitoring and evaluation of the effectiveness of adaptation strategies.

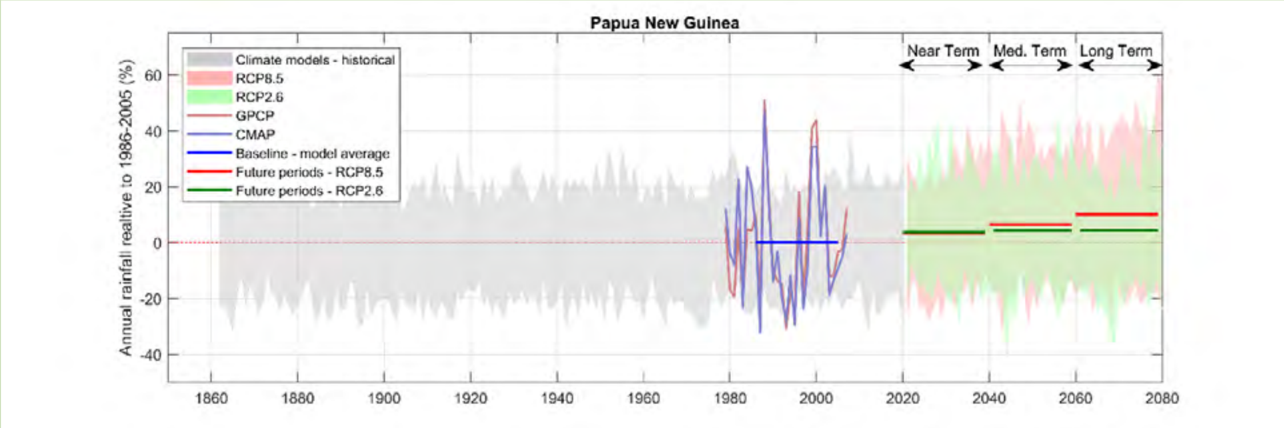


Figure 11 Average annual rainfall change in the PNG region (%) relative to 1986-2005 in two gridded observation datasets (GPCP and CMAP) and simulated in 40 CMIP5 climate models, showing the range of all models for the past period (grey), the future under a high emissions pathway (pink band) and a low emissions pathway (green band). Thick lines show the mean of all models for 1986-2005 (blue) and future 20-year periods centred on 2030, 2050 and 2070 (RCP8.5; red lines, RCP2.6; green lines) (CSIRO and SPREP, 2021).

Box 3: Near-term variability and change

Large variability and no clear long-term trend means the 10-year trend in 2021-2030 could be an decrease or increase. This is illustrated by the time-series in two examples below (Figure 12).

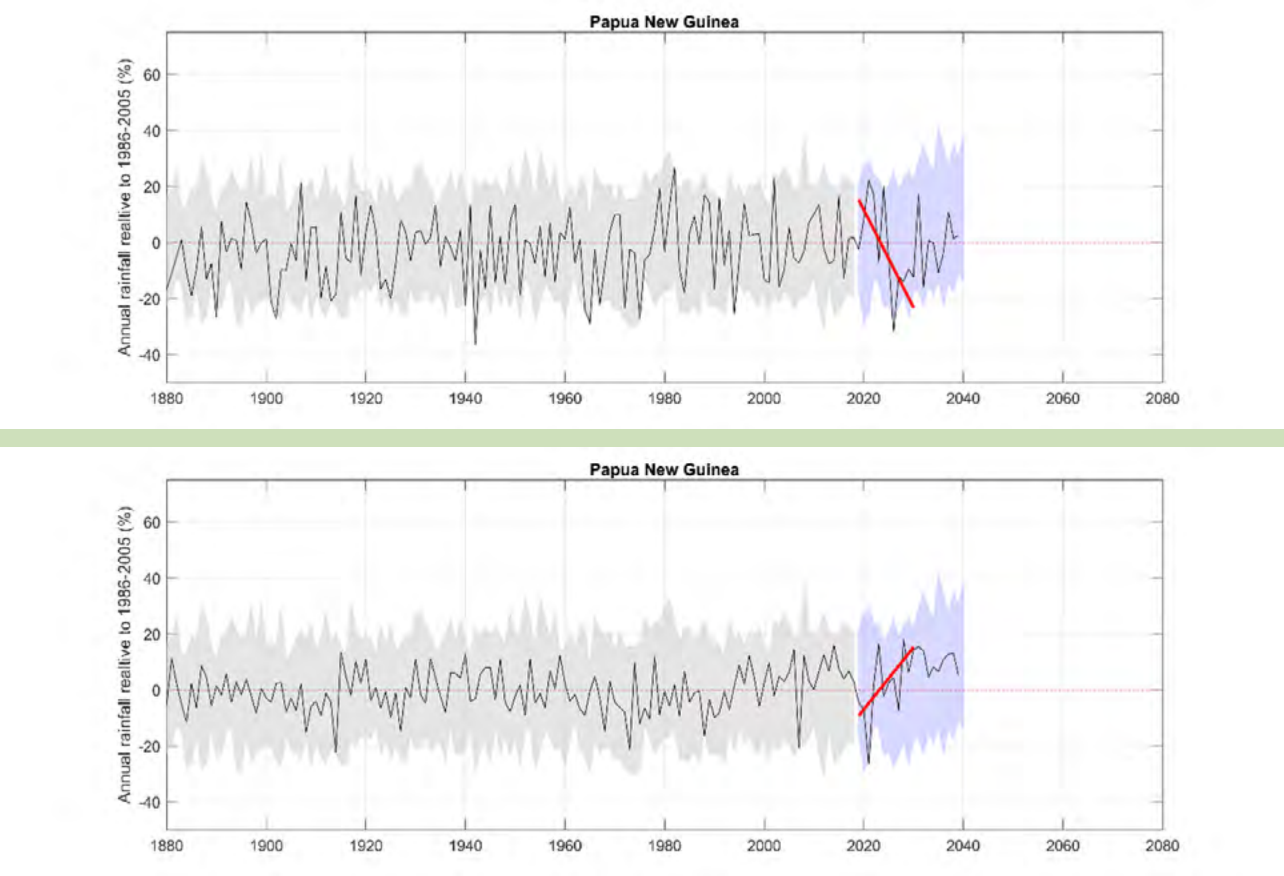


Figure 12 Annual rainfall anomaly (relative to 1986-2005) for the PNG (Mainland) region, with climate model simulations of historical variability (36 CMIP5 models; grey band) and future variability to 2040 (36 CMIP5 models, all RCPs; blue band). Individual climate model simulations produce hypothetical rainfall time-series (black lines) with short-term trends indicated (red lines) (top and bottom frames). (See NextGen PNG country report - CSIRO and SPREP, 2021).

The risk of CLR fungal disease is increased if rainfall is above 2500 mm per year. Since PNG already experiences risks from fungal disease partly due to existing rainfall patterns, then these rainfall projections suggest that this risk is very likely to remain, and possibly could become more intense or affect more areas in the future. This means that the industry is likely to continue needing to manage fungal disease into the future using techniques such as pruning, especially in wet years.

4.5.2 Will projected changes to intensity of extreme rainfall affect coffee growing in future?

Extreme rainfall can have implications for fungal disease as the higher moisture levels in the environment favour fungal growth. Additionally, extreme rainfall is also associated with flooding which can cause problems with drainage, soil erosion and accessibility to farms. Drainage is a critical component for selection of suitable sites for coffee farms (Harding et al. 1986).

PACSSAP projections indicate the frequency *and intensity of extreme rainfall events are projected to increase in PNG (Australian Bureau of Meteorology and CSIRO 2014). There is high confidence that the frequency and intensity of extreme rainfall events will increase because a warmer atmosphere can hold more moisture (Field et al. 2012). Furthermore, increases in extreme rainfall over PNG are projected in all available climate models.*

By 2030, the current 1-in-20-year daily rainfall amount (highest daily rainfall on average over a 20 year period) is projected to increase by approximately 14 mm under RCP2.6 and 12 mm under RCP8.5 on average. By 2090, it is projected to increase by approximately 21 mm for RCP2.6 and by 55 mm for RCP8.5 on average. By 2090, the majority of models project the current 1-in-20-year daily rainfall event will become, on average, a 1-in-7 year event for RCP2.6, and a 1-in-4 year event for RCP8.5 (Australian Bureau of Meteorology and CSIRO 2014).

The NextGen analysis performed for this case study highlighted that the annual maximum daily rainfall is also projected to increase in the future, though with a large variability. Figure 13 shows boxplots of the observed (1984-2013) and projected annual daily maximum rainfall over Aiyura. The median annual maximum daily rainfall amounts for 30 years centred on 2030 (2016-2045), 2050 (2036-2065) and 2070 (2056-2085) are projected to increase on average relative to 30 years centred on 2000 (1984-2013). Extreme rainfall over Aiyura both in hindsight and in projections are mostly less than 150 mm day-1. Rainfall projections have lower confidence compared to temperature projections, so changes outside the projected range are possible.

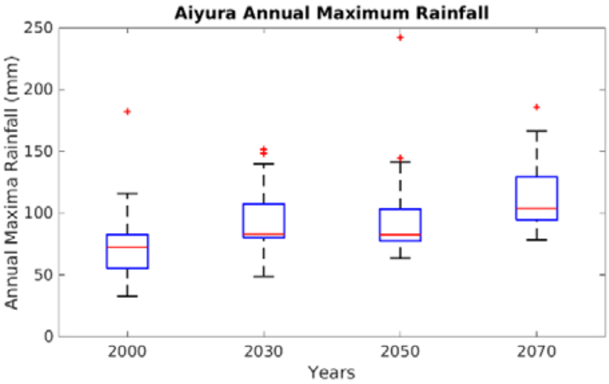


Figure 13 Boxplots of observed (1984 – 2013) and projected, 2030 (2016-2045), 2050 (2036-2065) and 2070 (2056-2085), annual maximum daily rainfall over Aiyura. Projections are made using the Hadley Centre Global Environment Model 2 - Earth System (HADGEM2-ES) under RCP8.5 scenario with Quantile-Quantile bias correction based on weather station data (see methods section).

4.6 Are drought conditions projected to change?

Droughts associated with El Niño can have major impacts on agriculture. The 2015–16 drought reduced food security in PNG (Iese et al, 2021). Drought and frost affected about 700,000 people and about 450,000 people faced critical food shortages, affecting peoples' health, diet and access to water (Iese et al., 2021).

The pattern of wetter and drier periods is also important for coffee growth, budding and flowering. Insufficient moisture can cause biennial bearing; wet conditions can delay ripening; small rainfall events can initiate flowering (Taylor et al. 2016) though there is agreement in the literature that a 2-month dry spell is important. Therefore, drought projections are relevant for coffee growers.

Future changes in rainfall variability for PNG are affected by the El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and Interdecadal Pacific Oscillation (IPO). An increase in strong El Niño and La Niña events is projected (Cai et al, 2014), along with more extreme positive phases of the IOD (Cai et al, 2018), but potential changes in the IPO are unknown (ESCC, 2020).

Drought projections are described in terms of changes in proportion of time in drought, frequency and duration by 2090 for RCP8.5 (Figure 14). For Papua New Guinea, the overall proportion of time spent in drought is expected to decrease in most locations, with the frequency and duration of drought in all categories projected to decrease. However, the intensity of drought is projected to increase.

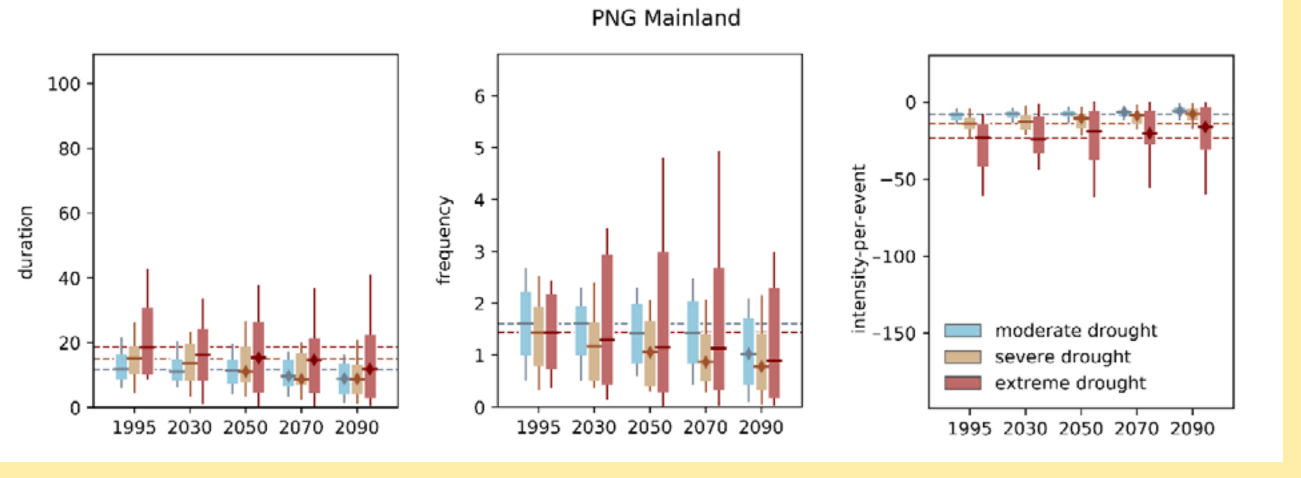


Figure 14 PNG mainland average of drought metrics (based on the Standardised Precipitation Index) for each drought category in the reference period (20 years centred on 1995) and future periods (20-year periods centred on 2030, 2050, 2070, 2090) (drought duration is in months, frequency is in "number of events per period", while intensity is unitless). The 34-model ensemble is shown as median, 10th and 90th percentile (bars) and minimum and maximum values (whiskers). The dashed lines show the multi-model median for the baseline period for each drought category. The diamond symbols denote that the median metric at a given period in the future statistically differs (with $p < 0.05$) to the mean metrics in the reference period (1995). For drought intensity, the more negative the value, the more intense the event (Iese et al. 2021).

5 Adaptation: Some preliminary notes

Coffee is likely to be affected by projected climate changes, potentially resulting in quality reductions (Taylor et al. 2016). The key impacts of climate change over PNG are an increase in annual mean temperature with more extremely high daily temperatures, and an increase in annual mean rainfall with more extremely high daily rainfall events.

The projected increase in annual mean temperature may slightly increase the area suitable for coffee by 2050, but the area may shrink slightly by 2090 if a high emissions pathway is followed (Figure 8). Temperature suitability may not translate to plantation suitability because shifting coffee production to the more elevated regions may be limited by terrain accessibility and land-ownership (e.g., including government-owned forest and/or nature reserves).

The increase in minimum temperatures, annual mean rainfall and extreme daily rainfall may increase exposure to pests and diseases such as CBB and CLR. Impacts are greater for the high emission scenario than the low emission scenario.

More extreme rainfall events may increase fungal disease, drainage problems, soil erosion and accessibility issues. A projected reduction in the frequency and duration of droughts would reduce food and water security risks.

There are several ways in which coffee producers can become more resilient to these challenges:

- Introduction of new farm management practices to minimise exposure to extremely high daily temperatures or extremely high daily rainfall, e.g. canopy management, soil management.
- Diversifying the farming system to incorporate other crops or products more suited to warmer growing conditions.
- Identifying whether coffee production in the PNG Highlands could be expanded further up the adjacent slopes of the catchment to follow the change in the optimal temperature growing envelope. Incursion into forested areas is of course subject to considerations of ongoing sustainability practices.
- Change aspect, e.g. less west facing, to reduce exposure to the hot afternoon sun, an adaptation strategy advised for grapevines in Australia (Webb et al. 2009).
- Introduce more shade trees to reduce heat stress (Teketay 1999, Taylor et al. 2016).
- Investigating changes through selective breeding to the crop variety could develop higher temperature tolerant varieties of coffee for production in existing farm areas of PNG (DaMatta and Ramalho 2006).
- Mulching reduces soil temperature, reduces soil erosion and conserves soil moisture (Teketay 1999).
- Where rainfall or moisture is adequate, it may be beneficial to plant cover crops with coffee (Teketay, 1999). The cover crops help to protect the soil from erosion, reduce soil temperature, build up the soil organic matter and fix atmospheric nitrogen if they are leguminous (Teketay 1999).
- Pruning to create greater freedom for air to pass through the coffee plot and individual trees, dries out the leaves more quickly after heavy rain, making conditions less favourable for the spread of certain diseases (Teketay 1999).

Further analysis of adaptation options can also be found in *Vulnerability of Pacific Island agriculture and forestry to climate change* (Taylor et al. 2016).

Coffee Nursery © Mr Rodney Sinaune (Niugini Digital Films) and Coffee Industry Corporation (CIC).

6 Methods details and data

The methodological framework used in this assessment can be found in the NextGen guidance document *Step-by-step: How to undertake a hazard-based climate change impact assessment* (CSIRO and SPREP 2022).

NextGen time series data Section 4: Box 2, Box 3

NextGen modelling reports results for 39 CMIP5 global climate models (Taylor et al. 2012) that are verified for use over the Pacific region (Grose et al. 2014). Changes for RCP8.5, RCP4.5 and RCP2.6, relative to the 'early industrial' period were calculated relative to 1850-1900, or 1880-1900 if data were available (e.g., BOX 2 and BOX 3). Trends over near-term periods were calculated using ordinary least squares linear fits.

Mean annual temperature was taken from the observed datasets HadCRUT4 (1850 to 2019; Morice et al. 2012), NOAA GlobalTemp (1880 to 2019; Zhang et al. 2017), Cowtan and Way (1850 to 2019; Cowtan and Way 2014) and GISTEMP (1880 to 2019; Lenssen et al. 2019). Seasonal average rainfall was taken from the observed datasets CMAP and GPCP (Xie and Arkin 1997, Adler et al. 2018).

Model and observed data were averaged over the exclusive economic zone (EEZ) of PNG, including all land and surrounding oceans, and regions are defined in Australian Bureau of Meteorology and CSIRO (2014) (Figure 15). For this coffee case study, the mainland region was used.

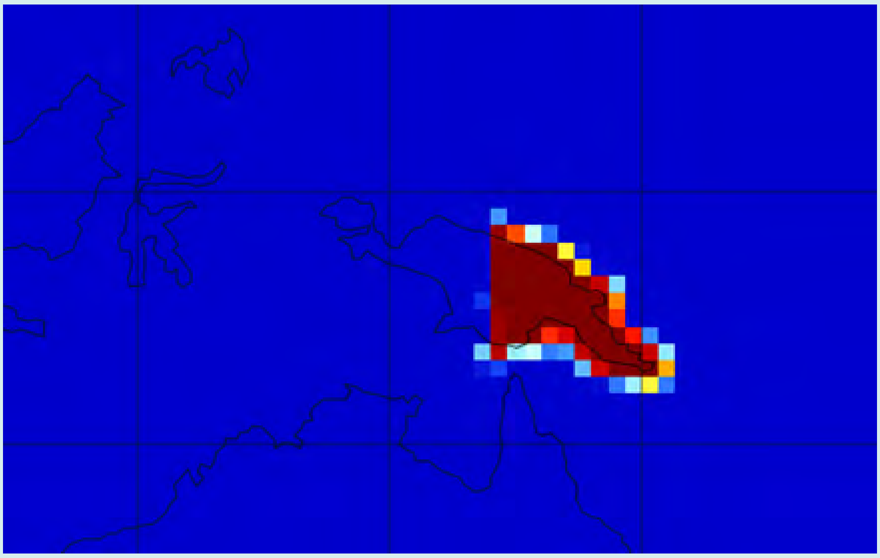


Figure 15 PNG Mainland region used for NextGen trend and projections analysis.

Climate projections future climatologies Sections 4.1, 4.2, 4.4, 4.5

Future climate data were produced using the delta change methodology (CSIRO and BoM 2015), where projected change data from CMIP5 models that perform well in the Pacific region (Grose et al. 2014) are applied to the Worldclim historical climatology as described in Figure 16. ‘Best case’ and ‘worst case’ climate models were selected using Climate Futures to capture the range of temperature and rainfall projections for PNG (CSIRO and BoM 2015).

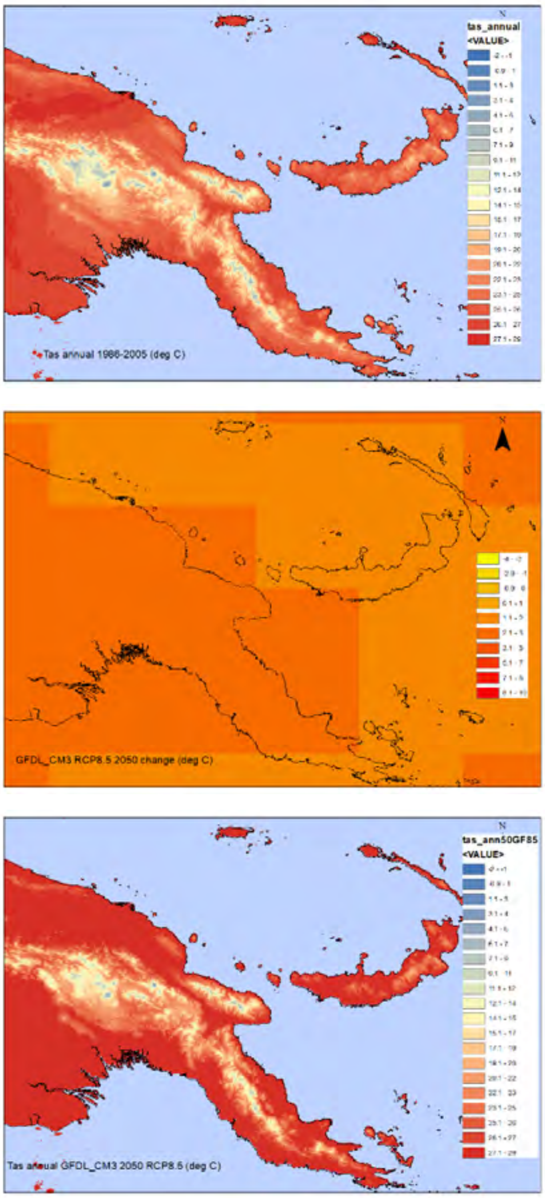


Figure 16 Delta change method for creating future climatologies (used to create Figures 5, 7, 9 and 10). Future annual mean temperature projection for 2050 (2036-2065) (GFDL-CM3 RCP8.5) (bottom) is created by adding projected temperature change (GFDL-CM3 RCP8.5 2050 change relative to 1995 (1986-2005)) (middle) to the observed current climate data (Modified Worldclim 1986-2005; see below in Methods section) (top).

Modified Worldclim temperature baseline dataset. Sections 4.1, 4.2, 4.4, 4.5

High-resolution climate surfaces for each month have been derived from Worldclim (Version 2) (Fick and Hijmans 2017) at www.Worldclim.org. Worldclim provides a globally consistent, high-resolution climatology of temperature. The Worldclim climatology represents the 30 years centred on 1985 (1970-2000) baseline period. This baseline has been modified for our analysis to represent 30 years centred on 1995 (1981-2010) period. This ensures consistency with CMIP5 projections used by PACCSAP based on a 1995 (1986-2005) baseline. The following steps were followed to produce modified Worldclim for use in this report:

1. Calculated average monthly global gridded temperature climatologies (CRU, GISS, Berkeley, NOAA, Cowtan-Way and JRA25anl) centred on the period 1985 and the period 1995 (for Cowtan and Way this was an anomaly dataset).
2. Calculated the differences in temperature across the two periods for each global gridded dataset.
3. Averaged the differences from all of the datasets.
4. Applied the average difference to the Worldclim 2.0 1985 climatology.

Digital elevation data. Section 4.5

Data (STRM) downloaded for the USGS world explorer website (https://earthexplorer.usgs.gov/).

Extremes. Section 4.6

For projections of annual maximum daily rainfall, the Hadley Centre Global Environment Model 2 - Earth System (HadGEM2-ES; (Collins et al. 2011)) outputs are used, obtained from the Infrastructure of the European Network for Earth System Modelling (IS-ENES) domain. HadGEM2 was found to be one of the models with substantial ability to reproduce not only a realistic climatology of tropical cyclones (TCs) but also the ENSO-TC relationship in the Pacific (Chand et al. 2017).

A Quantile-Quantile (QQ) scaling technique has been utilised to bias correct the projections against the Aiyura meteorological station daily-rainfall observations obtained from the Pacific data portal (http://www.bom.gov.au/climate/pccsp/) (QQ: https://www.climatechangeinaustralia.gov.au/en/obtain-data/application-ready-data/scaling-methods/.

Coffee in the landscape © Mr Rodney Sinaune (Niugini Digital Films) and Coffee Industry Corporation (CIC).

7 References

Adler, R. F., et al. (2018). "The Global Precipitation Climatology Project (GPCP) monthly analysis (new version 2.3) and a review of 2017 global precipitation." *Atmosphere* 9(4): 138.

AECOM (2018). PHAMA PNG Coffee Market Study. Queensland, Australia, Department of Foreign Affairs and Trade.

Australian Bureau of Meteorology and CSIRO (2011). Climate Change in the Pacific: Scientific Assessment and New Research. Volume 1: Regional Overview.

Australian Bureau of Meteorology and CSIRO (2014). Climate Variability, Extremes and Change in the Western Tropical Pacific: New Science and Updated Country Reports., Pacific-Australia Climate Change Science and Adaptation Planning Program, Australian Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organisation, Melbourne, Australia.

Bourke, R. M. and T. Harwood (2009). *Food and Agriculture in Papua New Guinea*, ANU E Press.

Bourke, R. M., et al. (1993). Mapping agricultural systems in Papua New Guinea. In Population, Family Health and Development. *Papers from 19th Waigani Seminar.* T. Taufa and C. Bass. University of Papua New Guinea, Port Moresby. Volume 1: 205-225.

Brown, J., et al. (1995). "The effect of temperature on the development of epidemics of coffee leaf rust in Papua New Guinea." *Crop Protection* 14(8): 671-676.

CABI, (2019). Invasive Species Compendium. Detailed coverage of invasive species threatening livelihoods and the environment worldwide *Hypothenemus hampei* (coffee berry borer)

Cai, W., et al. (2014). Increasing frequency of extreme El Nino events due to greenhouse warming. *Nature Climate Change*.

Cai, W., et al. (2018). Stabilised frequency of extreme positive Indian Ocean Dipole under 1.5 C warming. Nature communications, 9(1): 1-8.

Chand, S. S., et al. (2017). "Projected increase in El Niño-driven tropical cyclone frequency in the Pacific." *Nature Climate Change* 7(2): 123-127.

Collins, W., et al. (2011). "Development and evaluation of an Earth-System model–HadGEM2." *Geosci. Model Dev. Discuss* 4(2): 997-1062.

Cowtan, K. and R. G. Way (2014). "Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends." *Quarterly Journal of the Royal Meteorological Society* 140(683): 1935-1944.

CSIRO, Australian Bureau of Meteorology and SPREP (2014). Climate in the Pacific: a regional summary of new science and management tools, Pacific-Australia Climate Change Science and Adaptation Planning (PACCSAP) Program Summary Report. Melbourne, Australia, Commonwealth Scientific and Industrial Research Organisation.

CSIRO and BoM (2015). Climate Change in Australia Technical Report. M. Ekström, C. Gerbing, M. Grose et al. Melbourne, Australia, CSIRO Marine and Atmospheric Research and Bureau of Meteorology (CAWCR) and the Department of the Environment.

CSIRO and SPREP (2017). Developing Climate Change Information for the Pacific: Guidance Material to Raise Awareness and Facilitate Sectoral Decision-Making Using Science-Based Climate Change information and Services. Melbourne, Australia, Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat for the Pacific Regional Environment Program (SPREP).

CSIRO and SPREP (2021). Enhanced 'NextGen' Projections for the Western Tropical Pacific: Current and Future Climate for PNG. Final report to the Australia-Pacific Climate Partnership for the NextGen Climate Projections for the Western Tropical Pacific Project. Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat of the Pacific Regional Environment Programme (SPREP), CSIRO Technical Report, Melbourne, Australia.

CSIRO and SPREP (2022). Step-by-step: How to undertake a hazard-based climate change impact assessment. A report to the Australia-Pacific Climate Partnership-funded Climate Projections for the western tropical Pacific (NextGen) project. Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat of the Pacific Regional Environment Programme (SPREP), CSIRO Technical Report, Melbourne, Australia.

DaMatta, F. M. and J. D. C. Ramalho (2006). "Impacts of drought and temperature stress on coffee physiology and production: a review." *Brazilian Journal of Plant Physiology* 18(1): 55-81.

Davis, A. P., et al. (2012). "The impact of climate change on indigenous arabica coffee (Coffea arabica): predicting future trends and identifying priorities." *PloS one* 7(11): e47981.

De Jong, E., et al. (1987). "Temperature requirements for germination, germ tube growth and appressorium formation of urediospores of Hemileia vastatrix." *Netherlands Journal of Plant Pathology* 93(2): 61-71.

Dohmen, M. M., et al. (2018). Climate Smart Agriculture in Cocoa, World Cocoa Foundation.

ESCC (2020). Scenario analysis of climate-related physical risk for buildings and infrastructure: climate science guidance. Technical report by the National Environmental Science Program (NESP) Earth Systems and Climate Change Science (ESCC) Hub for the Climate Measurement Standards Initiative.

FAO (2019). "FAOSTAT." Retrieved 4/5/2020, 2020, from http://www.fao.org/faostat/en/#data/QC.

Fick, S. E. and R. J. Hijmans (2017). "WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas." *International Journal of Climatology* 37(12): 4302-4315.

Field, C. B., et al. (2012). "IPCC, 2012: Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of Working Groups I and II of the Intergovernmental Panel on Climate Change." *Cambridge University Press, Cambridge, UK, and New York, NY, USA* 30(11): 7575-7613.

Grose, M. R., et al. (2014). "Assessment of the CMIP5 global climate model simulations of the western tropical Pacific climate system and comparison to CMIP3." *International Journal of Climatology* 34(12): 3382-3399.

Hanson, L. W., et al. (1998). *Cocoa and coconut growing environments in Papua New Guinea*, Australian Agency for International Development.

Harding, P. E., et al. (1986). *A handbook for land suitability evaluation for rainfed arabica coffee production in Papua New Guinea*, PNG Coffee Research Institute.

Iese, V., et al. (2021). "Historical and future drought impacts in the Pacific islands and atolls." *Climatic Change 166*.

Jaramillo, J., et al. (2009). Thermal tolerance of the coffee berry borer Hypothenemus hampei: predictions of climate change impact on a tropical insect pest. *PloS one,* 4(8): e6487.

Jaramillo, J., et al. (2011). Some like it hot: the influence and implications of climate change on coffee berry borer (*Hypothenemus hampei*) and coffee production in East Africa. *PloS one,* 6(9): e24528.

Kushalappa, A., et al. (1983). "Application of survival ratio for monocyclic process of Hemileia vastatrix in predicting coffee rust infection rates." *Phytopathology* 73(1): 96-103.

Lenssen, N. J., et al. (2019). "Improvements in the GISTEMP uncertainty model." *Journal of Geophysical Research: Atmospheres* 124(12): 6307-6326.

Morice, C. P., et al. (2012). "Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set." *Journal of Geophysical Research: Atmospheres* 117(D8).

Nutman, F., et al. (1963). "Studies on the biology of Hemileia vastatrix Berk. & Br." *Transactions of the British Mycological Society* 46(1): 27-44.

Pepin, N., et al. (2015). "Elevation-dependent warming in mountain regions of the world." *Nature Climate Change* 5(5): 424.

Sengere, R. W. (2016). The rise, fall and revival of the Papua New Guinea coffee industry, Curtin University.

Taylor, K. E., et al. (2012). "An overview of CMIP5 and the experiment design." *Bulletin of the American Meteorological Society* 93(4): 485-498.

Taylor, M., et al. (2016). *Vulnerability of Pacific Island agriculture and forestry to climate change*, SPC.

Teketay, D. (1999). "History, botany and ecological requirements of coffee." *Walia* 20: 28-50.

Van Vuuren, D. P., et al. (2011). "The representative concentration pathways: an overview." *Climatic Change* 109(1-2): 5-31.

Webb, L., et al. (2009). "Extreme heat: managing grapevine response." *GWRDC and University of Melbourne: Melbourne*.

Wood, G. A. R. and R. Lass (2008). *Cocoa*, John Wiley & Sons.

Xie, P. and P. A. Arkin (1997). "Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs." *Bulletin of the American Meteorological Society* 78(11): 2539-2558.

Zhang, H., et al. (2017). NOAA Global Surface Temperature Dataset (NOAAGlobalTemp), Version 5.0. NOAA National Centers for Environmental Information.

8 Appendix

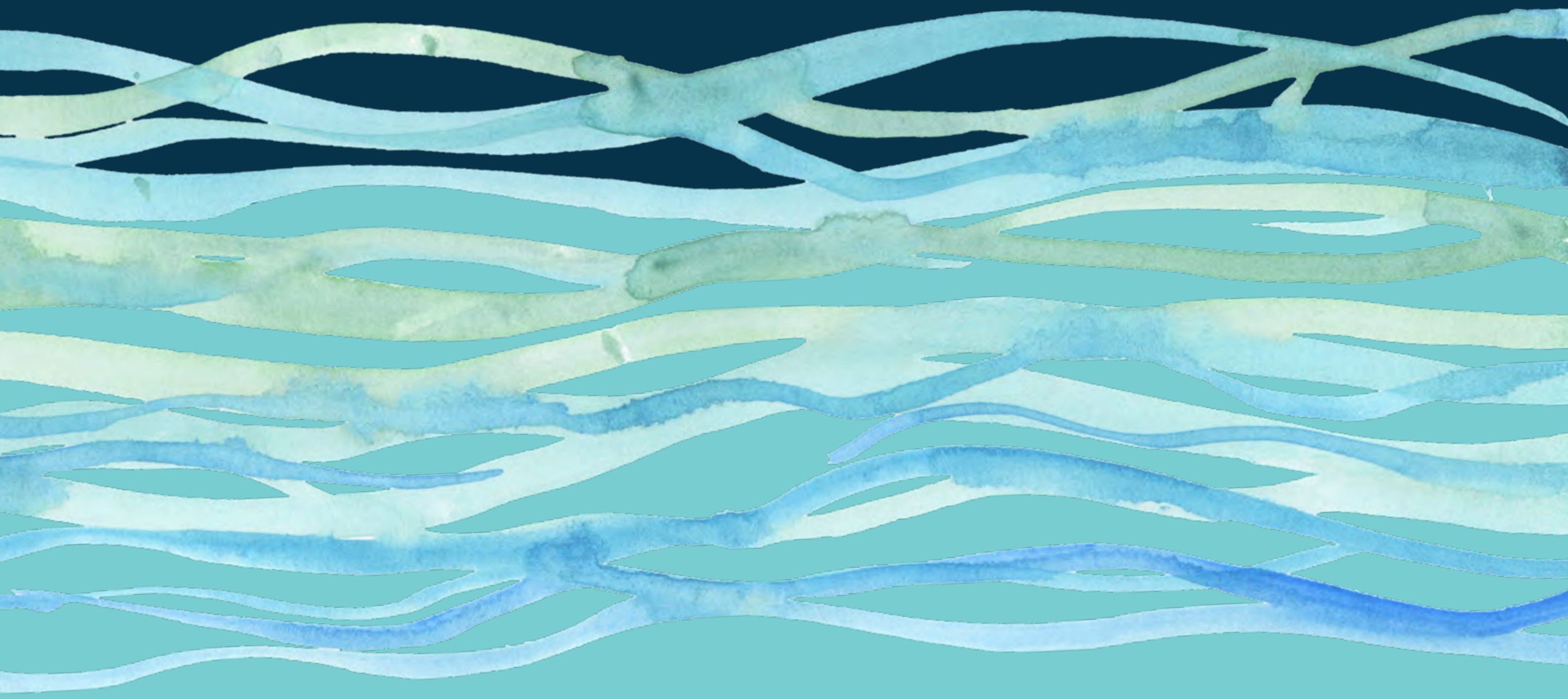
List of Workshop Attendees

Pacific Next Generation Climate Projections

Date: December 2020

Location: Port Moresby

Attendees	Organisation
Jacob Ekinye	Climate Change and Development Authority, PNG
Tom Kukhang	Coffee Industry Corporation, PNG
Chris Fidelis	Tavilo Cocoa Research Centre, Cocoa Board of PNG
Kasis Inape	National Weather Service, PNG
Kisolei Lina	National Weather Service, PNG
Kila Kila	National Weather Service, PNG
Allan Tobalbal Oliver	The World Bank, PNG
Adnan Falak	Market Development Facility, Pakistan
Nige Kaupa	Australian High Commission, Port Moresby
Nicholas Saunders	Australian High Commission, Port Moresby
Tanuvasa Semy Siakimotu	PHAMA+ Program, Australia
Dr John Moxon	Cocoa Board of Papua New Guinea
Potaisa Hombunaka	Coffee Industry Corporation, PNG
Bill Humphrey	Coffee Industry Corporation, PNG
Clement Kunandi Victor	Department of Agriculture and Livestock, PNG
Leanne Webb	CSIRO, Australia
Dewi Kirono	CSIRO, Australia
Johanna Johnson	Australia Pacific Climate Partnership, Australia
Gillian Starling	Australia Pacific Climate Partnership, Australia
Katie Frisch	Australia Pacific Climate Partnership, Australia
Hannah Barrowman	Australia Pacific Climate Partnership, Australia



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