National and sub-national climate projections for Vanuatu

TECHNICAL REPORT

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Contents

Acknowledgments

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Photo credits for the report: Dewi Kirono

Executive summary

This report presents information about long-term climate change projections for Vanuatu and its sub-national regions (see Figure below). This includes projections on mean and extreme temperature and rainfall, droughts, and tropical cyclones. Information about the respective historical climatology and trends are also provided as context for the projection information. The report also highlights implications of the study, including examples of application of the climate projections information, and future works.

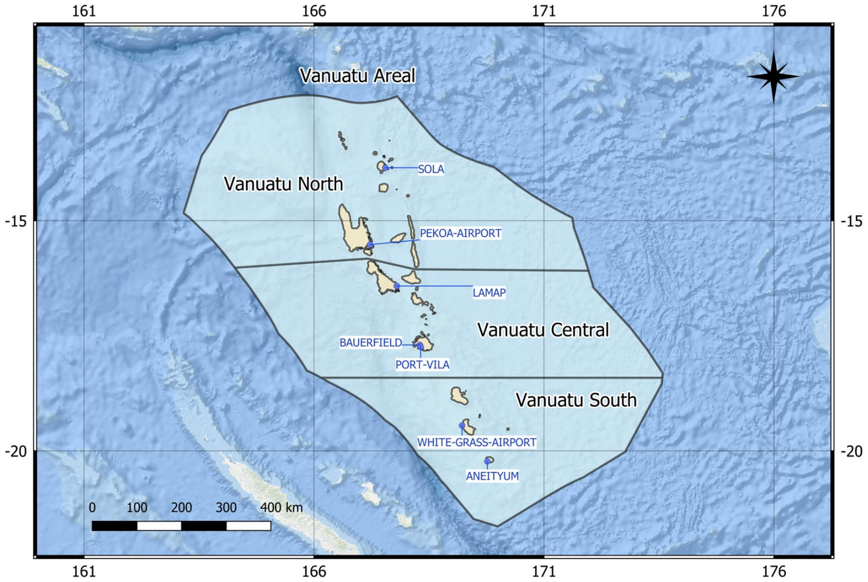

Figure ES. Map of Vanuatu and the three sub-national regions for which climate projections are reported. The locations of key meteorological observations stations used for the study are also shown. The pale blue shaded region delineates the Exclusive Economic Zone (EEZ) of Vanuatu

The report is developed by the Commonwealth Scientific and Industrial Research Organisation's Climate Science Centre (CSIRO CSC, Australia) as part of the Climate Projection Component for the *Climate Information Services for Resilient Development in Vanuatu (Van-KIRAP)* Project. Van-KIRAP is funded by the Green Climate Fund (GCF) and delivered by the Secretariat of the Pacific Regional Environment Programme (SPREP) and Vanuatu Meteorological and Geohazards Department (VMGD).

The study is built upon existing data and information. This includes analyses of observational and model simulation data, and literature review. The scope, methodology and presentation of results are guided by user needs identified through on-going stakeholder engagement over the project's lifetime. The report is designed to assist VMGD with their effort toward outreach and communications of climate projections information to their stakeholders or users, including the Van-KIRAP's targeted sectors (agriculture, fishery, infrastructure, tourism and water). The report also serves as a reference for other readers such as government officials, consultants, academia, NGOs, and donor agencies who have background knowledge about climate change and climate projections.

The key messages are summarised below.

Historical climatology and long-term trends, as context for climate projections

- Vanuatu's climate has two distinct seasons: a wet season (November to April) and a dry season (May to October). This climatology varies spatially, with the North tending to be hotter and wetter than the South.
- Extreme temperatures[1] vary little from one year to another across Vanuatu, whereas extreme rainfall[2] shows large variability depending on time and location.
- There is a clear long-term increase in mean annual temperature and in extreme hot temperatures in Vanuatu. In contrast, there is no significant long-term trend in mean annual rainfall and in extreme rainfall, with large year-to-year variability.
- The occurrence, duration and intensity of droughts[3] also varies with time and location, associated with El Niño Southern Oscillation (ENSO) phenomena. Long-term trends in drought vary spatially and are mostly not statistically significant.
- The average number of Tropical Cyclones (TCs)[4] is 33 per decade. The number of TCs over Vanuatu shows small decreasing trends, but the potential intensity of TCs has increased over recent decades.

Projections for mean climate

- The mean annual temperature is projected to increase, consistent with the observed historical warming. The projections are similar for all three sub-national regions and across the two seasons. However, the magnitude of warming varies temporally, with the greatest by the end of the 21st century; and is highly dependant on the Representative Concentration Pathways[5] (RCPs), with the largest for RCP8.5.
- There is no significant projected change in annual rainfall, consistent with the lack of observed historical trend, although some models project increase while others show decrease in rainfall. The projections are similar across the sub-national regions, although the Vanuatu South and Central regions show a small tendency towards drier conditions, particularly in the dry season.
- Projected changes in mean annual temperature and rainfall based on downscaled climate simulations using the CSIRO CCAM[6] model are in general consistent with those from the host Global Climate Models (GCMs).
- The projected changes in mean annual temperature and rainfall over the Southwest South Pacific Convergence Zone (SPCZ) region, where Vanuatu is located, are overall similar for both

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[1] Represented by the hottest day of the year (TXx), the hottest night of the year (TNx) and the coldest night of the year (TNn).

[2] Represented by the maximum daily rainfall of a given year (Rx1day).

[3] Represented by the Standardized Precipitation Index (SPI).

[4] With wind of at least 35 kt that passed through the VMGD area of responsibility between 1980-2021.

[5] RCPs are scenarios of future greenhouse gas concentrations in the atmosphere and the radiative forcing (i.e. additional energy taken up by the Earth system), caused by human activities.

[6] Conformal Cubic Atmospheric Model.

CMIP5[7] and CMIP6[8] GCMs. This implies that the results of this study would be relatively consistent if we were to use CMIP6 GCMs data.

Projections for extreme climate

- Extreme temperatures[9] are projected to rise by a similar magnitude to mean temperatures. The projected increase is similar across the sub-national regions, although slightly higher over Vanuatu South.
- Extreme rainfall[10] is generally projected to become more intense over Vanuatu South and Vanuatu Central. For Vanuatu North, the projections are unclear, with some models projecting decreases and others projecting increases.
- Projections for droughts duration and frequency are less clear, because there is a large range of projections across all the models, with both increases and decreases possible. However, most models agree in projecting a shift toward more intense droughts. The projections are similar across the sub-national regions.
- The number of TCs affecting the Vanuatu region is projected to slightly decrease, consistent with a small decreasing trend in the observed historical data. The projected change is also in agreement with those based on different TC modelling techniques for the broader South Pacific region.

[7] The coupled model intercomparison project phase 5 used in the IPCC's Fifth Assessment Report (AR5) (IPCC, 2013).

[8] The coupled model intercomparison project phase 6 used in the IPCC's Six Assessment Report (AR6) (IPCC, 2021).

[9] As represented by the annual hottest day, hottest night, coldest night and 1-in-20 year hottest temperature. The 1-in-20 year hottest temperature represents the temperature that has on average a 5 per cent chance of happening in any given year.

[10] Measured by the maximum daily rainfall of a given year (Rx1day) and 1-in-20 year extreme daily rainfall (i.e. daily rainfall value that has on average a 5% chance of happening in any given year).

Part I Introduction

1 Introduction

1.1 Vanuatu – contextual setting

The Republic of Vanuatu is located in the South Pacific Ocean between latitudes 13 to 21^{o}S and longitudes 166 to 171^{o}E. Consisting of over 80 individual islands, the country was inhabited by over 307,000 people in 2022. The combination of the nation's exposure to natural hazards, extensive low-lying coastal zone, development stage and dependence on the natural-resources-based economy makes Vanuatu one of the most vulnerable nations to climate change in the world (The World Bank Group, 2021).

The key important features of the climate system affecting Vanuatu are the South Pacific Convergence Zone (SPCZ), Trade Winds and the Sub-Tropical High systems (Figure 1) (Australian Bureau of Meteorology and CSIRO, 2011). As a results, the climate of Vanuatu is distinctly marked with a wet season from November to April and a dry season from May to October; Spatially, it varies from wet tropical in the north (with a mean annual rainfall of around 4000 mm) to subtropical in the south (with a mean annual rainfall of roughly 1500 mm); and is highly exposed to Tropical Cyclone (TC) activity and the El Niño Southern Oscillation (ENSO) variability.

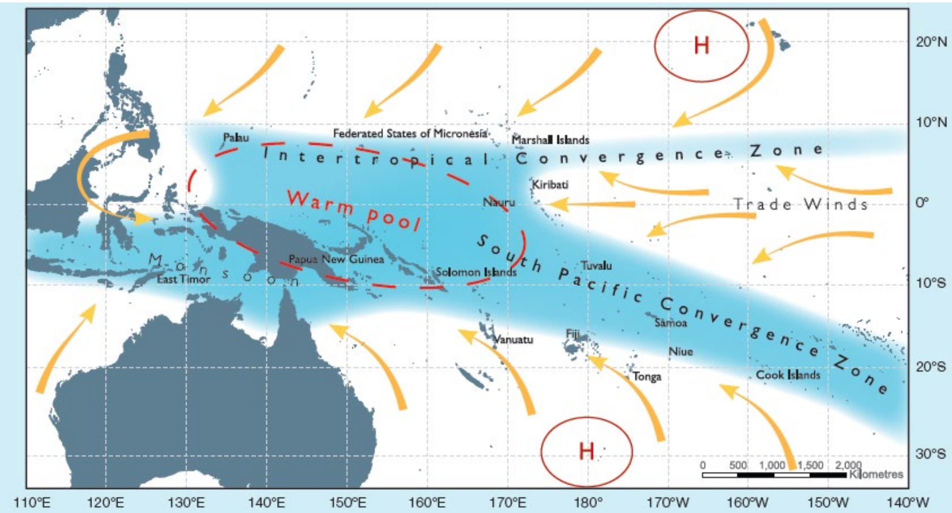

Figure 1 The average positions of the key climate features over the west Pacific region, where Vanuatu is located, in the wet season (November to April). The yellow arrows show near-surface and trade winds, the blue shading represents the convergence zones with relatively low pressures, and H represents the typical positions of moving high pressure systems. Source: Australian Bureau of Meteorology and CSIRO (2011)

Recognising the close link between Vanuatu's climate and development, there have been many climate change programs and projects implemented for the country over the years (MoCC, 2021). These include research on climate change as well as capacity building, education and training. One of the current related efforts is supported by the Vanuatu Climate Information System for Resilient Development project (Van-KIRAP).

1.2 Van-KIRAP: Project background and objectives

Launched in early 2018, Van-KIRAP is funded by the Green Climate Fund (GCF), implemented and managed by the Vanuatu Meteorological and Geohazards Department (VMGD) and the Secretariat of the Pacific Regional Environment Programme (SPREP). Three Delivery Partners, i.e. the Commonwealth Scientific and Industrial Research Organisation's Climate Science Centre (CSIRO CSC, Australia), the Bureau of Meteorology (BOM, Australia) and the APEC Climate Centre (APCC, South Korea), provide technical inputs to the Project.

Van-KIRAP's objectives are to build the technical capacity in Vanuatu to harness and manage climate data; develop and deliver practical Climate Information Services (CIS) tools and resources; support enhanced coordination and dissemination of tailored information; enhance CIS information and technology infrastructure; and support the application of relevant CIS through real-time development processes (see Box 1 for basic concepts related to CIS).

These objectives are achieved through five project's Components:

- Component 1: Strengthen the VMGD platform to provide quality climate data and information for Climate Information Services (CIS)
- Component 2: Demonstrating the value of CIS at the sectoral and community levels
- Component 3: Development of CIS tools and engaging with stakeholders through outreach and communications
- Component 4: Strengthening the institutional capacity for long-term implementation of CIS in decision-making
- Component 5: Project coordination and management

One of the expected outputs of Component 1, in particular, is "Research, modelling and prediction to support CIS tools and uptake". Under this component, there is an Activity 1.2.3 which is tasked with developing long-term climate projections (Box 2) for key climate variables and climate extremes for Vanuatu. This report describes the work of and findings from Activity 1.2.3.

Box 1: Basic definitions related to Climate Information Services (CIS)

Climate data: Historical and real-time climate observations along with direct model outputs covering historical and future periods. Information about how these observations and model outputs were generated ("metadata") should accompany all climate data.

Climate product: A derived synthesis of climate data. A product combines climate data with climate knowledge to add value.

Climate information: Climate data, climate products and/or climate knowledge.

Climate service: Providing climate information in a way that assists decision making by individuals and organisations. A service requires appropriate engagement along with an effective access mechanism and must respond to user needs.

(Source: GFCS, 2014)

Box 2: Definitions related to climate projections

Weather is the atmospheric conditions—like rain or hot day—that happens over a few hours, or days. For example, the weather in Vanuatu on 12 September shows air temperature of 28^{o}C and rainfall of 0 mm.

Climate is usually defined as the average weather conditions in a particular region over a long period of time (20 or 30 years or more). For example, the average weather in Vanuatu in September is characterised by an average air temperature of 27^{o}C and rainfall of 3 mm/day.

Climate change refers to a change in the state of the *climate* that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer (IPCC, 2007).

Long-term climate projections refer to climate change average weather conditions in a future period (e.g. 2040-2059) relative to a baseline period (e.g. 1986-2005).

1.3 About this report

The outputs of Activity 1.2.3 are disseminated through a range of climate information products (Box 3), including this report.

The purpose of this report is to describe: the objectives of the work (Chapter 1) and the scope and approaches (Chapter 2); methods (Chapter 3); findings, i.e. climate information[11] (Chapter 4 to 6); the contribution of this work to Vanuatu's effort in enhancing their CIS (Chapter 7); and suggested future works (Chapter 8).

The report serves as a communication tool for disseminating climate information product as well as a reference on how the information was generated, as part of a CIS[12]. This report complements the *'NextGen' Projections for the Western Tropical Pacific: Current and Future Climate for Vanuatu* report (CSIRO and SPREP, 2021) as well as the PCCSP and PACCSAP climate projections for the Pacific (Australian Bureau of Meteorology and CSIRO 2011 and 2014).

The main target audience is VMGD who is the authority to provide official Weather, Climate and Geohazards information for Ni-Vanuatu. Others such as Government Ministries and Departments, consultants, academia, NGOs, and donor agencies who have background knowledge about climate change and climate projections will also benefit from this report.

The report is designed to assist VMGD with their effort toward outreach and communications of climate change projections to their stakeholders or users, including Van-KIRAP targeted sectors.

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[11] As defined in Box 1

[12] Ibid 11

Following the inputs from stakeholders, the findings of the work are presented through synthesized forms such as figures or tables, accompanied by the key messages. Such figures, tables and the associated key messages can easily be used for developing a power point presentation or a leaflet, for instance. This approach has been found useful in assisting VMGD and the targeted sectors in enhancing their understanding as well as in communicating and disseminating technical climate projection information.

Box 3: Climate projection information products and disseminations – pathway to Vanuatu CIS

The outputs of Activity 1.2.3 are disseminated through a range of climate information products and services[13]. These include, but not limited to:

- this report, which contains climate information in a form of figures, tables and associated interpretations as well as how the information were generated. The report is provided to VMGD, Van-KIRAP targeted sectors and the public in digital format (Portable Document Format, pdf) by means of digital transfer and/or through VMGD / Van-KIRAP web-portal
- outreach activities such as in-person presentations and webinars to various audiences (e.g. government, sectoral and local representatives) through a series of events (workshops, meetings and site visits) (see Appendix 1 for details)
- digital distribution of PowerPoint (ppt) / pdf files and the records of the presentations / webinars to participants of a given event and upon request
- provision of relevant materials (e.g. text, figures, tables) and guidance for outreach activities which were undertaken by the Van-KIRAP project or VMGD (e.g. Van-KIRAP's presentation to the Vanuatu National Consultations on Climate Change, Disasters and Displacement run by the International Organisation for Migration, IOM UN Migration, in late August 2021)
- provision of selected datasets through the Van-KIRAP web-portal, which is developed by CSIRO through Van-KIRAP Activity 1.1.2 (Building and strengthening user interfaces to support CIS Decision-making)
- provision of relevant materials for the sectoral case studies and associated summary information products, which are developed by CSIRO
- expert advice for inclusion into Van-KIRAP sectoral case studies proposals, which were developed by sector coordinators.

[13] Aligned with the global standard definitions presented in Box 1 and other literatures (e.g. Bouroncle et al. 2019), we define climate information product as a publication that is made available to potential target group of users to support their need. Products can be in a form of data; information; expert advice; communication tools such as presentations, leaflets, reports, etc. Meanwhile, products delivery (i.e. Climate Service) can be provided through different channels such as websites, emails, social media etc.

2 Scope and approach

2.1 Stakeholder engagement: understanding user needs and consultation

A series of ongoing stakeholder engagements was undertaken to guide the scope and approach for this work (Appendix 1). Some of the engagements such as Project Inception Workshop and Project Technical Working Group meetings were part of and organised by Van-KIRAP Project Management Unit (PMU), while others were organised specifically by CSIRO and/or Activity 1.2.3.

Stakeholder engagements are important to facilitate iterative two-way communication, participation and social learning which are considered to be superior to one-way flows of information from research to practice (e.g. Kirono et al., 2014; Palutikof et al., 2019). This approach enables all parties involved to design and produce knowledge together, while also to build awareness and capacity of stakeholders on climate risks and adaptation issues. More importantly, the process helps ensure the study addresses the need of the users.

We define stakeholders as individuals or groups who are affected by, or affect, or have an interest in the outcomes of the project. This includes VMGD, Van-KIRAP targeted sectors, governmental organisations and others. The summary of Van-KIRAP user matrix is shown in Appendix 1.

The process started in February 2018 through the Van-KIRAP Project Inception Workshop. At this workshop, the team identified initial user needs and scope for the work. We used this finding along with other considerations to guide subsequent activities, including the ongoing stakeholder engagements through meetings, workshops, email communication and so on (Appendix 1) as well as defining the scope and approach for the analyses and for presenting results.

2.2 Timelines

The Van-KIRAP project began in January 2018 but underwent a review in early 2019 to ensure that the project was still relevant to align with the emerging priorities of the sectors and government (FCG New Zealand, 2021). This resulted in changes to the number and structure of Project Components, including Activity 1.2.3 which is the focus of this report.

Activity 1.2.3 was undertaken through several stages with pauses in between as follows:

- Van-KIRAP Project inception workshop in February 2018
- The 1st 6-months workplan implementation from October 2018 to June 2019
- The 2nd 6-months workplan implementation from August 2019 to February 2020
- The 3rd workplan implementation from November 2020 to December 2021
- Reporting period from August 2022 to June 2023

2.3 Scope and approach

The scope of the study, the method and the presentation of results are guided by user needs identified through a series of iterative and two-ways user consultations throughout the project lifetime (Appendix 1), generally known as a co-design process.

2.3.1 In scope

- Develop long-term projection information for key climate variables and climate extremes for Vanuatu (Table 1)
- The analyses are built upon existing data and information that are available publicly and/or upon request at the time of the study.

New analyses include:

- evaluation of climate model performance over Vanuatu
- projected changes for three sub-national regions (Figure 2) for selected climate variables and future periods (Table 1) as requested by stakeholders
- projected changes based on the 50 km resolution of CSIRO dynamical downscaling simulations data
- tropical cyclone projections based on synthetic track multi-model datasets.

2.3.2 Out of scope

- While historical climate change was not included in scope, some analyses on observed historical climate are undertaken and included in the report along with those from literature review to provide context for the projection information.
- Analyses of CMIP6 GCMs because at the time of the study, CMIP6 experiments were still underway, and not publicly available. Nonetheless, a broad comparison analysis using existing data is added in the report to understand how the results from this study relate to the recent CMIP6 GCMs simulations.

2.3.3 Approach

The approach to develop climate projections is based on existing understanding of the climate system, observed data and model simulations of the climate response to global scenarios of greenhouse gas and aerosol emissions (via the Representative Concentration Pathways, RCPs) used by the IPCC fifth assessment report, IPCC (2013)). In particular, the work used existing modelling data from CMIP5[14] Global Climate Models (GCMs), the high-resolution Conformal Cubic Atmospheric Model (CCAM) and the synthetic tropical cyclone data. More detailed descriptions are given in the following Chapter.

[14] Ibid 7

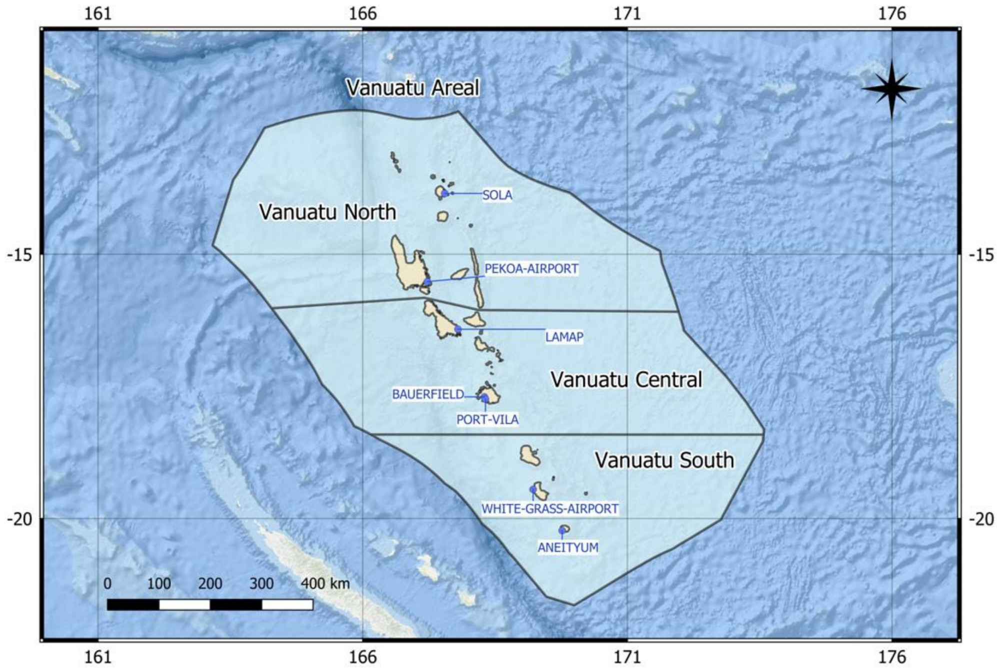

Figure 2 Vanuatu and the three sub-national regions for developing climate projections. The locations of meteorological observation stations used for the study are shown. The pale blue shaded region delineates the Exclusive Economic Zone (EEZ) of Vanuatu

Table 1 List of climate projection information developed through Van-KIRAP Activity 1.2.3

VARIABLES	REGION	FUTURE PERIOD	MODEL AND RCPS
Mean temperature and rainfall: Annual and seasonal temperature and rainfall	Vanuatu and sub-national regions	2030 (2020-2039), 2050 (2040-2059), 2070 (2060-2079), 2090 (2080-2099)	Up to 38 GCMs (RCP2.6, RCP4.5, RCP 8.5) CCAM run with 5 GCMs (RCP8.5)
Extreme temperature and rainfall: Temperature: annual hottest day (TXx), annual coldest night (TNn), annual hottest night (TNx) and 1-in-20 year extreme maximum daily temperature[15] Rainfall: annual wettest day rainfall (Rx1day) and 1-in-20 year extreme maximum daily rainfall[16]	Vanuatu and sub-national regions	Same as above	CCAM run with 5 GCMs (RCP8.5)[17]
Drought: Drought duration, frequency and intensity	Vanuatu and sub-national regions	Same as above	37 GCMs (RCP8.5)
Tropical cyclone (TC): Number of TCs and chance of occurrence for different TC intensity categories	Vanuatu	2041-2060, 2081-2100	8 GCMs (RCP8.5)

[15] Daily temperature value that has on average a 5% chance of happening in any given year.

[16] Daily rainfall value that has on average a 5% chance of happening in any given year.

[17] Results for RCP4.5 are not reported, but available upon request.

3 Methodology

3.1 Data

3.1.1 Observation

A range of observational data, including station data and global gridded climate datasets, was used to assess Vanuatu's historical climate. These data were also used to evaluate the model simulation for the historical period.

Station observations were sourced from the Pacific Climate Change Data Portal in 2019 following permission from the VMGD. Observations of daily and monthly rainfall and temperature (mean, minimum and maximum) are available from seven stations as shown in Figure 2 and described in Appendix 2. Most stations have data availability from roughly the 1950s and 1960s to 2017. Some station data was available in homogenised form while other stations only had unhomogenised data available[18]. The type of data from each station has been noted in the results (Chapter 4).

In addition, five different global gridded datasets were used to assess historical temperatures at a monthly timescale: GISTEMP ERSSTv5 (Lenssen et al., 2019), HadCRUT5 (Morice et al., 2021), Cowtan and Way (2014), NOAA Global Temp (Huang et al., 2020; Zhang et al. 2020), Berkley (Rohde and Hausfather, 2020), as outlined in Appendix 2. These datasets provide monthly temperature data starting between 1850 and 1880, with gridded spatial resolution of 1-5 degrees (i.e. approximately 110-550km).

For rainfall, three different gridded global datasets were used to assess rainfall at a monthly timescale: CMAP and GPCP merged gauge-satellite monthly precipitation datasets available from 1979 (Yin et al. 2004) and ERA5 reanalysis data (Hersbach et al., 2020). The gridded spatial resolution is approximately 31 km, 100 km, and 250 km for ERA5, GPCP and CMAP, respectively.

In addition, the ERA-Interim reanalysis data (Berrisford et al., 2009) was used to run CCAM for the period of 1986 to 2005. The results were used to evaluate CCAM performance (Chapter 3).

The historical monthly climatology for temperature (mean, minimum and maximum) and rainfall for the period 1970-2000 came from WorldClim version 2 (Fick and Hijmans, 2017). This dataset provides high resolution (approximately 1km) climatology over land areas, using input from station data[19], satellite data as well as information on elevation, distance to coast etc.

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[18] A homogenous climate time series is the one where variations are caused only by variations in weather and climate (Conrad and Pollak, 1950). Such data is necessary when studying historical climate variability and change (e.g. Kirono and Jones, 2007). However, non-climate factors such as changes in instruments and observation methods may introduce artificial discontinuities or inhomogeneities in climate time series. The process of identifying and correcting such inhomogenities is known as homogenisation (e.g. Aguilar et al., 2003; Domonkos, 2011; Riberio et al., 2016, Trewin et al., 2020). Unhomogenised data refer to those that have not been through homogenisation process.

At the time of the study, a "Digitization of climate data and quality assurance" for selected stations was initiated under the Van-KIRAP project in support of Climate Early Warning Systems (CLEWs) Activity.

[19] Worldclim data uses input from at least 10 stations spanning from the north to the south of Vanuatu. (WorldClim: Global weather stations, 2010; Hijmans et al, 2010 https://databasin.org/datasets/15a31dec689b4c958ee491ff30fcce75/).

3.1.2 Model simulation data

Historical and future simulations data from Global Climate Models (GCMs), the high-resolution Conformal Cubic Atmospheric Model (CCAM) and the synthetic tropical cyclone data were used to develop projected changes for the selected variables and future periods listed in Table 1. An overview is provided as follows.

Global Climate Models (GCMs)

The modelled monthly data come from more than 40 CMIP5 GCMs[20]. The same model data was also used in the Pacific-Australia Climate Science and Adaptation Planning (PACCSAP) reports (Australian Bureau of Meteorology and CSIRO, 2014) and the *'NextGen' Projections for the Western Tropical Pacific: Current and Future Climate for Vanuatu* report (CSIRO and SPREP, 2021). At the time of the study, CMIP6[21] experiments were still underway and model data were not publicly available.

We analysed models' historical *r1i1p1* run for 1900–2005 and future simulations under three different RCPs for 2006–2100. The *r1i1p1* refers to the first initial conditions (*r1*) for the first initialisation method (*i1*) using the first set of physics (*p1*). The three RCPs represent future scenarios in which anthropogenic emissions are rapidly reduced (RCP2.6), stabilise around mid century (RCP4.5) and continue to rise rapidly (RCP8.5). These three scenarios lead to atmospheric CO2 equivalent of 420ppm, 540ppm and 940ppm respectively by the end of the century, with associated global warming of around 2 ^{o}C, 2.4 ^{o}C and 4 ^{o}C for RCP2.6, RCP4.5 and RCP8.5 respectively.

RCP2.6 demonstrates the benefit of mitigation scenario. RCP8.5 is considered as a useful representation for quantifying physical climate risk, particularly for near- to mid-term policy relevant time horizons (e.g. Schwalm et al., 2020), noting studies such as Gasser et al. (2018) have shown evidence that highly likely, the earth will experience medium and high-end of warming scenarios than previously known.

In interpreting the results, it must be noted that the CMIP5 model simulations have a horizontal spatial resolution ranging from 60 to 410 km. This means their results may not incorporate finer-scale features such as island topography, land cover and land-sea boundaries, nor resolve certain atmospheric processes.

Conformal Cubic Atmospheric Model (CCAM)

To complement the projections from GCMs, the daily and monthly 50 km spatial resolution dynamically downscaled model data from CCAM were also used. These downscaled simulations were run for 1960-2099 with five GCMs from CMIP5 (i.e., GFDL-ESM2M, NORESM1-M, CANESM2, MIROC5 and ACCESS1.0) for the RCP8.5 emission pathway. These runs where also submitted to the Coordinated Regional Climate Downscaling Experiment (CORDEX), for scientific benchmarking by the international research community. Higher resolution 8 km simulations have been

[20] The coupled model intercomparison project phase 5 used in the IPCC's Fifth Assessment Report (AR5) (IPCC, 2013).

[21] The coupled model intercomparison project phase 6 used in the IPCC's Six Assessment Report (AR6) (IPCC, 2021).

developed in the past for the Pacific Climate Change Science Program (PACCSP), although these were based on the older CMIP3 generation of GCM projections and there was no CORDEX experiment at that time for benchmarking. See Box 4 for details about CCAM.

In interpreting the results, it must be noted that CCAM is an atmospheric model, not a coupled ocean-atmosphere model. This means CCAM simulations do not fully incorporate the atmosphere-ocean feedback mechanisms.

Synthetic Tropical Cyclone

The main dataset for tropical cyclone projections was provided by Prof. K. Emanuel (Massachusetts Institute of Technology, USA) in the form of “synthetic tracks” (hereafter, “MIT synthetic track model”) (Box 5). The model simulation was derived from a set of eight CMIP5 GCMs (CCSM4, CM3, HADGEM2-ES, IPSL-CM5A-LR, MPI-ESM-MR, MIROC5, EC-Earth3 and MRI-CGCM3) run with RCP8.5.

This approach complements the previously published information on projected change on TC for the region including those from the PCCSP and PACCSAP climate projections for the Pacific (Australian Bureau of Meteorology and CSIRO 2011 and 2014). As mentioned in Box 5, the major advantage of synthetic tracks, as opposed to explicitly simulated TCs, is that their computational efficiency allows for many thousands of events to be generated for a particular climate and location, which can then be used to assess risk. The second advantage is that the full spectrum of TC intensity - up to and including Category 5 TCs - can be simulated owing to the fine spatial resolution of the model, whereas many GCMs cannot capture the most intense TCs (i.e., Category 4+5 TCs) due to their relatively coarse resolutions.

We analyse three different 20-year time periods: a historical period from 1986 to 2005, a mid-century period from 2041 to 2060, and a late century period from 2081 to 2020.

The Vanuatu region used for the synthetic track analysis is a four-sided polygon bounded by latitudes 21°S and 12.5°S, and with eastern and western boundaries defined by two lines that intersect circles of radii 200 km centred on Port Vila and Luganville (see Figure 3).

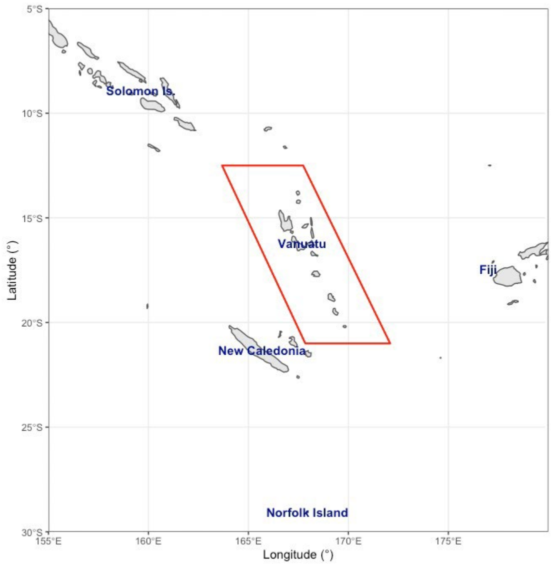


Figure 3 Map showing spatial filter (red polygon) used for MIT synthetic tracks model

Box 4. Conformal Cubic Atmospheric Model (CCAM)

Developed by CSIRO, CCAM is a regional climate model (RCM) that can be used for dynamically downscaling CMIP GCM projections to higher spatial and temporal resolution (McGregor 2005). Dynamical downscaling can be useful for investigating unresolved features in the GCM projections, such as extreme rainfall, cyclones, complex orography, coastlines, or urban areas, and "add value" to the resolved features. Unlike most other RCMs, CCAM employs a variable-resolution global grid that can be focused on a region of interest. In this way, CCAM is a high-resolution climate model, but without lateral boundaries, which can be a source of errors in regional climate simulations.

CCAM is based on a non-hydrostatic, semi-implicit, semi-Lagrangian dynamical core with a conformal cubic grid. CCAM supports modern atmospheric parametrisations that represent the various processes behind cloud microphysics (Rotstayn 1997 and Lin et al., 1983), convection, gravity wave drag (Chouinard et al., 1986), land-surface (Kowalczyk et al., 2013), radiation (Freidenreich and Ramaswamy, 1999 and Schwarzkopf and Ramaswamy, 1999), aerosols (Rotstayn and Lohmann, 2002 and Rotstayn et al., 2011) and turbulent mixing (Hurley 2007).

Due to its global stretched grid design, CCAM can be run in various configurations depending on the requirements of the stakeholder. For the CCAM regional projections used in this report, CCAM employed a spectral nudging method (Thatcher and McGregor 2009) to downscale an ensemble of GCMs to 50 km resolution at 3 hourly intervals, which is consistent with the CORDEX intercomparison experiment[22] and an important benchmark for regional climate simulations. The spectral nudging only perturbs large-scale information from the GCMs (i.e., features larger than 3,000 km) above 850 hPa (i.e., above the planetary boundary layer) for winds, air temperature, as well as surface pressure. This approach ensures that CCAM agrees with the large-scale projections from the host GCM but is also free to add fine-scale detail based on CCAM's representation of dynamical and physical atmospheric processes. Water vapour is not directly nudged with CCAM due to the highly non-linear processes in the hydrological cycle, providing more internally consistent projections. However, this does allow CCAM some flexibility in how rainfall can change in response to the projected global warming predicted by the GCMs.

[22] https://cordex.org/

Box 5. The MIT synthetic track model

The MIT synthetic track model has been used extensively to estimate the historical and future likelihood of TC winds and rainfall, and storm surges, for different regions around the world, including Texas and New York City (Emanuel 2017; Lin et al. 2010), Bangladesh (Emanuel 2021), Mumbai (Sobel et al. 2019), and the Mekong River Basin (Chen et al. 2020). One major advantage of synthetic tracks, as opposed to explicitly simulated TCs, is that their computational efficiency allows for many thousands of events to be generated for a particular climate and location, which can then be used to assess risk (e.g., what is the 1-in-500-year TC wind speed for Port Vila in the current climate and how might this change in the future?). A second advantage is that the full spectrum of TC intensity - up to and including Category 5 TCs - can be simulated owing to the fine spatial resolution of the model, whereas many GCMs cannot capture the most intense TCs (i.e., Category 4+5 TCs) due to their relatively coarse resolutions. The MIT synthetic track model is described in detail in Emanuel et al. (2006, 2008), but a brief summary is provided below.

The three main components of the synthetic track model are (i) genesis, (ii) track, and (iii) intensity. TC genesis is simulated using a “random seeding” technique, whereby many thousands of weak vorticities are placed randomly in space and time except for within two degrees of the equator. The vast majority of these “seeds” do not survive due to unfavourable environmental conditions (e.g., low SSTs or strong vertical wind shear). The survivors form the event set analysed herein. Once formed, the TCs are steered by the large-scale winds of each GCM in addition to a westward and poleward component owing to the Earth’s curvature and rotation. The intensity along each track is calculated using a deterministic, axisymmetric, cyclone model called “CHIPS” (Emanuel et al. 2004), which is coupled to a simple 1-D ocean model. Finally, only TCs that reach a maximum wind speed of at least 40 knots in the Vanuatu region are included in the synthetic event sets.

3.2 Model evaluation

3.2.1 Global Climate Models (GCMs)

Previous studies have examined the performance of CMIP5 GCMs over the world (Flato et al., 2013), western tropical Pacific (Brown et al., 2013; Grose et al., 2014), Australia (CSIRO and Bureau of Meteorology, 2015) and Southeast Asia (Hernaman et al., 2017). In general, they report that GCMs can simulate the key aspects of climate features and represent the seasonal and interannual climate in the Pacific. However, there are also some common model biases and errors, such as a tendency for sea-surface temperatures along the equator to be too cold. These studies also show that while CMIP5 models show improvement in simulating the key processes and climate features for the study regions, there remains a barrier in realistically simulating some key processes like ENSO. For Vanuatu, the most important model bias is that the rainfall maximum of the South Pacific Convergence Zone (SPCZ) is too zonally (east-west) oriented and extends too far east in May-October, therefore lowers confidence in the model projections (CSIRO and Bureau of Meteorology, 2015).

We assessed CMIP5 model performance by comparing their simulated mean monthly temperature and rainfall for Vanuatu and each of the three sub-regions with selected observation data and gridded global datasets (Figure 4 to Figure 7). The use of multiple observational datasets[23] is useful because there are usually differences in different observational datasets due to differences in input data and methods (e.g. Flato et al., 2013).

In general, CMIP5 models can represent the annual temperature cycle, with observed temperature peaking in February-March and dropping in July-September. The annual range increases the further south the region lies (Figure 4). However, most models tend to overestimate the observed temperature during the warmer months. Models tend to underestimate the diurnal range observed in the station data, with daily minimum temperatures overestimated (Figure 5) and daily maximum temperatures underestimated (Figure 6). This is expected since the coarse resolution of the GCM's can not resolve all the islands as land area and therefore does not capture the stronger daily temperature range experienced on land compared to over ocean. It is also important to note that the station data represent single land-based point locations, while the ERA5 and GCM data represent the areal average over entire regions (grid cells), including the ocean.

Most models also reproduce the observed seasonal pattern of rainfall (Figure 7). The modelled timing of peak rainfall can differ from the observed March peak by up to a few months on either side depending on the model, particularly in the Vanuatu North region. Most models tend to over-estimate the observed rainfall during the wet season and under-estimate during the dry season, resulting in a greater annual range than the observed. For Vanuatu South, models tend to under-estimate rainfall. The range of values among models are larger than the differences among observational data.

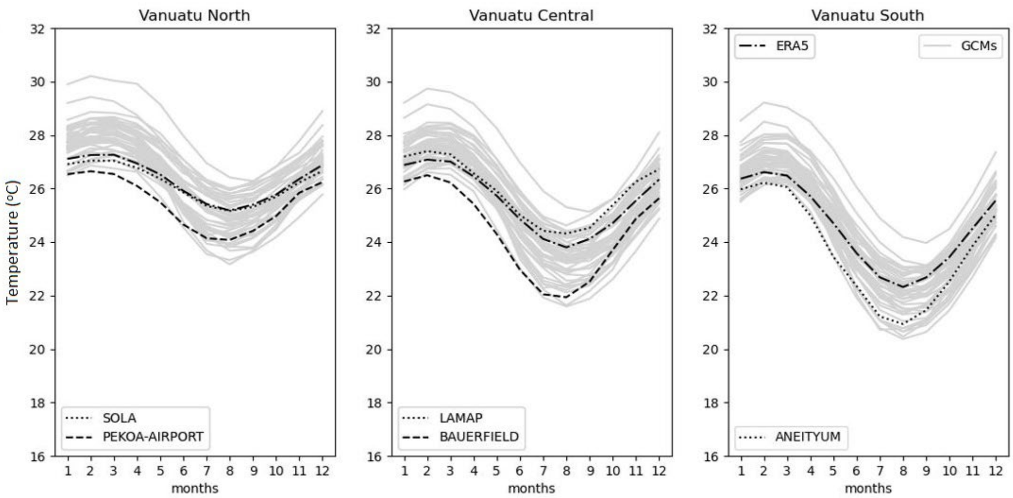


Figure 4 Monthly mean temperature for the three sub-regions, shown in Figure 2, for 1986-2005. Each grey line represents a GCM simulation, the dashed and dotted black lines represent an observed global data set (ERA5), the other dashed and dotted black lines represent observed station data (see Section 3.1. for details)

[23] While stations provide information for point locations, gridded data derived from computer modelling give information for a much wider areas depend on the spatial resolution of that particular data.

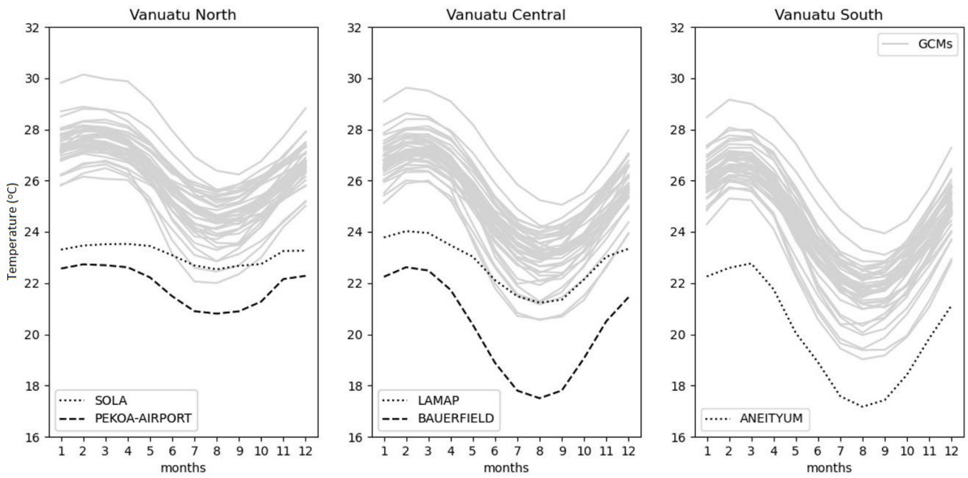


Figure 5 Monthly mean of minimum temperature for the three sub-regions for 1986-2005. Each grey line represents a GCM simulation, and the black lines represent observed station data (see Section 3.1. for details)

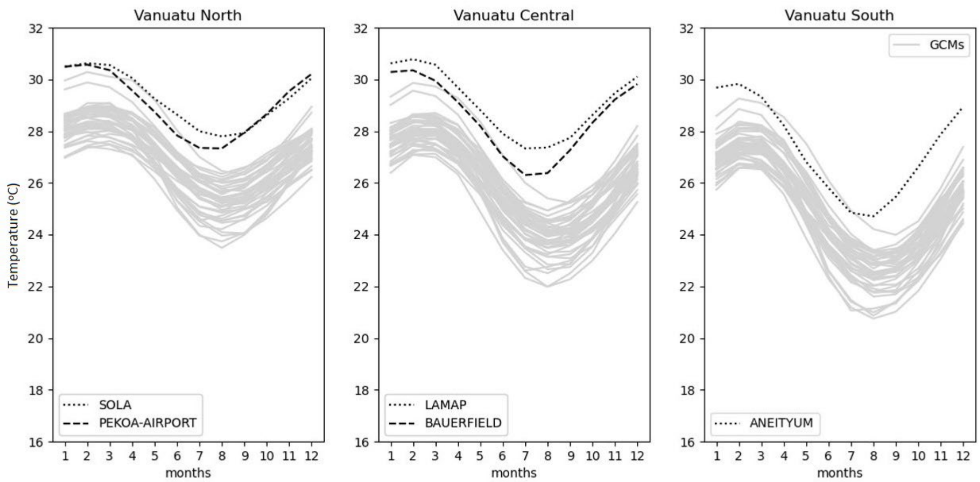


Figure 6 Monthly mean of maximum temperature for the three sub-regions for 1986-2005. Each grey line represents a GCM simulation, and the black lines represent observed station data (see Section 3.1. for details)

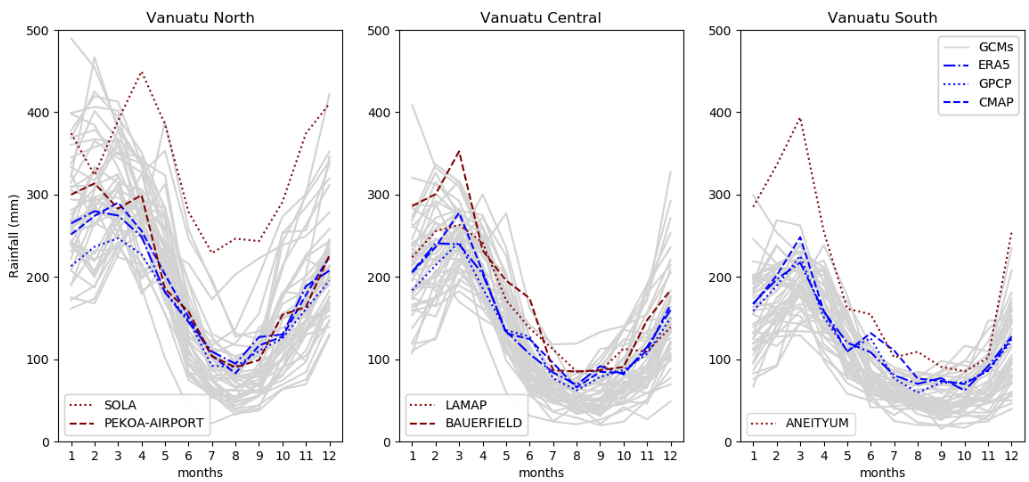


Figure 7 Mean monthly rainfall for the three sub-regions, shown in Figure 2, for 1986-2005. Each grey line represents a GCM simulation, the coloured lines each represents reanalysis/observed global data sets (ERA5, GPCP and CMAP) and observed station data (see Section 3.1. for details)

3.2.2 Conformal Cubic Atmospheric Model (CCAM)

Like GCMs, CCAM's performance has been previously assessed over many regions, including the western tropical Pacific (Australian Bureau of Meteorology and CSIRO, 2011), Australia (CSIRO and Bureau of Meteorology, 2015) and Asia (Katzfey et al. 2014). In general, they report that CCAM simulations are closer to the observations than those of the GCMs.

For this study, CCAM simulations of temperature and rainfall were evaluated against those in observed station datasets and gridded global datasets.

Temperature

Figure 8 shows that overall CCAM can simulate the annual cycle of mean temperature very well. CCAM simulation forced by ERA-Interim observation data (blue-line in the figure) is very close to those of the ERA5 observation data. When CCAM was run with GCMs inputs, model biases are apparent, but within the range of uncertainty across various observational data (in this case: the differences between ERA5 gridded data and station data such as Sola).

CCAM also reproduces the seasonality of the day-time temperature (or maximum temperature) and the night-time temperature (or minimum temperature) even though CCAM tends to underestimate the observed maximum temperature and overestimate the minimum temperature of all stations (Figure 9), like the GCMs. The similarity might be due to CCAM runs were nuged to GCMs (Box 4). The mean bias for maximum and minimum temperature is around -2 to -3 ^{o}C and +3 to +4 ^{o}C, respectively, depending on the sub-regions. This bias is overall lower compared to GCMs (where maximum and minimum temperature biases were roughly -3 to -4 ^{o}C and +2 to +6 ^{o}C, respectively).

The CCAM bias is expected because the 50 km model resolution still can not represent all the islands as land area, therefore does not capture the stronger daily temperature range experienced on land compared to over ocean. Aneityum and White Grass stations, for example, are both represented as ocean points, not land points, and daily temperature range is generally much lower over the ocean. The bias could be also related to inadequacy in model parameterisations to represent features such as atmospheric turbulence, cloud and land cover at a finer scale.

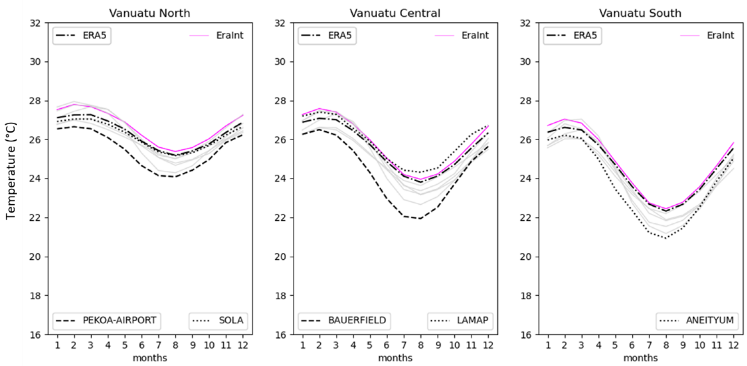


Figure 8 Average monthly mean temperature for the three sub-regions for 1986-2005. The pale grey lines represent the five CCAM simulations from GCMs, Eraint (magenta) representsthe CCAM run with ERA-Interim reanalysis data. The dash-dotted black is a gridded reanalysis global data set (ERA5), while the dotted and the dashed black lines each show observed station data (see Section 3.1. for details)

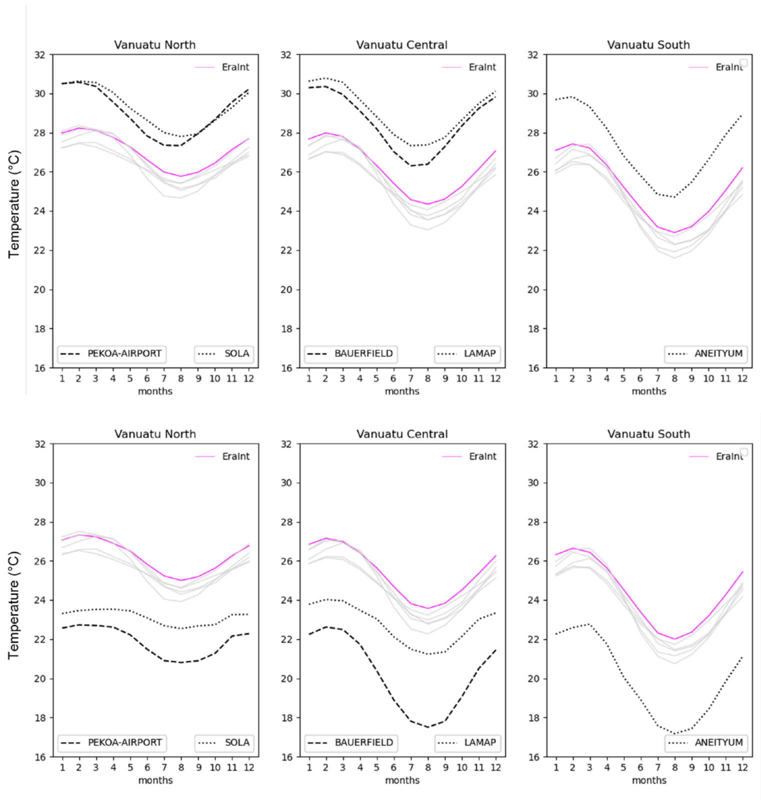


Figure 9 Average monthly maximum temperature (top) and minimum temperature (bottom) for the three sub-regions for 1985-2006. The pale grey lines represent the five CCAM simulations from GCMs while Eraint(magenta) represents CCAM run with ERA-Interim reanalysis data. The dash-dotted black and the dotted lines each show observed station data (see Section 3.1. for details).

Rainfall

CCAM also adequately reproduces the mean rainfall pattern (Figure 10). The temporal correlation coefficient between CCAM simulations (run with ERA-Interim) and observed station data are high and statistically significant for all the three sub-regions. For instance, the correlation coefficient for seasonal rainfall over Vanuatu North, Central and South is 0.78, 0.78 and 0.84 respectively (not shown); while those for monthly rainfall is 0.68, 0.64 and 0.71, respectively (Figure 11). The simulations tend to underestimate the observed mean daily rainfall by around -24 to -32 per cent. This underestimation could be due to the weak convection in this CCAM 50 km as it represents most of the stations points as ocean points.

When CCAM is run with GCMs input, the simulations tend to overestimate the wet season rainfall while underestimating the dry season rainfall (Figure 10). In contrast, the simulations tend to slightly underestimate rainfall for Vanuatu Central and South. The simulations biases are greater than the range of uncertainty across various observational data (i.e., ERA5, GPCP and CMAP).

Figure 12 shows that CCAM simulations on annual and seasonal rainfall tend to be better compared to the host GCMs, especially over Vanuatu Central and Vanuatu South.

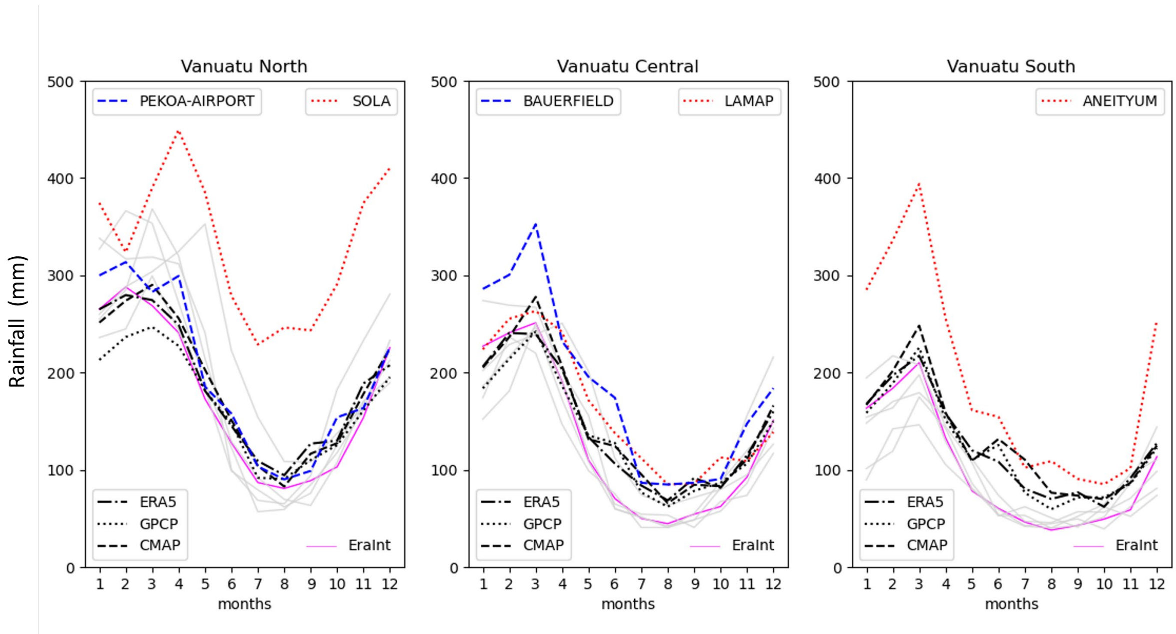


Figure 10 Average monthly rainfall for the three sub-regions for 1986-2005. The pale grey lines represent the five CCAM simulations from GCMs while Eraint means CCAM run with ERA-Interim reanalysis data. The patterned black lines each is gridded reanalysis and observed data (ERA5, GPCP and CMAP) (see Section 3.1. for details) and the blue and orange dashed/dotted lines represent station data (see Section 3.1. for details).

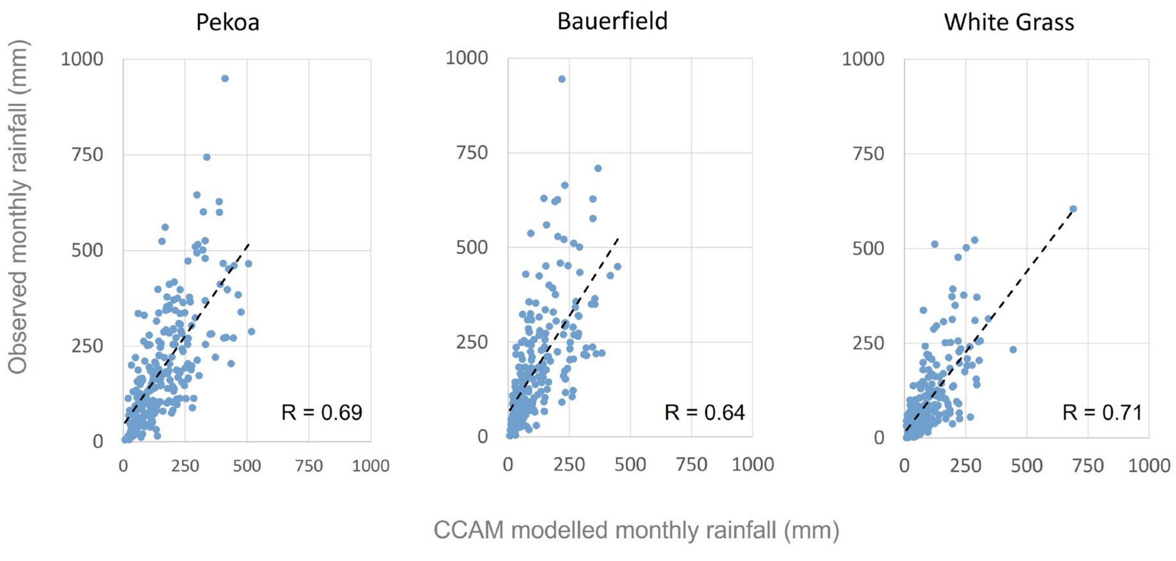


Figure 11 Scatter plot of observed monthly rainfall versus CCAM modelled monthly rainfall run with ERA-Interim reanalysis data for selected stations. The correlation lines (dashed black lines) and the corresponding correlation coefficients (R) suggest that CCAM simulation data has strong correlation to the observed station data, i.e. CCAM reproduces well the observation

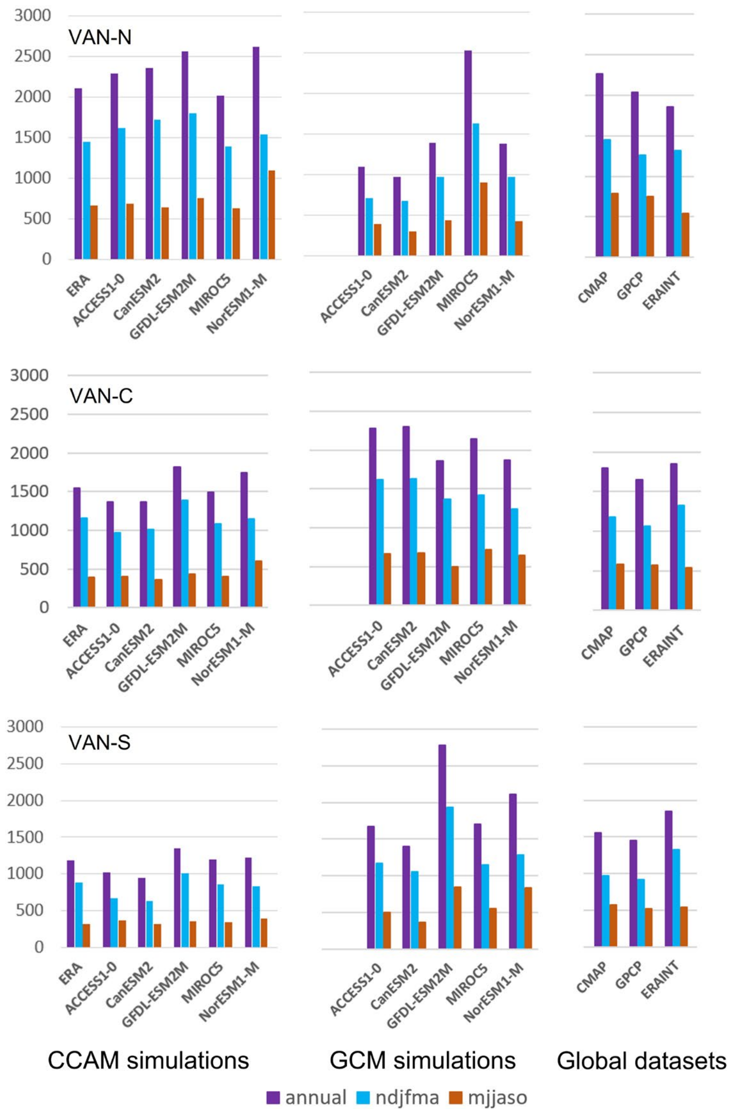


Figure 12 Modelled mean annual and seasonal rainfall (mm) as simulated by CCAM run with ERA reanalysis data and five GCMs (left column), and by the host GCMs (middle column), compared to three observed global datasets (right column) for 1986-2005. ndjfma = wet season, mjjaso = dry season

Daily and extreme rainfall

Evaluation of CCAM skill to simulate daily rainfall has also been performed against station data. This includes assessment of daily mean rainfall, light rainfall (10th percentile), heavy rainfall (90th percentile) and extreme rainfall (99th percentile); annual maximum daily rainfall (Rx1day); rain days; and number of days with a particular threshold rainfall (e.g., rainfall > 50 mm). The results are not shown but summarised below:

- tend to underestimate the daily mean rainfall, light rainfall, heavy rainfall and extreme rainfall as well as the annual maximum daily rainfall
- CCAM produces too many rainy days with a rainfall less than or equal to 20 mm, while very few days with a rainfall above 20 mm. It is a known problem with this version of CCAM.

3.2.3 Synthetic Tropical Cyclone (TC)

The ability of the MIT synthetic track model to simulate both global and regional tropical cyclone activity has been demonstrated by previous studies (e.g., Emanuel et al., 2008; Emanuel, 2013). The technique captures well the observed variability of tropical cyclones around the globe, as well as the effects of climate drivers such as ENSO and the Atlantic Meridional Mode (Emanuel et al., 2008). In the Southern Hemisphere, the MIT synthetic track model is able to reproduce the observed spatial characteristics of TCs as well as their seasonal cycle (Ramsay et al. 2018).

3.3 Projection method and presentation of results

The method adopted for developing climate change projections for this work has been to use available models at the time of the study. This means we used up to 28 GCM simulations, 5 CCAM-downscaled simulations and ensemble MIT synthetic track simulations based upon 8 GCMs for developing projections for mean climate variables, extremes, and tropical cyclones, respectively.

The reference period was 20-years centred on 1995 (1986-2005, as used in IPCC (2013)), while four future periods were centred on 2030 (2020-2039), 2050 (2040-2059), 2070 (2060-2079) and 2090 (2080-2099) unless otherwise stated. For TC projections, the future periods are 2041-2060 and 2081-2100.

The GCMs multi-model ensemble projections are shown by the multi-model median and 10^{th} and 90^{th} percentile range unless otherwise stated. As an illustration, say we have projected changes in future rainfall from 10 models as follows: -10%, +12%, -3%, -8%, +4%, +2%, -14%, -15%, -9% and -20%. From these values, a multi-model median of -8.5%, and a 10^{th}-90^{th} percentile range of 4.8% to -15.5% can be calculated. In other words, rainfall is projected to decline by -8.5%, but it may decline as much as -15.5%, or it may increase by +4.8%.

Unlike the GCMs, there is only five models available for CCAM ensemble. Therefore, the CCAM multi-model ensemble is shown by the multi-model median and the minimum-maximum range unless otherwise stated.

The projections are presented in Chapter 5 and 6 through a series of graphs and tables accompanied by key messages. Such communication approach enables targeted users to easily pick and use a given result for a particular purpose (e.g. a PowerPoint presentation and a leaflet). This approach has been proven to work well for facilitating VMGD and Van-KIRAP PMU in their outreach during the implementation of the Van-KIRAP Project.

Although the focus of this study is on long-term climate projection, selected information about historical climatology, variability and trends are also presented in the next chapter as a context.

Part II Results – Climate Information

4 Historical climate

4.1 Mean rainfall and temperature

4.1.1 Climatology

The seasonal pattern of rainfall and temperature for selected stations, representing the sub-national regions, are presented in Figure 13. Meanwhile, the spatial patterns of mean annual and seasonal rainfall and temperature are shown in Figure 14.

The key messages are:

- The climate of Vanuatu is distinctly marked with a wet season (November to April) and a dry season (May to October)
- The coolest and drier months are from July to September, while the warmest and wettest months are from January to March
- There is spatial variation from North to South, with the North tends to be hotter and wetter than the South region

McGree et al. (2022) report that the rainfall seasonal cycle is strongly affected by the SPCZ, which is most intense during the wet season (November to April), while the temperature cycle is strongly connected with the surrounding ocean temperature.

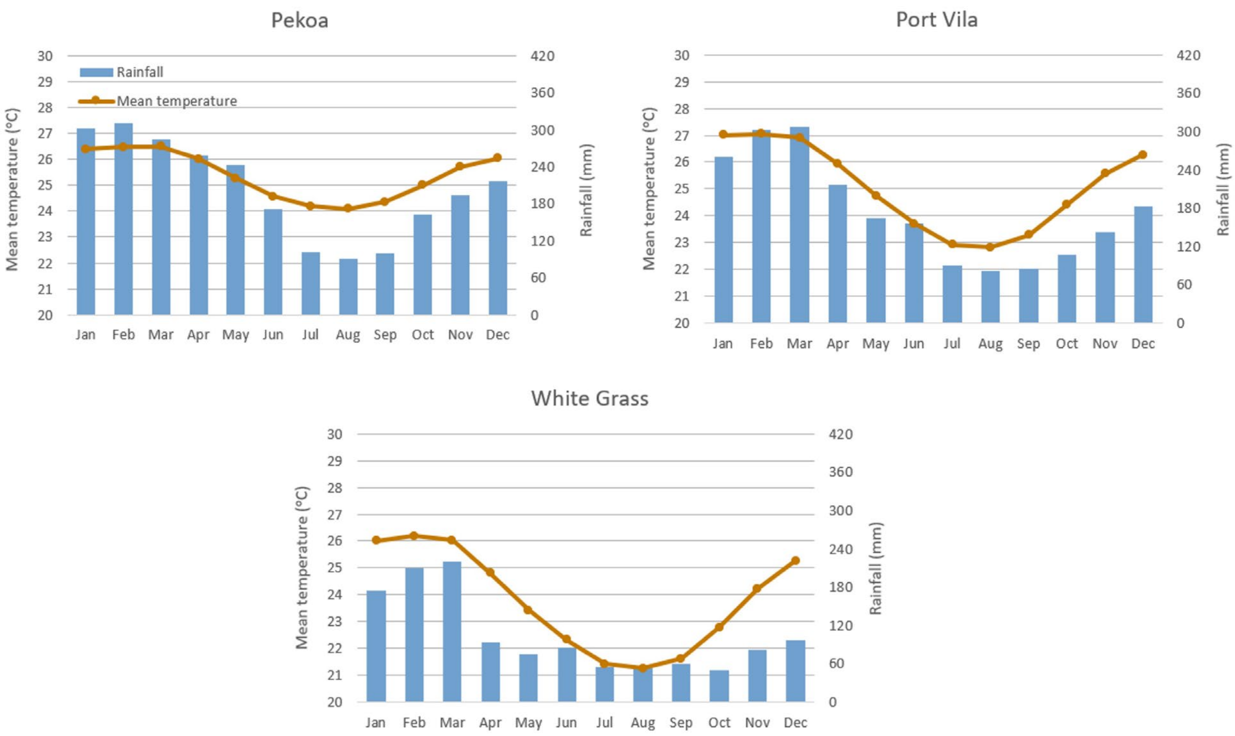
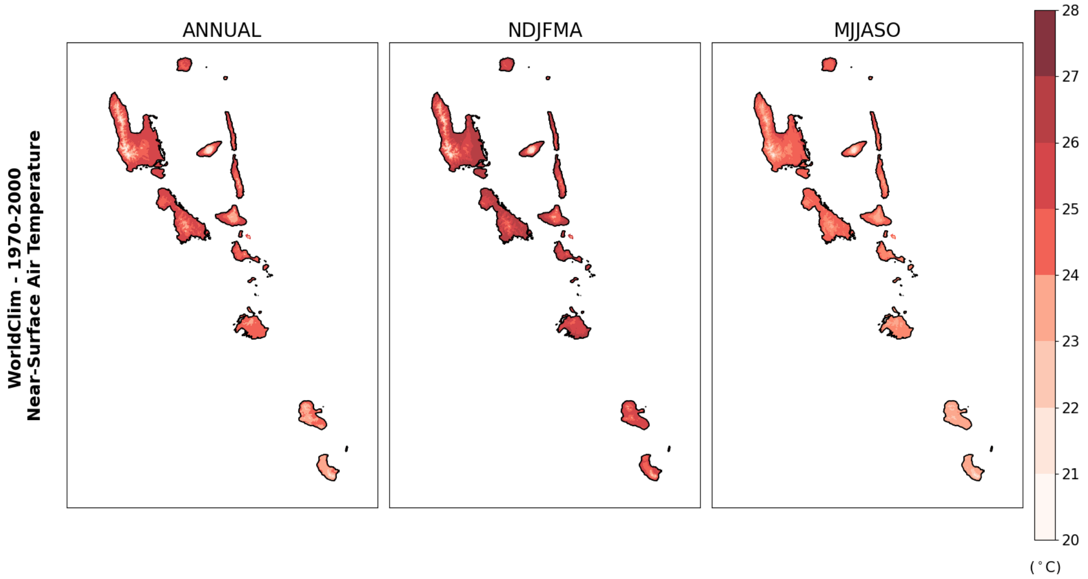


Figure 13. Mean monthly rainfall (bars) and temperature (lines) for Pekoa, Port Vila and White Grass airport for 1971-2000 (this period is chosen for consistency with that of WorldClim data used in Figure 14). See Figure 2 for locations. Data source: the Pacific Climate Change Data Portal (2018)



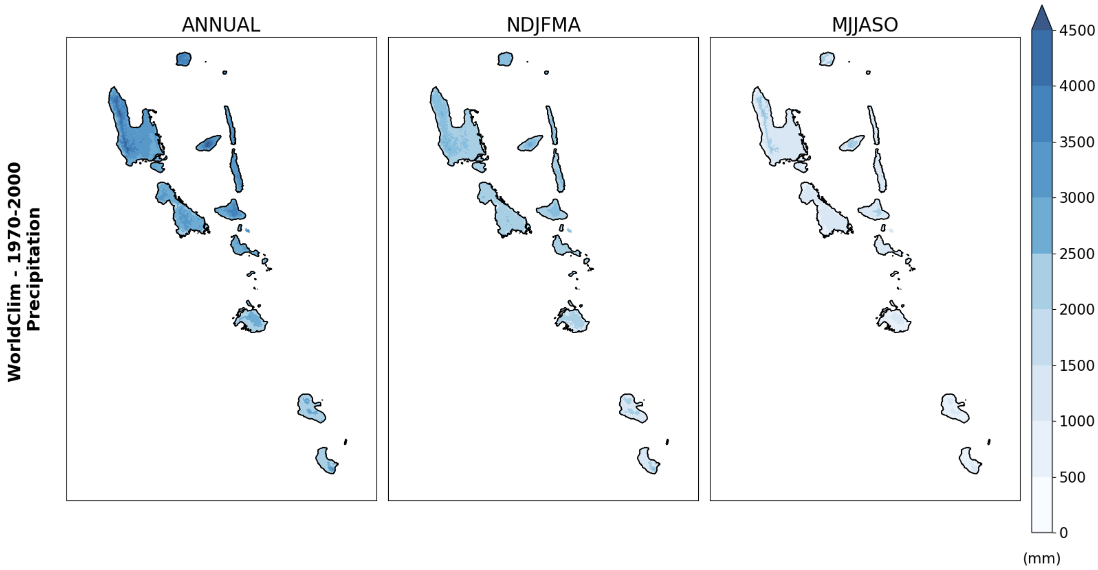


Figure 14 Map of annual and seasonal mean temperature (top) and rainfall (bottom) in Vanuatu for 1970-2000. NDJFMA = wet season, MJJASO = dry season. Data source: WorldClim

4.1.2 Trends

The temporal variability and trends in mean annual rainfall and temperature for selected sites are presented in Figure 15. The results for the whole Vanuatu and three sub-national regions are presented in Figure 16 to Figure 18. These results are consistent with and complementary to those reported in CSIRO and SPREP (2021) and McGree etal. (2022).

The key messages are:

- Warming trends are evident at the selected sites as well as for the whole Vanuatu (Figure 15 and Figure 16). The warming is at a faster rate in recent decades for the entire region of Vanuatu including surrounding oceans.
- MCGree et al. (2022) reported that for Aneityum, the wet season temperatures have increased faster than the dry season temperatures, and maximum temperatures have increased faster than minimum temperatures.
- Annual rainfall variability varies with ENSO (Figure 15), particularly for the more southerly locations where there is a clearer relationship between wetter years and La Niña.
- There is no significant long-term trend in annual rainfall at the selected sites (Figure 15) as well as for the entire region of Vanuatu and the sub-national regions including surrounding oceans (Figure 17 and Figure 18).
- Rainfall year-to-year variability is similar across the sub-national regions (Figure 18)

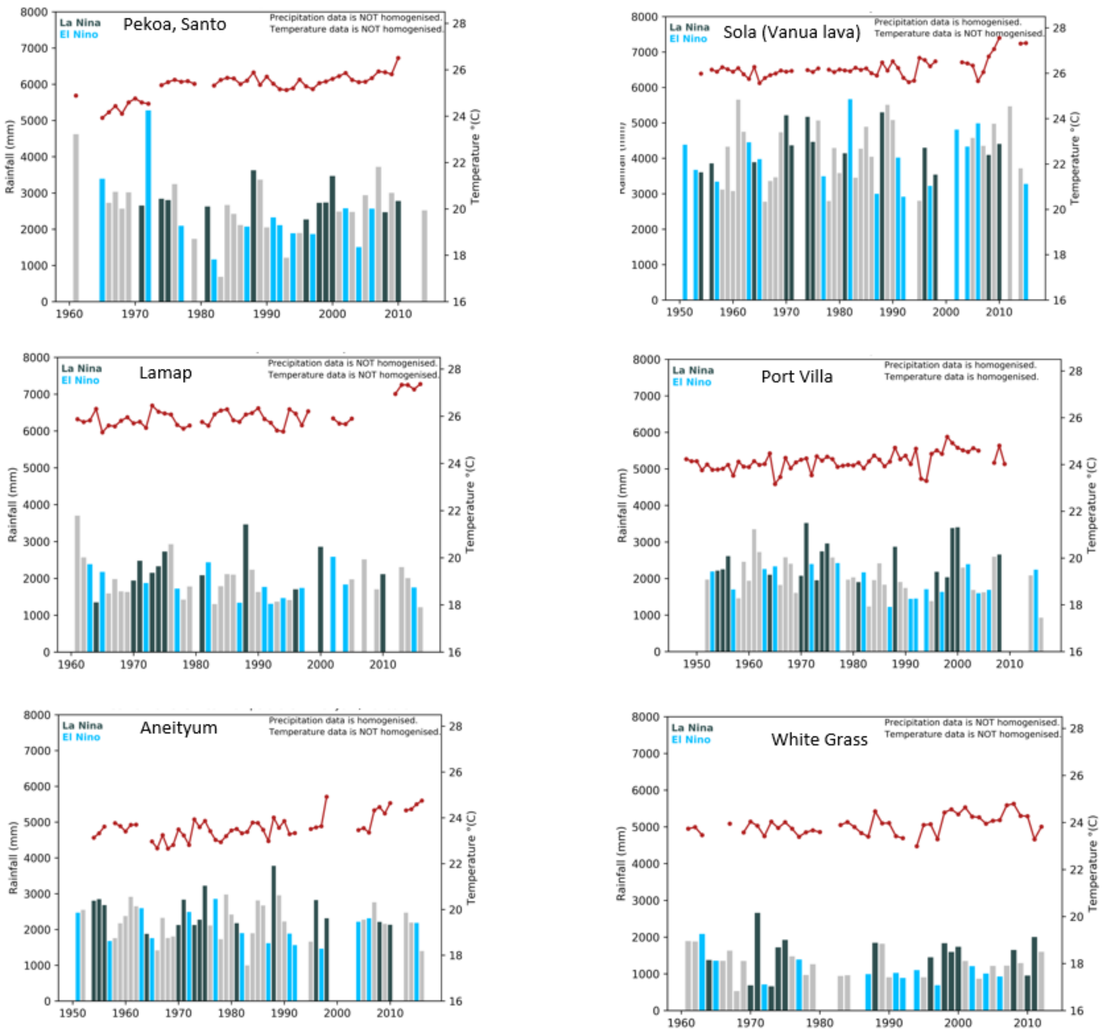


Figure 15 Annual mean temperature (red line with markers) and rainfall (bar) in selected stations for a period of up to 2017. Light blue, dark blue and grey bars denote El Niño, La Niña and neutral years, respectively. Information regarding whether the data has been homogenised or not is also shown. Data source: Pacific Climate Change Data Portal (2018)

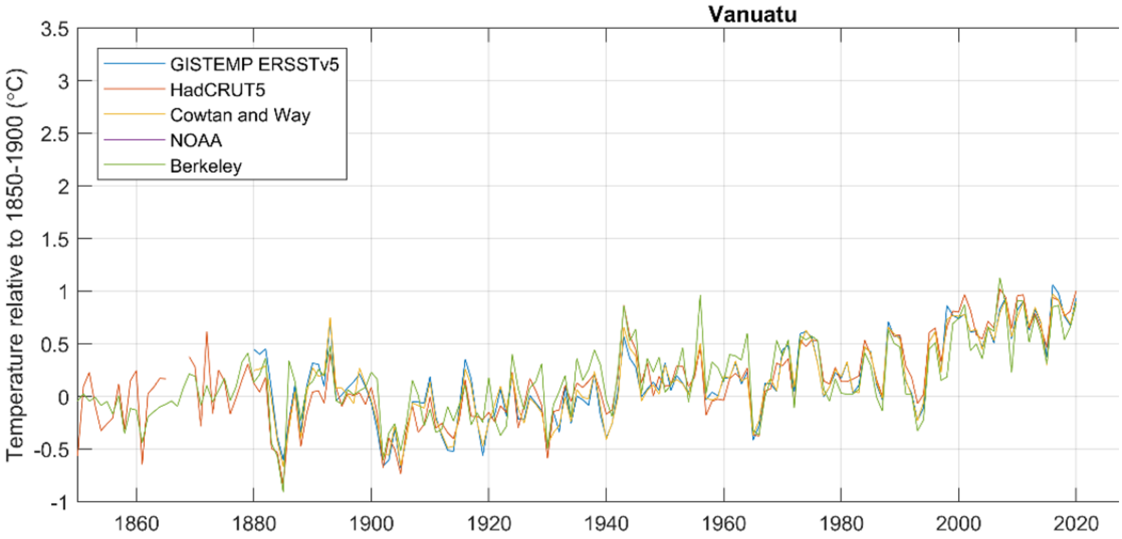


Figure 16 Time series of mean annual temperature anomaly of the Vanuatu region relative to 1850-1900 in five global datasets (See Section 3.1.1. for details. See also CSIRO and SPREP, 2021)

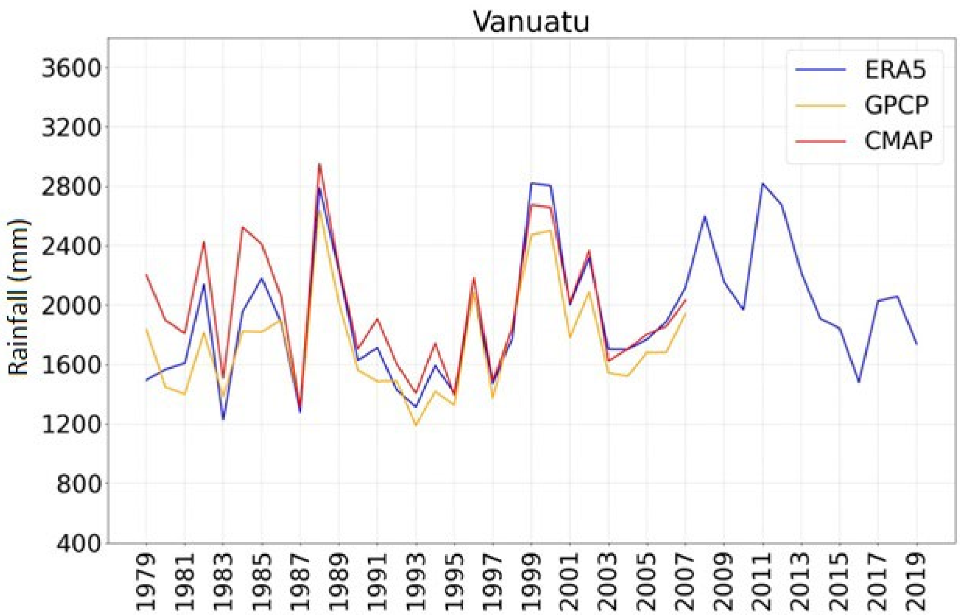


Figure 17 Time series of annual rainfall of the Vanuatu region according to three global datasets for 1979-2019 (See Section 3.1.1. for details. See also CSIRO and SPREP, 2021)

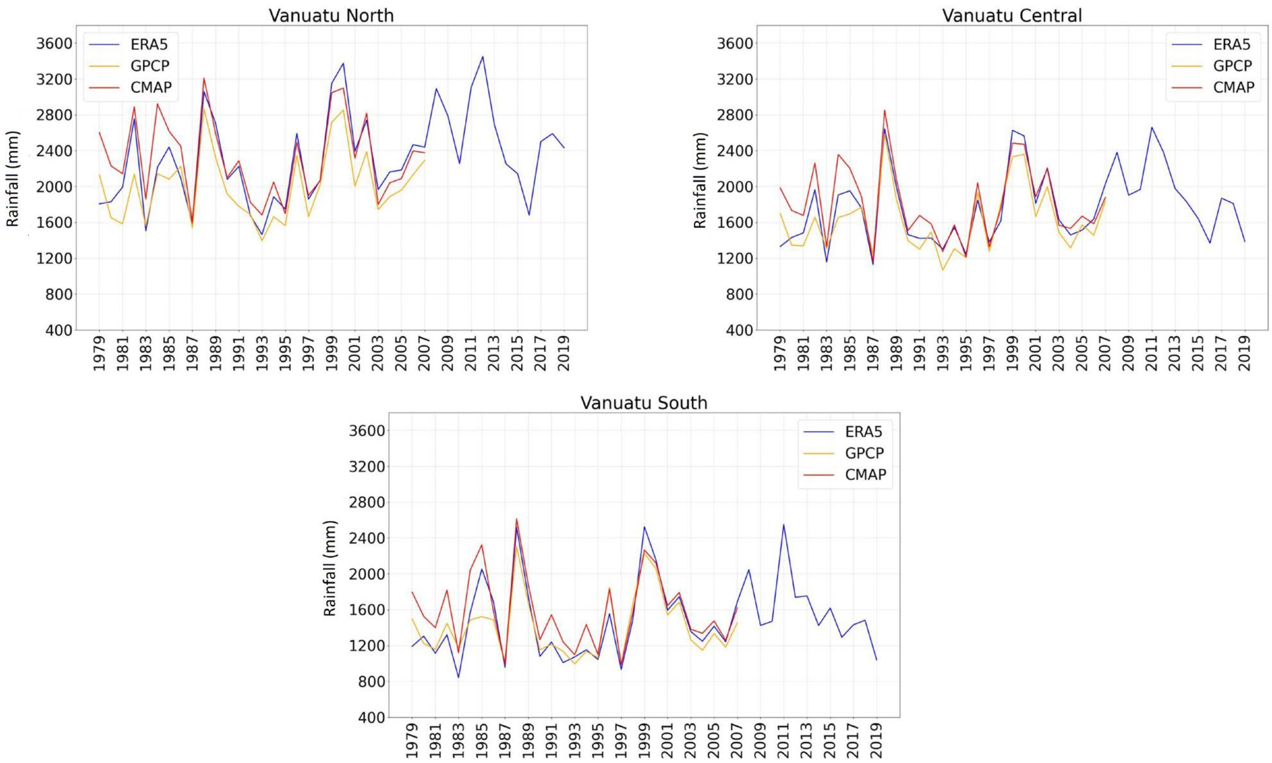


Figure 18 Time series of annual rainfall of the three sub-regions according to three global datasets for 1979 to 2019 (see Section 3.1. for details)

4.2 Extreme rainfall and temperature

4.2.1 Climatology

The climatology for the annual hottest day (TXx), annual hottest night (TNx), annual coldest night (TNn) and annual maximum daily rainfall (Rx1day) have been calculated for the 1986-2005 baseline period for selected meteorological stations across Vanuatu[24]. The results are presented in Table 2 showing the average and the minimum-maximum annual values.

The key messages are:

- The hottest day of the year (TXx) doesn't vary much from one year to another. The variation range is within 2°C at most stations with a slightly larger range for the more southerly locations. For the 1986-2005 baseline, the hottest day of the year was, on average, 32-33 °C at all stations, with the hottest day over that period being 33-34 °C.
- There is relatively low year-to-year variability in coldest night of the year (TNn) and the average value ranges from 11 °C at the more southerly stations to 18 °C at the northernmost station of Sola. Similarly, the hottest night of the year (TNx) varies little year to year and there is also very

[24] Since these extremes metrics are sensitive to outliers, quality control was applied to manually remove obviously erroneous outliers in annual extremes. Outliers removed for minimum temperature included value with likely misplaced decimal point (Lamap station, 7/3/1971 value 2.4 °C) and value which was identical to the maximum temperature (White Grass Station (Tanna) station, 10/12/2012, value 30.5 °C). Years with more than 10% of data missing were also excluded.

little variation between stations from north to south with the average hottest night between 25 - 26.5 °C for all stations.

- In contrast, the maximum daily rainfall of a given year (Rx1day) varies a lot from one year to another and between different locations. The average maximum daily rainfall of the year ranges from 122 mm at White Grass to 204 mm at Sola over the 1986-2005 baseline period.

Table 2 Observed climate extremes from station data. Values given are the average annual value with the minimum and maximum annual values in brackets, calculated over the 1986-2005 baseline period. Unless otherwise noted, the values are from unhomogenised data. *Temperature data for Bauerfield and Port Vila is homogenised. #Rainfall data for Sola, Port Vila and Aneityum is homogenised. Additionally, years with more than 10% missing data were removed and manual quality control was applied to remove obvious data errors (see also footnote 24). Source of data: Pacific Climate Change data Portal (2018)

STATION	ANNUAL HOTTEST DAY (TXx ANNUAL) (°C)	ANNUAL HOTTEST NIGHT (TNx ANNUAL) (°C)	ANNUAL COLDEST NIGHT (TNn ANNUAL) (°C)	ANNUAL MAXIMUM DAILY RAINFALL (Rx1day) (mm)
Sola#	32.7 (31.5 – 33.2)	26.4 (25.7 - 27.8)	18.4 (17.0 – 19.9)	204 (106 – 301)
Pekoa Airport	32.7 (32.0 – 34.0)	25.4 (24.5 - 26.5)	15.0 (12.6 - 16.9)	162 (79 – 267)
Lamap	32.9 (32.0 – 34.0)	26.2 (25.0 - 27.0)	16.8 (13.5 – 19.9)	153 (83 – 341)
Bauerfield*	33.0 (32.1 – 34.0)	25.9 (24.8 - 27.3)	11.7 (9.1 - 14.1)	201 (71 – 539)
Port Vila*#	34.7 (34.0 – 35.4)	26.0 (25.2 - 26.9)	11.7 (10.3 – 13.8)	167 (77 – 377)
White Grass Airport	32.6 (31.4 – 34.0)	25.7 (24.6 - 27.0)	12.9 (11.0 - 15.0)	122 (60 – 447)
Aneityum#	32.5 (31.0 – 34.0)	25.7 (24.0 - 27.6)	12.4 (11.0 - 15.0)	196 (86 – 347)

4.2.2 Trends

The temporal variability and trends in observed extreme temperature and rainfall have been calculated based on selected station data. The results are presented in Figure 19 to Figure 22, respectively. The key messages are:

- There is clear warming of the hottest day of the year especially over the past few decades (Figure 19).
- There is clear warming of the hottest night of the year, especially in the most recent decades (Figure 20).
- There is little change in the coldest night of the year over time (Figure 21).
- Maximum daily rainfall is very variable year-to-year, but highest values appear to have increased in recent decades, although it is unclear whether some of the highest values could be artificial outliers (Figure 22)

In addition:

- McGree et al. (2022) reported that the number of cold nights at Port Vila is decreasing, while hot days are increasing.

- For the Western Pacific Islands regional observation, where Vanuatu located, McGree et al. (2019) showed:
  - the number of cold nights and cold days decreased, while the number of warm nights and warm days increased
  - there is a clear increase in the interannual variability from around 1988 for the number of warm nights and cold days
  - trends in annual total rainfall and extreme rainfall are small and statistically nonsignificant.

Additional information regarding trends on extreme rainfall for the entire southwest SPCZ region, where Vanuatu is located, according to McGree et al. (2019) are summarised in Table 3.

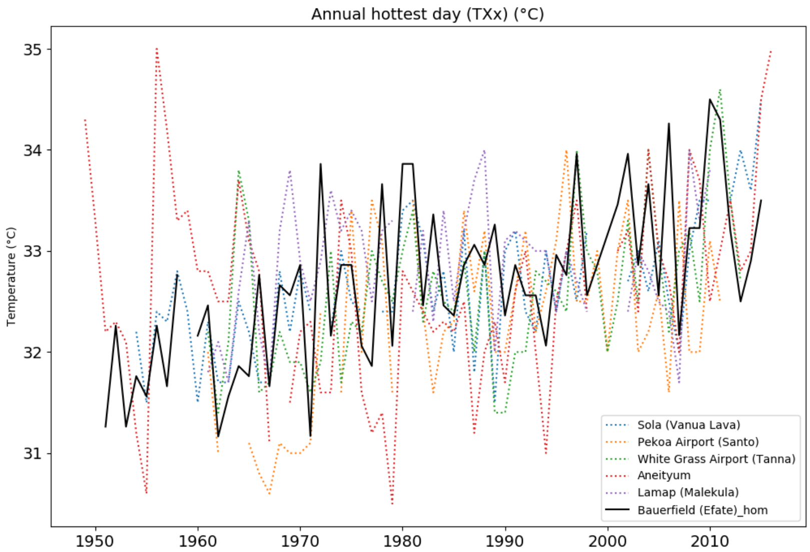


Figure 19 Time series of annual hottest day (TXx) for selected stations across Vanuatu. The station with homogenised data (Bauerfield (Efate)_hom) is shown with solid line. Data source: Pacific Climate Change Data Portal (2018)

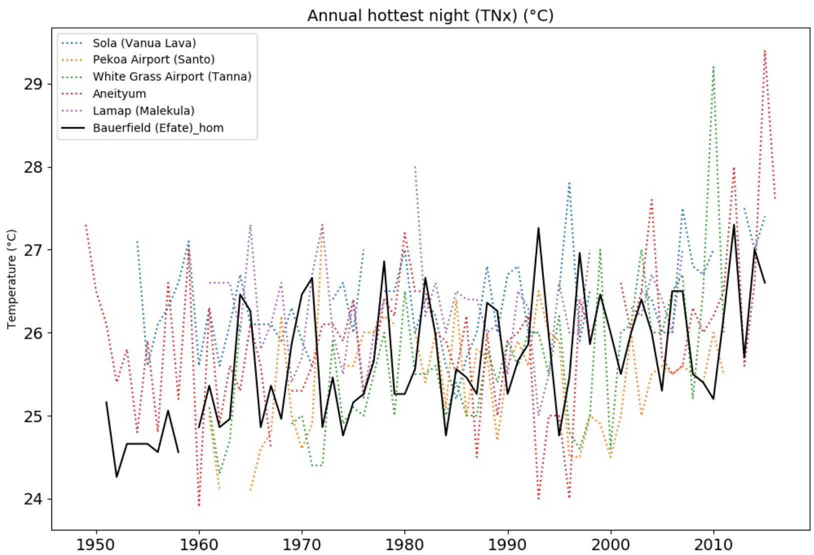


Figure 20 Time series of annual hottest night (TNx) for selected stations across Vanuatu. The station with homogenised data (Bauerfield (Efate)_hom) is shown with solid line. Data source: Pacific Climate Change Data Portal (2018)

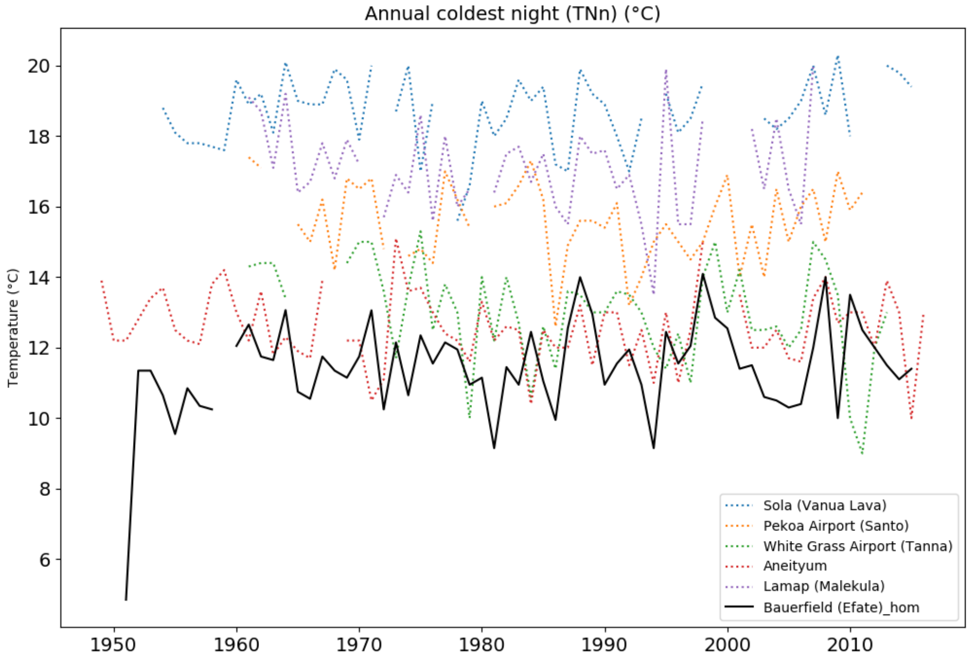


Figure 21 Time series of annual coldest night (TNn) for selected stations across Vanuatu. The station with homogenised data (Bauerfield (Efate)_hom) is shown with solid line. Please note two outliers in the data for Lamap and Bauerfield which could not be confirmed. Data source: Pacific Climate Change Data Portal (2018)

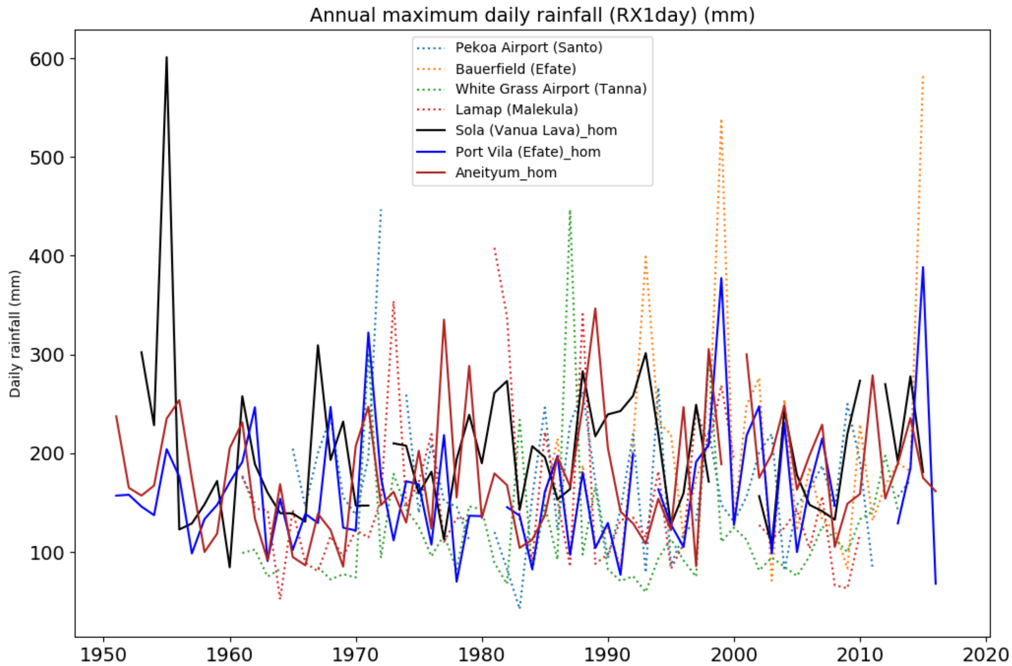


Figure 22 Time series of annual maximum daily rainfall (Rx1day) for selected stations across Vanuatu. The stations with homogenised data are shown with solid line and suffixed with "_hom". Data source: Pacific Climate Change Data Portal (2018)

Table 3 Trends for annual extreme precipitation for 1951-2015 (units per 10 years) for the southwest SPCZ region, where Vanuatu is located. The 95% statistical confidence intervals are shown in parentheses. Source of information: McGree et al. (2019)

VARIABLES (UNIT)	TRENDS
Rx1day (Max 1-day rainfall) (mm)	-0.14 (-3.05, +3.07)
R1mm (number of 1 mm rain days) (days)	+0.52 (-2.30, +3.31)
CDD (Consecutive dry days) (days)	-0.54 (-2.50, +1.67)
CWD (Consecutive wet days) (days)	-0.10 (-0.65, +0.48)
R95p (Total annual rainfall from heavy-rain days) (mm)	-7.73 (-32.69, +20.58)
SPI-12 Jun (Standardized Precipitation Index, a measure of 'drought' on time scale 12 months)	-0.03 (-0.14, +0.08)
SPEI-12 Jun (Standardized Precipitation Evapotranspiration index, a measure of 'drought' on time scale 12 months)	-0.05 (-0.15, +0.06)

4.3 Droughts

4.3.1 Climatology

The information for observed drought is based on existing literature. The key messages are:

- ENSO is one of the key factors for drought in the Pacific region, including Vanuatu (e.g., Tigona and de Freitas, 2012; McGree et al., 2016; Table 4), with the El Niño phase associated with droughts.
- The occurrence, duration and intensity of meteorological droughts[25] can differ within Vanuatu. For instance, the 1982 drought in Vanuatu started in Pekoa (Vanuatu North) a year earlier than Port Vila (Vanuatu Central) and 16 months before White Grass (Vanuatu South) (Table 4).
- Drought usually ended by rainfall associated with a TC according to the selected examples shown in Table 4.

[25] Meteorological drought is generally defined as a period of months to years with below-normal rainfall (e.g. Dai, 2011; Kirono et al., 2020)

Table 4 Meteorological droughts during selected major El Niño events for three locations in Vanuatu (adapted from Iese et al., 2021). Start and end refer to the first and last month of a drought, where drought is declared if the rainfall total in the previous 3-month period is in the bottom 25% of historical rainfall totals for that corresponding 3-month period. See Figure 2 for location

1982-1983 El Niño

VARIABLES	PEKOA (VANUATU NORTH)	PORT VILA (VANUATU CENTRAL)	WHITE GRASS (VANUATU SOUTH)
Start - End	Mar 1982 - May 1984	Mar 1983 - Dec 1983	Jun 1983 - Dec 1983
Duration (months)	27	10	7
Total rainfall received during the drought (mm)	3030	920	230
Long-term average rainfall (mm) between start and end months	5518	1568	461
Per cent decrease from average rainfall during the drought	45	41	50
Notes	This long drought for the north was unusual. TC Joti passed close to Pekoa on the 4th Nov 1982 and brought some relieving rain	Drought ended around the same time TC Atu was close to Port Vila	Drought ended by rainfall associated with TC Atu

1997-1998 El Niño

VARIABLES	PEKOA (VANUATU NORTH)	PORT VILA (VANUATU CENTRAL)	WHITE GRASS (VANUATU SOUTH)
Start - End	Oct 1997 – Mar 1988	Sep 1997 – Mar 1998	Mar 1997 – Mar 1998
Duration (months)	5	7	13
Total rainfall received during the drought (mm)	720	1097	1186
Long-term average rainfall (mm) between start and end months	1423	1387	1414
Per cent decrease from average rainfall during the drought	49	21	16
Notes	Drought started here 6 months after the drought started in Southern Vanuatu. Drought in North Vanuatu broken by rainfall associated with TC Zuman in March 1998	Drought started here 5 months after the drought started in Southern Vanuatu. Drought in Central Vanuatu broken by rainfall associated with TC Yali in March 1998	-

2015 – 2016 El Niño

VARIABLES	PEKOA (VANUATU NORTH)	PORT VILA (VANUATU CENTRAL)	WHITE GRASS (VANUATU SOUTH)
Start - End	Oct 2015 – Apr 2016	Aug 2015 – Nov 2016	Apr 2015 – May 2015
Duration (months)	7	16	1
Total rainfall received during the drought (mm)	1053	1134	210
Long-term average rainfall (mm) between start and end months	1706	2540	340
Per cent decrease from average rainfall during the drought	38	55	38
Notes	Drought ended by rainfall associated with TC Zena, 5 Apr 2016	Worst drought in Luganville according to SCOPIC	-

4.3.2 Trends

The trends in observed drought are obtained from McGree et al. (2016) (Figure 23). Values for observed trends in SPI and SPEI for the southwest SPCZ region, where Vanuatu is located, are taken from McGree et al. 2019 (see Table 3 shown earlier). The key messages are:

- Over Vanuatu, trends in drought frequency, duration and magnitude are mostly statistically nonsignificant.
- The trends are mixed spatially, with Bauerfield showing a positive trend while Sola and Aneityum indicate negative trends.

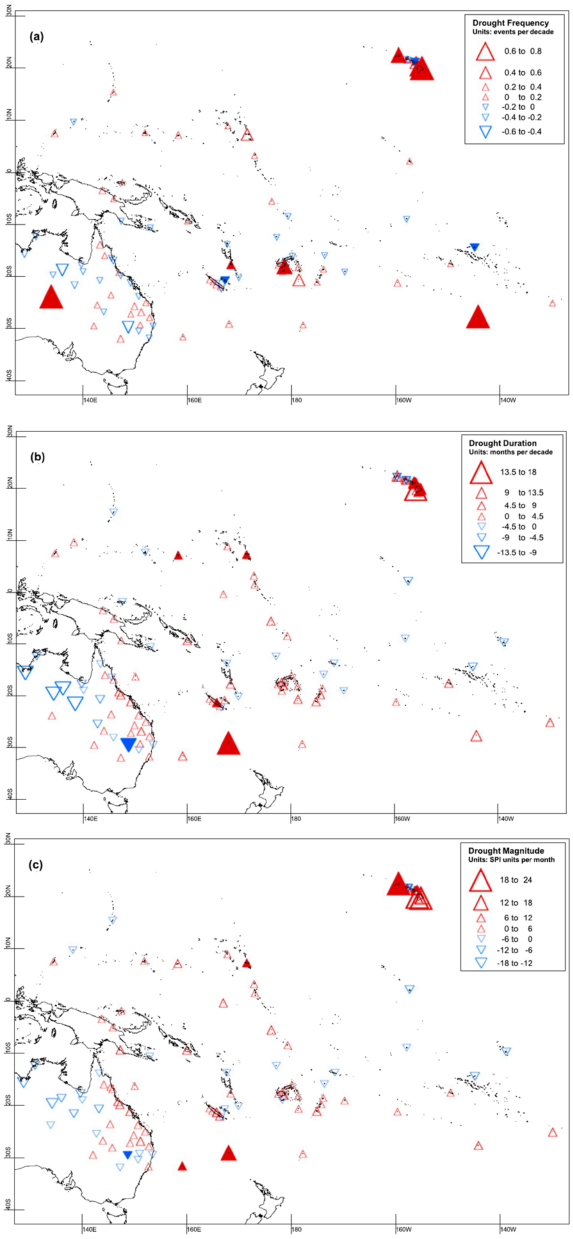


Figure 23 Linear trends of drought frequency (top), total drought duration (middle) and total drought magnitude over the Pacific and part of Australia for 1951-2010. Filled triangles represent trends significant at the 95% level. Vanuatu is represented by three stations: Sola (Vanua Lava) in the north, Bauerfield (Efate) in the centre, and Aneityum in the south. Source of figure: McGree et al. (2016)

4.4 Tropical cyclone (TC)

4.4.1 Climatology

The observed tropical cyclone (TC) tracks and numbers are analysed and presented in Figure 24 and Figure 25, respectively. Figure 26 shows the number of TC that appeared within different distances from selected stations in Vanuatu.

The key messages are:

- There were 138 TCs with winds of at least 35 kt that passed through the VMGD area of responsibility between 1980-2021 seasons (i.e, 3.3 per year, or 33 per decade) (Figure 24 and Figure 25). This finding is consistent with Deo et al. (2021) results, which show the average occurrence of TCs over Vanuatu ranges from 30 to 35 per decade during 1970-2018, although they used a slightly different spatial filter[26].
- During 1969-2002, the number of TCs passing within 50 km, 100 km and 200 km from selected stations varies between 9 to 14, 23 to 32 and 51 to 61, respectively (visualised in Figure 26).

In addition, according to Deo et al. (2021):

- TCs in the Southwest Pacific region varies from season-to-season and year-to-year depending on some key factors such as the SPCZ, Madden-Julian Oscillation (MJO), and ENSO.
- Over the Southwest Pacific, TC contributions to extreme rainfall are enhanced during active phases of the MJO and by ENSO conditions because the increased TC activity during these event periods.
- For Vanuatu, the fractional TC contributions to 1- , 2- and 3-day maximum daily rainfall for November-April are 31.22%, 34.62% and 34.99%, respectively.

[26] Deo et al. (2021) considered TCs occurring within 500 km of select weather stations in Vanuatu. It is worth noting that McGree et al. (2022), who analysed TCs using the “Vanuatu EEZ“ as the spatial filter and also considered tropical depressions (winds<=34 kt), found an average of 24 cyclones per decade

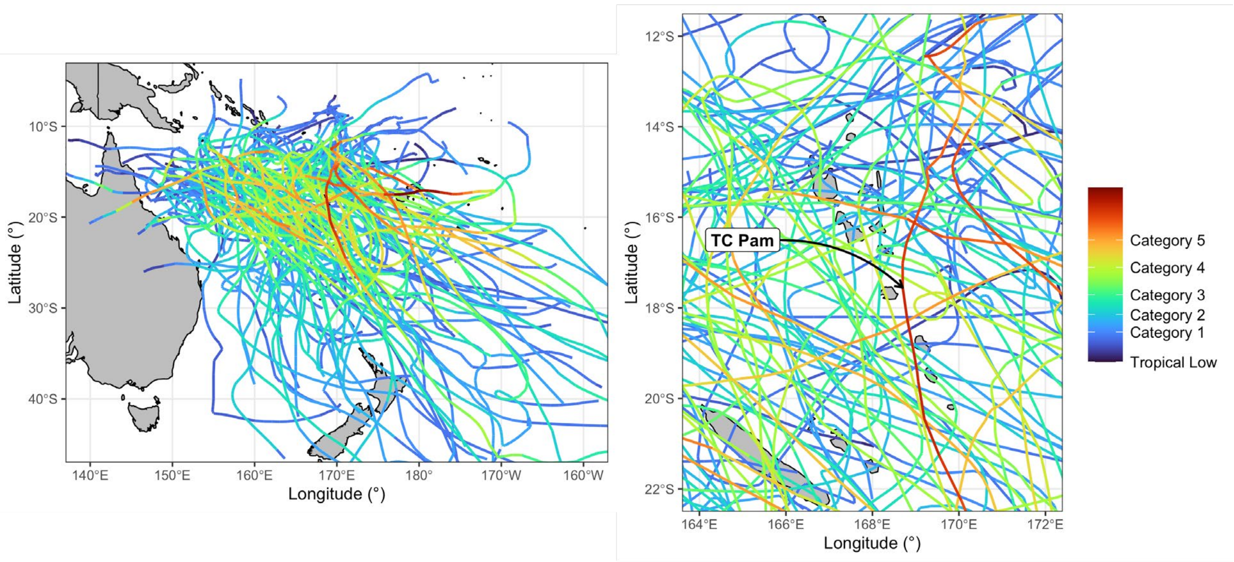


Figure 24 TC tracks with wind speeds of at least 35 kt that pass through the VMGD region of responsibility. Tracks are coloured by categorical TC intensity, based on maximum 10-minute wind speed (kt), following the Australian Bureau of Meteorology's TC intensity categorisation scheme. The Left panel shows all tracks, while the Right panel showing the same data zoomed to Vanuatu region. Data source: IBTrACS dataset for TC seasons 1980–2021

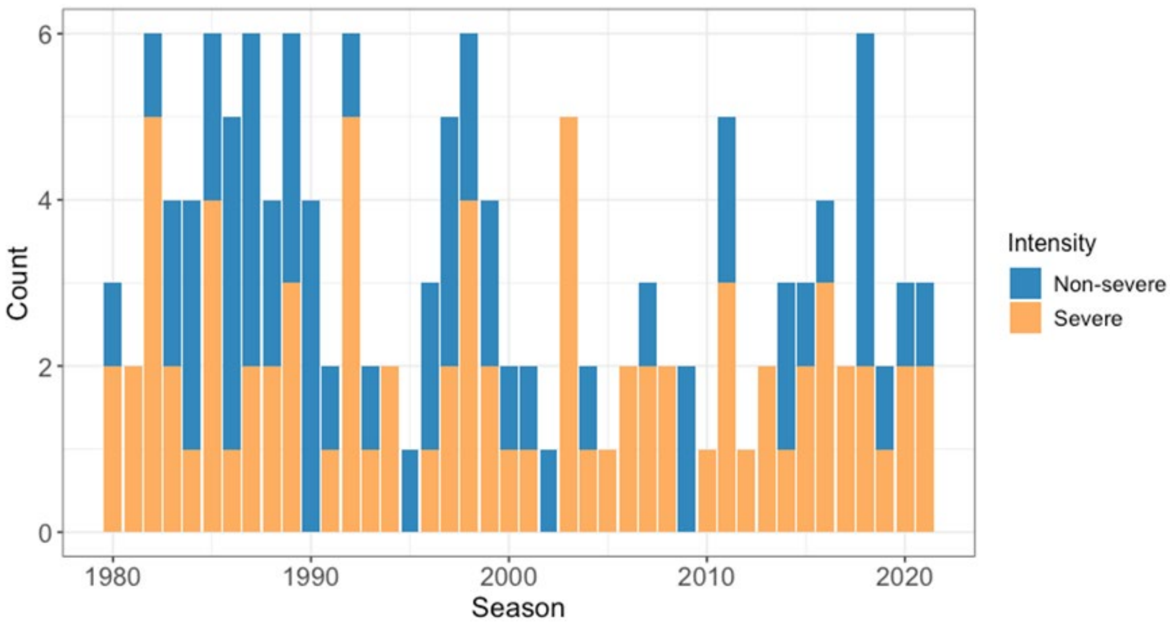


Figure 25 Seasonal TC count (1980-2021), for tracks that pass through VMGD area of responsibility. The bars are stacked according to intensity: non-severe, < 64 kts, and severe, >= 64 kt. Data source: IBTrACS dataset for TC seasons 1980–2021

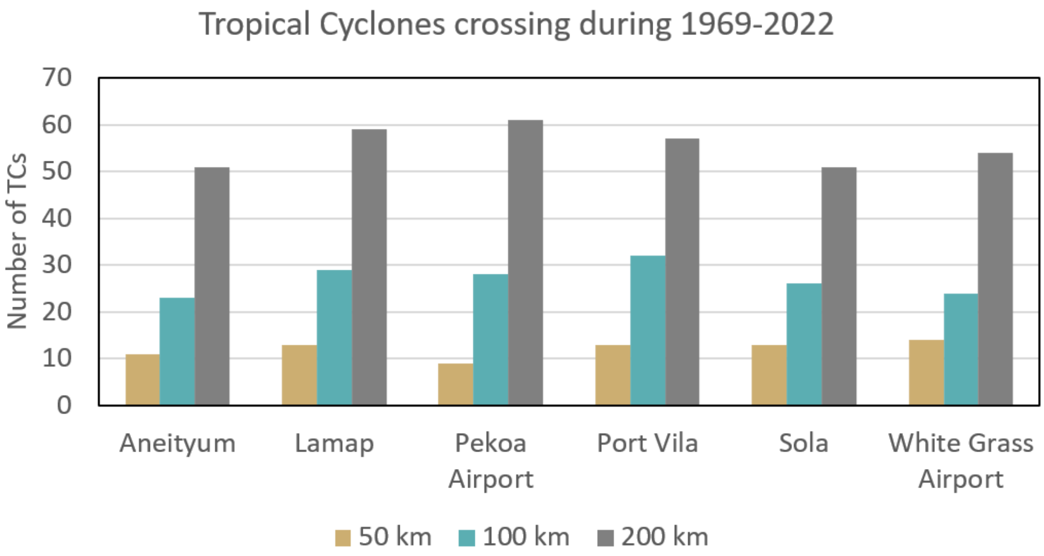


Figure 26 Number of TCs appeared within 50 km, 100 km, and 200 km from selected stations in Vanuatu for 1969-2022. Data source: The Southern Hemisphere Tropical Cyclone Data Portal (2022)

4.4.2 Trends

Trends in observed tropical cyclone that appeared within various distance from Port Vila for the past 50 years are analysed and shown in Figure 27. Observed trends in TC frequency and intensity over the globe and South Pacific region reported by literatures are shown in Figure 28 to Figure 31, as complement.

The key messages for Vanuatu are:

- There has been a slight, statistically insignificant, decreasing trend in the seasonal number of TCs in recent decades (Figure 25, Figure 27 to Figure 29), consistent with a longer-term downward trend in TC numbers since around 1900 (Chand et al. 2022)
- The proportion of severe tropical cyclones (winds >= 64 kt), relative to total number, has increased over recent decades in the VMGD region of responsibility (Figure 25), consistent with expectations due to climate change (Kossin et al., 2020; Figure 30)[27].
- The potential intensity of tropical cyclones has increased over recent decades due to an increase in greenhouse gases (Emanuel, 2020; Figure 31).

[27] Noting that McGree et al (2022), who used different region encompassing the broader South Pacific basin, found a negative trend in the number of severe tropical cyclone over 1981/82 to 2020/21 seasons.

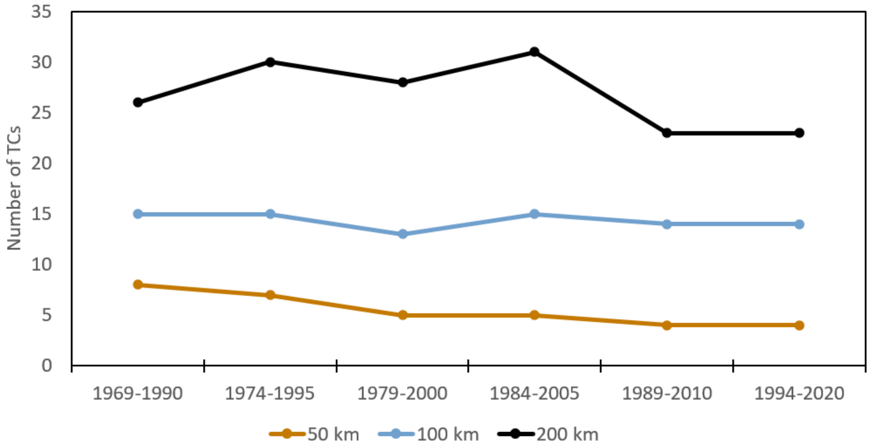


Figure 27 Twenty-one year moving average of tropical cyclone occurrence within 50 km, 100 km, and 200 km from Port Vila. Data source: The Southern Hemisphere Tropical Cyclone Data Portal (2022)

Figure 28 Number of tropical cyclones appeared within the Vanuatu exclusive economic zone (EEZ) for each season, which defined by the ENSO status (light blue, dark blue and grey bars denote El Niño, La Niña and neutral ENSO years, respectively). Source of figure: McGree et al., (2022)

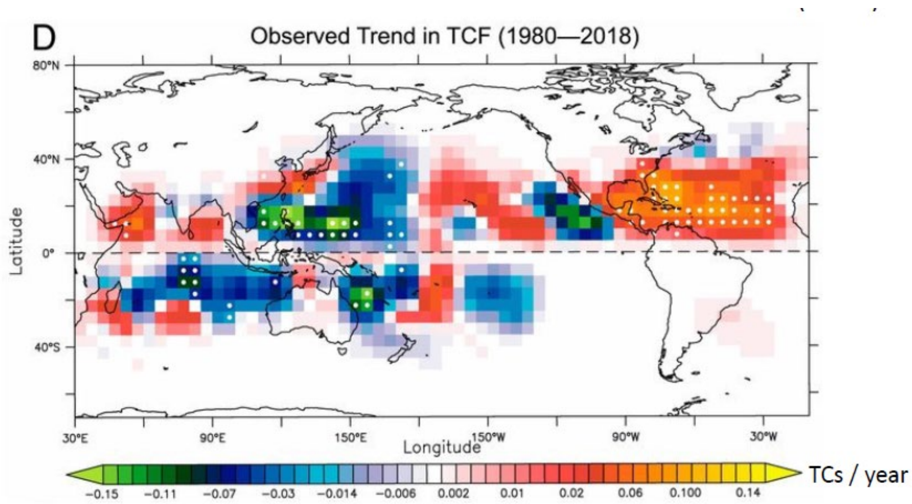


Figure 29 Observed trends in tropical cyclone frequency for 1980-2018. Source of figure: Murakami et al. (2020)

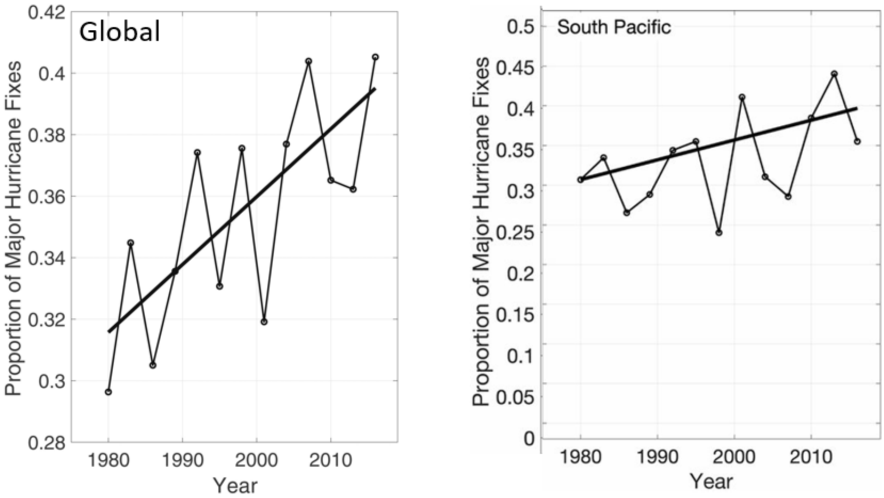


Figure 30 Trends in the fractional proportion of major tropical cyclone (U.S. Saffir-Simspon Categories 3-5) satellite estimates to all estimates in based on global data (left) and South Pacific data (right). Source of figures: Kossin et al. (2020)

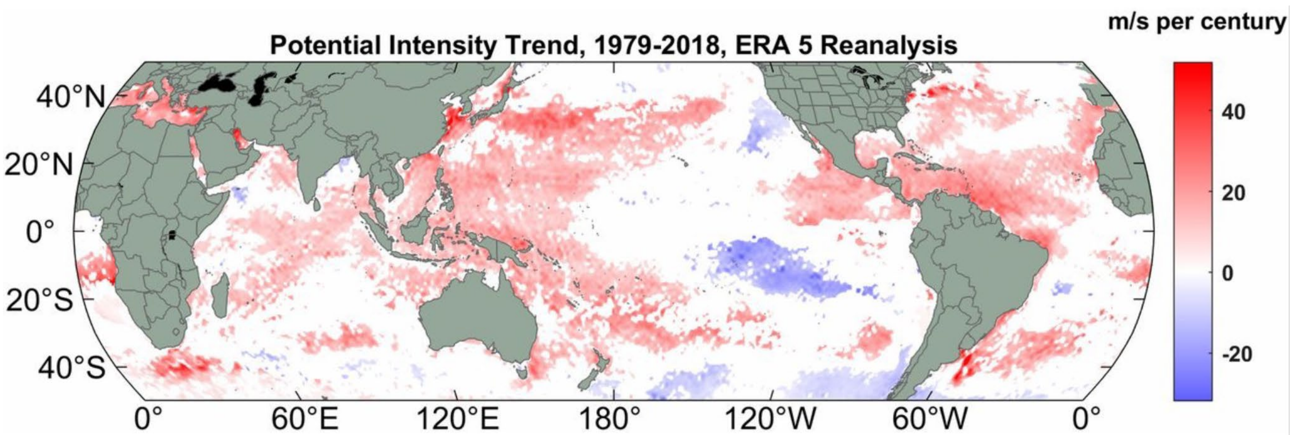


Figure 31 Trends in potential intensity of tropical cyclones over the globe. Source of figure: Emanuel (2020)

5 Projections for mean climate

5.1 Projections based on Global Climate Models (GCMs)

5.1.1 Temperature

Projections for average temperature based on CMIP5 GCMs under three RCPs, for Vanuatu and the three sub-regions, are shown in Figure 32 and Table 5. The key messages are:

- The mean annual temperature is projected to continue increasing over Vanuatu, with the magnitude of warming becoming strongly dependant on the RCPs.
  - Under RCP2.6, the projected temperature increase stabilises at an average of 0.6 °C (0.4 – 1.0 °C range) above the 1986-2005 baseline by around mid century.
  - Under RCP8.5, projected temperatures reach 2.7 °C (2.0 to 3.4 °C range) warmer by the end of the century.
- The projections are similar for each of the three sub-national regions, and also similar across the wet and dry seasons (see Appendix 3).

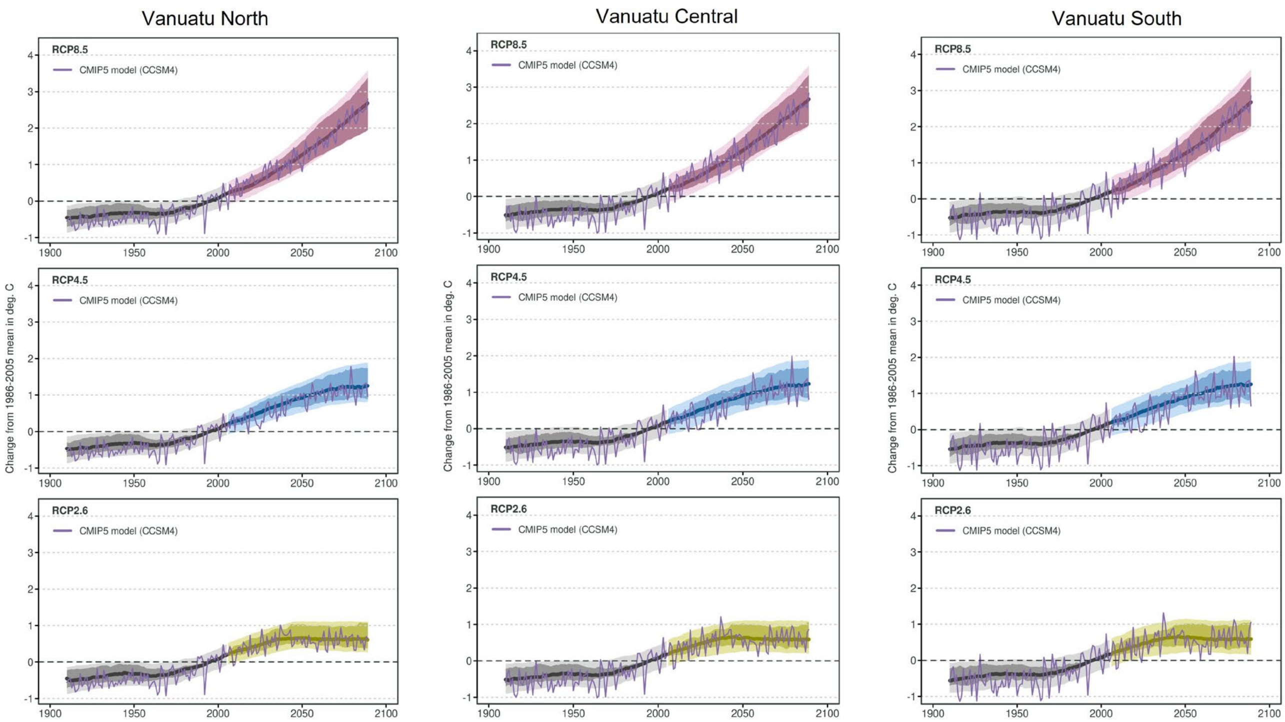


Figure 32 Vanuatu sub-national average temperature for 1910-2090 as simulated by GCMs relative to the 1986-2005 mean. The black line is the multi-model median value, and the shading is the 10th and 90th percentile range of 20-year running means (inner) and single year values (outer). The grey shading indicates the period of the historical simulation, while the future scenarios are shown with colour-coded shading: RCP8.5. (purple), RCP4.5 (blue) and RCP2.6 (green). An example of a climate model time annual series is shown as the thin purple line

Table 5 Summary of projected changes for annual mean temperature (°C) for Vanuatu and the three sub-national regions, based on CMIP5 GCMs. Projected change is relative to 1995 and represents four different future periods (2030, 2050, 2070 and 2090) and two RCPs (RCP2.6 and RCP8.5). The multi-model ensemble median value is given with the 10th to 90th percentile range in brackets

PERIODS	RCP	VAN	VAN-N	VAN-C	VAN-S
2020-2039	RCP2.6	0.5 (0.4 to 0.7)	0.5 (0.4 to 0.8)	0.5 (0.4 to 0.7)	0.5 (0.3 to 0.7)
	RCP8.5	0.7 (0.5 to 0.8)	0.7 (0.5 to 0.8)	0.7 (0.5 to 0.8)	0.7 (0.5 to 0.8)
2040-2059	RCP2.6	0.6 (0.5 to 1.0)	0.7 (0.5 to 1.0)	0.6 (0.5 to 1.0)	0.6 (0.4 to 1.0)
	RCP8.5	1.2 (0.9 to 1.6)	1.2 (0.9 to 1.6)	1.2 (0.9 to 1.6)	1.2 (0.9 to 1.6)
2060-2079	RCP2.6	0.6 (0.4 to 0.9)	0.6 (0.5 to 1.0)	0.6 (0.4 to 0.9)	0.6 (0.4 to 0.9)
	RCP8.5	2.0 (1.5 to 2.4)	1.9 (1.4 to 2.4)	1.9 (1.5 to 2.4)	1.9 (1.5 to 2.4)
2080-2099	RCP2.6	0.6 (0.4 to 1.0)	0.6 (0.4 to 1.0)	0.6 (0.4 to 1.0)	0.6 (0.4 to 1.0)
	RCP8.5	2.7 (2.0 to 3.3)	2.7 (2.0 to 3.3)	2.7 (2.0 to 3.3)	2.7 (2.0 to 3.4)

5.1.2 Rainfall

Projections for average rainfall based on GCMs under three RCPs, for Vanuatu and the three sub-regions, are presented in Figure 33 to Figure 34 and Table 6.

The key messages are:

- There is no significant projected change in annual rainfall, consistent with the lack of observed historical trend. Some climate models show an increase, others show a decrease. There is also no clear difference between different RCPs.
- There is a slight tendency for the multi-model ensemble to show a reduction in rainfall in the dry season, especially in Vanuatu Central and Vanuatu South, and this signal becomes more pronounced in the later part for the 21st century under all RCPs (Table 6).

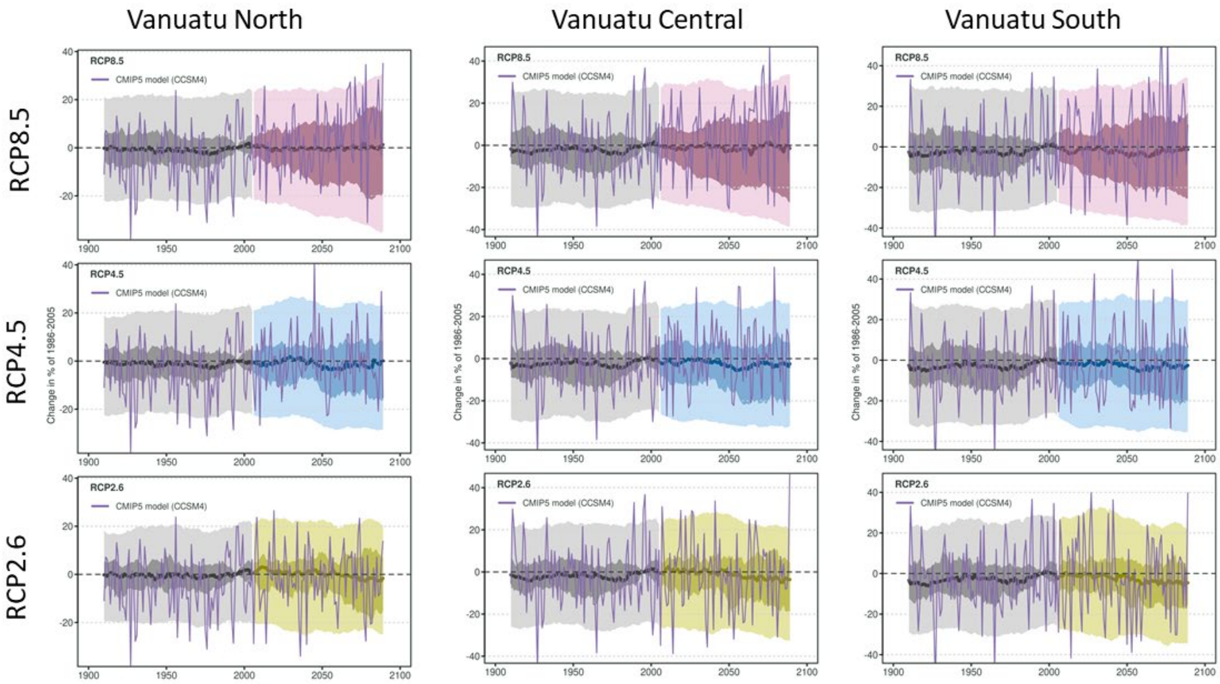


Figure 33 Time series for Vanuatu regional rainfall anomaly for 1910-2090 as simulated in CMIP5 GCMs relative to the 1986-2005 mean. The central line is the multi-model median value, and the shading is the 10th and 90th percentile range of 20-year running means (inner) and single year values (outer). The grey shading indicates the period of the historical simulation, while the future scenarios are shown with colour-coded shading: RCP8.5 (purple), RCP4.5 (blue) and RCP2.6 (green). An example of a climate model is shown by the thin purple line

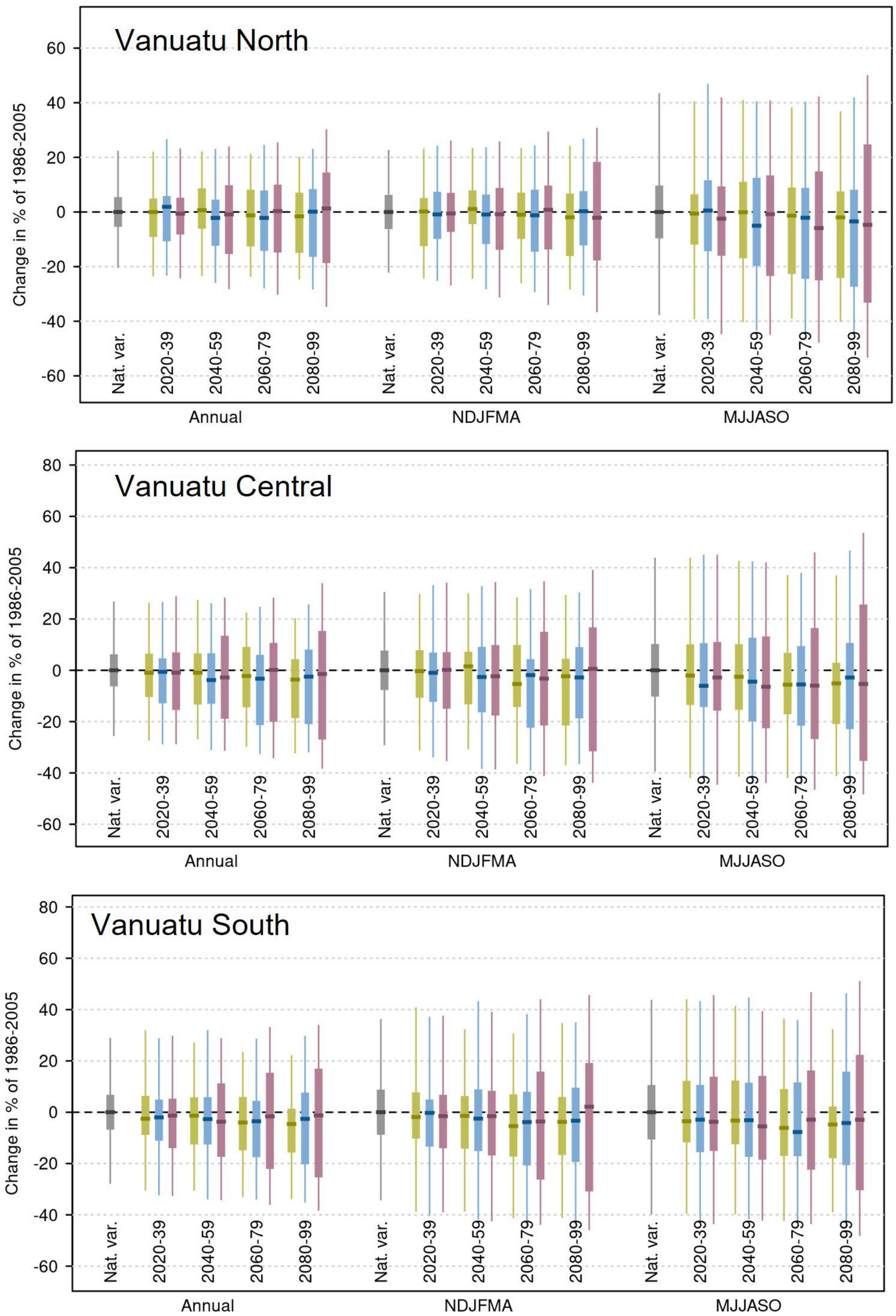


Figure 34 Projected changes for annual and seasonal rainfall for future periods relative to the 1986-2005 period (grey bar) for RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (purple). The solid bar shows the multi-model median and 10th to 90th percentile range, the fine lines show the range of individual years. NDJFMA = November-April (wet season), MJJASO = May-October (dry season)

Table 6 Summary of projected changes for seasonal mean rainfall for Vanuatu and the three sub-national regions, based on GMCs. Projected changes are relative to 1986-2005 and represent four future periods (2030, 2050, 2070 and 2090) and two RCPs (RCP2.6 and RCP8.5). The multi-model ensemble median value is given with the 10th to 90th percentile range in brackets. NDJFMA = November-April (wet season), MJJASO = May-October (dry season). Unit: % change

FUTURE PERIOD	RCP	VAN		VAN-N		VAN-C		VAN-S	
		NDJFMA	MJJASO	NDJFMA	MJJASO	NDJFMA	MJJASO	NDJFMA	MJJASO
2030	RCP2.6	-1 (-9 to 6)	-2 (-12 to 8)	-0 (-10 to 5)	-1 (-12 to 7)	-2 (-10 to 7)	-2 (-12 to 9)	-2 (-9 to 7)	-3 (-11 to 12)
	RCP8.5	0 (-12 to 6)	-3 (-15 to 10)	-1 (-7 to 6)	-2 (-15 to 10)	0 (-15 to 7)	-2 (-16 to 13)	-2 (-14 to 7)	-4 (-15 to 14)
2050	RCP2.6	0 (-8 to 7)	-2 (-12 to 10)	1 (-4 to 7)	-0 (-14 to 12)	2 (-10 to 8)	-3 (-13 to 9)	-2 (-12 to 7)	-3 (-12 to 12)
	RCP8.5	-2 (-16 to 9)	-1 (-22 to 15)	-1 (-13 to 9)	-0 (-23 to 15)	-2 (-17 to 10)	-4 (-22 to 13)	-1 (-17 to 8)	-5 (-18 to 14)
2070	RCP2.6	-3 (-12 to 6)	-4 (-18 to 7)	-1 (-10 to 7)	-1 (-22 to 8)	-4 (-15 to 8)	-5 (-17 to 9)	-5 (-17 to 7)	-5 (-15 to 10)
	RCP8.5	-2 (-18 to 15)	-2 (-24 to 16)	1 (-13 to 9)	0 (-25 to 16)	-3 (-21 to 17)	-5 (-26 to 18)	-3 (-24 to 19)	-3 (-21 to 17)
2090	RCP2.6	-3 (-17 to 7)	-4 (-19 to 5)	-2 (-14 to 6)	-2 (-21 to 7)	-2 (-19 to 8)	-5 (-20 to 4)	-3 (-16 to 6)	-5 (-17 to 4)
	RCP8.5	2 (-22 to 19)	-4 (-34 to 26)	-2 (-17 to 18)	-3 (-34 to 27)	0 (-26 to 18)	-4 (-32 to 28)	2 (-31 to 22)	-2 (-30 to 25)

5.2 Projections based on downscaled simulations (CCAMs)

5.2.1 Temperature

Projected changes in temperature based on CCAMs for RCP8.5 are presented in Figure 35 to Figure 37, and Table 7.

The key messages are:

- Projected increase is shown for all regions and for all seasons; and are consistent with the projections based on GCMs.
- The warming is similar for all temperature variables (mean, minimum and maximum temperatures).
- The warming is the greatest by the end of the 21st century.

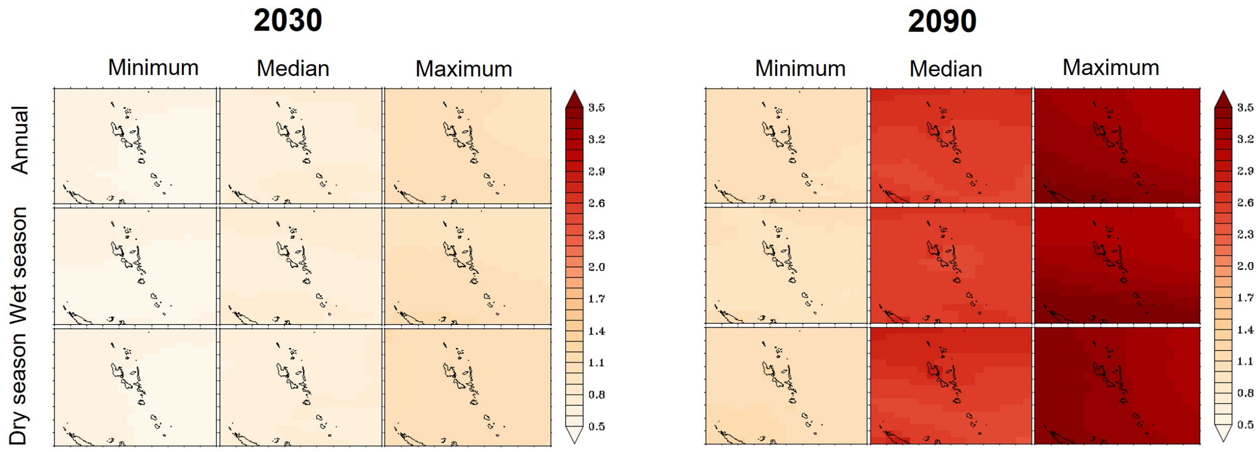


Figure 35 Projected changes in mean temperature for 2030 and 2090 relative to 1995 period under RCP8.5 according to five CCAM simulations. The multi-model ensemble is shown as minimum, median, and maximum

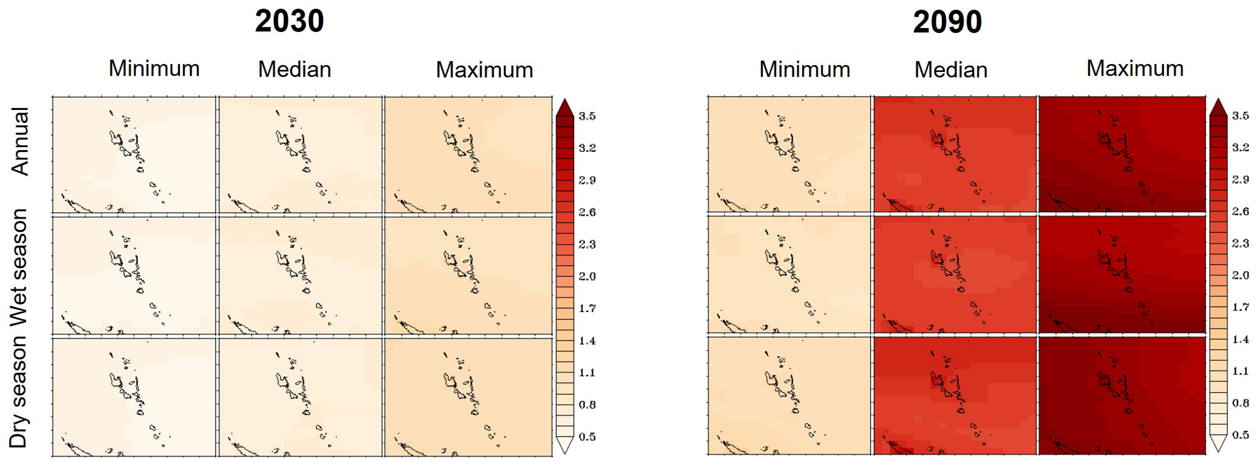


Figure 36 As per Figure 35 but for minimum temperature

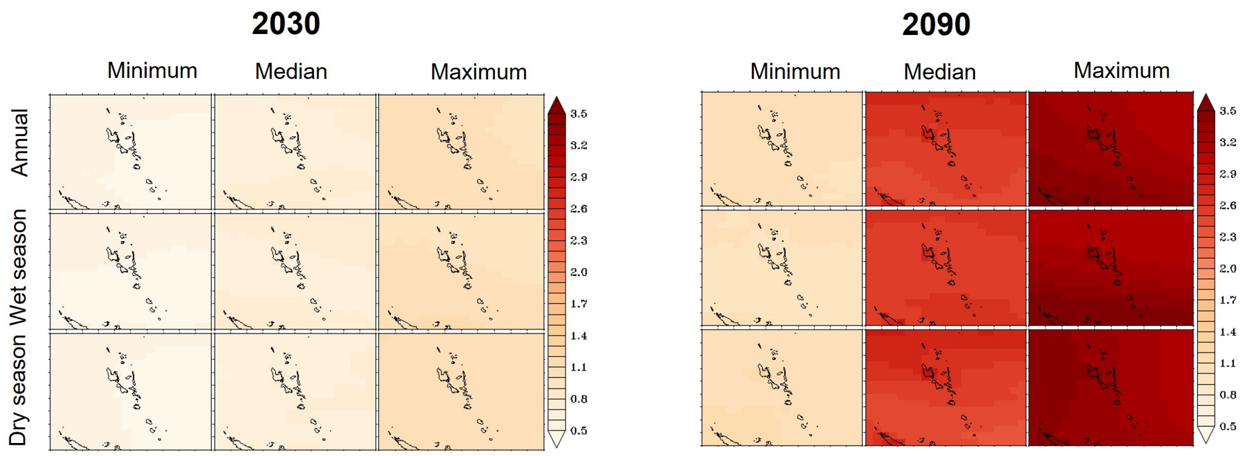


Figure 37 As per Figure 34 but for maximum temperature

Table 7 Summary of projected changes for annual maximum and minimum temperature (°C) for the three sub-national regions, based on CCAM. Projected change is relative to 1995 and represents four different future periods (2030, 2050, 2070 and 2090) under RCP8.5. The multi-model median value is given with the minimum-maximum range in brackets

PERIODS	VAN-N	VAN-C	VAN-S
Maximum temperature			
2020-2039	0.7 (0.5 to 1.0)	0.7 (0.5 to 1.0)	0.7 (0.4 to 1.0)
2040-2059	1.2 (0.9 to 1.6)	1.1 (0.9 to 1.6)	1.1 (1.0 to 1.6)
2060-2079	2.0 (0.8 to 2.4)	1.9 (0.8 to 2.4)	1.9 (0.8 to 2.4)
2080-2099	2.6 (2.3 to 3.2)	2.6 (2.3 to 3.2)	2.7 (2.4 to 3.2)
Minimum temperature			
2020-2039	0.6 (0.5 to 1.0)	0.7 (0.5 to 1.0)	0.7 (0.5 to 1.0)
2040-2059	1.2 (0.8 to 1.6)	1.1 (0.9 to 1.6)	1.2 (1.0 to 1.6)
2060-2079	2.0 (0.8 to 2.4)	1.9 (0.8 to 2.4)	1.9 (0.8 to 2.4)
2080-2099	2.6 (1.0 to 3.3)	2.5 (1.0 to 3.3)	2.5 (1.0 to 3.4)
2020-2039	0.6 (0.5 to 1.0)	0.7 (0.5 to 1.0)	0.7 (0.5 to 1.0)

5.2.2 Rainfall

Projected changes in mean rainfall based on CCAMs, for RCP8.5, are presented in Figure 38 and Table 8.

The key messages are:

- The multi-model median shows little change in the near term (2030), with model projections showing potential increase or decrease for all areas.
- The multi-model median for end of the century (2090) projects increasing wet season rainfall over most of Vanuatu, except the south. For the dry season, there is potential increase or decrease for most area, except the south where all models showing reduction.

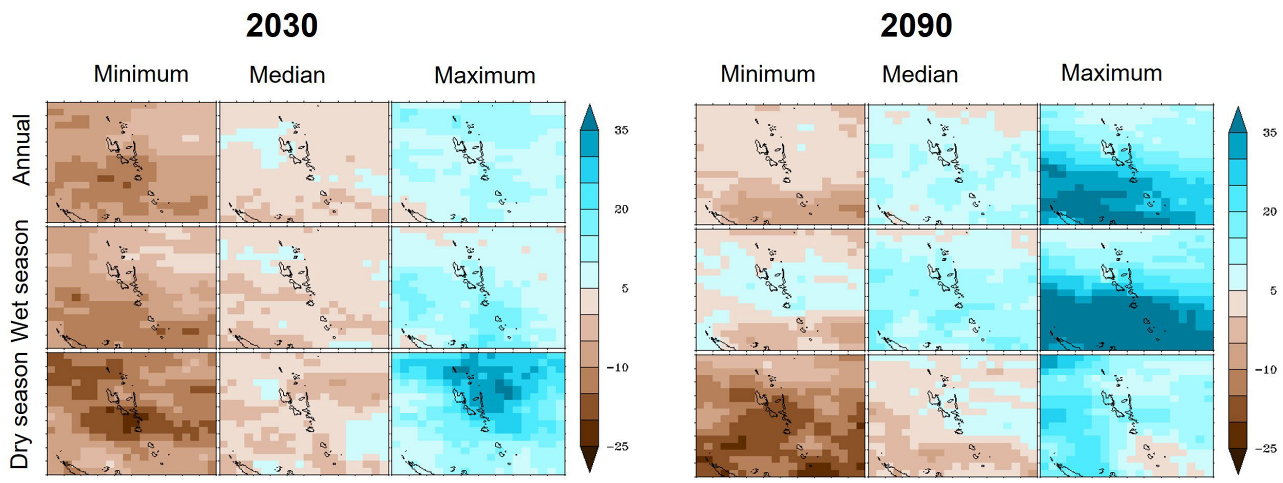


Figure 38 Projected changes in mean rainfall for 2030 and 2090 relative to 1995 period under RCP8.5 according to five CCAM simulations. The multi-model ensemble is shown as minimum, median, and maximum

Table 8 Summary of projected changes for seasonal rainfall (%) for the three sub-national regions, based on CCAM. Projected change is relative to 1995 and represents four different future periods (2030, 2050, 2070 and 2090) for RCP8.5. The multi-model median value is given with the minimum-maximum range in brackets

PERIODS	VAN-N		VAN-C		VAN-S	
	NDJFMA	MJJASO	NDJFMA	MJJASO	NDJFMA	MJJASO
2020-2039	3 (-3 to 7)	1 (-12 to 26)	1 (-7 to 11)	2 (-16 to 21)	3 (-11 to 14)	3 (-8 to 12)
2040-2059	-1 (-6 to 9)	4 (-8 to 16)	-2 (-4 to 10)	1 (-3 to 22)	-4 (-12 to 17)	5 (-10 to 14)
2060-2079	3 (-3 to 12)	5 (-5 to 9)	8 (3 to 18)	7 (-14 to 18)	14 (0.7 to 26)	5 (-15 to 22)
2080-2099	9 (6 to 14)	4 (-9 to 10)	13 (9 to 31)	5 (-16 to 12)	11 (-0.9 to 44)	-1.0 (-17 to 5)

5.3 Comparison of projected changes based on GCMs and CCAMs

To understand how the results from CCAMs relate to those from the host GCMs, Figure 39 and Figure 40 compares projected changes in temperature and in rainfall, respectively.

For temperature the key messages, displayed in Figure 39, are:

- For the near future (2030), projected changes based on CCAMs are in general similar to those from the host GCMs, for both minimum and maximum temperatures.
- For the end of the 21st Century (2090), the projection ranges based on CCAMs are greater than those based on the GCMs, with one model (NorESM1-M) showing significantly lower amount of warming in the CCAM simulation than the host GCM.

The fact that the two modelling approaches produce similar results gives confidence to the projection.

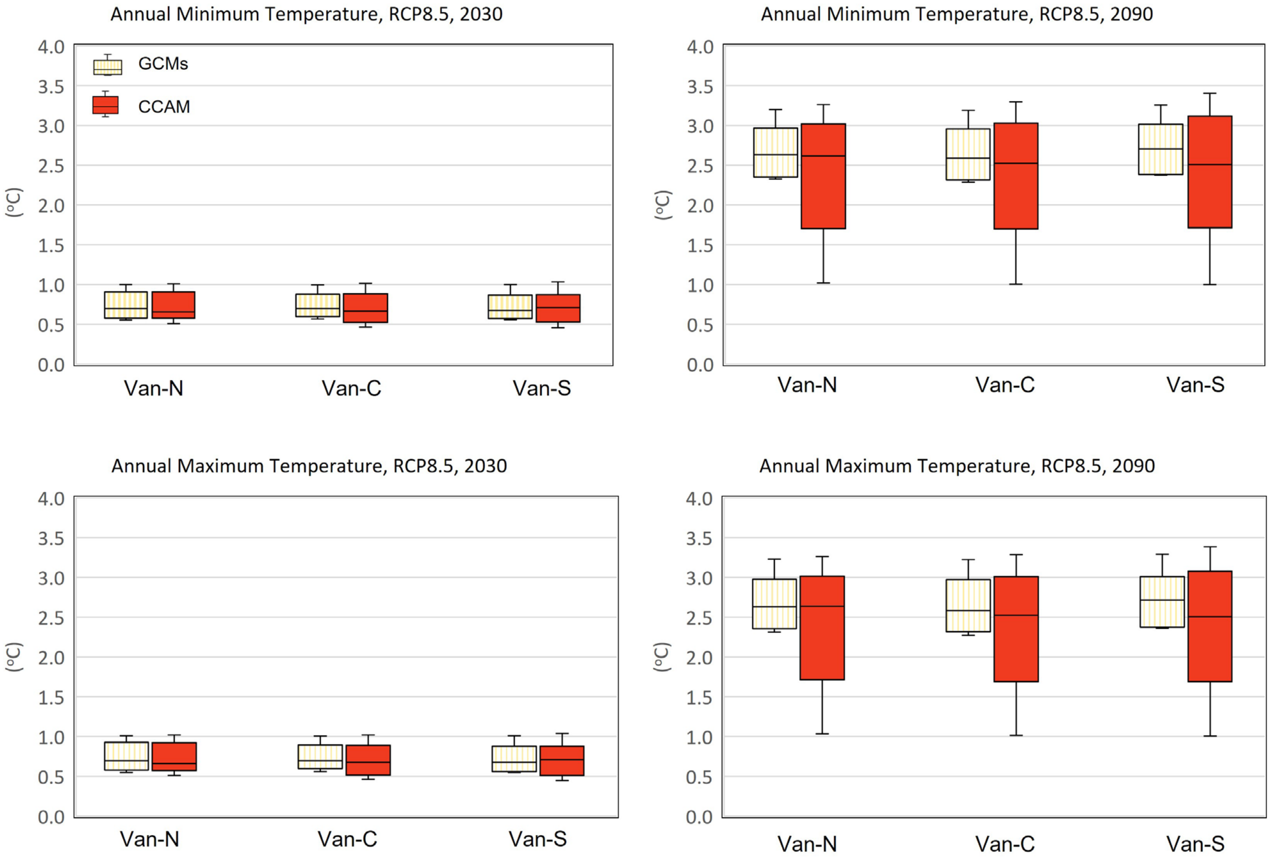


Figure 39 Comparison of projected change in annual minimum temperature (top) and maximum (bottom) temperature for 2030 (left) and 2090 (right) based on five GCMs and CCAMs RCP8.5 simulations. The box plots show the multi-model minimum and maximum; 25th and 75th percentile; and median (50th percentile)

For rainfall the key messages, displayed in Figure 40, are:

- For the near future (2030), the results from CCAMs are quite similar to those of the GCMs, with the multi-model median showing only small differences. However, the range of projections for Vanuatu North and Vanuatu Central, tend to show a shift to less drying and more wetting in the CCAM model ensemble.
- For the long-term future (2090), the multi-model median and ranges show larger differences between the CCAM modelling and the GCMs. For Vanuatu North and Vanuatu Central, the CCAM multi-model median shows a greater increase in rainfall than the GCMs, and the CCAM multi-model range shows increasing rainfall for all models whereas some of the GCMs show decreasing rainfall. On the other hand, for Vanuatu South the CCAM multi-model median shows less increase in rainfall than the GCMs, but a roughly similar range with both wetter and drier conditions projected.

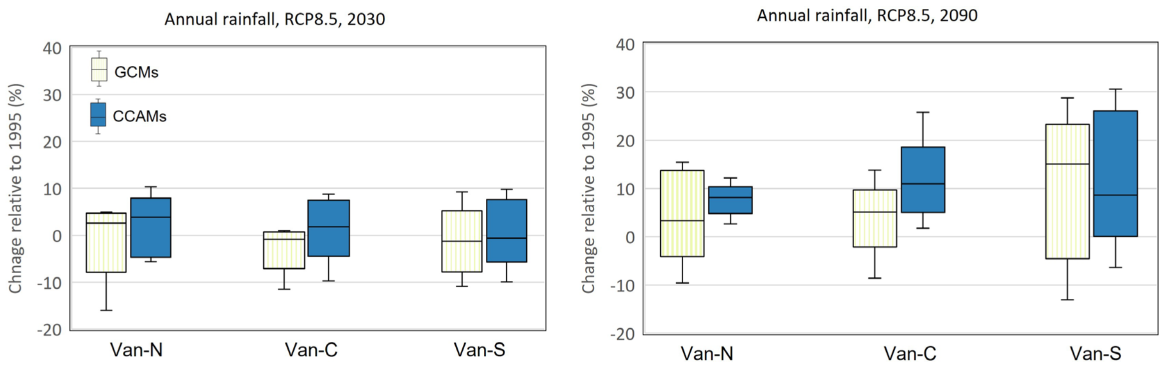


Figure 40 Comparison of projected change in annual rainfall for 2030 (left) and 2090 (right) developed based on five GCMs and CCAMs RCP8.5 simulations. The box plots show the multi-model ensemble minimum and maximum; 25th and 75th percentile; and median (50th percentile)

As mentioned in Chapter 3, the CCAM downscaled simulations were run with only five GCMs (i.e., GFDL-ESM2M, NORESM1-M, CANESM2, MIROC5 and ACCESS1.0). To understand how CCAM and these five host GCMs capture the range of projected changes from all CMIP5 GCMs, we can examine Figure 41. The figure indicates that the CCAM results and the five GCMs capture a significant portion of the range, even though not always capturing the full range of plausible projected changes in each of the future periods.

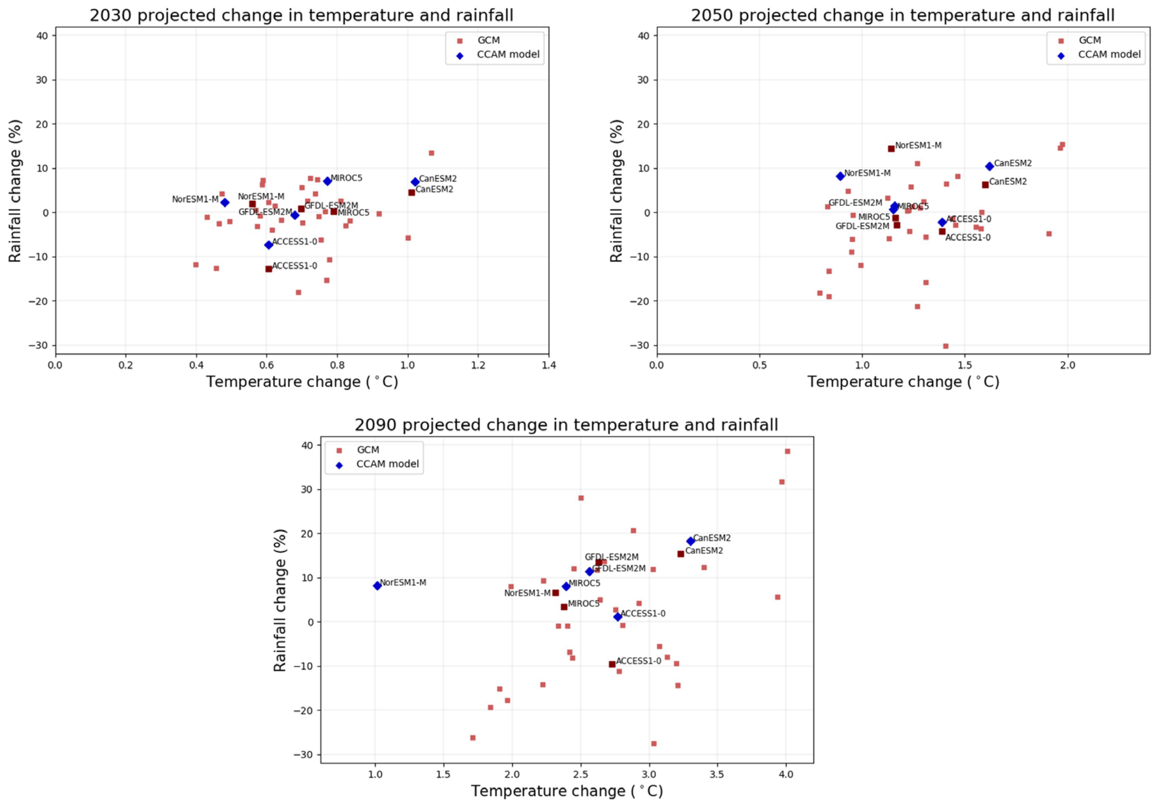


Figure 41 Projected changes in mean temperature and rainfall in the Vanuatu region from all CMIP5 GCMs run with RCP8.5, showing the five GCMs that were used to run CCAM

5.4 Comparison of projected changes between CMIP5 and CMIP6 GCMs

This study used CMIP5 GCMs simulation data. To provide context of how the results from this study relate to the recent CMIP6 GCMs simulations, we analysed the projected changes data for Southwest SPCZ region, where Vanuatu located. These regional data[28] are available recently and are discussed in Iturbide et al. (2021) and Gutiérrez et al. (2021). The results are shown in Figure 42 and Figure 43.

The key messages are:

- The projected changes in mean annual temperature are overall the same for both CMIP5 and CMIP6 GCMs. The only exception is for the medium- and long-term periods where CMIP6 GCMs show greater warming for the median and the upper range of the projections.
- For annual rainfall, CMIP6's results are also similar to those of CMIP5 GCMs although there is a tendency among the CMIP6 GCMs to show less rainfall increase in the medium- and long-term. The ranges of projected change are slightly greater for the CMIP5 GCMs than those of CMIP6.

These implies that the results of this study would be relatively consistent with results from CMIP6 simulations data. Such analyses are not undertaken here but could form a component of future work.

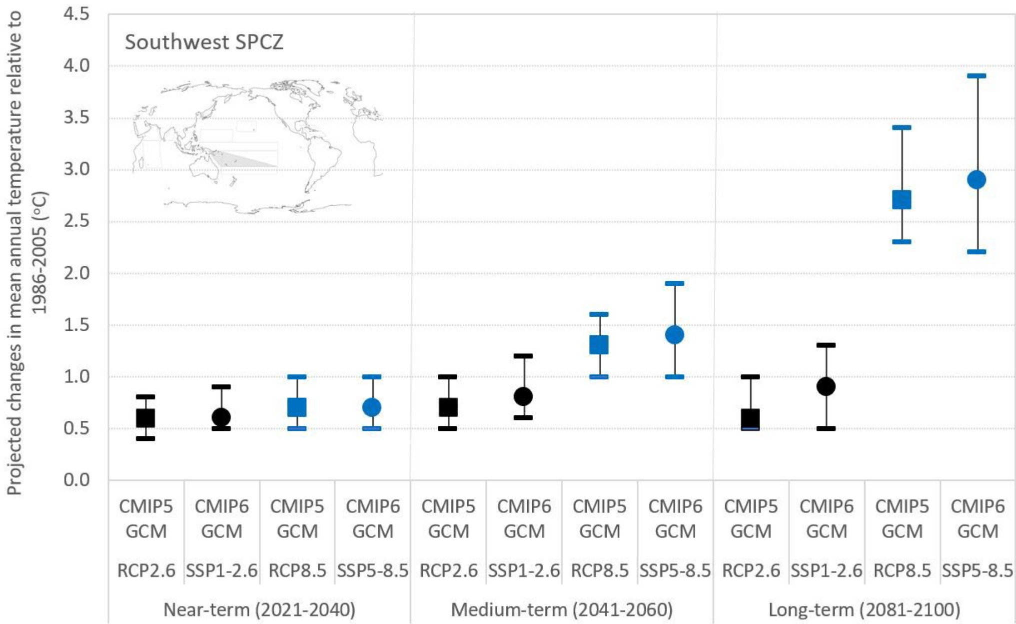


Figure 42 Comparison of projected change in annual mean temperature for Southwest SPCZ (shaded in the inset map) for RCP2.6 in the case of CMIP5 GCM (black and square) and SSP1-2.6 in the case of CMIP6 GCMs (black and circle), and for RCP8.5 in the case of CMIP5 GCM (blue and square) and SSP5-8.5 in the case of CMIP6 GCMs (blue and circle). The box plots show the multi-model median and the 10th – 90th percentiles. Data source: Iturbide et al. (2021) and Gutiérrez et al. (2021)

[28] Please note the number of models that are used to generate these projections data differ for different scenarios, depending on data availability. For RCP2.6, RCP8.5, SSP1-2.6 and SSP5-8.5 it is 21 CMIP5 GCMs, 29 CMIP5 GCMs, 31 CMIP6 GCMs, and 33 CMIP6 GCMs, respectively.

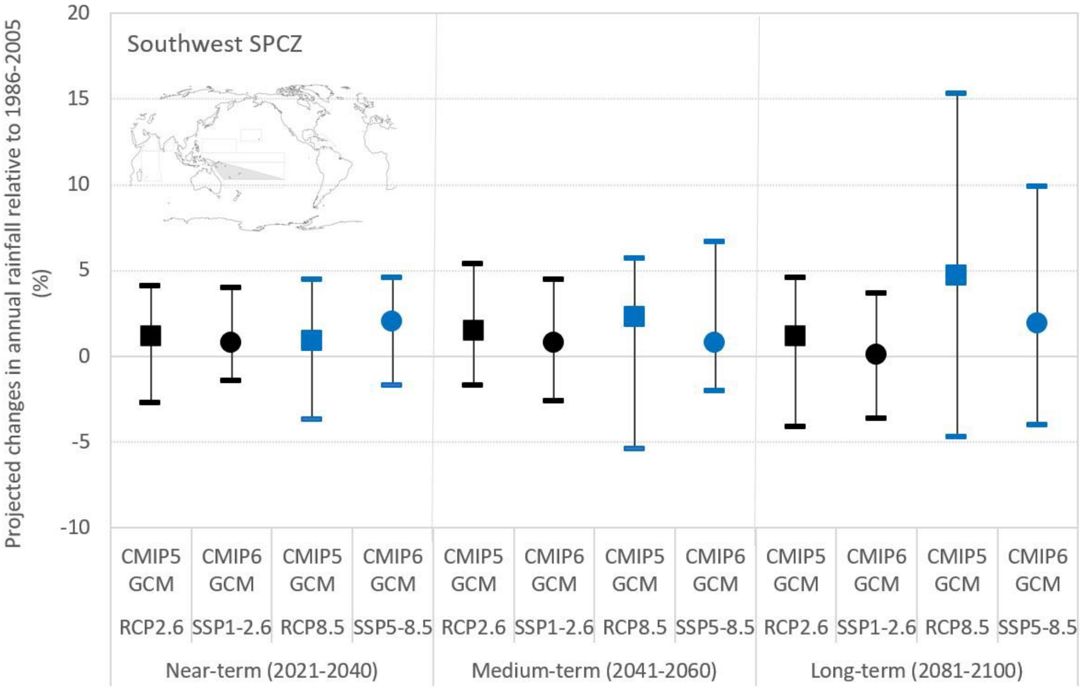


Figure 43 Comparison of projected change in annual rainfall for Southwest SPCZ (shaded in the inset map) for RCP2.6 in the case of CMIP5 GCM (black and square) and SSP1-2.6 in the case of CMIP6 GCMs (black and circle), and for RCP8.5 in the case of CMIP5 GCM (blue and square) and SSP5-8.5 in the case of CMIP6 GCMs (blue and circle). The box plots show the multi-model ensemble median and the 10^{th} – 90^{th} percentiles. Data source: Iturbide et al. (2021) and Gutiérrez et al. (2021)

6 Projections for extremes climate

6.1 Extreme temperature

As global temperatures increase, so too do temperature extremes. Projected changes in various types of temperature extremes are presented in this section, based on the 5 CCAM downscaled simulations. The variables included are: the annual hottest temperature (TXx) and the 1-in-20 year hottest temperature[29] (Table 9 and Figure 44); and the annual coldest night (TNn) and the annual hottest night (TNx) (Table 10 and Figure 45).

The key messages are:

- Extreme temperatures are projected to rise, consistent with the observed trends and projected warming in average temperatures. Under RCP8.5 which represents the 'worst case' for warming, extreme temperatures are projected to be approximately 0.6 – 1.8 degrees hotter by 2050 and 1 – 3.5 degrees hotter by the end of the century.
- All measures of extreme temperature mentioned above are projected to warm by similar amounts and are similar to projections of average maximum temperature change (Figure 46). This suggests that the mean temperature change is a good proxy for change in the whole temperature statistical distribution.
- Projected increase in extreme temperatures is similar for the sub-national regions, although projected warming of hot days over Vanuatu South is very slightly higher.
- Temperature extremes are projected to increase more under RCP8.5 than under RCP4.5 (not shown), in line with the projections of average temperature (Sections 5.1, 5.2).

Table 9 Projected change in the annual hottest day (TXx) and the 1-in-20 year extreme maximum daily temperature (i.e. temperature that has on average a 5 per cent chance of happening in any given year) for the three sub-regions, and four future time periods (2030, 2050, 2070 and 2090). Values shown are the multi-model median with range (minimum to maximum) in brackets based on five CCAM models. Units: °C

REGION	TXx (HOTTEST DAY OF THE YEAR)				1-IN-20 YEAR EXTREME DAILY MAX TEMPERATURE			
	2030	2050	2070	2090	2030	2050	2070	2090
Vanuatu North	0.7 (0.5 - 1.0)	1.3 (0.7 - 1.7)	1.9 (1.0 - 2.4)	2.7 (1.0 - 3.3)	0.7 (0.4 - 0.8)	1.2 (0.6 - 1.6)	1.9 (0.8 - 2.3)	2.7 (0.9 - 3.1)
Vanuatu Central	0.7 (0.5 - 0.9)	1.3 (0.8 - 1.6)	2.0 (0.9 - 2.4)	2.7 (1.0 - 3.3)	0.7 (0.4 - 0.7)	1.2 (0.7 - 1.7)	1.9 (0.7 - 2.2)	2.7 (0.9 - 3.1)
Vanuatu South	0.6 (0.5 - 0.9)	1.4 (0.8 to 1.5)	2.1 (0.8 - 2.5)	2.9 (1.0 - 3.6)	0.6 (0.5 - 0.9)	1.5 (0.6 - 1.7)	2.0 (0.7 - 2.4)	2.7 (0.7 - 3.5)

[29] The 1-in-20 year hottest temperature represents the temperature that has on average a 5 per cent chance of being happening in any given year.

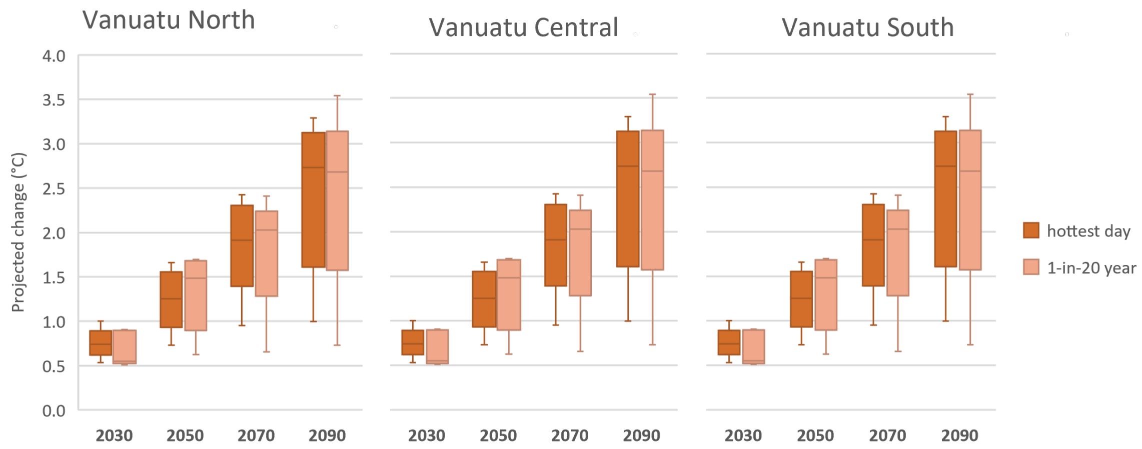


Figure 44 Projected changes in the annual hottest day of the year (TXx) and the 1-in-20 year hottest day (i.e. temperature that has on average a 5 per cent chance of happening in any given year) for the three sub-regions over four future time periods (2030, 2050, 2070, 2090). The box plots show the multi-model minimum and maximum; 25th and 75th percentile; and median (50th percentile) based on the five CCAM simulations under RCP8.5

Table 10 Projected change in the coldest night of the year (TNn) and the hottest night of the year (TNx) for the three sub-regions, and four future time periods (2030, 2050, 2070 and 2090). Values shown are the multi-model median with range (minimum to maximum) in brackets based on five CCAM models. Units: °C

REGION	TNn (COLDEST NIGHT OF THE YEAR)				TNx HOTTEST NIGHT OF THE YEAR			
	2030	2050	2070	2090	2030	2050	2070	2090
Vanuatu North	0.6 (0.5 - 1.1)	1.3 (1.0 - 1.8)	2.1 (0.8 - 2.6)	2.8 (1.1 - 3.4)	0.7 (0.5 - 1.0)	1.2 (0.7 - 1.7)	1.9 (0.9 - 2.4)	2.7 (1.0 - 3.3)
Vanuatu Central	0.7 (0.5 - 1.2)	1.3 (1.1 - 1.7)	2.1 (0.8 - 2.7)	2.6 (1.1 - 3.6)	0.7 (0.5 - 0.9)	1.2 (0.7 - 1.5)	2.0 (0.9 - 2.4)	2.7 (0.9 - 3.3)
Vanuatu South	0.6 (0.5 - 1.1)	1.3 (1.1 - 1.6	1.9 (0.8 - 2.6)	2.5 (1.1 - 3.4)	0.6 (0.6 - 0.8)	1.3 (0.9 - 1.5)	2.0 (0.9 - 2.5)	2.8 (1.0 - 3.5)

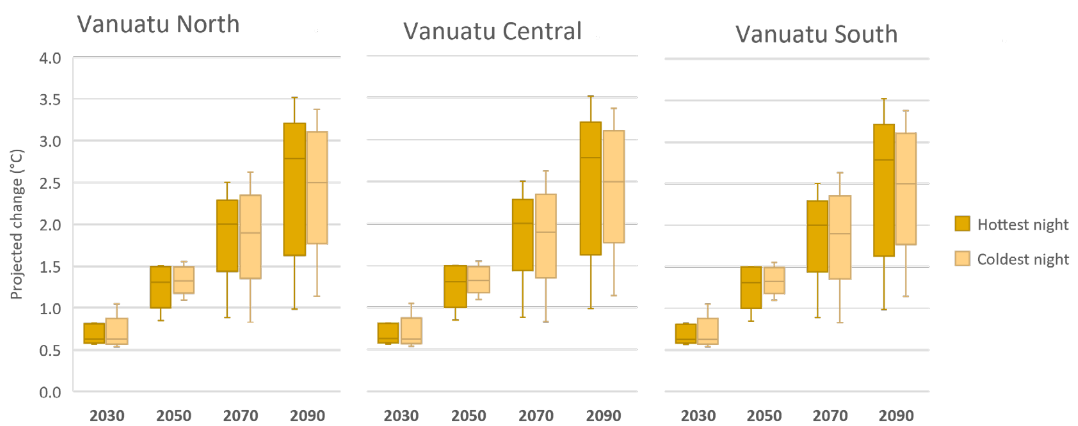


Figure 45 Projected changes in the annual hottest night (TXx) and the annual coldest night (TXn) for the three sub-regions over four future time periods (2030, 2050, 2070, 2090). The box plots show the multi-model ensemble minimum and maximum; 25th and 75th percentile; and median (50th percentile) based on the five CCAM simulations under RCP8.5

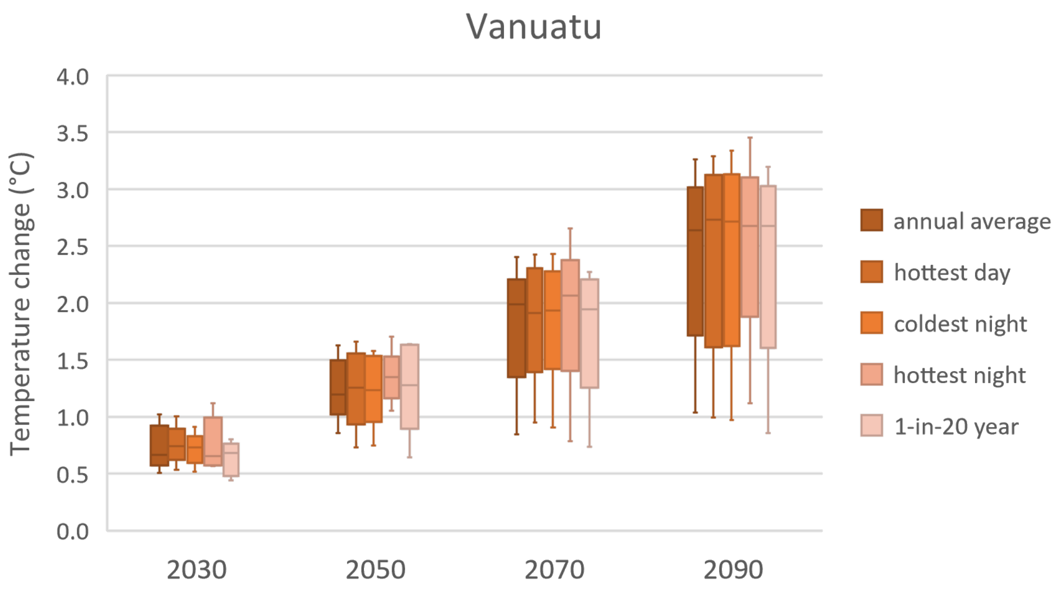


Figure 46 Projected changes in various extreme temperature metrics: annual hottest day (TXx), annual coldest night (TNn), annual hottest night (TNx) and 1-in-20 year hottest day, compared to the projected change in annual average temperature, for the whole of Vanuatu region over four future time periods (2030, 2050, 2070, 2090). The box plots show the multi-model minimum and maximum; 25th and 75th percentile; and median (50th percentile) based on the five CCAM simulations under RCP8.5

6.2 Extreme rainfall

Projected changes in the annual maximum daily rainfall (Rx1day, also known as the wettest day of the year) and the 1-in-20 year extreme daily rainfall[30] are presented in Figure 47 and Table 11.

The key messages are:

- Extreme daily rainfall is generally projected to become more intense in the Vanuatu Central and South. There is significant variation between the different models, but most models indicate more intense Rx1day and 1-in-20 year daily rainfall in most future time periods for these regions.
  - For the near-term (2030), the signal is less clear even though the multi-model median shows a decrease for both extreme daily rainfall metrics for Vanuatu South.
  - For the mid- and long-term (2050, 2070, 2090) the median of the multi-model ensemble shows that extreme daily rainfall could be 6-14% greater for Vanuatu Central and 14-41% greater for Vanuatu South, depending on the time period and extreme rainfall measure.
- There is no clear direction in projected change for the extreme daily rainfall measures for the Vanuatu North region. There is a large range in projections, with some models projecting decreases and others projecting increases in both measures of extreme daily rainfall. This could be because extreme rainfall in Vanuatu North is more impacted by shifts in the SPCZ, an effect

[30] The 1-in-20 year extreme daily rainfall represents the daily rainfall amount that has on average a 5 per cent chance of happening in any given year.

which may override the increased extreme rainfall capacity associated with warming air temperatures.

- In general, the more extreme 1-in-20 year daily rainfall metric shows greater increases than the Rx1day annual wettest day metric.

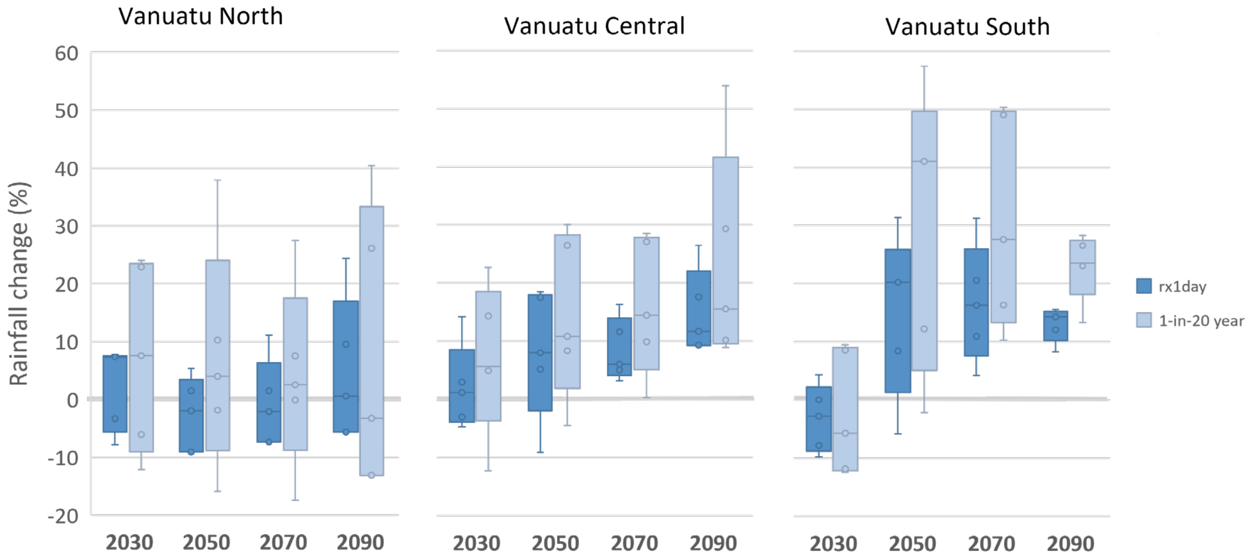


Figure 47 Projected percent change in annual maximum daily rainfall (Rx1day) and 1-in-20 year extreme maximum daily rainfall (i.e., an event that has on average a 5 per cent chance of happening in a particular year) for the three Vanuatu sub-regions and four future time periods. The box plots show the multi-model ensemble minimum and maximum; 25th and 75th percentile; and median (50th percentile) based on the five CCAM simulations under RCP8.5. The small circles show the individual models

Table 11 Projected change in annual maximum daily rainfall (Rx1day) and 1-in-20 year extreme maximum daily rainfall (i.e., an event that has on average a 5 per cent chance of happening in a particular year) for the three Vanuatu sub-regions and four future time periods. Projections are based on five CCAM models and the values shown are the multi-model median with range (minimum to maximum) in brackets. Units: percent change

REGIONS	Rx1day (ANNUAL MAXIMUM DAILY RAINFALL)				EXTREME DAILY RAINFALL (1-IN-20 YEAR)			
	2020-2039	**2040-2059**	**2060-2079**	**2080-2099**	**2020-2039**	**2040-2059**	**2060-2079**	**2080-2099**
Vanuatu North	7 (-8 to 8)	-2 (-9 to 5)	-2 (-7 to 11)	1 (-6 to 24)	8 (-12 to 24)	4 (-16 to 38)	3 (-17 to 28)	-3 (-13 to 40)
Vanuatu Central	1 (-5 to 14)	8 (-9 to 18)	6 (3 to 16)	12 (9 to 26)	6 (-12 to 23)	11 (-5 to 30)	14 (0 to 28)	16 (9 to 54)
Vanuatu South	-3 (-10 to 4)	20 (-6 to 31)	16 (4 to 31)	14 (8 to 16)	-6 (-12 to 9)	41 (-2 to 57)	28 (10 to 50)	23 (13 to 28)

6.3 Drought

Projected changes in drought for Vanuatu and sub-national regions are based on GCMs data using the Standardised Precipitation Index (SPI-12), an index that is used by VMGD for determining meteorological drought in Vanuatu. The results are presented in Figure 48.

Key messages:

- There is a large range of projections across all the models, with both increases and decreases possible for all drought metrics. However, there is greatest agreement between models in projecting a shift to more severe droughts. Droughts in the moderate and severe category are projected to occur less often but severe droughts are projected to occur more often, especially in Vanuatu Central and Vanuatu South.
- Drought duration is projected to change little, consistent with the observed drought reported in McGree et al. (2019, see Table 3). However later in the century, the range of projections increases, with some models showing large increases in extreme drought duration while others show a slight decrease. There is a tendency for the models to show extreme droughts becoming longer, and moderate and severe droughts becoming shorter.
- There is not much projected change in the intensity of moderate or severe droughts. The multi-model mean in extreme drought does not show much projected change, however the range is large with some models showing large increases in extreme drought severity.

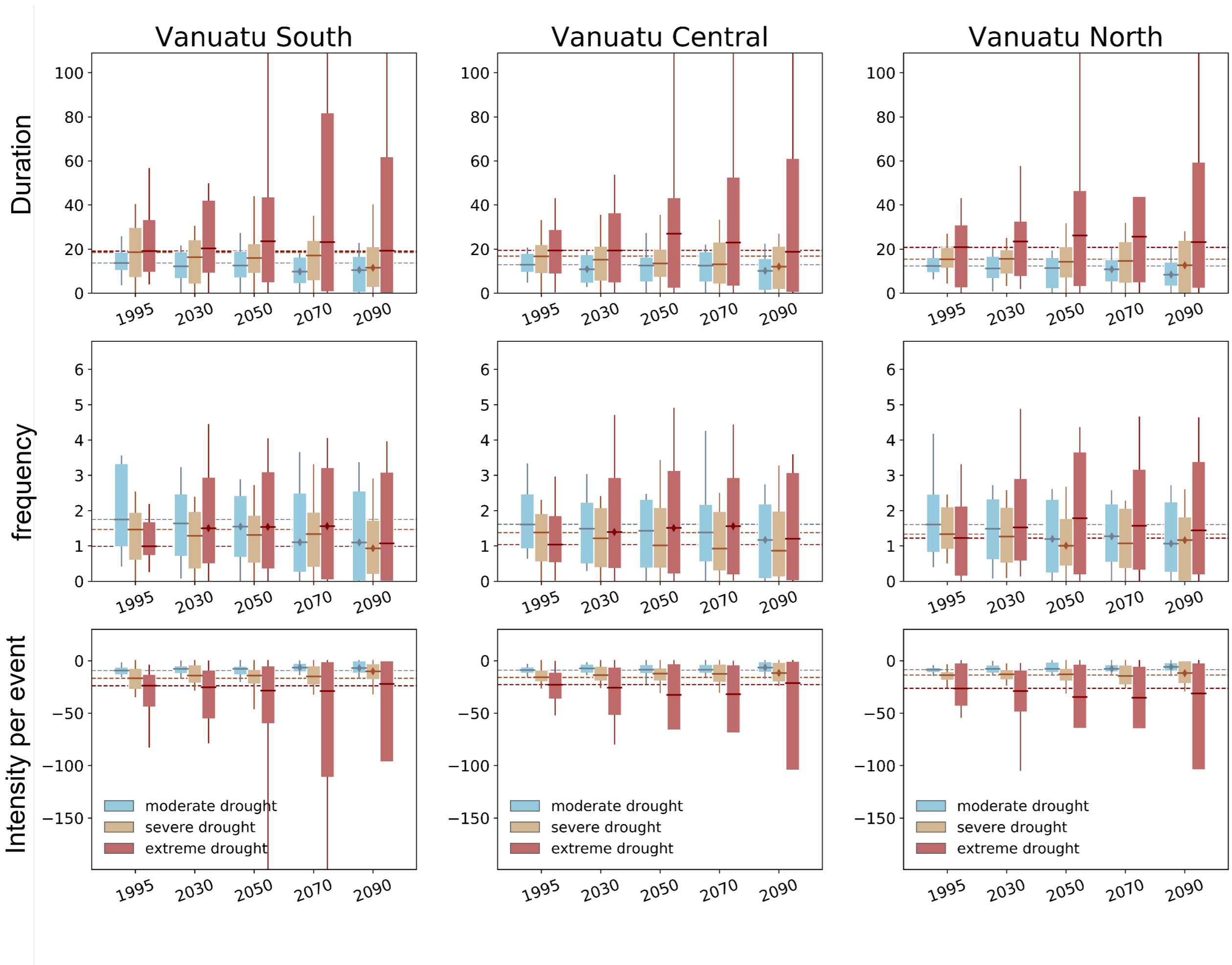


Figure 48 Regional average of drought duration (top row), frequency (middle row) and intensity (bottom row) in the reference (20 years centred on 1995) and future (20-year periods centred on 2030, 2050, 2070, 2090) periods for different drought category (moderate, severe and extreme). Drought duration is in months, frequency is in "number of drought events per period", while intensity is unitless but relates to both the duration and severity of the drought. For drought intensity, the more negative the value, the more intense the event. The multi-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). See Kirono et al. (2020) and Iese et al. (2021) for more details about the method for the analyses

6.4 Tropical cyclone

The projections for tropical cyclone (TC) are based on the MIT synthetic tracks model driven by a set of eight CMIP5 GCMs (see Section 3.1). The results are shown in Figure 49 and Figure 50.

The key messages are:

- There is a small decrease in the number of TCs affecting the Vanuatu region by the mid- and late-century periods, particularly to the northeast of the country. The projected decrease is less than one TC per decade in most grid cells.
- The projected decrease is consistent with projections based on different TC modelling techniques for the broader South Pacific region (e.g., Chand, 2019; Bell et al. 2019; Knutson et al. 2020) hence adds confidence in the projection.
- There is a projected decline in the annual exceedance frequency of all TC intensities (Cat 1- 5) affecting the Vanuatu region by the mid- and late- century periods (Figure 50), consistent with results from projections based on different TC modelling techniques for the broader south Pacific region (Knutson et al. 2020).

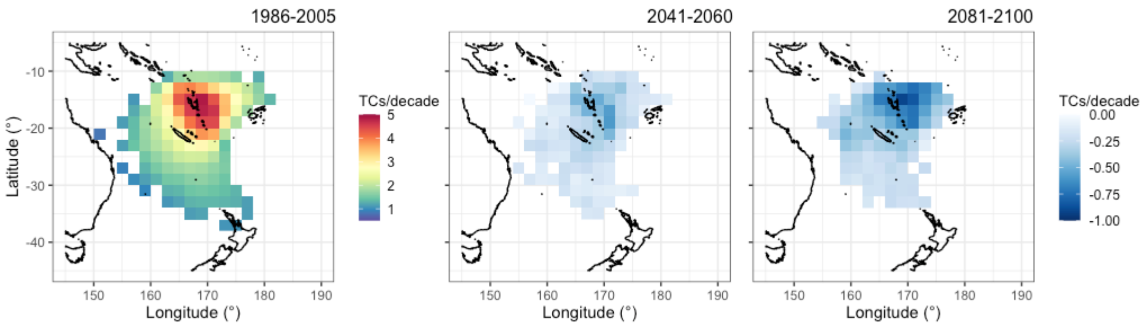


Figure 49 Ensemble-mean TC track density for the historical period (left panel), and the projected change in track density for the mid-century (middle panel) and late-century (right panel) time periods

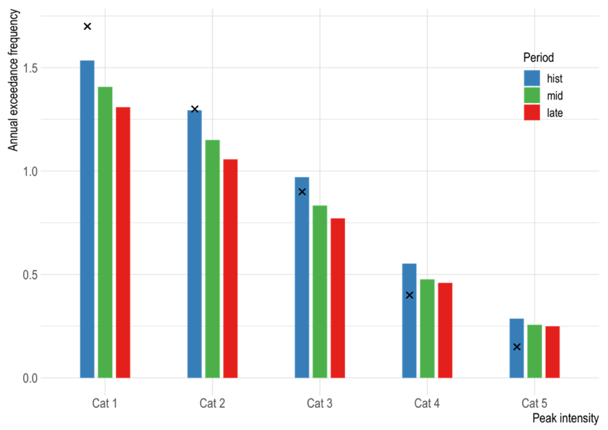


Figure 50 The modelled annual exceedance frequencies for different TC intensity categories (Cat 1 to 5) over three periods ("hist": 1986-2005, "mid": 2041-2060, and "late": 2081-2100). The "x" symbols show the observed exceedance frequencies for the historical period 1986-2005. The annual exceedance frequency here is the probability that at least one TC at a given intensity will occur in any given year. The bars suggest that the chance of Cat 1 events likely to occur in a particular year is high, while that of a Cat 5 is low, and a projected decline in the annual likelihood of all TC intensities

Part III Synthesis and future work

7 Synthesis - the study and its implications

This report presents the long-term climate projections information for Vanuatu and its sub-national regions which have been developed and disseminated as part of the Van-KIRAP Project.

In this Chapter, we discuss the implications of the study for Vanuatu. The key points are on the study's contribution to the implementation of the Vanuatu Climate Services Framework (VCSF) (Section 7.1) and on the selected examples of potential application of the climate projections information (Section 7.2 to 7.4). These examples have been presented and discussed through stakeholder engagements and outreaches to date (Appendix 1).

7.1 The study's contribution to implementation of VCSF

The goal of the Van-KIRAP Project is to increase the ability of decision makers, development partners, communities and individuals across five targeted sectors to plan for and respond to the long- and short-term impacts of climate variability and change. This is a response to the VMGD Strategic Development Plan 2014-2023.

VMGD is the authority mandated by law to provide official Weather, Climate and Geohazards information for Ni-Vanuatu. VMGD's Climate Information Services (CIS), in particular, is guided by the Vanuatu Climate Services Framework (VCSF) developed in 2016 (SPREP, 2016). The VCSF identifies eighteen recommendations for actions and activities required to strengthen VMGD climate information development, provision, understanding and use throughout Vanuatu. The Van-KIRAP Project is designed to address eleven out of those eighteen recommendations through five Project components, each with some specific Activities.

This report focuses on Activity 1.2.3, which has the objective of developing long-term projections for key climate variables and climate extremes for Vanuatu. This activity and its outputs have contributed to meeting some of the needs identified by the VCSF as follows.

- Addressing the need for VMGD to provide climate information that spans all time scales, in particular, climate change projections for the next several decades.
- Meeting the need for updating some aspects of Vanuatu-specific climate change projection information previously produced by the Pacific-Australia Climate Change Science Adaptation Planning (PACCSAP) program in 2014. New analyses described in the report include evaluation of climate model performance specifically for Vanuatu (Section 3.2); projected change for three sub-national regions for selected climate variables and future periods as per request by stakeholders (Chapter 5 and 6); projected change based on the 50 km resolution of CSIRO dynamical downscaling simulations data (e.g., Section 5.2, 6.1 and 6.2); and tropical cyclone projections based on synthetic track multi-model datasets (Section 6.4).
- The new projections for Vanuatu's three sub-national regions (Chapter 5 and 6) help to meet the need for more detailed information for each province.
- The newly Vanuatu-specific climate models evaluation results (Section 3.2) provide additional information that can be considered in assessing confidence in a climate projection statement.

- The presentations of multiple climate models considerations (Section 5.3 and 5.4) contribute to advancing the *Research, Modelling and Prediction* pilar of the VCSF.
- The stakeholder engagement and outreach activities (Appendix 1) assist VMGD with the dissemination of climate information to the public or specific users (e.g. National and Provincial Government, Government Ministries and Department, NGOs, Donors and Private Sector).

A part of the outputs of Activity 1.2.3 is delivered through the Van-KIRAP web portal, which is developed by Van-KIRAP Activity 1.1.2, as mentioned in Chapter 1. This report can be used as a reference for those who obtain or use the relevant data and information through that web portal.

The results of Activity 1.2.3 have also been presented to various audiences in a form of in-person presentations, webinars, distribution of PowerPoint and/or pdf files, and so on (Box 3 and Appendix 1). This report is another form of climate information product (also a technical reference) for future disseminations, outreaches or services.

Through those presentations we also gave various examples of how climate projections information developed from this activity can be used by VMGD and the five targeted sectors and/or others. The summary of some of these examples is described in Section 7.2 to 7.3. below[31].

7.2 Example of application 1 – Informing policies, strategies and planning

Vanuatu's long-term climate action vision is governed by the Vanuatu National Policy on Climate Change and Disaster Risk Reduction for 2016-2030 (GoV, 2016). The policy ensures that climate change risks are identified, assessed, reduced and managed. In this context, the new climate projections for Vanuatu's three sub-national regions (Chapter 5 and 6) can be used to analyse risks at the sub-national level, which were lacking previously.

Results from this activity can also be used to inform the next iteration of national adaptation policies and strategies. For example, the latest Vanuatu National Adaptation Programme of Action (NAPA) was developed in 2007 (NACCC, 2007); the third National Communication Report was submitted in 2020 (MoCC, 2020); and the first Nationally Determined Contribution (NDC) was submitted in 2020 (GoV, 2020).

From sectoral perspectives, the results described in Chapter 5 and 6 can be used, for example, to inform climate risk assessment for tourism that will be undertaken in all provinces to support Vanuatu Sustainable Tourism Strategy 2021-2025 Actions number 1.2.6 (MTTCNVB, 2021); and to inform mapping of current and future water resources required for guiding investments in water resource diversification as per recommendation of the Vanuatu National Water Policy 2017-2030 (MLNR, 2017).

[31] Separate sectoral case studies are also available here (https://vanclimatefutures.gov.vu/dashboard/home#CaseStudies)

7.3 Example of application 2 – Informing communities

Adaptation or resilience to climate change is a local to regional issue (e.g. Füssel, 2007). Therefore, building awareness and capacity of local actors, including communities, are important determinants for climate adaptive capacity of a region (Füssel and Klein, 2006). A common challenge for building community's awareness and capacity is in the translation of information at global or regional scales (e.g. changes in global temperature) to the relevant effects on what the local cares about (e.g. drinking water availability at home). To address this challenge, we developed some examples of ideas on how VMGD and the targeted sectors could use the climate projections information for their community outreach during and after Van-KIRAP implementation. Anecdotal evidence[32] indicate that such examples were well received by and helpful for the audiences.

The selected examples, presented in this section, focus on broad assessment and communication of the potential impacts of projected changes in the mean climate on two key cash crops (kava and coffee) and water availability at home (rainwater potential). They are designed as simple and effective illustrations for understanding the potential impacts of global/regional climate change on local affairs. They are intended as starting points, not in-depth impact assessments[33].

As we learn from Chapter 5 and 6, there is a range of possible future changes in climate. For annual rainfall, for instance, some models project an increase (wetter) while others indicate a decrease (drier). Therefore, it is advisable to assess the impact of projected climate based on, not just one, but a range of plausible future climate scenarios. CSIRO and SPREP (2021) have identified a set of representatives for Vanuatu that can be considered in an assessment (see Box 6). For the RCP8.5, the selected models are GISS-E2-H and IPSL-CM5A-LR that are representing a warm-dry future and a hot-wet future, respectively. Accordingly, we used the projections from these two models in the examples described in Section 7.3.1 and 7.3.2.

Box 6 Standardised future climate scenarios for impacts / risks assessment[34]

The future human-induced climate change of a given region is dependent on some factors: the greenhouse gas and aerosol emission pathways due to human activities; the sensitivity of the global climate to increase in atmospheric greenhouse gas concentrations; and the regional climate response to the global climate.

Chapter 5 and 6 show that different climate models can result in a range of future projections. Therefore, it is necessary to consider a range of future climate scenarios, not just one, for examining impacts / risks of human-induced climate change where possible.

[32] Feedback taken from workshops, meetings, webinars, etc (see Appendix 1 for the list of events)

[33] An in-depth assessment may require a more comprehensive consideration such as multiple climate variables (rainfall, temperature, windspeed, solar radiation, etc); multiple drivers (climate and non-climate); different set of scenarios to align with specific purposes, regions, systems etc.

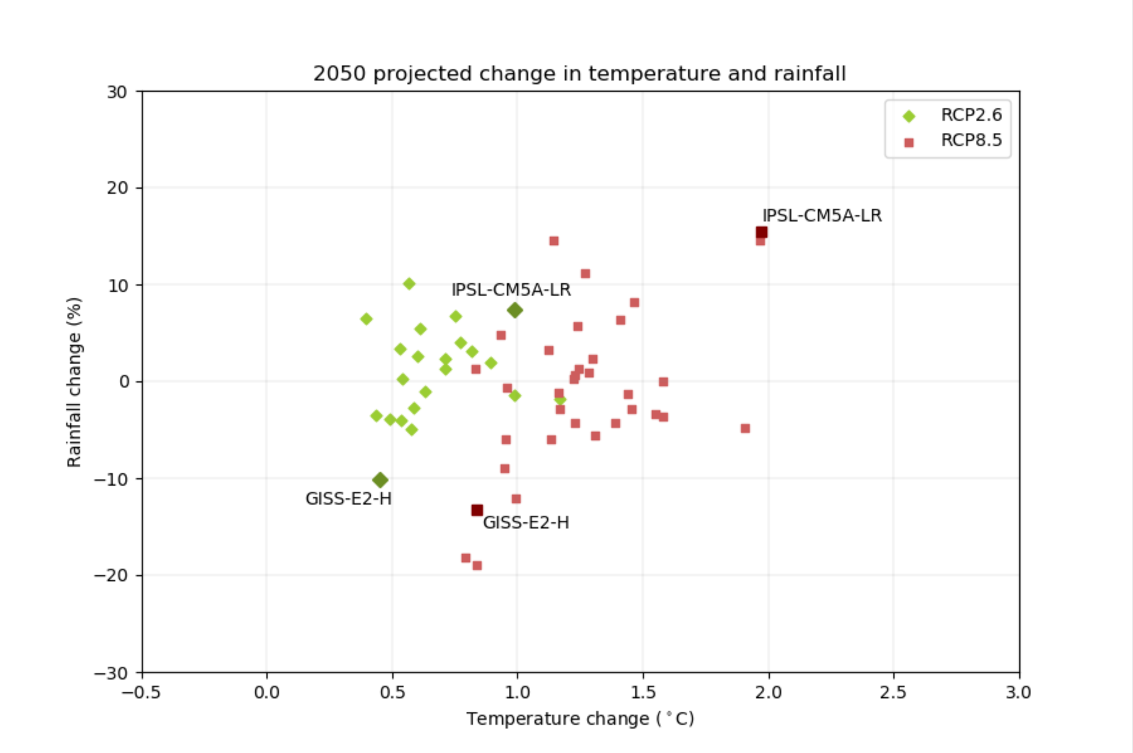
[34] See also the Van-KIRAP guidance materials for understanding hazard-based climate change impact assessment developed by CSIRO (https://vanclimatefutures.gov.vu/dashboard/guide)

According to CSIRO and SPREP (2021), these scenarios need to be both *representative* and *internally consistent*:

- *Representative* means covering or sampling the full range of plausible future climates including the range of plausible emissions pathways (RCPs) and the range of plausible climate responses to each emissions pathway – assessed using multiple lines of evidence including the results from different climate models.
- *Internally consistent* means that the changes in different climate variables (e.g. temperature and rainfall) make physical sense. When conducting risk assessments, a useful approach is to employ projections of different variables from a single climate model to ensure that projections are internally consistent. Mixing variables from different models (e.g. taking temperature from Model A while rainfall from Model B) into a single scenario may result in physically implausible combinations and is not recommended as best practice.

In response to this need, CSIRO and SPREP (2021) has introduced a standardised future climate scenarios approach that can be applied for an initial scan of risks assessment in the Western Tropical Pacific's countries. For Vanuatu, the identified models that are representative of warm-dry future and a hot-wet future are the GISS-E2-H and IPSL-CM5A-LR, respectively, for both RCP8.5 and RCP2.6.

Figure below shows the projected changes of these two models in comparison to other models; see also Fig 6.1. of CSIRO and SPREP (2021). The projections data for these two models are presented in Appendix 3 (Table 16 and Table 17).



Projected change in mean annual temperature and rainfall in the Vanuatu region for 2050 (2040-2059) from all CMIP5 GCMs for RCP 2.6 (green diamonds) and RCP8.5 (red squares), showing the GISS-E2-H and IPSL-CM5A-LR which have been selected by the CSIRO and SPREP (2021) to represent a warm-dry future and a hot-wet future for Vanuatu.

7.3.1 Communicating impacts on climate suitability for Kava and Arabica Coffee

Over 80% of Vanuatu's population relies on agriculture for their daily subsistence and well-being (GoV, 2017). Climate change may directly affect agriculture because the climate of a given place affects the types of plants which can grow there. Some climates are better for growing particular crops than others, and most plants are dependent on rainfall and temperature.

For example, kava[35] grows best in humid subtropical to tropical regions with deep, friable, well-drained, well-aerated, and fertile soils; with good protection from high winds (Nelson, 2011). The ideal temperature for growing kava is between 20 – 25°C while the mean annual rainfall is between 1900 – 4600 mm (Nelson, 2011; Taylor et al., 2016).

The map on the left of Figure 51 shows climate suitability for kava for the historical period (1970-2000) in terms of mean annual temperature and rainfall. It indicates that all islands in the south region (i.e. Efate, Erromango, Tanna and Anatom) have ideal climate everywhere, whilst those in the north (e.g. Espiritu Santo and Malakula) have ideal conditions only over the high-altitude areas. The map in the middle and on the right indicate that these suitable areas will decrease in the future. For instance, most of the Efate's coastal areas will not be suitable by 2050. The mapping capability for exploring future climatology and threshold analysis, as demonstrated in Figure 51, is being developed as an interactive tool in the Van-KIRAP portal.

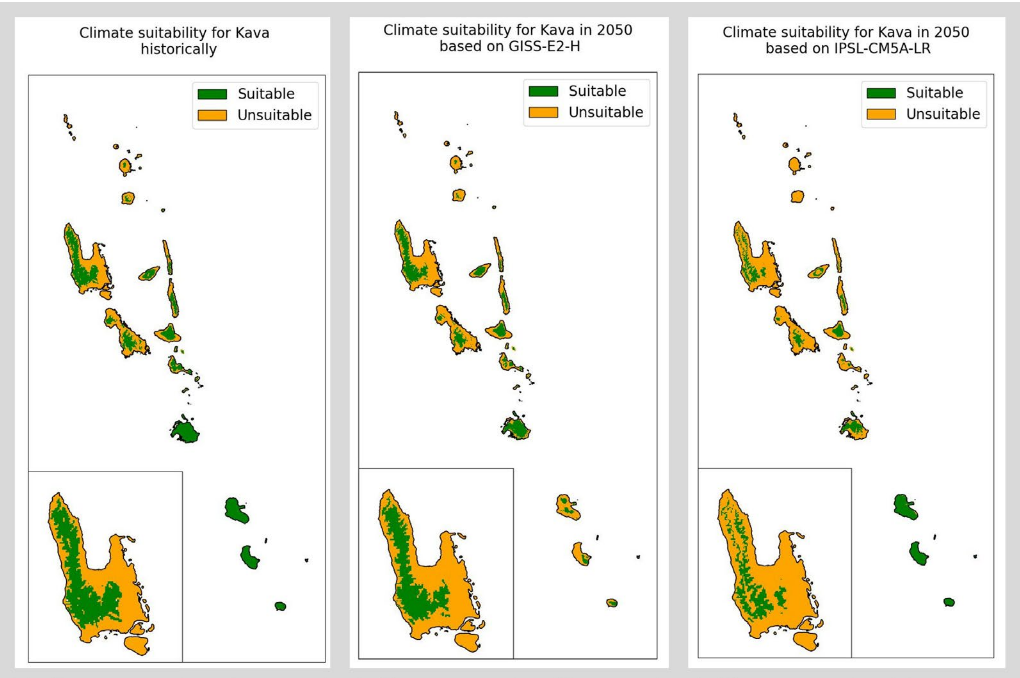


Figure 51 Map of climate suitability in terms of annual mean temperature and rainfall for kava for the historical period (1970-2000) and future period (2050) based on two GCMs run with RCP8.5. The GISS-E2-H and the IPSL-CM5A-LR are representative of a warm-and-dry future and a hot-and-wet future, respectively, as reported by CSIRO and SPREP (2021), see also Box 6. Data source for the historical period is WordClim. Insets show Santo Island

[35] Kava is a major commodity in Vanuatu Agriculture sector. It is the third largest export commodity from Vanuatu and is a significant cash crop in the country. An estimate figure indicates 30 thousand households are involved in kava cultivation and 3 thousands people work on kava trade and retail in Vanuatu.

Another example is to use the information to communicate the potential impact of climate projections on climate suitability for coffee, which is one of the major cash crops of Vanuatu, along with kava and coconut. Cool to warm tropical climates, rich soils, and few pests or diseases are some conditions required for optimal coffee farming. The seven main coffee producing islands in Vanuatu are Tanna, Erromango, Efate, Epi, Santo, Aore and Malo.

For Arabica coffee's optimal growing, the ideal rainfall is between 1000 to 2700 mm per year and a range of temperature between 14 to 26^{o}C (Ahmed et al., 2021). Figure 52 shows the climate conditions in Pekoa (Santo), Bauerfield (Efate) and White Grass (Tanna) for the historical period (1970-2000) and the future periods (2020-2039 and 2040-2059). Historically, the climate of all locations fall within the optimal growing envelope. This is also the case for the near future period (2020-2039), except Pekoa. For 2040-2059, however, most stations will be no longer ideal because of the projected increase in temperature and/or decrease in rainfall, depending on the climate scenario under consideration.

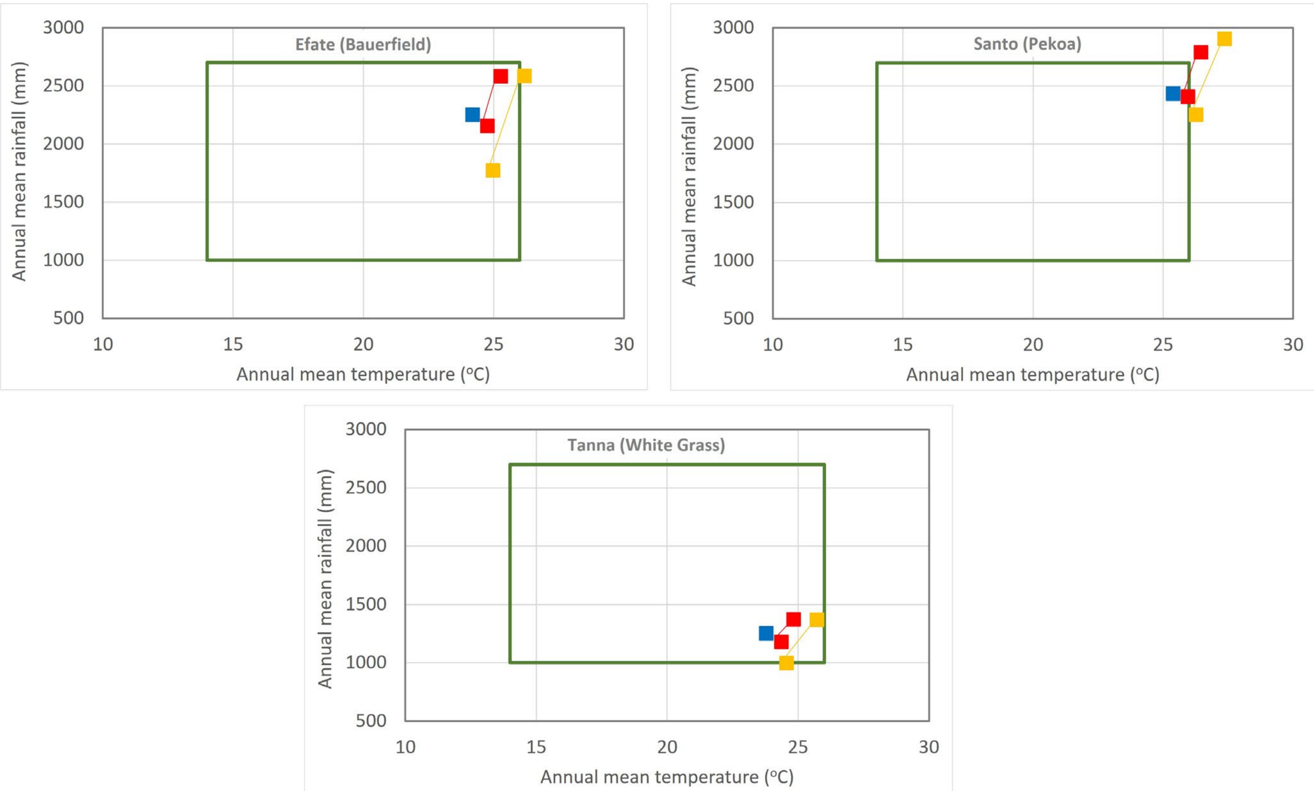


Figure 52 Ideal climate envelope (green box) for Arabica coffee according to Ahmed et al. (2021), along with the climate condition of selected stations representing Santo, Efate and Tanna islands, respectively. Blue colours indicate historical climate (1970-2000) for consistency with those used in Figure 51, while the reds and orange show the range of future climates in 2020-2039 and 2040-2059 according to two Global Climate Models (GISS-E2-H and IPSL-CM5A-LR) run with RCP8.5. The GISS-E2-H represents a warm-and-dry future scenario, while the IPSL-CM5A-LR represents a hot-and-wet future scenario, as reported by CSIRO and SPREP (2021); see also Box 6

7.3.2 Communicating impacts on water resource – rainwater

Access to safe water is a fundamental human need hence a basic human right. The Vanuatu 2020 national census finds that the main source of water in Vanuatu varies across provinces. Water sources for drinking and washing come from piped water system, groundwater (boreholes and wells), surface water (rivers and lakes) and rainwater (rainwater tank, see Figure 53). Piped water is largely used for drinking water in urban areas (44%), more so than in rural areas (14%). Meanwhile, rainwater tank is used for drinking water by 42% of households in rural areas compared to 14% in urban areas. Overall, rainwater is a critical to water security in Vanuatu (Foster et al., 2021) even though Vanuatu is highly sensitive to seasonal variations in rainfall (Foster et al. 2018).

Recognising the importance of rainwater source for the communities, the Vanuatu Department of Water Resources (DoWR) has implemented the Rainwater Harvesting (RWH) Project under the TC Pam Recovery Water Sector Program in 2020. That project constructed 75 RWH systems in locations impacted by TC Pam across the provinces of Penama, Malampa, Shefa and Tafea. Each RWH is built into a house with a 50m^2 roof catchment to provide water to a 10,000 L rainwater tank.

The information on historical and projected change in mean annual rainfall, described in Chapter 4 and 5, can be used to broadly assess, and communicate the amount of rainwater harvesting potential at a given location now and in the future. Figure 54 shows the annual rainwater potential from a 50m^2 roof catchment in three locations: Bauerfield, Lamap, and White Grass which represents Shefa, Malampa and Tafea province, respectively.

The figure suggests that the annual rainwater potential in the future will slightly reduce or increase, depending on the standard climate scenarios being used. This is consistent with the overall range of projected changes in mean annual rainfall presented in Chapter 5. Bauerfield has a 2,300 L rainwater potential per year over the historical period. This amount will either reduce (to 1,823 L) in a warm-and-dry future scenario or increase (to 2,635 L) in a hot-and-wet future scenario. A similar projected change pattern is also found for Lamap and White Grass.

Figure 53 Rainwater harvesting systems in Santo Island

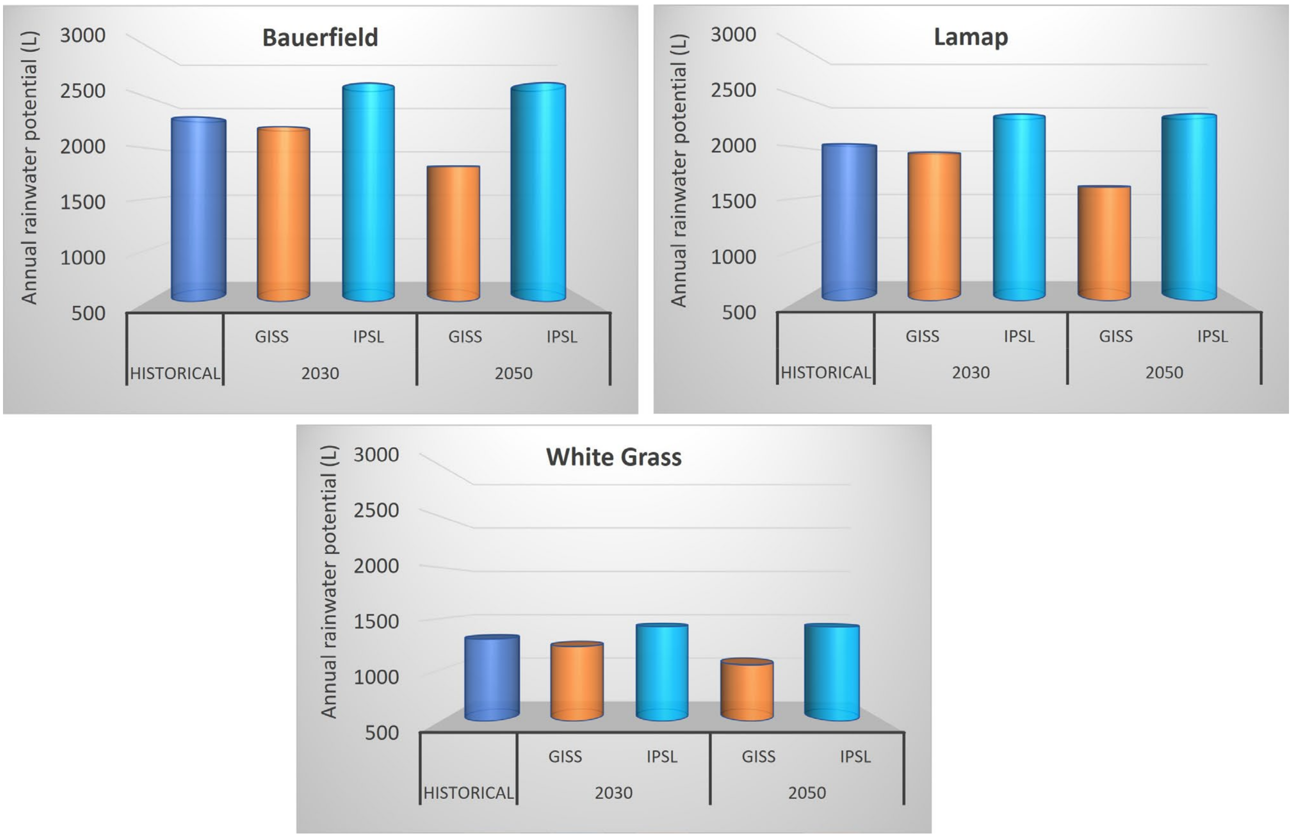


Figure 54 Annual rainwater potential from a 50m² roof catchment in Bauerfield, Lamap, and White Grass. The historical value was calculated based on observed mean annual rainfall for the 1970-2000 period (for consistency with those used in Figure 51). The future values were calculated based on mean annual rainfall for 2030 and 2050, which was developed by scaling the historical's mean annual rainfall with the respective projected change from two Global Climate Models (GISS-E2-H and IPSL-CM5A-LR) run with RCP8.5. The GISS-E2-H represents a warm-and-dry future scenario, while the IPSL-CM5A-LR represents a hot-and-wet future scenario, as reported by CSIRO and SPREP (2021); see also Box 6

7.4 Example of application 3 – Informing projects or initiatives

7.4.1 Crude estimation of soil erosion in the future

Through stakeholder engagement, it was known that soil erosion is a serious issue in some river catchments in Vanuatu. Soil erosion occurs when soil is moved from one place to another by water or wind-related force triggered by extreme rainfall and/or tropical cyclone. It is a major issue for agriculture because erosion washes away topsoils, which is the most fertile layer of the soil and is most important for plants and animals. When the eroded soil (or sediment) enters rivers, it negatively impacts the rivers and their entire ecosystems, including the quality of fresh-water resources and the reef along the coastal areas hence affecting the water sector and tourism industry.

The erosion rate for a given area is a function of many physical variables (including climate, soil properties and topography) and human activities (e.g., land use). RUSLE[36] is the most widely used model to calculate average annual erosion for a given place. RUSLE considers six factors, whereby climate factor is represented directly through "the rainfall-runoff erosivity factor or *R*". The value of *R* depends on the amount of rainfall and the highest rainfall intensity sustained over a period of time. Therefore, soil erosion can be directly affected by climate change through changes in extreme rainfall (e.g., Nearing et al., 2004). To estimate the impact of climate change on soil erosion was beyond the scope of this work.

However, Section 6.2 indicates that the wettest day rainfall (Rx1day) is projected to increase in the future for most regions in Vanuatu. This means that if all non-climate factors stay constant, it can be assumed that soil erosion could increase in the future due to climate change.

For the period of 1984-1994, Dumas and Fossey (2009) estimated an average of 8 t/ha/yr or 0.75 mm of annual soil loss over Efate Island. They calculated the annual erosion on a grid basis by overlaying the GIS layers of all factors required by RUSLE. They computed *R* based on the average annual rainfall using the following equation:

$R = 0.5 \times P \times 1.73$ with P = average annual rainfall

They created a gridded *R*-value for the whole Efate Island by firstly calculating *P* as a function of altitude (*z*):

$P = 4.0241z + 1573.4$ with z = the altitude of the site

Thus, VMGD together with the water sector can coarsely estimate projected changes in soil erosion in the future following the same approach as Dumas and Fossey (2009). In this regard, "the rainfall-runoff erosivity factor or *R*" for the future can be computed based on the projected changes in average annual rainfall (Chapter 5) while all other data (topography, soil map, vegetation map and land cover map) can be obtained from other sources.

7.4.2 Designing climate observation network

A climate observation network is generally established to serve a variety of purposes, ranging from short-term weather forecasts to long-term monitoring of change over a given region. Ideally, the network can give a satisfactory representation of all-terrain and climate characteristic in that particular region. Generally, however, station site selection has been made based on practical considerations such as site accessibility and operational cost (e.g. Mauger et al. 2013).

Figure 55 presents maps of observed mean annual and seasonal rainfall and temperature for Santo Island during 1970-2000 (the same maps for Vanuatu regions are shown in Figure 14), along with the location of the Pekoa climate station. Apparently, the Pekoa station represents only the dry side and the hot side of the island as it is located on a coastal area. There is a need for more stations to represent other terrain and climate conditions. Such climatological maps like Figure 14

[36] RUSLE method states: $A = R \times K \times L \times S \times C \times P$, where *A* = computed spatial and temporal average soil loss per unit of area; *R* = rainfall-runoff erosivity factor; *K* = soil erodibility factor; *L* = slope length factor; *S* = slope steepness factor; *C* = cover-management factor; *P* = support practice factor (Renard et al., 1997)

and Figure 55 can give objective consideration when augmenting or revising the current climate network.

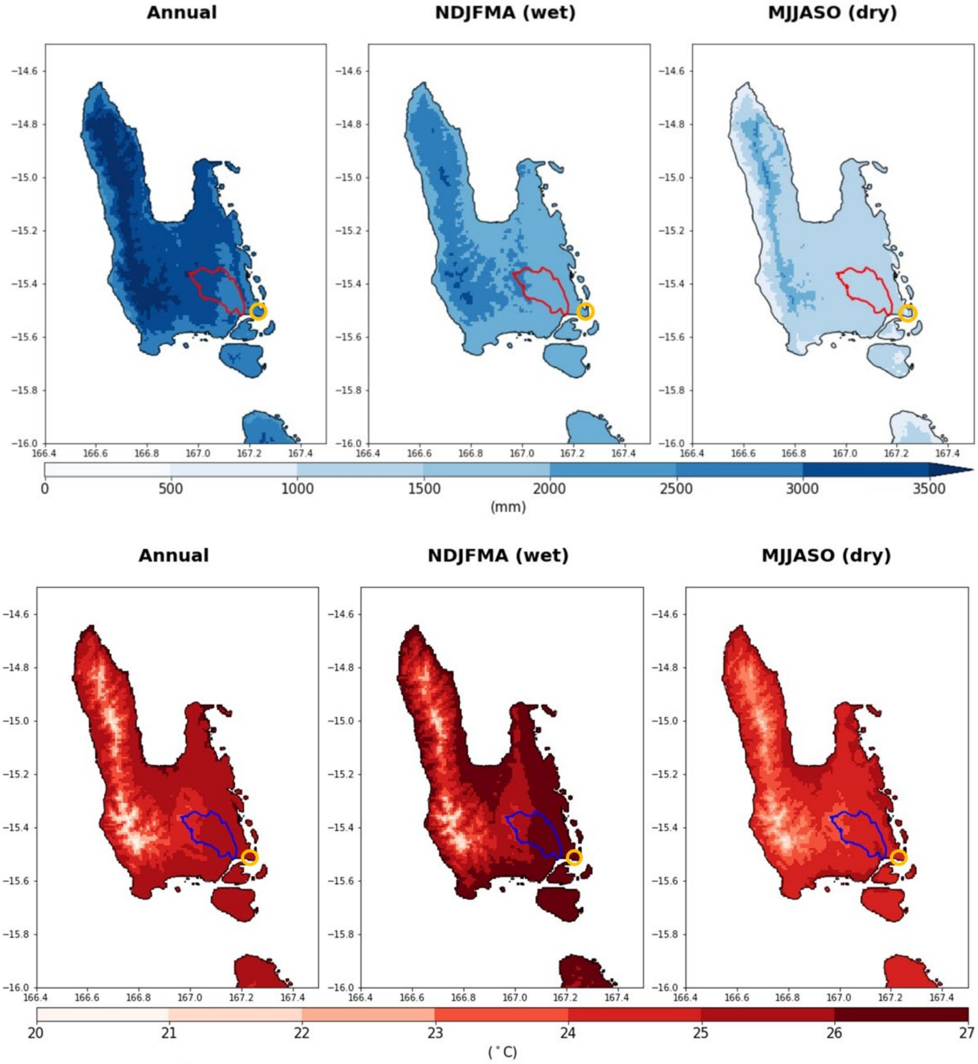


Figure 55 Maps of observed mean annual and seasonal rainfall (top) and temperature (bottom) in Santo Island during 1970-2000. The Sakata river's catchment area is shown, along with the location of Pekoa station (yellow circle). Source of climate gridded data: Wordclim

7.5 Example of application 4 - Informing hazard-based climate change impacts at sectoral level

As mentioned in Box 3, the outputs of this study have been and will be disseminated through a range of climate information products and services. These include informing the Van-KIRAP sectoral case studies and associated guidance materials which are currently developed (CSIRO, *in prep*); and informing the Van-KIRAP web portal functionality for future applications of the projections science reported in this document. The Van-KIRAP web-portal[37] is currently developed by CSIRO through Activity 1.1.2 (Building and strengthening user interfaces to support CIS Decision-making).

For instance, the Van-KIRAP web-portal will have an interactive facility that will enable user to explore future climatology and undertake threshold analysis, as demonstrated in Figure 51.

[37] Ibid 15

8 Future works

While this study has progressed some aspects of science-based climate change projections for Vanuatu and its three sub-national regions, there is still further work needed to advance the *Research, Modelling and Prediction* pilar of the VCSF. In particular, strengthening the scientific understanding of Vanuatu's climate change is required to inform adaptation and mitigation at the local scale.

8.1 Improve climate projections modelling analyses

This study used CMIP5 GCMs because, at the time of the study, CMIP6 experiments were still underway, and not publicly available. A broad comparison between the results of CMIP5 and CMIP6 GCMs for the Southwest SPCZ region indicates similarity (Section 5.4). However, there is a need to advance the analyses with the latest generation GCMs experiments to ensure Vanuatu is at the forefront of international practice.

There is also an opportunity to analyse the new CORDEX downscaled results for CCAM at 12 km (Marcus Thatcher, *pers comm*, 2023). Our analyses of the preliminary results of CORDEX-12km modelling experiment (not shown) indicates that they generally perform better than those of the CCAM-50km experiment that was used for this study.

One important aspect of tropical cyclone projections that has not been addressed explicitly by the synthetic track analysis in this report is future changes in TC-associated rainfall. It is likely that extreme rainfall from TCs will increase with climate warming (Knutson et al. 2020), even if TC maximum intensity remains the same, or even decreases slightly, because a warmer atmosphere can hold more moisture. Given the detrimental impacts from TC-related flooding to different sectors, this will be an important topic for future research. Worth to note that a work on TC related extreme rainfall is currently undertaken as part of the sectoral case studies.

The stakeholder engagements indicated the need for a better understanding of Traditional Knowledge (TK) around climate variability and change; and how the TK can be integrated with the science and vice versa. Such improvement will be useful in improving the robustness of the science and increasing buy-in and local capability for building climate resilience. Rarai et al. (2022) presented evidence that TK is an important enabler for resilience and facilitation of climate adaptation in some regions in Vanuatu.

8.2 Improve modelling for climate change impact assessments

Some examples of the applications of long-term climate change projections that have been presented and discussed through stakeholder engagements and outreachs to date are described in Section 7.1 to 7.4[38]. This includes ideas for raising awareness of the potential impacts of projected climate change in the absence of well-developed climate-impact modelling tools. However, these examples did not yet consider all possible factors that influence a particular subject matter (that is, Figure 51 in the case of Kava, Figure 52 in the case of Robusta coffee and Figure 54 in the case of rainwater potential).

For a better understanding of the impacts, it is advisable to undertake ground truthing such information with local farmers or households. This can be done, for instance, in tandem with future outreach activities and/or through specifically designed surveys.

Furthermore, there are many other non-climatic factors that need to be considered. This is possible, for example, using a biophysical crop model like the Decision Support System for Agrotechnology Transfer (DSSAT) that can be used for modelling growth for over 42 crops. However, such a model needs to be calibrated with site-specific data before it can be applied. Leo (2016), for instance, has calibrated the DSSAT model and used it to evaluate the impacts of projected changes in rainfall and in temperature as well some management practice scenarios on Taro at the Vanuatu Agriculture and Research Training Centre (VARTC) in Santo (Figure 56). His simulation results indicate that taro yield is expected to increase for the year 2030, 2055 and 2090.

Through stakeholder engagements, it has also been known that scientific understanding and/or modelling tools that can be used to assess the impacts of climate change on particular sectors in Vanuatu rarely exist. There is a need to develop, test and apply modelling that can facilitate a deeper assessment of climate change impacts and risks. Such assessment is often a prerequisite for informing various climate change adaptation and disaster risk management, especially for the sub-national to the local level.

In the tourism sector, stakeholders in Santo Island, for instance, are keen to know the potential impact of climate change and human activities on the water quality of blue holes[39] (Figure 57). Their anecdotal evidence indicates discolouration of some blue holes in Santo Island. Again, addressing this need was beyond the scope of the current study. In doing so, one needs to first develop an understanding of the concerned blue hole. Typically, inland blue holes are characterised by surface freshwater overlying anoxic[40] saline groundwater of marine origin (Mylroie et al., 1995). In this context, climate can directly affect the surface freshwater component (e.g., via rainfall) and indirectly influence the groundwater component (e.g., via rainfall, stream flow and baseflow) of the blue hole. Understanding the biogeochemical and/or the hydrogeological aspects of the blue hole system can serve as a starting point, followed by knowledge on other factors, including the cause of the observed discolouration of the water. The acquired knowledge can be used to develop a conceptual or physical model that represents the blue-hole system. Such a model can then be applied to assess what will happen if one (e.g.,

[38] While section 7.5 notes that sectoral case studies, being developed at the time of writing of this report, explore potential climate impacts on a variety of crops in Vanuatu in more depth.

[39] Freshwater blue waterholes – a must visit tourist destination in Vanuatu

[40] Does not contain dissolved oxygen (DO)

climate), two (e.g., climate and human activities) or all influencing factors undergo long-term change.

In the fishery sector, stakeholders see opportunities to use fish catch data available from the Vanuatu Fishery Department (VFD) to develop understanding about the relationship between fish catch and climate variables. Once this is done, the results can be combined with climate projections for estimating future fish catch. Dey et al. (2016), for example, have developed a supply-and-demand model to assess climate change and climate change adaption impacts on the fishery sector in four Pacific countries, including Vanuatu. Their results indicate that the production of oceanic fish is projected to increase, while the coastal fish to decrease during 2010-2050; Vanuatu will have to import coastal fish to meet the increasing demand; Freshwater fish demand will exceed domestic production in 2035, and 2050 hence Vanuatu will need to rely on imports to meet this demand.

In the water and/or infrastructure sector, there is an opportunity to use GIS-based techniques for undertaking spatial multivariate (or multilayer) analyses for climate risk assessment. Section 7.4.1, for instance, discusses the idea of how that technique can be applied for estimating current and future soil erosion by overlying six layers of information representing rainfall-runoff erosivity, soil erodibility, slope length, slope steepness, land-cover / management and support practice for reducing erosion factors.

More importantly, stakeholders also indicated the need to enhance the capability of VMGD and the sectors to work together in using climate projections information and climate-related impacts knowledge to undertake climate change impact assessments.

Figure 56 Automatic weather station, which was set up as part of Van-KIRAP project, and an experimental site for Taro at the Vanuatu Agriculture and Research Training Centre (VARTC) in Espiritu Santo

Figure 57 Nanda Blue Hole in Santo Island

References

Aguilar, E., Auer, I., Brunet, M., Peterson, T.C. and Wieringa, J., 2003. Guidance on metadata and homogenization. *WMO Td*, *1186* (January 2003), pp.1-53.

Ahmed, S., Brinkley, S., Smith, E., Sela, A., Theisen, M., Thibodeau, C., Warne, T., Anderson, E., Van Dusen, N., Giuliano, P. and Ionescu, K.E., 2021. Climate change and coffee quality: systematic review on the effects of environmental and management variation on secondary metabolites and sensory attributes of Coffea arabica and Coffea canephora. *Frontiers in plant science*, *12*, p.708013.

Australian Bureau of Meteorology and CSIRO. 2011. Climate Change in the Pacific. Scientific Assessment and New Research. Volume 1: Regional Overview. Volume 2: Country Reports.

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 Technical Report, Australian Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organisation, Melbourne, Australia.

Bell, S.S., Chand, S.S., Tory, K.J., Dowdy, A.J., Turville, C. and Ye, H., 2019. Projections of southern hemisphere tropical cyclone track density using CMIP5 models. *Climate Dynamics*, *52*, pp.6065-6079.

Berrisford, P., Dee, D.P.K.F., Fielding, K., Fuentes, M., Kallberg, P., Kobayashi, S. and Uppala, S., 2009. The ERA-interim archive. *ERA report series*, (1), pp.1-16.

Bouroncle, C., Müller, A., Giraldo, D., Rios, D., Imbach, P., Girón, E., Portillo, F., Boni, A., Van Etten, J. and Ramirez-Villegas, J., 2019. A systematic approach to assess climate information products applied to agriculture and food security in Guatemala and Colombia. *Climate Services*, *16*, p.100137.

Brown, J.R., Moise, A.F. and Colman, R.A., 2013. The South Pacific Convergence Zone in CMIP5 simulations of historical and future climate. *Climate dynamics*, *41*, pp.2179-2197.

Chand, S.S., Dowdy, A.J., Ramsay, H.A., Walsh, K.J., Tory, K.J., Power, S.B., Bell, S.S., Lavender, S.L., Ye, H. and Kuleshov, Y., 2019. Review of tropical cyclones in the Australian region: Climatology, variability, predictability, and trends. *Wiley Interdisciplinary Reviews: Climate Change*, *10* (5), p.e602.

Chen, A., Emanuel, K.A., Chen, D., Lin, C. and Zhang, F., 2020. Rising future tropical cyclone-induced extreme winds in the Mekong River Basin. *Science Bulletin*, *65* (5), pp.419-424.

Chouinard, C., Béland, M. and McFarlane, N., 1986. A simple gravity wave drag parametrization for use in medium-range weather forecast models. *Atmosphere-Ocean*, *24* (2), pp.91-110.

Conrad, V. and Pollak, L.W., 1950. Methods in climatology. In *Methods in Climatology*. Harvard university press.

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

CSIRO and Bureau of Meteorology. 2015. Climate change in Australia Information for Australia's Natural Resource Management Regions: Technical Report, CSIRO and Bureau of Meteorology, Australia.

CSIRO and SPREP, 2021. 'NextGen' Projections for the Western Tropical Pacific: Current and Future Climate for Vanuatu. Final report to the Australia-Pacific Climate Partnership for the Next Generation Climate Projections for the Western Tropical Pacific project. Commonwealth and Industrial research Organisation (CSIRO) and Secretariat of the Pacific Regional environmental Programme (SPREP), CSIRO Technical Report, Melbourne Australia.

Dai, A., 2011. Drought under global warming: a review. Wiley Interdisciplinary Reviews: Climate Change, 2 (1), pp.45-65.

Deo, A., Chand, S.S., Ramsay, H., Holbrook, N.J., McGree, S., Magee, A., Bell, S., Titimaea, M., Haruhiru, A., Malsale, P. and Mulitalo, S., 2021. Tropical cyclone contribution to extreme rainfall over southwest Pacific Island nations. *Climate Dynamics*, *56*, pp.3967-3993.

Dey, M.M., Rosegrant, M.W., Gosh, K., Chen, O.L. and Valmonte-Santos, R., 2016. Analysis of the economic impact of climate change and climate change adaptation strategies for fisheries sector in Pacific coral triangle countries: Model, estimation strategy, and baseline results. *Marine Policy*, *67*, pp.156-163.

Domonkos, P., 2011. Homogenising time series: beliefs, dogmas and facts. *Advances in Science and Research*, *6* (1), pp.167-172.

Dumas, P. and M. Fossey. 2009. Mapping Potential Soil Erosion in the Pacific Islands. A case study of Efate Island (Vanuatu). *11ème Inter-Congrès des Sciences du Pacifique et 2èmes Assises de la Recherche française dans le Pacifique. Les Pays du Pacifique et leur environnement océanique face aux changements locaux et globaux*, Mar. 2009, Papeete, French Polynesia.

Emanuel, K., DesAutels, C., Holloway, C. and Korty, R., 2004. Environmental control of tropical cyclone intensity. *Journal of the atmospheric sciences*, *61* (7), pp.843-858.

Emanuel, K., Ravela, S., Vivant, E. and Risi, C., 2006. A statistical deterministic approach to hurricane risk assessment. *Bulletin of the American Meteorological Society*, *87* (3), pp.299-314.

Emanuel, K., Sundararajan, R. and Williams, J., 2008. Hurricanes and global warming: Results from downscaling IPCC AR4 simulations. *Bulletin of the American Meteorological Society*, *89* (3), pp.347-368.

Emanuel, K.A., 2013. Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proceedings of the National Academy of Sciences*, *110* (30), pp.12219-12224.

Emanuel, K., 2017. Assessing the present and future probability of Hurricane Harvey's rainfall. *Proceedings of the National Academy of Sciences*, *114* (48), pp.12681-12684.

Emanuel, K., 2020. Evidence that hurricanes are getting stronger. *Proceedings of the National Academy of Sciences*, *117* (24), pp.13194-13195.

Emanuel, K., 2021. Tropical cyclone risk in Bangladesh. *MAUSAM*, *72* (1), pp.27-34.

FCG New Zealand. 2021. Mid-term review of "Climate Information Services for Resilient Development in Vanuatu" (CISRD) or Vanuatu Klaemet Infomesen blong redy, adapt mo protect (Van-KIRAP) Project. Final Mid-term Review Report submitted to the Secretariat of the Pacific Regional Environment Programme (SPREP).

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

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S.C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V. and Forest, C., 2013. Evaluation of climate models. In *Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 741-866). Cambridge University Press.

Foster, T. and Willetts, J., 2018. Multiple water source use in rural Vanuatu: are households choosing the safest option for drinking?. *International Journal of Environmental Health Research*, *28* (6), pp.579-589.

Foster, T., Rand, E.C., Kotra, K.K., Sami, E. and Willetts, J., 2021. Contending with water shortages in the Pacific: Performance of private rainwater tanks versus communal rainwater tanks in rural Vanuatu. *Water Resources Research*, *57* (11), p.e2021WR030350.

Freidenreich, S.M. and Ramaswamy, V., 1999. A new multiple-band solar radiative parameterization for general circulation models. *Journal of Geophysical Research: Atmospheres*, *104* (D24), pp.31389-31409.

Füssel, H.M., 2007. Adaptation planning for climate change: concepts, assessment approaches, and key lessons. *Sustainability science*, *2*, pp.265-275.

Füssel, H.M. and Klein, R.J., 2006. Climate change vulnerability assessments: an evolution of conceptual thinking. *Climatic change*, *75* (3), pp.301-329.

Gasser, T., Kechiar, M., Ciais, P., Burke, E.J., Kleinen, T., Zhu, D., Huang, Y., Ekici, A. and Obersteiner, M.J.N.G., 2018. Path-dependent reductions in CO2 emission budgets caused by permafrost carbon release. *Nature Geoscience*, *11* (11), pp.830-835.

GFCS. 2014. Implementation Plan of the Global Framework for Climate Services. World Meteorological Organization, Switzerland, 70 pp.

GoV. 2016. Vanuatu Climate Change and Disaster Risk Reduction Policy 2016-2030. Government of the Republic of Vanuatu.

GoV. 2017. Vanuatu National Kava Strategy 2016-2025. Department of Agriculture and Rural Development, Ministry of Agriculture, Livestock, Forestry, Fisheries and Biosecurity. Government of the Republic of Vanuatu (GoV).

GoV. 2020. Vanuatu's Revised and Enhanced 1st Nationally Determined Contribution 2021-2030. Government of Vanuatu (GoV).

Grose, M.R., Brown, J.N., Narsey, S., Brown, J.R., Murphy, B.F., Langlais, C., Gupta, A.S., Moise, A.F. and Irving, D.B., 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), pp.3382-3399.

Gutiérrez, J.M., R.G. Jones, G.T. Narisma, L.M. Alves, M. Amjad, I.V. Gorodetskaya, M. Grose, N.A.B. Klutse, S. Krakovska, J. Li, D. Martínez-Castro, L.O. Mearns, S.H. Mernild, T. Ngo-Duc, B. van den Hurk, and J.-H. Yoon. 2021. Atlas. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L.Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K.Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press. Interactive Atlas available from Available from http://interactive-atlas.ipcc.ch/

Hernaman V, Grose M and Clarke JM. 2017. Evaluating the performance of the latest climate models over Southeast Asia. CSIRO, Australia.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D. and Simmons, A., 2020. The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146* (730), pp.1999-2049.

Huang, B., Menne, M.J., Boyer, T., Freeman, E., Gleason, B.E., Lawrimore, J.H., Liu, C., Rennie, J.J., Schreck, C.J., Sun, F. and Vose, R., 2020. Uncertainty estimates for sea surface temperature and land surface air temperature in NOAAGlobalTemp version 5. *Journal of Climate*, *33* (4), pp.1351-1379.

Hurley, P., 2007. Modelling mean and turbulence fields in the dry convective boundary layer with the eddy-diffusivity/mass-flux approach. *Boundary-layer meteorology*, *125* (3), pp.525-536.

Iese, V., Kiem, A.S., Mariner, A., Malsale, P., Tofaeono, T., Kirono, D.G., Round, V., Heady, C., Tigona, R., Veisa, F. and Posanau, K., 2021. Historical and future drought impacts in the Pacific islands and atolls. *Climatic Change*, *166* (1-2), p.19.

IPCC. 2007. Climate change 2007: the physical science basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin., M., Manning, Z. Chen, M. Marquis, KB. Averyt, M. Tignor and HL. Miller (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 996 pp.

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex And P. M. Midgley (Ed.).

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press.

Iturbide, M., Fernández, J., Gutiérrez, J.M., Bedia, J., Cimadevilla, E., Díez-Sierra, J., Manzanas, R., Casanueva, A., Baño-Medina, J., Milovac, J., Herrera, S., Cofiño, A.S., San Martín, D., García-Díez, M., Hauser, M., Huard, D., Yelekci, Ö. 2021. Repository supporting the implementation of FAIR principles in the IPCC-WG1 Atlas. Zenodo, DOI: 10.5281/zenodo.3691645. Available from: https://github.com/IPCC-WG1/Atlas

Katzfey, J., McGregor, J., Suppiah, R. 2014. High-resolution climate projections for Vietnam. Technical Report. CSIRO, Australia, 352 pp.

Kirono, D.G. and Jones, R.N., 2007. A bivariate test for detecting inhomogeneities in pan evaporation. *Australian Meteorological Magazine*, *56* (2), p.93.

Kirono, D.G., Larson, S., Tjandraatmadja, G., Leitch, A., Neumann, L., Maheepala, S., Barkey, R., Achmad, A. and Selintung, M., 2014. Adapting to climate change through urban water management: a participatory case study in Indonesia. *Regional Environmental Change*, *14*, pp.355-367.

Kirono, D.G., Round, V., Heady, C., Chiew, F.H. and Osbrough, S., 2020. Drought projections for Australia: Updated results and analysis of model simulations. *Weather and Climate Extremes*, *30*, p.100280.

Kossin, J.P., Knapp, K.R., Olander, T.L. and Velden, C.S., 2020. Global increase in major tropical cyclone exceedance probability over the past four decades. *Proceedings of the National Academy of Sciences*, *117* (22), pp.11975-11980.

Kowalczyk, E., Stevens, L., Law, R., Dix, M., Wang, Y., Harman, I., Haynes, K., Srbinovsky, J., Pak, B. and Ziehn, T., 2013. The land surface model component of ACCESS: description and impact on the simulated surface climatology. *Australian Meteorological and Oceanographic Journal*, *63* (1), pp.65-82.

Knutson, T., Camargo, S.J., Chan, J.C., Emanuel, K., Ho, C.H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K. and Wu, L., 2020. Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society*, *101* (3), pp.E303-E322.

Lenssen, N.J., Schmidt, G.A., Hansen, J.E., Menne, M.J., Persin, A., Ruedy, R. and Zyss, D., 2019. Improvements in the GISTEMP uncertainty model. *Journal of Geophysical Research: Atmospheres*, *124* (12), pp.6307-6326.

Leo, P. 2016. Growth and developmental responses of taro ((*Colocasia Esculenta (L.) Schott*) to Three Nitrogen Fertilizer Levels: Developing Key Insights for the Purpose of Simulating Management Impacts Using a Biophysical Crop Model, Unpublished Thesis, The University of the South Pacific.

Lin, N., Emanuel, K.A., Smith, J.A. and Vanmarcke, E., 2010. Risk assessment of hurricane storm surge for New York City. *Journal of Geophysical Research: Atmospheres*, *115* (D18).

Lin, Y.L., Farley, R.D. and Orville, H.D., 1983. Bulk parameterization of the snow field in a cloud model. *Journal of Applied Meteorology and climatology*, *2 2*(6), pp.1065-1092.

McGregor, J. 2005. C-CAM: Geometric Aspects and Dynamical Formulation. CSIRO Atmospheric Research Technical Paper No 70.

McGree, S., Schreider, S. and Kuleshov, Y., 2016. Trends and variability in droughts in the Pacific Islands and Northeast Australia. *Journal of Climate*, *29* (23), pp.8377-8397.

McGree, S., Herold, N., Alexander, L., Schreider, S., Kuleshov, Y., Ene, E., Finaulahi, S., Inape, K., Mackenzie, B., Malala, H. and Ngari, A., 2019. Recent changes in mean and extreme temperature and precipitation in the Western Pacific Islands. *Journal of Climate*, *32* (16), pp.4919-4941.

McGree, S., G. Smith, E. Chandler, N. Herold, Z. Begg, Y. Kuleshov, P. Malsale and M. Ritman. 2022. Climate Change in the Pacific 2022: Historical and Recent Variability, Extremes and Change. Climate and Oceans Support Program in the Pacific. Pacific Community, Suva, Fiji.

Mauger, G.S., Bumbaco, K.A., Hakim, G.J. and Mote, P.W., 2013. Optimal design of a climatological network: Beyond practical considerations. *Geoscientific Instrumentation, Methods and Data Systems*, *2* (2), pp.199-212.

MLNR. 2017. Vanuatu National Water Policy (2017–2030). Ministry of Lands and Natural Resources (MLNR), The Government of the Republic of Vanuatu, Port Vila, Vanuatu.

MoCC. 2020. The Republic of Vanuatu Third National Communication to the United Nations Framework Convention on Climate Change. The Ministry of Climate Change (MoCC), The Government of the Republic of Vanuatu

MoCC. 2021. The Republic of Vanuatu First Biennal Update Report. The Ministry of Climate Change Adaptation, Meteorology and Geo-Hazards, Energy, Environment and National Disaster Management (MoCC), The Government of the Republic of Vanuatu, Port Vila, Vanuatu.

Morice, C.P., Kennedy, J.J., Rayner, N.A., Winn, J.P., Hogan, E., Killick, R.E., Dunn, R.J.H., Osborn, T.J., Jones, P.D. and Simpson, I.R. 2021. An updated assessment of near-surface temperature change from 1850: the HadCRUT5 dataset. Journal of Geophysical Research. doi:10.1029/2019JD032361

MTTCNVB. 2021. Vanuatu Sustainable Tourism Strategy 2021. 2025. Minister for Tourism, Trade, Commerce and Ni Vanuatu Business (MTTCNVB). The Government of the Republic of Vanuatu, Port Vila, Vanuatu.

Murakami, H., Delworth, T.L., Cooke, W.F., Zhao, M., Xiang, B. and Hsu, P.C., 2020. Detected climatic change in global distribution of tropical cyclones. *Proceedings of the National Academy of Sciences*, *117* (20), pp.10706-10714.

Mylroie, J.E., Carew, J.L. and Moore, A.I., 1995. Blue holes: definition and genesis. Carbonates and Evaporites, 10, pp.225-233.

NACCC. 2007. Republic of Vanuatu National Adaptation Programme for Action (NAPA). National Advisory Committee on Climate Change (NACCC), Government of Vanuatu, Port Vila, Vanuatu.

Nearing, M.A., Pruski, F.F. and O'neal, M.R., 2004. Expected climate change impacts on soil erosion rates: a review. Journal of soil and water conservation, 59 (1), pp.43-50.

Nelson, S.C. 2011 (revised). Farm and Forestry Production and Marketing Profile for Kava (Piper methysticum). In: Elevitch, C.R. (ed.). Specialty Crops for Pacific Island Agroforestry. Permanent Agriculture Resources (PAR), Holualoa, Hawaiʻi. http://agroforestry.net/scps

Palutikof, J.P., Street, R.B. and Gardiner, E.P., 2019. Looking to the future: guidelines for decision support as adaptation practice matures. *Climatic Change*, *153*, pp.643-655.

Ramsay, H.A., SS Chand, and SJ Camargo, 2018: A statistical assessment of Southern Hemisphere tropical cyclone tracks in climate models. *J. Climate*, *31* (10), pp.081-10.

Rarai, A., Parsons, M., Nursey-Bray, M. and Crease, R., 2022. Situating climate change adaptation within plural worlds: The role of Indigenous and local knowledge in Pentecost Island, Vanuatu. *Environment and Planning E: Nature and Space*, *5*(4), pp.2240-2282.

Rohde, R.A. and Hausfather, Z., 2020. The Berkeley Earth land/ocean temperature record. *Earth System Science Data*, *12* (4), pp.3469-3479.

Rotstayn, L.D., 1997. A physically based scheme for the treatment of stratiform clouds and precipitation in large-scale models. I: Description and evaluation of the microphysical processes. *Quarterly Journal of the Royal Meteorological Society*, *123* (541), pp.1227-1282.

Rotstayn, L.D., Collier, M.A., Mitchell, R.M., Qin, Y., Campbell, S.K. and Dravitzki, S.M., 2011. Simulated enhancement of ENSO-related rainfall variability due to Australian dust. *Atmospheric Chemistry and Physics*, *11* (13), pp.6575-6592.

Rotstayn, L.D. and Lohmann, U., 2002. Simulation of the tropospheric sulfur cycle in a global model with a physically based cloud scheme. *Journal of Geophysical Research: Atmospheres*, *107* (D21), pp.AAC-20.

Schwalm, C.R., Glendon, S. and Duffy, P.B., 2020. RCP8. 5 tracks cumulative CO2 emissions. *Proceedings of the National Academy of Sciences*, *117* (33), pp.19656-19657.

Schwarzkopf, M.D. and Ramaswamy, V., 1999. Radiative effects of CH4, N2O, halocarbons and the foreign-broadened H2O continuum: A GCM experiment. *Journal of Geophysical Research: Atmospheres*, *104* (D8), pp.9467-9488.

Sobel, A.H., Lee, C.Y., Camargo, S.J., Mandli, K.T., Emanuel, K.A., Mukhopadhyay, P. and Mahakur, M., 2019. Tropical cyclone hazard to Mumbai in the recent historical climate. *Monthly Weather Review*, *147* (7), pp.2355-2366.

SPREP. 2016. Vanuatu Framework for Climate Services. Prepared by: Tait, A. and Macara, G., National Institute of Water & Atmospheric Research Ltd (NIWA), New Zealand, in consultation with the Vanuatu Meteorological and Geo-Hazards Department (VMGD), Government of the Republic of Vanuatu. NIWA Client Report no. 2016022WN to Secretariat of the Pacific Regional Environment Programme (SPREP). 67p.

Taylor, M., McGregor, A. and Dawson, B., 2016. *Vulnerability of Pacific agriculture and forestry to climate change*. Secretariat of the Pacific Community.

Thatcher, M. and McGregor, J.L., 2009. Using a scale-selective filter for dynamical downscaling with the conformal cubic atmospheric model. *Monthly Weather Review*, *137* (6), pp.1742-1752.

The World Bank Group. 2021. Climate risk country profile: Vanuatu.

Tigona, R.S. and de Freitas, C.R., 2012. Relationship between the Southern Oscillation and rainfall in Vanuatu. *Weather and Climate*, *32* (1), pp.43-50.

Trewin, B., Braganza, K., Fawcett, R., Grainger, S., Jovanovic, B., Jones, D., Martin, D., Smalley, R. and Webb, V., 2020. An updated long-term homogenized daily temperature data set for Australia. *Geoscience Data Journal*, *7* (2), pp.149-169.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A. and Richardson, K., 2010. WorldClim: Global weather stations. https://databasin.org/datasets/15a31dec689b4c958ee491ff30fcce75/

Yin, X., Gruber, A. and Arkin, P., 2004. Comparison of the GPCP and CMAP merged gauge–satellite monthly precipitation products for the period 1979–2001. *Journal of Hydrometeorology*, *5* (6), pp.1207-1222.

Zhang, H.M., Huang, B., Lawrimore, J., Menne, M. and Smith, T.M., 2020. NOAA Global Surface Temperature Dataset (NOAAGlobalTemp).

Abbreviations

APCC	APEC Climate Centre
BOM	Australian Bureau of Meteorology
CCAM	Conformal Cubic Atmospheric Model
CIS	Climate Information Services
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
CORDEX	Coordinated Regional Climate Downscaling
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DARD	Department of Agriculture and Rural Development
DLA	Department of Local Authorities
DoT	Department of Tourism
DoWR	Department of Water Resources
DSSAT	Decision Support System for Agrotechnology Transfer
ENSO	El Niño-Southern Oscillation
GCF	Green Climate Fund
GCM	General Circulation Model
GISTEMP	GISS Surface Temperature Analysis
ITCZ	Intertropical Convergence Zone
MIT	Massachusetts Institute of Technology
MJO	Madden-Julian Oscillation
MLNR	Ministry of Lands and Natural Resources
MoCC	Ministry of Climate Change
NAPA	National Adaptation Programme of Action
NDA	National Designated Authority
NDC	Nationally Determined Contribution
NGO	Non-government Organisations
NOAA	National Oceanic and Atmospheric Administration
PACCSAP	Pacific-Australia Climate Change Science and Adaptation Planning Program
PCCSP	Pacific Climate Change Science Program
PMU	Project Management Unit

RCP	Representative Concentration Pathway
RUSLE	Revised Universal Soil Loss Equation
SPCZ	South Pacific Convergence Zone
SPI	Standardised Precipitation Index
SPREP	Secretariat of the Pacific Regional Environment Programme
SST	Sea Surface Temperature
TC	Tropical Cyclone
TK	Traditional Knowledge
VAN-CIS-RDP	Climate Information Services for Resilient Development in Vanuatu
Van-KIRAP	*Vanuatu Klaemaet Infomesen blong Redy, Adapt mo Protekt*
VART	Vanuatu Agriculture and research Training Centre
VCSF	Vanuatu Climate Services Framework
VMGD	Vanuatu Meteorological and Geo-hazards Department

Appendix 1 Stakeholder engagement

Table 12 List of relevant stakeholder engagement activities. * denotes activities organised by SPREP PCU and PMU

ACTIVITY AND DATE	PURPOSE	PARTICIPANTS
Pre-Inception Workshop Meeting, 14 February 2018*	Preparation for the Inception Workshop	SPREP and Delivery Partners (CSIRO, BOM and APCC)
Van-KIRAP Inception Workshop, 20-26 February 2018*	• Officially launch and commence the implementation of the Project. • Clarify roles and responsibilities of key stakeholders, including VMGD, SPREP, the 5 priority Sectors and Delivery Partners. • Raise awareness amongst key stakeholders about the project and identify areas of possible engagement with other stakeholders such as non-government organisations.	SPREP, VMGD, five priority sectors and the health sector, Delivery Partners (CSIRO, BOM and APCC), Steering Committee, representatives from government ministry/department (MOCC, NDA, Ministry of Women), representatives from Provinces and Communities; representatives from other Organisations and Initiatives.
The first Delivery Partners coordination meeting (Review of the Van-KIRAP Project), 4-8 February 2019*	Review and revise the Van-KIRAP work plan and budget, including: • develop project Design Plan • map project activities against sector CIS priorities identified in the five sector action plans • map project activities against community CIS needs • identify where Van-KIRAP can build on existing activities of VMGD, the Ministry of Climate Change and other projects and organisations working in this field • revise the 4-year project work plan and implementation • develop individual Delivery Partner work schedules and budgets for revised activities.	Van-KIRAP PMU, VMGD, SPREP Project Coordination Unit (CPU), Information Communication Technology (ICT), CSIRO, BOM, APCC, five priority sectors coordinators
Van-KIRAP Technical Working Group (TWG) meeting, 23 May 2019*	Discuss various technical aspects of the project, including technical guidance and direction of the project and its implementation, scientific methods and approaches, provide advice on the sector case studies, etc	Van-KIRAP Manager, SPREP, DoWR, DLA, VMGD, VANGO, DoT, DARD, CSIRO, BOM, APCC, PMU
The 1st Engagement Workshop, 9-13 September 2019	• Establish and build key networks and working relationships between CSIRO scientists, sectors, VMGD and SPREP PMU. • Identify key climate change impacts and priority CIS (data, information) and capacity development needs. • Identify agreed delivery and support modalities, platforms, tools, products, where possible, using sectoral case study as contexts. • Identify next steps and to update workplan over the next period, as appropriate. • Run one-day activity to raise awareness and facilitate sectoral planning using climate change information and services.	CSIRO scientists, sectors, VMGD and SPREP PMU, PCU
CSIRO Cross Project Technical workshop between Van-KIRAP and the NextGen Pacific, 12 Dec 2019	• Present workplan and preliminary results • Discuss projects for coordination and harmonization of project methods and technical activities	CSIRO Van-KIRAP project team and NextGen Pacific Project team

ACTIVITY AND DATE	PURPOSE	PARTICIPANTS
In-Country Mission and Stakeholder Engagement Workshop 17 – 20 February 2020, Port Vila and Luganville, Vanuatu	• Raise awareness of stakeholders in Santo Island about Van-KIRAP, VMGD Services, climate change and its impacts, and sectoral case studies • Communicate results of the CSIRO 6-month work plan (Aug 2019 - Jan 2020) and seek feedback from VMGD, SPREP and sectoral/other local Van-KIRAP project stakeholders. • Further strengthen networks and collaborative partnership between CSIRO project team, VMGD, SPREP, sector coordinators and other local Van-KIRAP project stakeholders. • Undertake further project planning with VMGD, SPREP and sectoral coordinators, including to identify lessons learned, next steps and to update workplan for the full project.	VMGD, SPRP PMU, CSIRO, sector coordinators, local community rep, local official
Van-KIRAP PICOF-9 Prep meeting 12 Oct 2020	Discuss and provide input for Van-KIRAP participation to the PICOF (Pacific Islands Climate Outlook Forum)	PMU, VMGD, CSIRO
CSIRO and Van-KIRAP sectoral meeting on 17 (Infrastructure), 18 (Water), 19 (Tourism) and 20 (Agriculture) 24 (Fishery) November 2020	To review and provide input to sectors case study work plan	PMU, CSIRO, Sector coordinators
CSIRO Cross Project Technical workshop between Van-KIRAP and the NextGen Pacific, 4 February 2021	Present workplan and results toward coordination and harmonization of project methods and technical activities	CSIRO Van-KIRAP project team and NextGen Pacific Project team
Implementation Support Mission Virtual Meeting, 28-30 April 2021*	• Review the 2021 workplans • Discuss impacts and challenges on implementation of activities including COVID-19 impacts and mitigation actions • Discuss future plans beyond 2021 • Review the project management aspects • Discuss and prepare for the Mid-Term Review	PMU, SPREP, VMGD, BOM, APCC, CSIRO, Sectors, SPREP CCR, Van-KIRAP Community Coordinator
Van-KIRAP mid-term review 9 June 2021*	Participate to the Van-KIRAP mid-term review undertaken by FCG New Zealand	See the Mid-term Review Report (FCG New Zealand, 2021)
Van-KIRAP Technical Working Group (TWG) meeting 29 June 2021 and Steering Committee meeting, 1 Jul 2021*	Discuss project progress against work plan, technical feedback and recommendations	PMU, VMGD, Sectors, APCC, BOM, CSIRO, UoN, Gender Research assistant, Community Coordinator
Working remotely with Van-KIRAP PMU on contribution to CLIPSSA Project Concept Note developed by *Agense Française de Developpement* (AFD), 14-16 July 2021; Virtual participation to the CLIPSSA Project Planning Meeting, 19 July 2021	Review and provide input to the CLIPSSA Project Concept Note as part of coordination and harmonisation (not duplicate) of relevant activities in Vanuatu	Van-KIRAP PMU, AFD, CSIRO Climate Projection Activity leader
Working remotely with Van-KIRAP PMU, 28 July to 17 August 2021	Review and provide inputs to VMGD Climate Team's presentation for the Vanuatu National Consultations on Climate Change, Disasters and Displacement run by the	Van-KIRAP PMU, CSIRO Climate Projection Activity leader

ACTIVITY AND DATE	PURPOSE	PARTICIPANTS
	International Organisation for Migration (IOM UN Migration) in late August 2021. The presentation was largely based on the preliminary results developed by Van-KIRAP Climate Projection Team (Activity 1.2.3) The presentation could be considered by IOM in assisting Vanuatu Government to plan for an upcoming National Consultation on Climate Change, Disasters and Migration in the Pacific, which means the results of Van-KIRAP work were considered by end-users	
Van-KIRAP Technical Working Group (TWG) meeting 26 August 2021*	Discuss project progress against work plan, technical feedback and recommendations	PMU, VMGD, Sectors, APCC, BOM, CSIRO, Community Coordinator, etc
Virtual Workshop: Projections and portal 23 Sep 2021	Present results and seek feedbacks	PMU, VMGD, Sectors, CSIRO, BOM, FrontierSI, NGIS
Webinar on Climate Projections and Portal, 12 October 2021	Outreach activity to present results to non-technical audiences and seek feedbacks	PMU, VMGD, CSIRO, sectors, provincial government, DRMO, local communities
Workshop: coastal and vulnerability mapping 10 Nov 2021	Participation to the workshop	PMU, VMGD, Sectors, CSIRO, FrontierSI, NGIS
Webinar: coastal and vulnerability mapping	Participation to the webinar	PMU, VMGD, CSIRO, sectors,
Ongoing SPREP and Delivery Partner (DP) coordination meetings	Discuss various matters, including work plan and delivery; progress update; data agreement, etc	SPREP, PMU, CSIRO, BoM, APCC
Ongoing Discussion with PMU via email and meetings	Discuss various matters related to CSIRO work, including workplan and delivery; progress update; coordination and seek inputs	PMU, CSIRO
Ongoing discussion and working with VMGD and sector coordinators via email and meetings	Discuss and work on various matters such as defining scope and approach for the analysis and presentation; defining subdivision for sub-national regions for analysis; obtaining permission to use observed station data; reviewing sectors case study workplan; etc.	PMU, VMGD, five sector coordinators, CSIRO
Ongoing discussion and working with team Activity 1.1.2 (Building and strengthening user interfaces to support CIS Decision-making) via email and meetings	Discuss and work on various matters related to how the results of Activity 1.2.3 are presented through the Van-KIRAP Portal, this include defining data/information to be shown; display demonstrations to internal team and to users; provision of projections data to FrontierSI, NGIS and Data61; testing results; etc	CSIRO, ForntierSI, NGIS, Data61; with SPREP PMU, VMGD, Sector coordinators as needed
Ongoing discussion and working with NextGen Pacific Project team, December 2020 – June 2021	Discuss and work together toward coordination and harmonization of projection methods, including input to the NextGen Pacific Report for Vanuatu (CSIRO and SPREP, 2021)	NextGen Pacific team, Van-KIRAP Climate Projection team

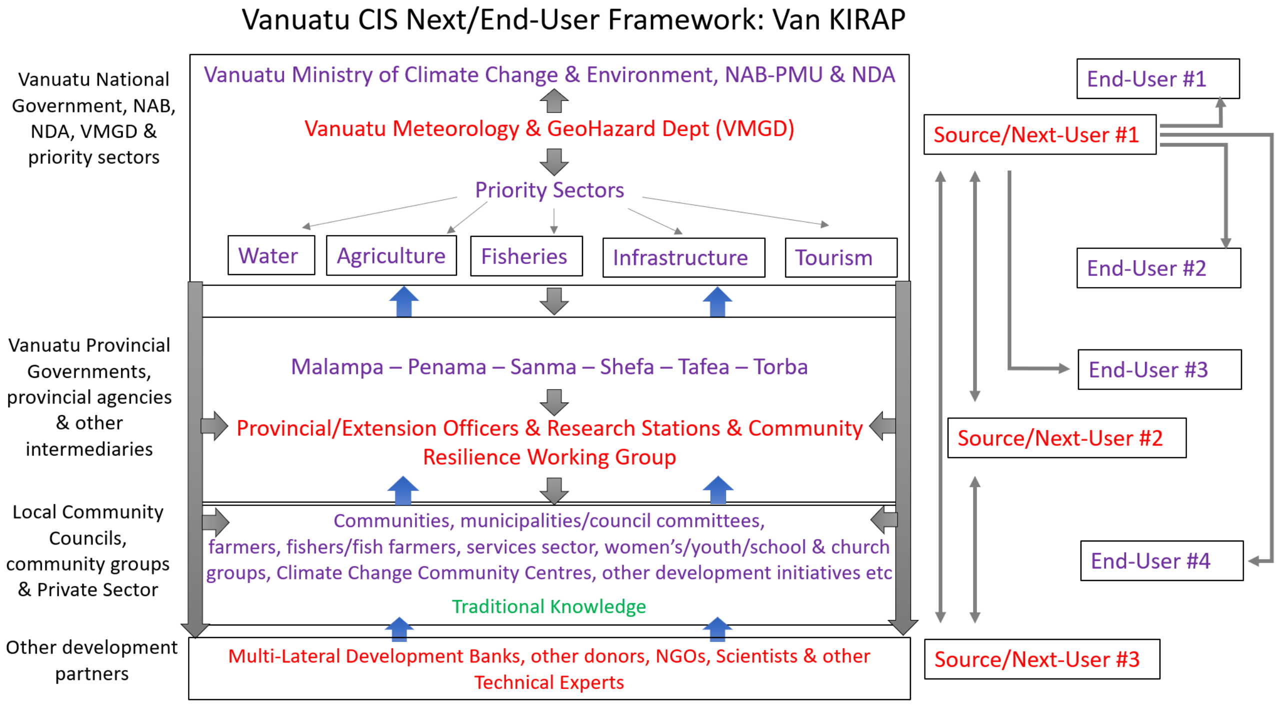


Figure 58 Summary of the next and/or the end users of Van-KIRAP

Appendix 2 Observational data

Table 13 Details of meteorological stations with an indication of data availability for raw data and homogenised data where specified obtained from the Pacific Climate Change Data Portal (2018)

STATION NAME AND SITE CODE	WMO NUMBER	PRECIPITATION DATA (RAIN)	TEMPERATURE DATA (MEAN, MAXIMUM AND MINIMUM TEMPERATURES)
Sola (Vanua Lava) VUT_000002	91551	Dec 1948 - Apr 2017 (raw) Jan 1951 - Apr 2017 (homogenised)	Sep 1953 - Apr 2017
Pekoa Airport (Santo) VUT_000003	91554	Jan 1960 - Dec 2015	Jan 1960 - Dec 2015
Bauerfield (Efate) VUT_000005	91557	Jun 1984 - Dec 2017	Apr 1983 - Dec 2017 (raw) Jan 1951 - Dec 2016 (homogenised)
Port Vila (Efate) VUT_000008	91558	Apr 1905 - Jun 2017 (raw) Jan 1951 - Jun 2017 (homogenised)	Nov 1947 -Jun 2010 (raw) Mar 1947 - Dec 2010 (homogenised)
White Grass Airport (Tanna) VUT_000006	91565	Jan 1961-Jun 2016	Jan 1961 - July 2016
Aneityum VUT_000007	91568	Aug 1948 - Apr 2017 (raw) Jan 1951 - Apr 2017 (homogenised)	Oct 1953 - Apr 2017
Lamap (Malekula) VUT_000004	91555	Jul 1960-Dec 2016	Jul 1960 - Dec 2016

Table 14 Global gridded datasets used in this study

DATASET	TIME PERIOD	REFERENCE
Global gridded temperature datasets		
GISTEMP ERSSTv5	1880-2019	Lenssen et al., 2019
HadCRUT5	1850-2020	Morice et al., 2021
Cowtan and Way	1850-2019	Cowtan and Way, 2014
NOAA Global Temp	1880-2019	Huang et al., 2020; Zhang et al. 2020
Berkley Earth	1850-2019	Rohde and Hausfather, 2020
Global gridded precipitation datasets		
CMAP	1979-	Yin et al. 2004
GPCP	1979-	Yin et al. 2004
ERA5	1979-2020	Hersbach et al. 2020
ERA-Interim	1979-2019	Berrisford et al., 2009

Appendix 3 Additional climate projections information

Table 15 Projected changes in seasonal average temperature over the whole of Vanuatu and for the three sub regions, for the wet season (NDJFMA = November-April) and dry season (MJJASO = May-October) based on CMIP5 GCMs. Projected changes are relative to 1985-2006 and are shown for four different future periods (2030, 2050, 2070 and 2090) and two RCPs (RCP2.6 and RCP8.5). Unit: °C

PERIODS	RCP	VAN		VAN-S		VAN-N		VAN-C	
		ndjfma	mjjaso	ndjfma	mjjaso	ndjfma	mjjaso	ndjfma	mjjaso
2020-2039	RCP2.6	0.6 (0.4 to 0.8)	0.5 (0.4 to 0.7)	0.5 (0.4 to 0.8)	0.5 (0.3 to 0.7)	0.6 (0.4 to 0.7)	0.5 (0.4 to 0.8)	0.6 (0.4 to 0.8)	0.5 (0.4 to 0.7)
2020-2039	RCP 8.5	0.7 (0.5 to 0.9)	0.7 (0.4 to 0.8)	0.6 (0.5 to 0.9)	0.7 (0.4 to 0.8)	0.7 (0.5 to 0.9)	0.7 (0.5 to 0.8)	0.7 (0.5 to 0.9)	0.7 (0.4 to 0.8)
2040-2059	RCP 2.6	0.7 (0.5 to 1.0)	0.6 (0.4 to 1.0)	0.7 (0.4 to 1.0)	0.6 (0.4 to 1.0)	0.7 (0.5 to 1.0)	0.7 (0.5 to 1.0)	0.7 (0.4 to 1.1)	0.6 (0.4 to 0.9)
2040-2059	RCP 8.5	1.2 (0.9 to 1.6)	1.2 (0.9 to 1.6)	1.2 (0.9 to 1.6)	1.2 (0.9 to 1.6)	1.2 (0.9 to 1.6)	1.3 (0.9 to 1.6)	1.2 (0.9 to 1.6)	1.3 (0.9 to 1.6)
2060-2079	RCP 2.6	0.6 (0.4 to 0.9)	0.6 (0.5 to 0.9)	0.6 (0.4 to 1.0)	0.5 (0.5 to 1.0)	0.7 (0.5 to 1.0)	0.6 (0.5 to 1.0)	0.6 (0.4 to 0.9)	0.6 (0.5 to 0.9)
2060-2079	RCP 8.5	1.9 (1.4 to 2.5)	1.9 (1.5 to 2.3)	1.9 (1.4 to 2.5)	1.9 (1.6 to 2.3)	1.8 (1.5 to 2.5)	2.0 (1.5 to 2.4)	1.9 (1.4 to 2.5)	1.9 (1.5 to 2.3)
2080-2099	RCP 2.6	0.6 (0.3 to 1.0)	0.6 (0.4 to 1.0)	0.6 (0.3 to 1.0)	0.6 (0.4 to 1.0)	0.6 (0.4 to 1.0)	0.6 (0.4 to 1.0)	0.6 (0.3 to 1.0)	0.6 (0.4 to 1.0)
2080-2099	RCP 8.5	2.7 (2.0 to 3.4)	2.7 (2.0 to 3.3)	2.7 (2.0 to 3.4)	2.7 (2.1 to 3.4)	2.6 (2.0 to 3.4)	2.7 (2.0 to 3.3)	2.7 (2.0 to 3.4)	2.7 (2.0 to 3.3)

Table 16 Projected changes in annual mean temperature over the three sub-regions based on two CMIP5 GCMs. Projected changes are relative to 1985-2006 and are shown for four different future periods (2030, 2050, 2070 and 2090) and two RCPs (RCP2.6 and RCP8.5). Unit: °C

REGION	MODEL	2020-2039	2040-2059	2060-2079	2080-2099	2020-2039	2040-2059	2060-2079	2080-2099
		RCP2.6				RCP8.5			
Vanuatu North	GISS-E2-H	0.4	0.5	0.4	0.4	0.6	0.9	1.4	1.9
	IPSL-CM5A-LR	0.8	1.0	1.0	1.1	1.1	2.0	2.9	4.0
Vanuatu Central	GISS-E2-H	0.4	0.4	0.3	0.4	0.6	0.8	1.4	1.8
	IPSL-CM5A-LR	0.8	1.0	1.0	1.1	1.1	2.0	2.9	4.0
Vanuatu South	GISS-E2-H	0.3	0.4	0.3	0.4	0.6	0.8	1.4	1.8
	IPSL-CM5A-LR	0.7	0.9	1	1	1.1	2	2.8	3.9

Table 17 Projected changes for annual rainfall for the three sub-national regions, based on two CMIP5 GMCs. Projected changes are relative to 1986-2005 and represent four future periods (2030, 2050, 2070 and 2090) and two RCPs (RCP2.6 and RCP8.5). Unit: % change

REGION	MODEL	2020-2039	2040-2059	2060-2079	2080-2099	2020-2039	2040-2059	2060-2079	2080-2099
		RCP26				RCP8.5			
Vanuatu North	GISS-E2-H	-5.6	-6.5	-7.3	-0.1	-1.1	-7.5	-11.8	-13.9
	IPSL-CM5A-LR	9.7	12.0	12.1	6.2	14.7	19.4	28.2	36.6
Vanuatu Central	GISS-E2-H	-7.3	-13.4	-9.3	-0.7	-4.2	-15.7	-19.9	-21.6
	IPSL-CM5A-LR	5.3	6.7	8.8	5.0	14.6	14.8	24.3	33.1
Vanuatu South	GISS-E2-H	-6.2	-12.4	-8.1	-6.1	-5.8	-20.2	-20.5	-26.2
	IPSL-CM5A-LR	2.5	-0.1	5.9	0.7	9.7	9.4	20.0	21.4

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