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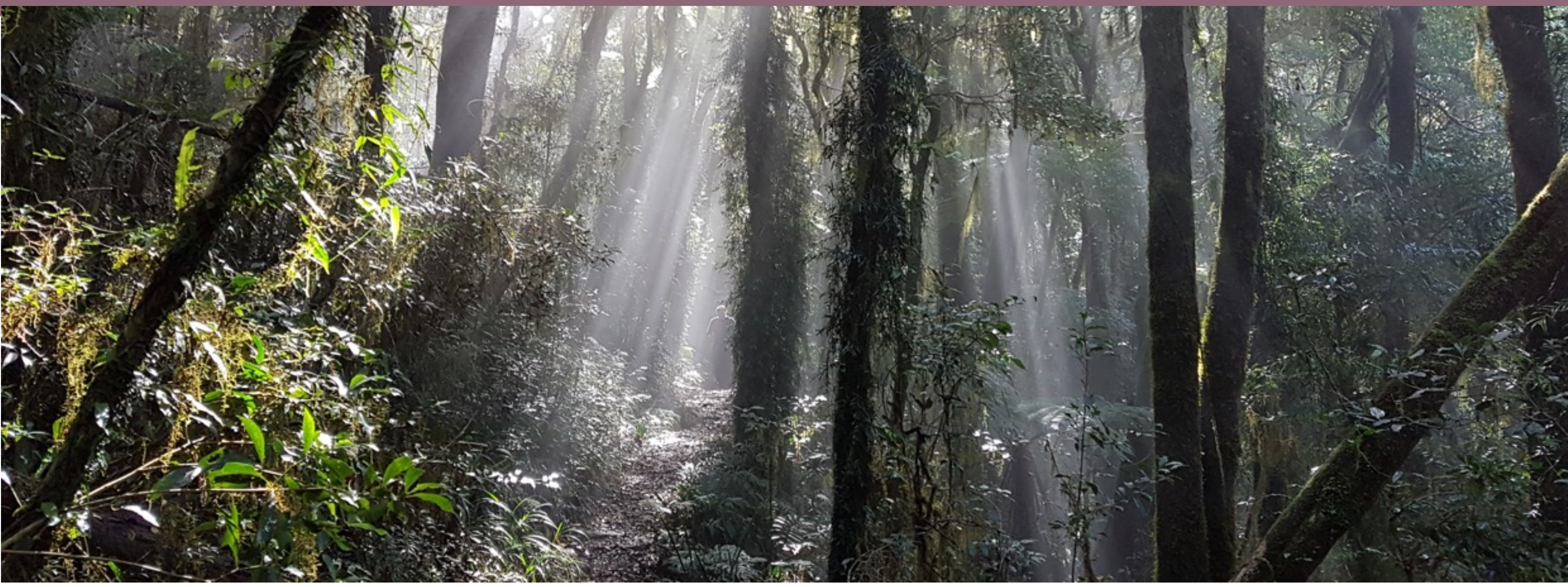

Understanding the impact of climate change on cloud forests in the Gondwana Rainforests of Australia World Heritage Area

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Cover photo: Melinda Laidlaw

Important disclaimer

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Executive summary

Climate change is the primary threat to the Gondwana Rainforests of Australia World Heritage Area, with many of its rainforest communities already restricted to climate refugia on the escarpment and east coast. Research into the potential impacts of climate change on these biotic communities is hampered by a lack of data about the current and projected future rainfall and cloud variables.

This impact assessment examines the effect of projected changes in temperature, rainfall and relative humidity on both the high-elevation forests in the Gondwana Rainforests and the key species that live there. The focus of this study is on cloud base height given the reliance of forest species on precipitation received directly from clouds. This information will be used to inform risk assessments for the conservation management of the World Heritage values for the property.

Gondwana Rainforests of Australia World Heritage Area

The Gondwana Rainforests of Australia is a serial World Heritage property that includes parts of 28 rainforest reserves in north-eastern New South Wales, five major national parks in south-east Queensland, and several smaller parcels of land. The mosaic of rainforest and associated vegetation communities within these reserves contains a range of plant and animals with close relationships to those in the fossil record, having changed relatively little since their ancient origins in Gondwana. The Gondwana Rainforests also provides the principal habitat for many relict, endemic and threatened species of plants and animals.

The high-elevation rainforests in the Gondwana Rainforests property receive up to 40% of their annual water requirement from clouds and fog. Movement of the cloud base up or down the mountains due to climate change will have important conservation and management implications for rainforest species and communities.

The changing climate of the Gondwana Rainforests

The Gondwana Rainforests reserves sit across multiple climatic zones, where their climate is shaped by geography, topography, seasonality and climate variability, which all occur against a backdrop of climate change.

The eastern coast of Australia has clearly experienced a warming trend over the past century, although changes in rainfall and humidity are less clear. The impacts of the combination of these changes are likely to be exacerbated under future climate change.

The results of this assessment of climatic change indicate that, by 2030, the Gondwana Rainforests can expect an increase in temperature and a slight decrease or little change in relative humidity. Rainfall changes are unclear. Lifting condensation level (LCL), a proxy for cloud base height, shows increases (moving up the mountainsides) or little change.

By 2050, projections indicate an increase in temperature and slight decrease or little change in relative humidity. Rainfall changes are unclear. LCL projections show increases or little change.

By 2070, temperatures will continue to increase. Relative humidity is expected to decrease overall and rainfall projections are unclear. A range of LCL change is projected, with the assessment of this report being that moderate increases can be expected.

Detecting biodiversity changes along climatic gradients

LCL projections have been applied to inform a long-term study of climate impacts on the biodiversity of the Gondwana Rainforests.

Initial findings suggest that even modest increases in LCL may have significant implications for cloud-water dependent species, especially those located at elevations adjacent to the current cloud base. Reduced cloud water inputs, especially during the dry season, may increase moisture stress beyond the tolerance of some species, resulting in community change. Observed patterns in canopy species recruitment may already be an indicator of this change.

Implications for climate change adaptation planning

The development of downscaled climate projections and their analysis in combination with ecological and other data can support improved risk assessment, climate adaptation planning and management of the Gondwana Rainforests of Australia World Heritage Area. The projections resulting from this study can inform future risk assessments for the Gondwana Rainforests, complementing other spatial tools used by land management agencies to assess and mitigate risk.

1. Introduction

The Gondwana Rainforests of Australia World Heritage Area (Gondwana Rainforests) is one of 20 listed World Heritage properties in Australia. It is a collection of 40 separate reserves located in north-east New South Wales and south-east Queensland.

The reserves cover more than 366,500 hectares and contain a diversity of rainforest types including warm temperate, cool temperate, subtropical and dry rainforests. Rainforests were the dominant vegetation that covered the ancient supercontinent Gondwana. The remnant rainforests are biodiversity hot-spots and are home to many relict, endemic and threatened plants and animals.

Previous studies of high elevation rainforests adjacent to the Gondwana Rainforests have identified the importance of cloud water to their distribution. Hutley et al. (1997) found that at 1000 m elevation, up to 40% of water reaching the rainforest floor was attributable to cloud rather than to rain. Such dependence on cloud water suggests that variation in cloud height due to climate change could have significant implications for the rainforests, the values of the Gondwana Rainforest reserves and their ongoing management. For this reason, this study has sought to fill gaps in our understanding of the current and future role of cloud water within the Gondwana Rainforests.

1.1 About this impact assessment

This impact assessment examines the effect of changes in temperature, rainfall and relative humidity on both the high-elevation forests in the Gondwana Rainforests and the key species that live there. The focus of this study is on cloud base height given the reliance of forest species on moisture received directly from clouds. This information will be used to inform risk assessment for the conservation management of the World Heritage values for the property.

1.1.1 Geographic boundaries

The assessment focuses on the region covered by the Border Ranges Rainforest Biodiversity Management Plan (DECCW 2010), an area nationally recognised as a Biodiversity Hotspot which includes the Tweed Caldera section of the Gondwana Rainforests of Australia.

The Border Ranges Biodiversity Hotspot refers to the rainforest and related vegetation communities that occur in the Border Ranges region of north-east New South Wales (NSW) and south-east Queensland (Figure 1.1).

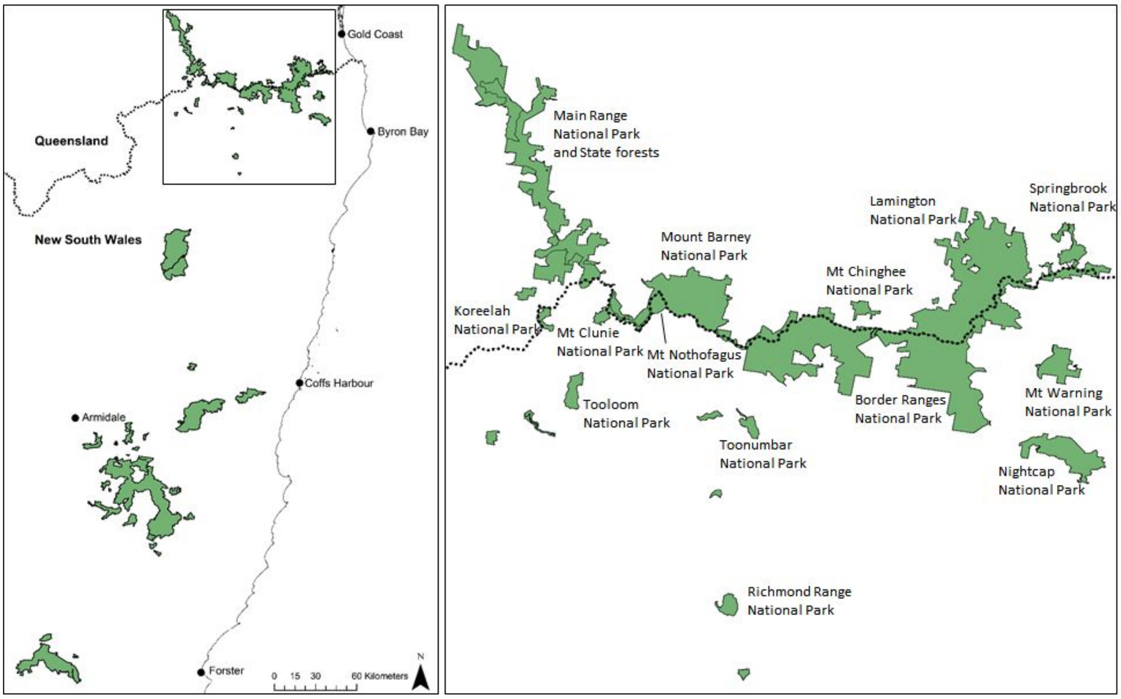

Figure 1.1: (left) Map of the Gondwana Rainforests of Australia (with inset of study area) and (right) Gondwana Rainforests reserves within the study area

1.1.2 Climate change information

The assessment uses projections for temperature, rainfall and lifting condensation level (LCL), a derived variable that serves as a proxy for cloud base height. LCL is the height at which we expect clouds may form when a moist airstream encounters topography. Physically the LCL represents the height that a surface 'parcel' of air must be raised to until that parcel is cool enough for the water vapour to condense into droplets – i.e. cloud droplets. (See Appendix 1 for additional information about LCL.)

These variables are projected for three future time periods – 2030 (2020–2039), 2050 (2040–2059) and 2070 (2060–2079) – under high (A2 and RCP8.5) and lower (RCP4.5) emissions scenarios.

1.2 Process

This assessment has been guided by a five-step climate change health check process developed by the ESCC Hub to facilitate the incorporation of climate change information into sectoral decision making. The process is summarised in Figure 1.2.

A feature of this process is the co-design of the research to clarify and provide information for the issue being investigated. This highly collaborative and responsive approach to understanding climate change impacts serves to deliver useful and useable information as well as build understanding of, and capacity to use, climate change data.

The following sections provide an overview of how the process was applied in this instance.

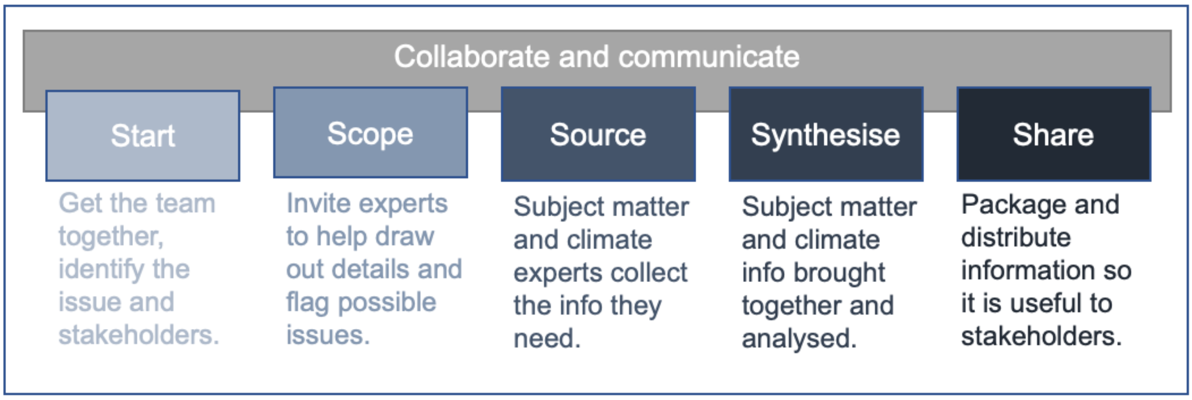

Figure 1.2: The five-step climate change health check process. Collaboration and communication occur throughout.

1.2.1 Start

While the importance of understanding changes in cloud base height in the Gondwana Rainforests was recognised, data to explore these changes was limited, with researchers using cloud base height data collected at a nearby airport. Given the clear risks presented by the changing climate to the World Heritage property, the Gondwana Rainforests Technical and Scientific Advisory Committee (TSAC) identified a need for further research in this area. As World Heritage was identified as a cross-cutting theme for the Australian Government's National Environmental Science Program (NESP), contact was made with two of the program's research hubs to investigate a potential partnership project between the Earth Systems and Climate Change (ESCC) Hub and the Threatened Species Recovery (TSR) Hub.

Working with the Gondwana Rainforests Executive Officer, the ESCC Hub established a core project team to explore options for research and collaboration with members of the TSAC and the TSR Hub.

1.2.2 Scope

The ESCC Hub convened a workshop at the University of Queensland in Brisbane on 8 October 2018, bringing together experts from key agencies to discuss available climate projections and identify specific data needs for ongoing climate change adaptation planning for the Gondwana Rainforests. Details of the workshop are available in the workshop report (NESP ESCC Hub 2019).

Discussions at the workshop clarified the management need for further information about how cloud base height and associated moisture availability may change in a changing climate to assist in risk management of flora and fauna in the upland rainforests. Existing ESCC Hub climate projections data and knowledge gaps were identified, with the potential for additional data and information after a period of research and evaluation.

The scope of this research and evaluation was determined at a meeting between the ESCC Hub and representatives from the managing agencies for the Gondwana Rainforests in

February 2019. It was decided that the Hub would deliver temperature, rainfall and lifting condensation level projections, which could be used in ecological assessments to help determined the impact of climate change in the Gondwana Rainforests.

1.2.3 Source

With the assessment clearly scoped, climate and ecology specialists each undertook the required data collection and generation. While these specialist teams worked independently, they remained in close contact to ensure that the data being collected and generated were appropriate for the assessment. The development of this information is documented in this report.

1.2.4 Synthesise

Synthesis occurred concurrently with the Source step, as climate information was generated, incorporated into ecological assessments and interpreted. This was an iterative and collaborative process, building capacity and understanding for both the project’s climate and ecology researchers.

1.2.5 Share

This report represents the primary means of sharing the results of this assessment. A technical note was also produced to accompany the dataset developed for this assessment (Narsey 2020).

2. Gondwana Rainforests of Australia World Heritage Area

The Gondwana Rainforests of Australia is a serial World Heritage property that includes parts of 28 rainforest reserves in north-eastern New South Wales, five major national parks in south-east Queensland and several smaller parcels of land. The mosaic of rainforest and associated vegetation communities within these reserves contains a range of plant and animal lineages and communities with ancient origins in Gondwana. The Gondwana Rainforests also provides the principal habitat for many endemic and threatened species of plants and animals.

2.1 Value and significance

The Gondwana Rainforests reserves support a variety of rainforest communities distributed where soil, topography and climate act together to provide a stable refuge from seasonal moisture stress, drought and fire. The altitudinal range and mountainous topography provide a mosaic of habitat for a diversity of species, both ancient and more recently evolved. Many of these species are endemic to these pockets of rainforest and many are rare and/or threatened.

Rainforests are, by definition, communities with a closed canopy. The canopy provides shelter and shade, retaining moisture needed by many of the species that persist in this forest type. In broad terms, dry rainforest communities are able to persist under low or seasonal rainfall with an annual mean of 600–1100 mm. Subtropical and warm temperate rainforest communities require higher rainfalls of approximately 1300 mm while cool temperate rainforest communities generally cannot thrive below annual rainfalls of 1750–3500 mm (Floyd 2008).

Some rainforest communities and species are regularly associated with cool, damp mountaintops which are regularly immersed in low cloud (Webb 1959, 1968; Baur 1965; Young and McDonald 1987; Adam 1992). Many of the species in these forests depend on consistent high moisture, with a proportion of this contributed by cloud condensing on the canopy and then dripping onto the forest floor. These moist, cool and generally fire-resistant micro-habitats provide refuge for some of the endemic and evolutionarily unique species for which the Gondwana Rainforests are renowned.

Rainforests once covered the vast supercontinent of Gondwana. When the supercontinent broke up and Australia moved north, climate became warmer and drier and species were forced to evolve and adapt to the changed conditions. Some 38 million years ago, the first eucalypts appeared and since then eucalypt forests and woodlands have come to dominate the landscape with rainforest only persisting in refuge areas (Floyd in Kitching et al. 2010). These pockets of rainforest support species which have persisted largely unchanged in the relative stability of these remnants of the once widespread Gondwanan rainforests.

The Gondwana Rainforests contain a large number of families whose ancestry stretches back to the evolution of ferns, conifers and cycads and the early flowering plants. The

Gondwana Rainforests are of international conservation significance as they contain numerous species which demonstrate phylogenetic endemism, species with deep ancestry whose close relatives are now extinct, yet they have persisted over evolutionary history into the present day. These species remain closely related to those in the fossil record from the early development of life on earth. Genetic studies are continuing to reveal the relationships between the species we see in these rainforests today and those of the ancient past.

As extensive rainforests have become fragmented over millennia due to climatic changes and fire, isolated plants and animals within them have developed into new and distinct species. These remaining rainforests contain species that were once widespread across the continent but are now restricted to these refuge areas, such as the mountain mist frogs *(Philoria spp).* There are five species of this frog found in different, separated locations in the cool mountaintops. The genus is found in the Riversleigh fossil deposits, demonstrating that rainforests once existed in what is now desert country.

2.2 World Heritage status and implications for management

The Gondwana Rainforests were first listed as a World Heritage Area in 1986 and were the first serial property to be listed. The original listing was as Australian East Coast Temperate and Subtropical Rainforest Parks. Additions were listed in 1994 and the name changed to Central Eastern Rainforest Reserves of Australia. The name was changed to Gondwana Rainforests of Australia in 2007.

World Heritage properties are sites of global natural or cultural significance that have been recognised through the World Heritage Convention. The Convention, adopted in 1972 through UNESCO, came into force in 1975. It recognises the need to preserve a balance between World Heritage values and how people interact with nature.

All States Parties signed up to the World Heritage Convention – currently 167 countries (including Australia) – agree to adhere to the Convention and to nominate properties for inclusion on the World Heritage List. They commit to protecting World Heritage values, which includes having management plans in place to protect these values and report on their condition.

2.2.1 Outstanding Universal Value

World Heritage properties are listed on the basis of their outstanding universal value (OUV). Each property has a statement of OUV which is:

- the principal reference for all plans and legislation relating to future protection and management of the property
- a point of reference for all monitoring, state of conservation reporting and the management responsibility to maintain the values as per the listing.

The fundamental concept is passing on the World Heritage values of the property to future generations as they are recorded in the statement of outstanding universal value.

There are 10 criteria for outstanding universal value – four natural and six cultural[1]. Gondwana Rainforests meets three of the four natural criteria:

> viii. be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.
>
> ix. be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals.
>
> x. contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.

An outline of how the property meets these criteria are included in the statement of outstanding universal value, reproduced below.

EXTRACT FROM THE STATEMENT OF OUTSTANDING UNIVERSAL VALUE for the Gondwana Rainforests of Australia World Heritage Area

Source: http://www.environment.gov.au/heritage/places/world/gondwana

Brief synthesis

The Gondwana Rainforests of Australia is a serial property comprising the major remaining areas of rainforest in south-east Queensland and northeast New South Wales. It represents outstanding examples of major stages of the Earth's evolutionary history, ongoing geological and biological processes, and exceptional biological diversity. A wide range of plant and animal lineages and communities with ancient origins in Gondwana, many of which are restricted largely or entirely to the Gondwana Rainforests, survive in this collection of reserves. The Gondwana Rainforests also provides the principal habitat for many threatened species of plants and animals.

Criterion (viii): The Gondwana Rainforests provides outstanding examples of significant ongoing geological processes. When Australia separated from Antarctica following the breakup of Gondwana, new continental margins developed. The margin which formed along Australia's eastern edge is characterised by an asymmetrical marginal swell that runs parallel to the coastline, the erosion of which has resulted in the Great Divide and the Great Escarpment. This eastern continental margin experienced volcanicity during the Cenozoic Era as the Australian continental plate moved over one of the planet's hot spots. Volcanoes erupted in sequence along the east coast resulting in the Tweed, Focal Peak, Ebor and Barrington volcanic shields. This sequence of volcanos is significant as it enables the dating of the geomorphic evolution of eastern Australia through the study of the interaction of these volcanic remnants with the eastern highlands.

The Tweed Shield erosion caldera is possibly the best preserved erosion caldera in the world, notable for its size and age, for the presence of a prominent central mountain mass (Wollumbin/Mt Warning), and for the erosion of the caldera floor to basement rock. All three stages relating to the

[1] http://whc.unesco.org/en/criteria/

erosion of shield volcanoes (the planeze, residual and skeletal stages) are readily distinguishable. Further south, the remnants of the Ebor Volcano also provides an outstanding example of the ongoing erosion of a shield volcano.

Criterion (ix): The Gondwana Rainforests contains outstanding examples of major stages in the Earth's evolutionary history as well as ongoing evolutionary processes. Major stages represented include the 'Age of the Pteridophytes' from the Carboniferous Period with some of the oldest elements of the world's ferns represented, and the 'Age of Conifers' in the Jurassic Period with one of the most significant centres of survival for Araucarians (the most ancient and phylogenetically primitive of the world's conifers). Likewise the property provides an outstanding record of the 'Age of the Angiosperms'. This includes a secondary centre of endemism for primitive flowering plants originating in the Early Cretaceous, the most diverse assemblage of relict angiosperm taxa representing the primary radiation of dicotyledons in the mid-Late Cretaceous, a unique record of the evolutionary history of Australian rainforests representing the 'golden age' of the Early Tertiary, and a unique record of Miocene vegetation that was the antecedent of modern temperate rainforests in Australia. The property also contains an outstanding number of songbird species, including lyrebirds (Menuridae), scrub-birds (Atrichornithidae), treecreepers (Climacteridae) and bowerbirds and catbirds (Ptilonorhynchidae), belonging to some of the oldest lineages of passerines that evolved in the Late Cretaceous. Outstanding examples of other relict vertebrate and invertebrate fauna from ancient lineages linked to the break-up of Gondwana also occur in the property. The flora and fauna of the Gondwana Rainforests provides outstanding examples of ongoing evolution including plant and animal taxa which show evidence of relatively recent evolution. The rainforests have been described as 'an archipelago of refugia, a series of distinctive habitats that characterise a temporary endpoint in climatic and geomorphological evolution'. The distances between these 'islands' of rainforest represent barriers to the flow of genetic material for those taxa which have low dispersal ability, and this pressure has created the potential for continued speciation.

Criterion (x): The ecosystems of the Gondwana Rainforests contain significant and important natural habitats for species of conservation significance, particularly those associated with the rainforests which once covered much of the continent of Australia and are now restricted to archipelagos of small areas of rainforest isolated by sclerophyll vegetation and cleared land. The Gondwana Rainforests provides the principal habitat for many species of plants and animals of outstanding universal value, including more than 270 threatened species as well as relict and primitive taxa.

Rainforests covered most of Australia for much of the 40 million years after its separation from Gondwana. However, these rainforests contracted as climatic conditions changed and the continent drifted northwards. By the time of European settlement rainforests covered only 1% of the landmass and were restricted to refugia with suitable climatic conditions and protection from fire. Following European settlement, clearing for agriculture saw further loss of rainforests and only a quarter of the rainforest present in Australia at the time of European settlement remains.

The Gondwana Rainforests protects the largest and best stands of rainforest habitat remaining in this region. Many of the rare and threatened flora and fauna species are rainforest specialists, and their vulnerability to extinction is due to a variety of factors including the rarity of their rainforest habitat. The Gondwana Rainforests also protects large areas of other vegetation including a diverse range of heaths, rocky outcrop communities, forests and woodlands. These communities have a high diversity of plants and animals that add greatly to the value of the Gondwana Rainforests as habitat for rare, threatened and endemic species. The complex dynamics between rainforests and tall open forest particularly demonstrates the close evolutionary and ecological links between these communities.

Species continue to be discovered in the property including the re-discovery of two mammal species previously thought to have been extinct: the Hastings River Mouse (*Pseudomys oralis*) and Parma Wallaby (*Macropus parma*).

2.2.2 Management

World Heritage properties must be managed in a manner consistent with the World Heritage Convention. This includes the identification, protection, conservation, presentation and, where necessary, rehabilitation of World Heritage values. To support this, the Australian Government included World Heritage properties as Matters of National Environmental Significance under the *Environment Protection and Biodiversity Conservation Act 1999* and a set of World Heritage management principles are included as a schedule under this Act. These management principles include requirements for the monitoring and reporting on World Heritage values, and the involvement of community, technical and scientific input into management.

On-ground management of the Gondwana Rainforests is carried out by the NSW National Parks and Wildlife Service (NPWS) and the Queensland Parks and Wildlife Service (QPWS). Cross-jurisdictional management and advisory committees work to support a strategic approach to the protection, conservation and presentation of the World Heritage values of the property. There are a range of mechanisms to support this within each state, both within the parks services, as well as across the natural resource management groups that support complementary land management on neighbouring lands.

World Heritage properties provide periodic reports to the World Heritage Centre, including updates on management, visitation and funding. In addition to this, the International Union for the Conservation of Nature (IUCN) has commenced a program of World Heritage Conservation Outlook reports which provide information on the status and trend of World Heritage values. The 2017 report concluded that the values of the Gondwana Rainforests were “good with some concerns” (Osipova et al. 2017, p. 60). These concerns include the high level of threats to the property, including from the changing climate. The recent unprecedented bushfires, the impacts of which are still being investigated, have highlighted the vulnerability of this World Heritage property. The complex nature of the serial property, being separated reserves across a wide geographic range, provides both challenges for conservation management, but also opportunities for innovation to support the continued persistence of these rainforests and related vegetation, and their precious cargo of endemic and threatened species.

2.2.3 Information needs for management in a changing climate

Climate change is identified as the primary threat to the Gondwana Rainforests of Australia World Heritage Area (ANU 2009). The implications of changing climate for the Gondwana Rainforests have been under assessment through several Commonwealth-funded projects since 2009. Many of these rainforest communities, already restricted to climate refugia on the escarpment and east coast, are now facing critical changes in temperature and rainfall.

One of the rainforest types which is considered to be under particular threat from climate change is the microphyll fern forests, typically dominated by Antarctic beech (*Nothofagus moorei*) (Taylor et al. 2005 in ANU 2009). These areas, commonly known as ‘cool temperate rainforests’, receive moisture inputs from cloud and meet the criteria for cloud forests under international definitions.

Research into the potential impacts of climate change on these biotic communities is hampered by a lack of data about the current and projected rainfall and cloud variables. This project focusses on the specific question of how to obtain better data and information on these parameters to assist in adaptation planning.

3. The changing climate of the Gondwana Rainforests

3.1 Climate influences

3.1.1 Geography and topography

The Gondwana Rainforests of Australia are spread over a large stretch of the eastern seaboard of Australia, from south-east Queensland to north-east New South Wales. As such, the reserves sit across multiple climatic zones.

Climate differences between the reserves are also affected by variations in topography, which has created microclimates that species have adapted to over long periods. The Gondwana Rainforests consists largely of elevated subtropical and temperate rainforests. In these unique environments local temperatures can be decreased due to elevation, while exposure to prevailing winds and passing low clouds is increased. On the leeward side of these topographic features, sheltered zones can exist, receiving less rainfall than the wind-ward side of the topography, but also sheltered from prevailing winds.

3.1.2 Seasonality

The subtropical locations of the Gondwana Rainforests reserves experience a strong seasonality, along with regional variation due to topographic influences. The seasonal cycle can be broadly described as a transition from a warm and wet summer, to a cooler and drier winter and spring, as seen for Murwillumbah (Figure 3.1) which is located within the Tweed Caldera in the vicinity of the Gondwana Rainforests.

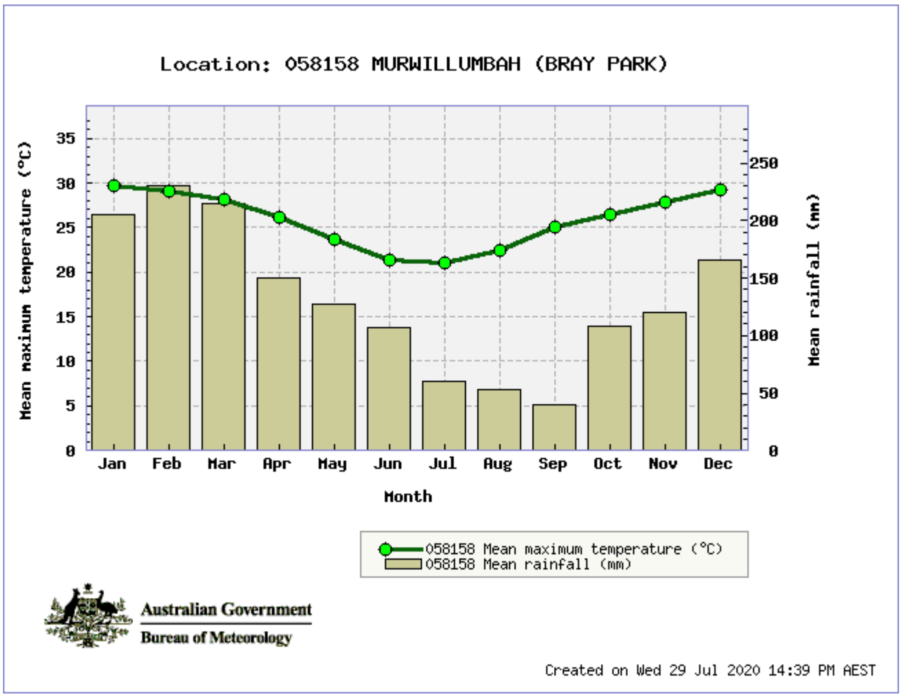

Figure 3.1: Seasonal cycle of rainfall and mean maximum temperature at Murwillumbah, located within the Tweed Caldera. The seasonal cycles are calculated as the average of observations from 1972 to 2020.

It is in those driest months of the year that the Gondwana Rainforests are particularly susceptible to moisture stress. September is typically the driest month for many of the Gondwana Rainforests reserves. During those times many species rely on water harvested directly from passing low clouds which deposit condensate on high elevation surfaces (sometimes referred to as 'occult' rainfall).

3.1.3 Climate variability

In addition to a reasonably strong seasonal cycle, the eastern seaboard of Australia also experiences large variability in weather and climate conditions on timescales ranging from days to decades. For example, annual rainfall at Numinbah, located at the edge of the Tweed Caldera, varies fivefold (from 1000 to 5000 mm per year). While it may be remarkable that the flora and fauna of these ecosystems have adapted to such variations, minor changes to the climate super-imposed over such large natural variations could result in extreme local conditions.

There are multiple drivers, or sources, of the observed variability in climatic conditions over the subtropical eastern seaboard. On daily to weekly timescales weather changes result in rainfall and temperature variations. These transient weather systems include frontal systems originating from the south as well as low pressure systems that may be either mid-latitude or tropical in origin (see Figure 3.2). Given the near-coastal location of many of the Gondwana Rainforests reserves, coastal effects such as land-sea breeze circulations may also play a role in the day to day variations in rainfall, temperature and humidity.

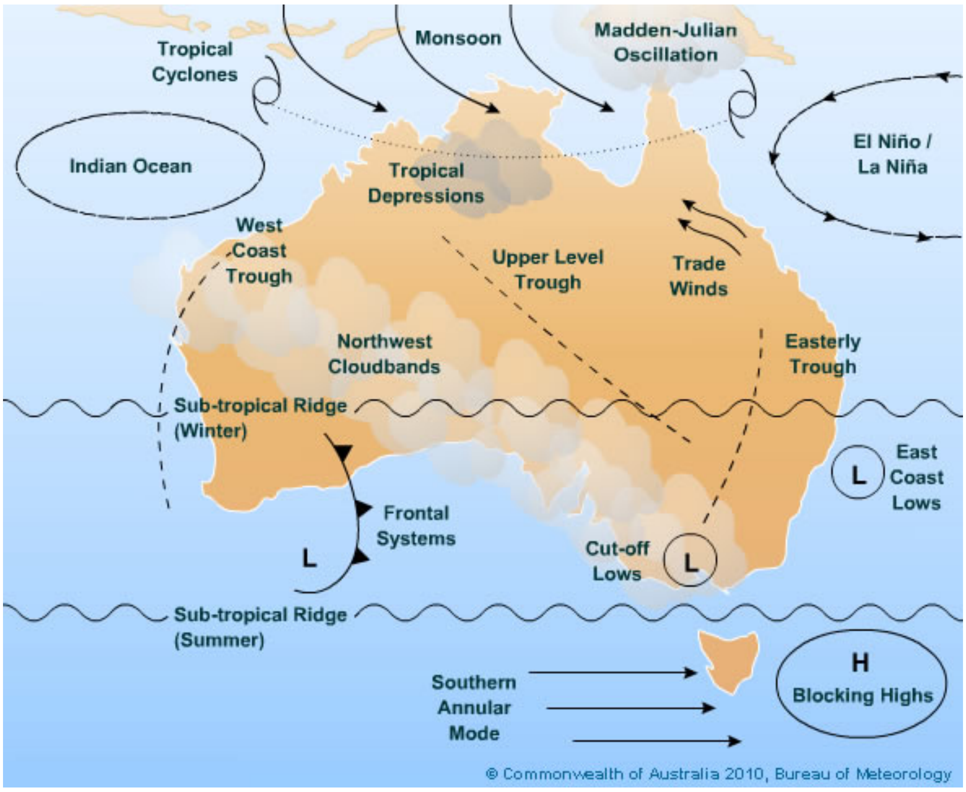

Figure 3.2: Schematic of several key climate drivers and weather features of relevance for the Australian continent (www.bom.gov.au/climate)

On longer timescales, naturally occurring modes of variability modulate climatic conditions over the east coast of Australia. These include El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM) (Figure 3.2), which influence local rainfall and other climate conditions by modifying the direction of wind at large-scales. This, in turn, modifies climate and weather features affecting the region.

ENSO is perhaps the best-known mode of variability that affects eastern Australia. During its El Niño phase, the central or eastern equatorial Pacific is unusually warm. As a result of changes in the large-scale atmospheric circulation patterns, eastern Australia tends to receive lower than average rainfall. In its opposite phase (La Niña), the west Pacific Ocean surface is unusually warm compared to the east Pacific. The resulting circulation response generally leads to greater than average rainfall over eastern Australia.

It is important to note that while it is clear that these modes of variability have an influence on Australian climatic conditions, they do not guarantee their associated conditions in any given year, they merely indicate such conditions to be more likely. Multiple modes of variability can also occur simultaneously and can act to either reinforce or counteract each other. Furthermore, while these modes of variability lead to short-term anomalies in climate conditions, alone they cannot explain observed long-term changes to the climate.

3.2 A changing climate

Greenhouse gases are those which trap heat within the Earth's atmosphere. The concentration of these gases has steadily risen since pre-industrial times and it is now well-understood that these increases in greenhouse gases have led to increased surface temperatures globally. While there is some regional variation in this trend, the eastern coast of Australia has clearly experienced a warming trend over the past century (Figure 3.3).

The accompanying changes for other variables such as rainfall and humidity are less obvious. Although there is no clear long-term trend in annual rainfall (Figure 3.4), or September rainfall (Figure 3.5), for Eastern Australia as a whole, regional variations do exist. The south-east coast of Australia has generally experienced below-average rainfall in the cooler months (April to October) in the past two decades (BoM and CSIRO 2018).

While the possible changes to average rainfall may be small compared to the natural year-to-year variability, in combination with other changes (e.g. changes to temperature, humidity, soil moisture, and clouds), the impacts on natural habitats of these changes in rainfall may be significant. Potential future climate changes are likely to further exacerbate these climatic pressures.

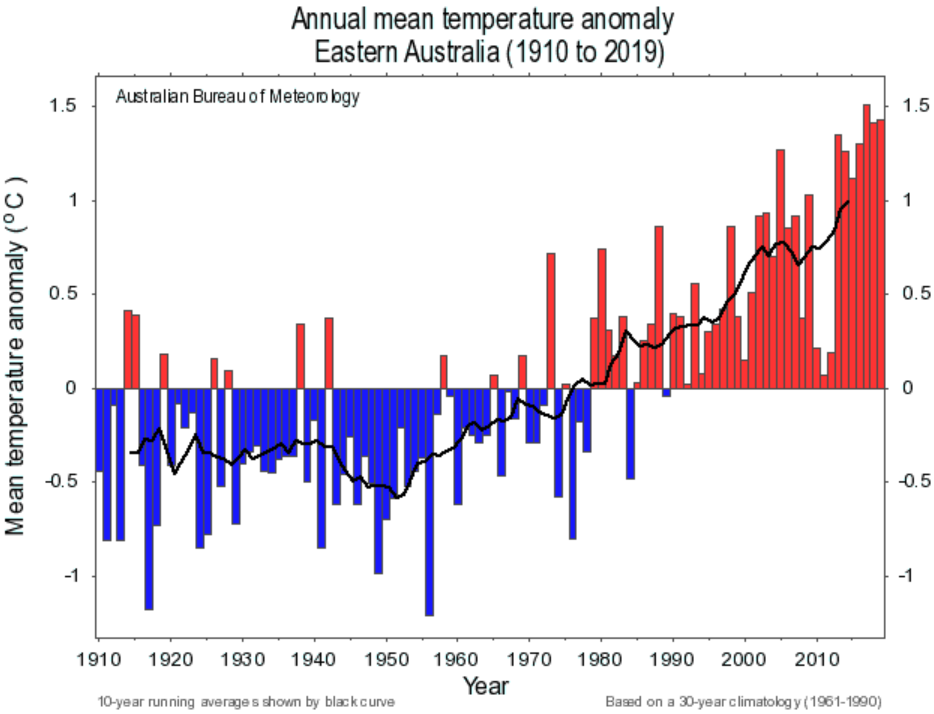

Figure 3.3: Annual average temperature anomaly for Eastern Australia (Queensland, New South Wales and Victoria). Anomalies are calculated as departures from the 1961–1990 mean (www.bom.gov.au/climate)

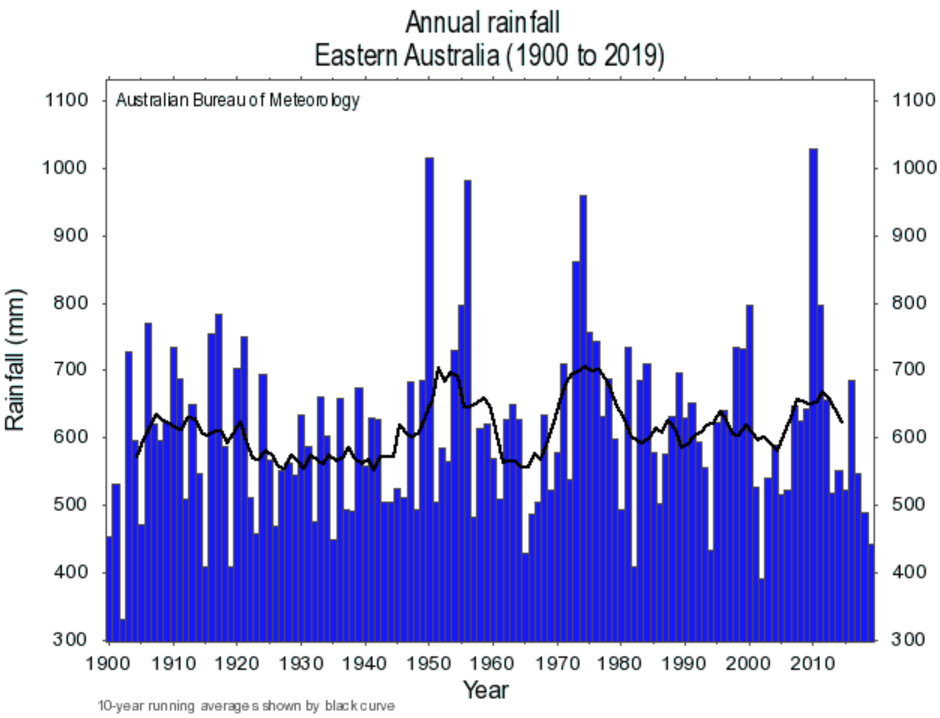

Figure 3.4: Annual rainfall timeseries for Eastern Australia, with the 10-year running mean shown in black (www.bom.gov.au/climate)

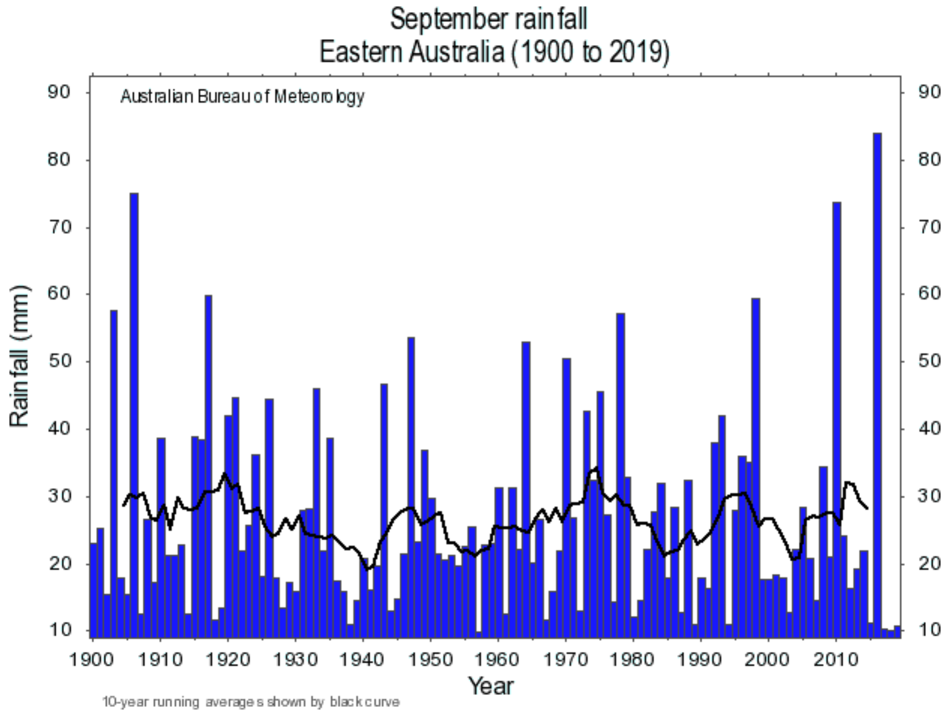

Figure 3.5: September rainfall timeseries for Eastern Australia with the 10-year running mean shown in black (www.bom.gov.au/climate)

3.3 Modelling future climate change

Using basic first principles alone we can already make some important and consequential inferences about the Earth's future climate. If greenhouse gas concentrations continue to rise, fundamental laws of interaction of radiation in the atmosphere dictate that the surface of the planet will become warmer on average. The increases in heat may have severe consequences for the natural environment, which can be sensitive not just to the amount of heat, but also the rate of warming (IPCC 2018). However, detailed aspects of future regional climate change are difficult to predict from theory and observations alone. For example, the strength of climate 'feedbacks', such as changes in atmospheric water vapour and temperature structure, which can either exacerbate or dampen the influence of greenhouse gas changes on our climate. Most relevant here, the regional changes experienced in any location are sensitive to the changes in the wind and rainfall patterns, sometimes referred to as atmospheric circulation. These circulation changes with global warming are difficult to predict from theory, especially at regional scales, since they involve the complex interaction of the atmosphere, ocean, and land, and sometimes the chemical, biological and physical processes within each of those spheres.

3.3.1 Global climate models

State-of-the-art climate models, sometimes referred to as general circulation models or global climate models (GCMs), are computer simulations of the fundamental processes occurring in the Earth's climate system. They aim to realistically simulate the complex interactions in the climate so we can better understand how the climate may change with increases in greenhouse gases.

From extremely extensive testing of models over the past 20 years, the Intergovernmental Panel on Climate Change (IPCC) concluded that there is "substantial confidence that climate models provide credible quantitative estimates of future climate change, particularly at larger scales. This confidence comes from the foundation of the models in accepted physical principles and from their ability to reproduce observed features of current climate and past climate changes. Confidence in model estimates is higher for some climate variables (e.g., temperature) than for others (e.g., precipitation)." (Randall et al. 2007, p. 601)

GCMs are very useful for understanding global and even regional scale changes; however, their spatial resolution, typically in the order of 50–200 km, is too coarse to adequately represent many finer scale features and microclimatic zones, such as those found on steep terrain, or in coastal zones. With many of the Gondwana Rainforests reserves located on complex topography, and near the eastern coast of Australia, projections at a finer spatial scale may offer additional information to that available from GCMs.

3.3.2 Regional climate models

Regional climate models can be used to 'downscale' climate change information from relatively coarse global models to a finer spatial scale. These models are run over a relatively small (by global modelling standards) region, such as over the eastern half of Australia, to estimate the influence of a global climate simulation over a particular region. They are run at much finer scales than GCMs to seek to better account for local processes and influences such as topography. Regional modelling is very computationally expensive to run, as the grid being used is so much finer than for the global models so there is much more data to process. Therefore, pragmatically only a subset of global models, greenhouse gas emissions scenarios and time periods can be downscaled at any one time.

It is important to note that using a finer resolution alone will not necessarily produce a better representation of the current climate or of future climate change. This is because the climate simulated as a result of downscaling is the result of a complex interaction between the processes represented both in the 'host' GCM and the regional climate model. Although we might expect better representation in the downscaling of local processes such as sea breezes and the effects of complex topography, biases can be retained in the downscaling from the GCM or introduced by the regional climate model. Therefore, as with GCMs themselves, simulations from regional models need to be assessed against observational data at fine resolution, our physical understanding of the processes and changes involved, and the consistency with other lines of evidence, such as other regional models and the host GCMs.

3.3.3 Downscaled data for the study area

As the Gondwana Rainforests reserves are in Queensland and New South Wales, there are two relevant downscaled data products: Queensland Future Climate (QFC) and the NSW and ACT Regional Climate Modelling project (NARCliM). These products, considered together with results from the host GCMs and our physical understanding, represent the best information currently available for investigating the possible future moisture and temperature stress due to climate change in the Gondwana Rainforests reserves.

The Queensland Government's QFC project (Syktus et al. 2020) provides dynamically downscaled projections from 11 models from the Coupled Model Intercomparison Project 5 (CMIP5; Taylor et al. 2012) for two future scenarios. The model used to downscale the projections is the CSIRO Conformal Cubic Atmospheric Model (CCAM) (Thatcher et al. 2015), run at 10 km resolution over Queensland, as well as the northern parts of NSW. The experiments consist of continuous runs spanning the period 1980 to 2099. The scenarios chosen for future climate change are a medium emissions scenario (RCP4.5) and a high emissions scenario (RCP8.5). Further description of these scenarios can be found in the CMIP5 documentation (https://pcmdi.llnl.gov/about.html).

The NARCliM project (Evans et al. 2014) is a joint effort from the NSW and ACT governments along with the Climate Change Research Centre at the University of New South Wales. Using the US Weather Research and Forecasting (WRF) regional model, they dynamically downscale projections from four CMIP3 models, running each experiment with three different configurations of the regional model, at a resolution of 10 km. This produced an ensemble of 12 experiments. Each experiment was run for three time slices, spanning the recent historical period as well as a future high emissions scenario (A2). The four models chosen for downscaling were selected to represent the spread of the full set of CMIP3 model projections.

It is important to note that the NARCliM project used an earlier generation of climate model projections (CMIP3) than those used in the QFC experiments (CMIP5). As such, the future scenarios differ. Nevertheless, the A2 scenario used in NARCliM is approximately comparable with the RCP8.5 CMIP5 scenario used in the QFC experiments. Further information can be found in the CMIP3 documentation as well as the NARCliM documentation (Evans et al. 2012).

Both NARCliM and QFC were evaluated for their ability to replicate the features of the climate in the vicinity of the Gondwana Rainforest reserves, which they were found to do adequately for this assessment. Full details of the model evaluation are included in Appendix 1 of this report.

3.4 Projected changes for the Gondwana Rainforests of Australia

Global climate models project an increase in temperature (with extremely high confidence) and generally project a decrease in humidity and cool season rainfall (with medium confidence) over the east coast of Australia (Dowdy et al. 2015). Similarly, most CMIP5 GCMs project an increase in the base height of clouds in a warmer future using the estimated LCL as a proxy (see Appendix 5).

This assessment considered downscaled climate change projections from the NARCliM and QFC ensembles. For brevity we only present projected September change for three future periods centred on 2030 (2020–2039), 2050 (2040 to 2059) and 2070 (2060 to 2079). The changes are calculated by subtracting the corresponding monthly climatologies from the period 1990–2009. The periods analysed here were chosen to maximise the concurrent times between the NARCliM and QFC ensembles. QFC ensembles use the RCP4.5 (medium) and RCP8.5 (high) emissions scenarios, while NARCliM uses the A2 scenario, which is comparable with RCP8.5. Note that the 2050 projections are only available for the QFC ensembles.

While the following results appear to show the three model runs with equal weight, it is important to note that the NARCliM ensemble downscales only four GCM simulations, while the QFC ensemble uses 11 global simulations. These differences need to be taken into account when considering which ensemble may better capture the range of future changes.

3.4.1 Projected changes by 2030

3.4.1.1 Temperature, relative humidity and rainfall

By 2030, all models in both ensembles, for all scenarios, predict an increase in temperature along the east coast of Australia. The projected mean September temperature increases over the Gondwana Rainforests region (149.6°E to 153.8°E, 32.3°S to 27.5°S) for each of the ensembles respectively is 1°C ± 0.3°C (QFC RCP4.5), 1°C ± 0.3°C (QFC RCP8.5), and 0.9°C ± 0.3°C (NARCliM A2).

Most models in both ensembles project a slight decrease or little change in relative humidity in the region by 2030.

Models in each ensemble for each scenario generally do not agree on the direction or magnitude of change in rainfall along the east coast of Australia by 2030. These results are expected and are consistent with GCMs values: rainfall changes over such a short interval into the future are expected to be small compared to natural variability and, as noted above, this region has very strong variability in September.

See Appendix 2 for the maps for these projections.

3.4.1.2 Lifting condensation level

The estimated cloud base height (LCL) generally increases slightly along the east coast of Australia by 2030 in the NARCliM experiments, while the QFC experiments show little change over most of the east coast of Australia in most models and scenarios by 2030 (Figures 3.6–3.8).

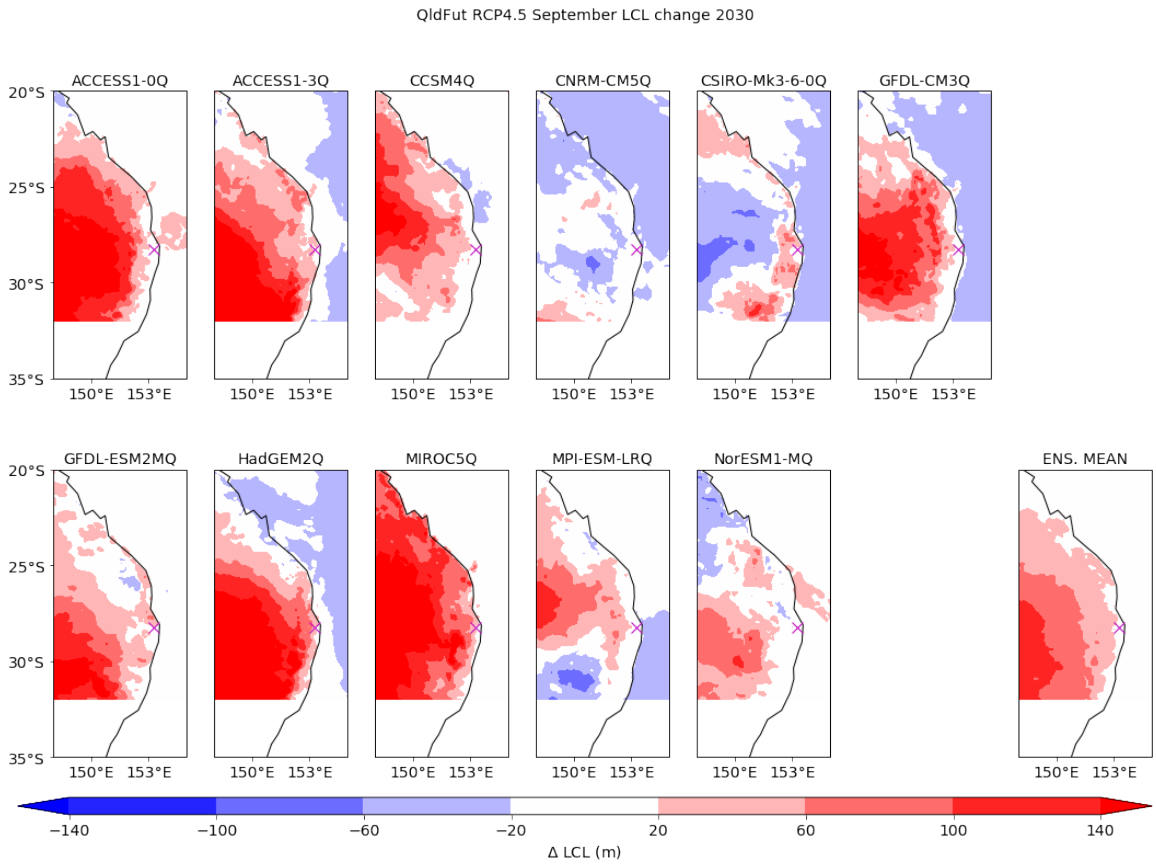

Figure 3.6: September lifting condensation level (LCL) change by 2030 for the QFC RCP4.5 (medium emissions) experiments. Changes are calculated by comparing the 2020–2039 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

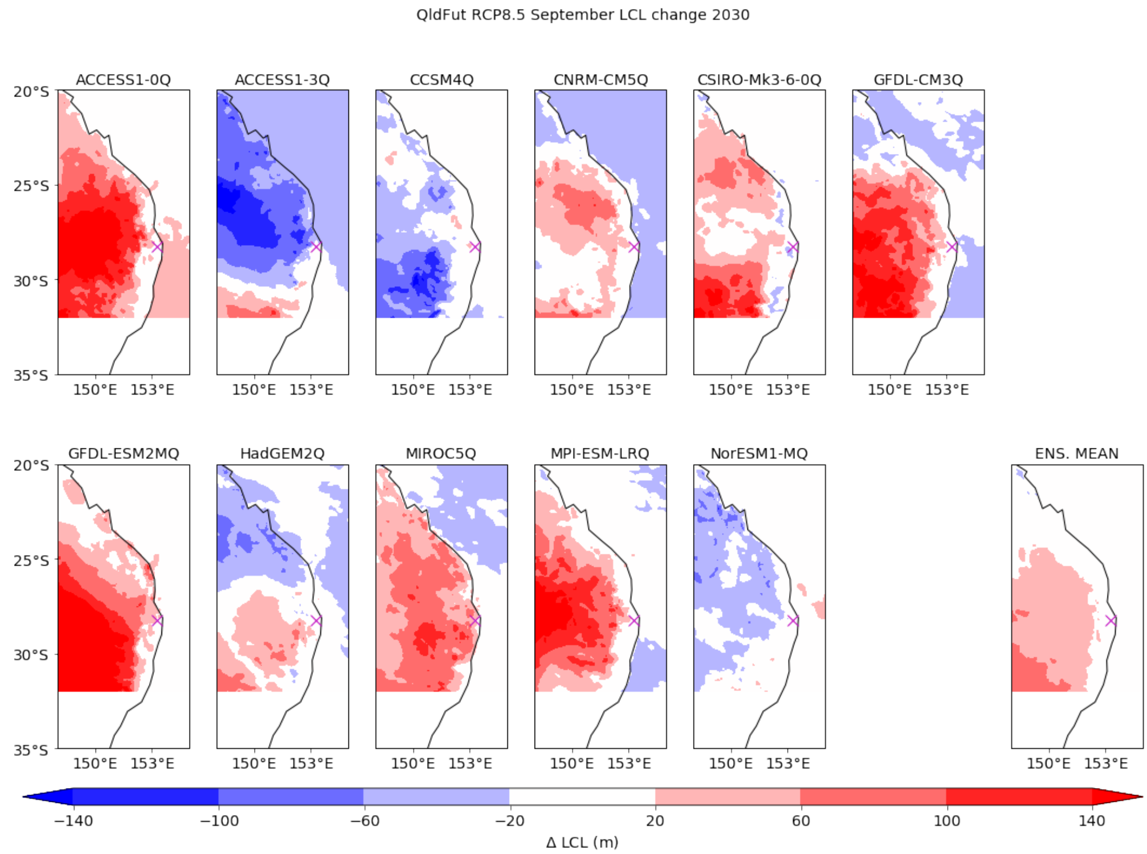

Figure 3.7: September lifting condensation level (LCL) change by 2030 for the QFC RCP8.5 (high emissions) experiments. Changes are calculated by comparing the 2020–2039 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

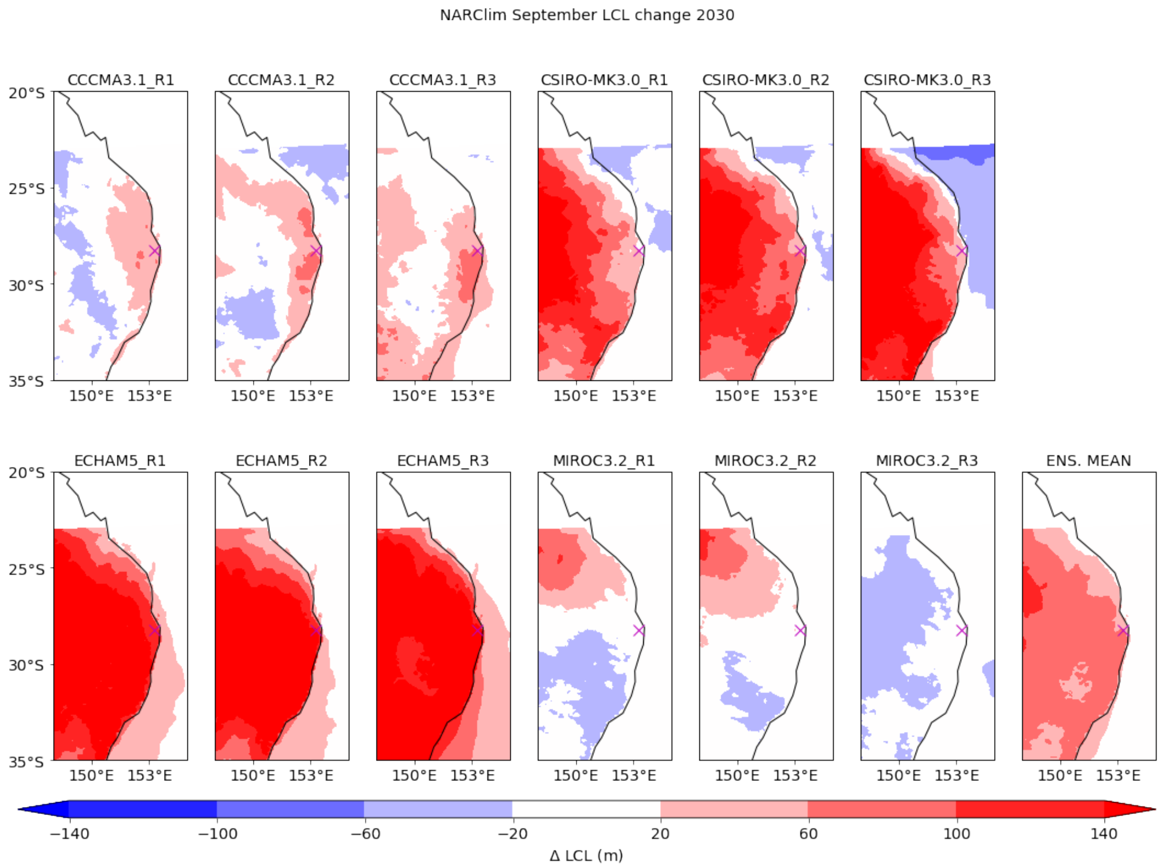

Figure 3.8: September lifting condensation level (LCL) change by 2030 for the NARCliM A2 (high emissions) experiments. Changes are calculated by comparing the 2020–2039 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

3.4.2 Projected changes by 2050

3.4.2.1 Temperature, relative humidity and rainfall

The NARCliM ensemble did not include timeslice experiments for this period, so only QFC projections are presented here.

By 2050, all models in the QFC ensemble, for all scenarios, predict an increase in temperature along the east coast of Australia. The projected mean September temperature increases over the Gondwana Rainforests region (149.6°E to 153.8°E, 32.3°S to 27.5°S) for each of the ensembles respectively is 1.5°C ± 0.5°C (RCP4.5), and 2°C ± 0.6°C (RCP8.5).

Most models project a slight decrease or little change in relative humidity in the region by 2050.

Models in each ensemble for each scenario generally do not agree on the direction or magnitude of change in rainfall along the east coast of Australia by 2050. These results are expected and are consistent with GCMs values: rainfall changes are strongly related to circulation changes, which climate models generally do not agree on.

See Appendix 3 for the maps for these projections.

3.4.2.2 Lifting condensation level

The estimated cloud base height (LCL) increases over most of the east coast of Australia in most models for both the RCP4.5 and RCP8.5 scenarios by 2050 (Figures 3.9 and 3.10).

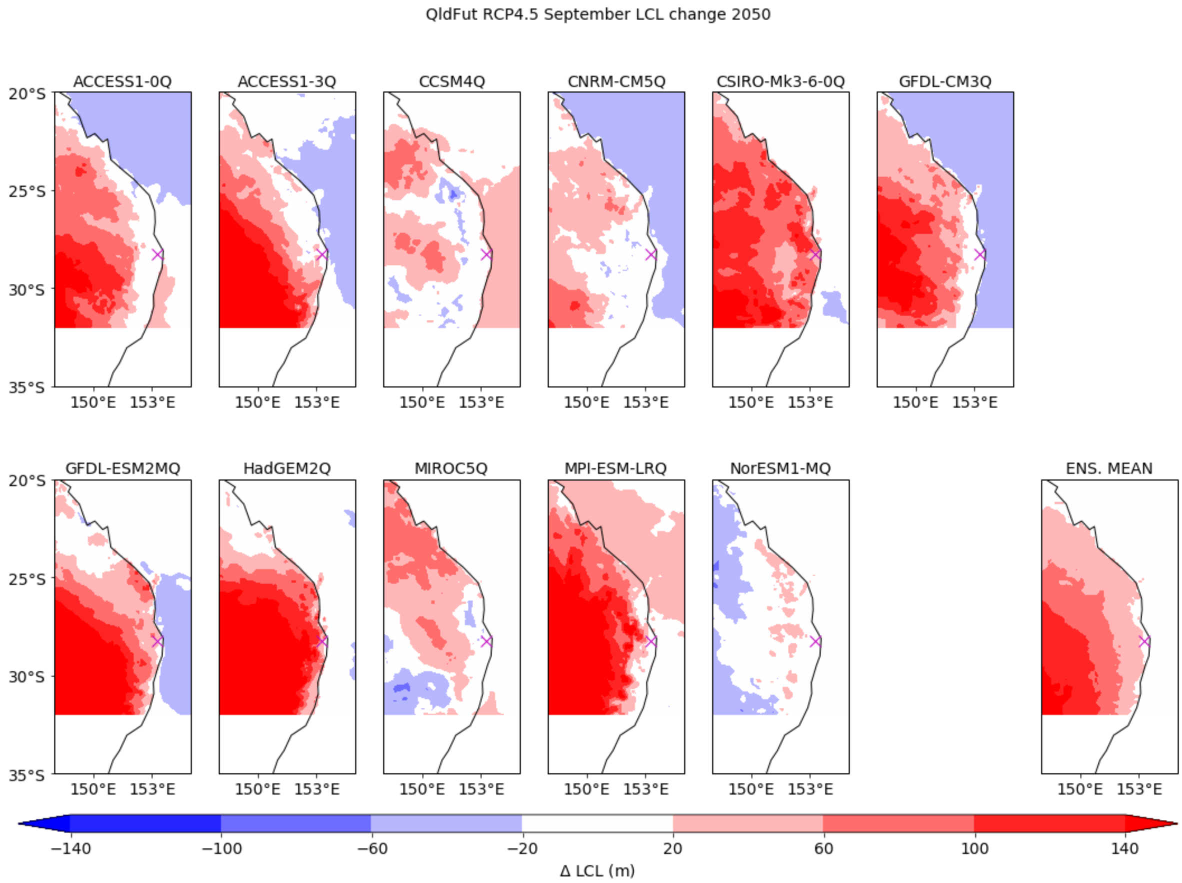

Figure 3.9: September lifting condensation level (LCL) change by 2050 for the QFC RCP4.5 (medium emissions) experiments. Changes are calculated by comparing the 2040–2059 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

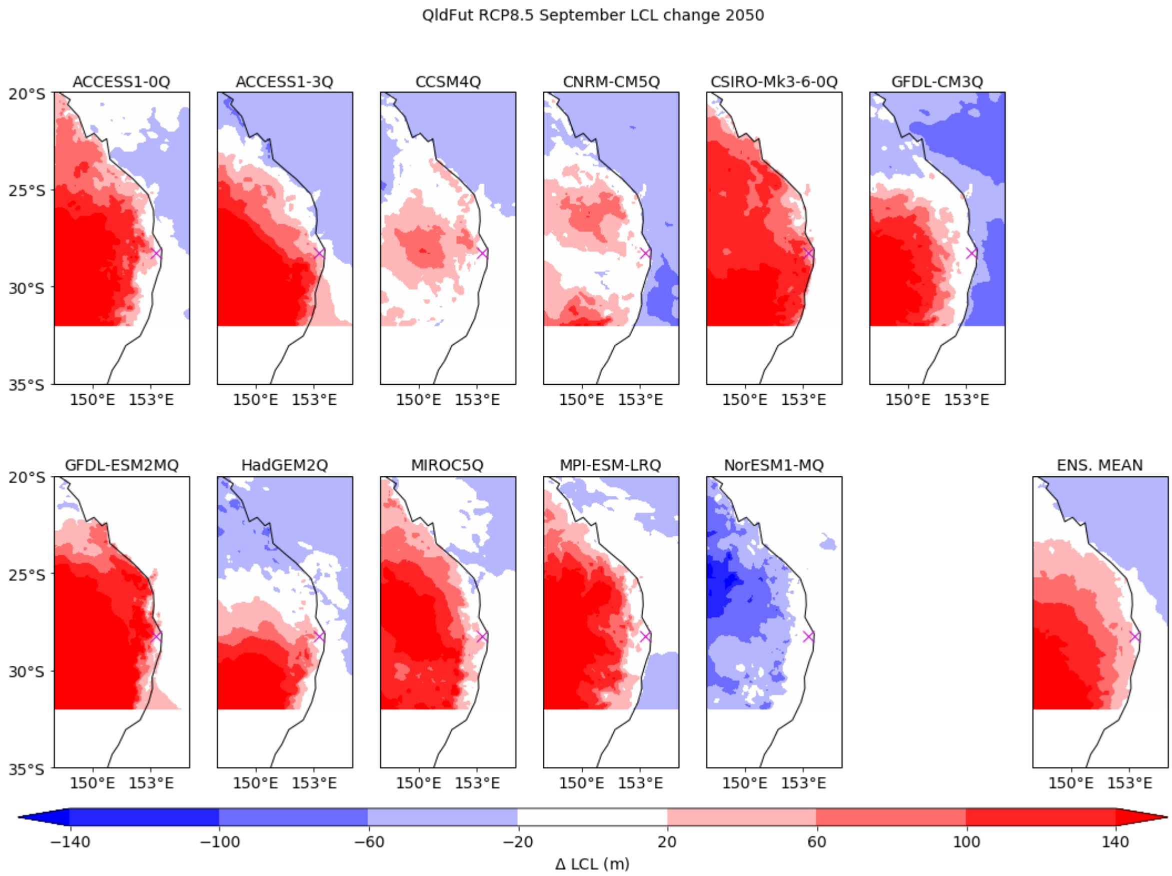

Figure 3.10: September lifting condensation level (LCL) change by 2050 for the QFC RCP8.5 (high emissions) experiments. Changes are calculated by comparing the 2040–2059 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

3.4.3 Projected changes by 2070

3.4.3.1 Temperature, relative humidity and rainfall

By 2070, all models in both ensembles, for all scenarios, predict an increase in temperature along the east coast of Australia. The projected mean September temperature increases over the Gondwana Rainforests region (149.6°E to 153.8°E, 32.3°S to 27.5°S) for each of the ensembles respectively is 2°C ± 0.5°C (QFC RCP4.5), 3.1°C ± 0.9°C (QFC RCP8.5), and 2°C ± 0.3°C (NARCliM A2).

Near surface relative humidity changes are important because they affect evapotranspiration and they are critical for LCL changes, which are derived from surface specific humidity (along with temperature). The two ensembles disagree on September relative humidity changes by 2070. The QFC ensemble models generally project a decrease or little change in relative humidity over the east coast in both the RCP4.5 and RCP8.5 scenarios. The NARCliM ensemble models on the other hand show large spatial as well as inter-model variation in relative humidity changes, with the majority of models actually projecting an increase in relative humidity in the coastal regions by 2070.

As with the relative humidity changes, the rainfall changes by 2070 projected by the two ensembles are nuanced. The QFC RCP4.5 experiments project a range of rainfall changes, from a slight decrease to a slight increase along the east coast of Australia. The QFC RCP8.5 experiments project a decrease or little change in rainfall along the east coast by 2070. The NARCliM experiments project a mix of changes, from decreases in rainfall to strong increases in rainfall in the same region.

See Appendix 4 for the maps for these projections.

3.4.3.2 Lifting condensation level

The two ensembles project a range in cloud base height changes (based on the estimated LCL). For both QFC experiments cloud base heights increase or show little change over most of the east coast of Australia by 2070 (Figures 3.11 and 3.12). No experiments suggest decreases. The NARCliM experiments disagree on the changes to cloud base height by 2070, with changes ranging from decreases in cloud base height to slight increases in cloud base height along the east coast of Australia (Figure 3.13).

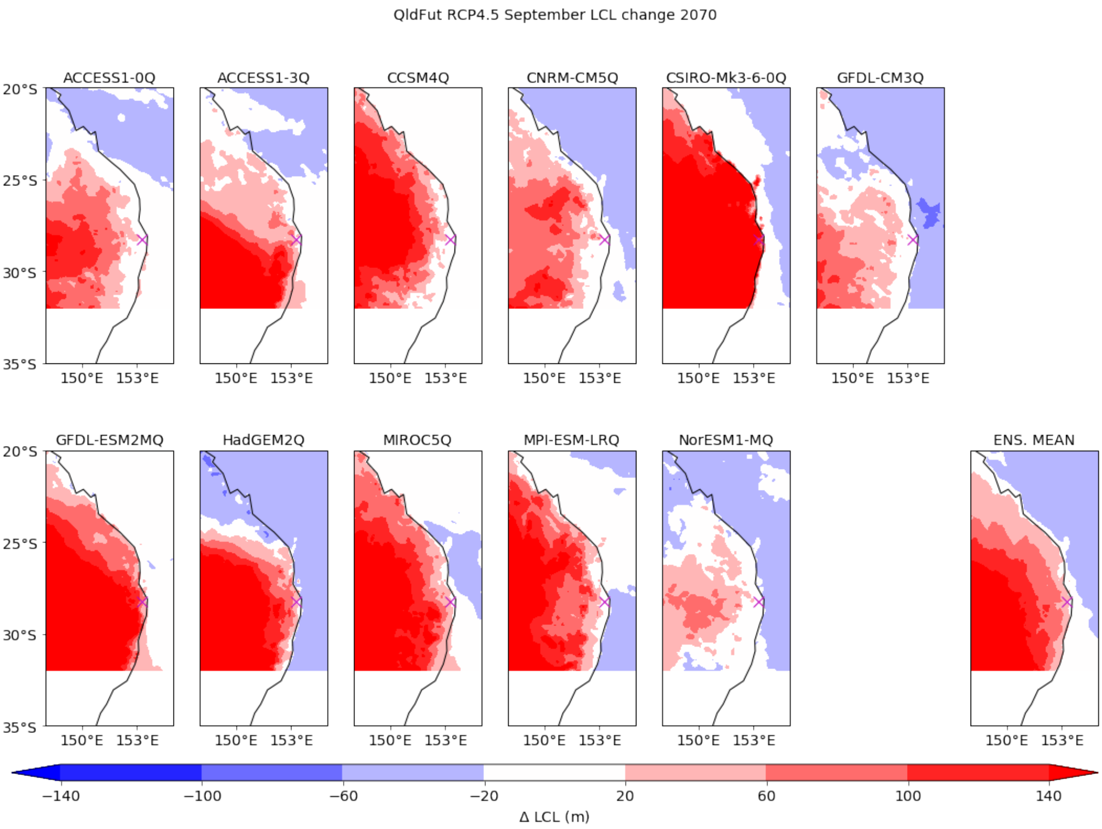

Figure 3.11: September lifting condensation level (LCL) change by 2070 for the QFC RCP4.5 (medium emissions) experiments. Changes are calculated by comparing the 2060–2079 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

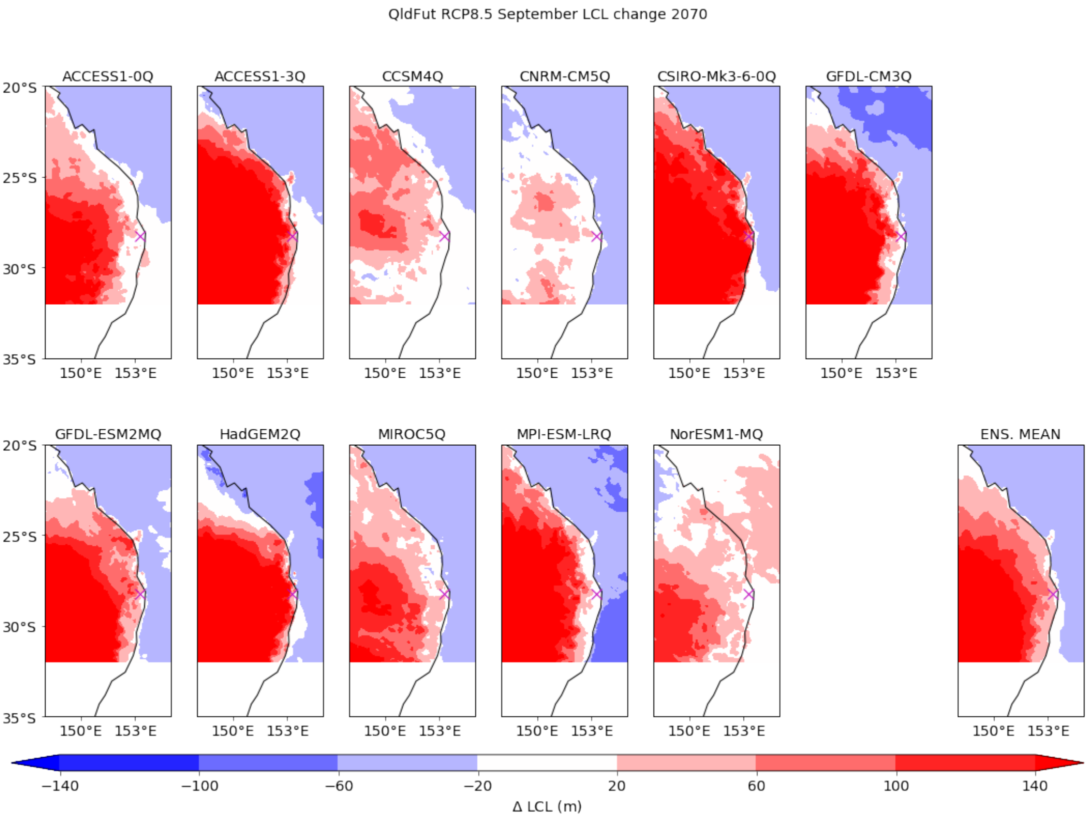

Figure 3.12: September lifting condensation level (LCL) change by 2070 for the QFC RCP8.5 (high emissions) experiments. Changes are calculated by comparing the 2060–2079 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

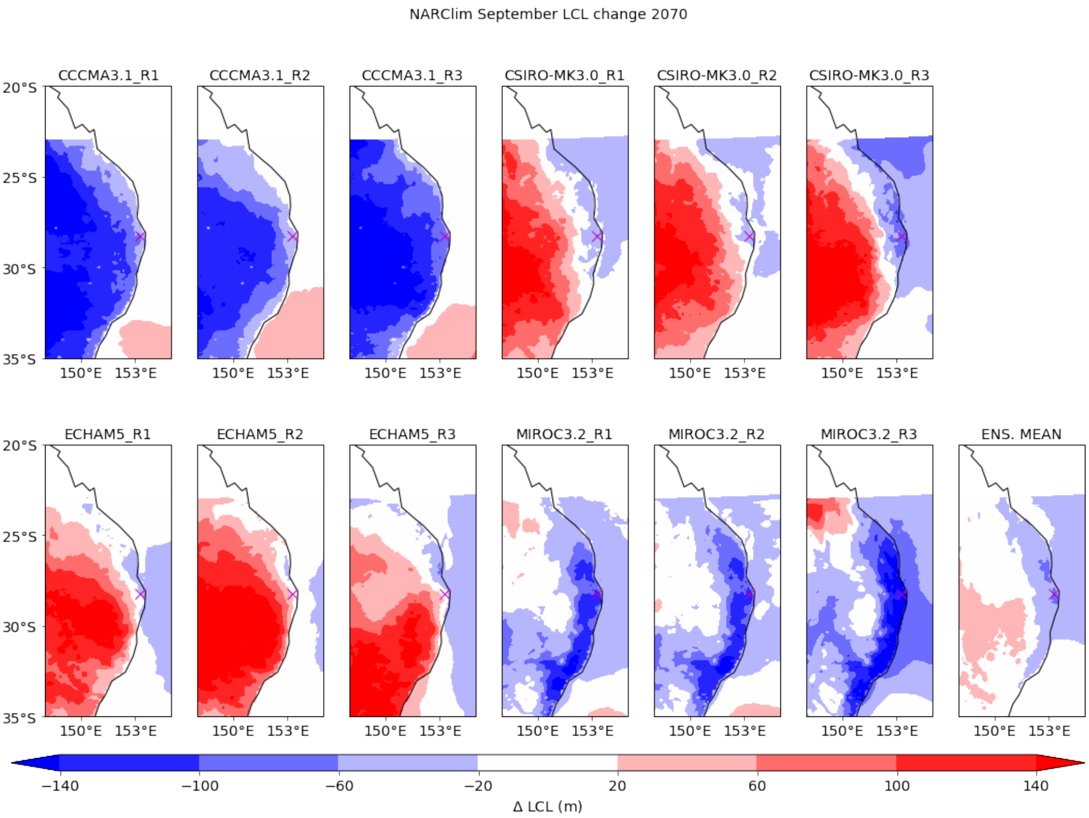

Figure 3.13: September lifting condensation level (LCL) change by 2070 for the NARCliM A2 (high emissions) experiments. Changes are calculated by comparing the 2060–2079 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

3.4.4 Discussion

While it is not feasible to present all projections for all months and all locations in this report, we present the spread in ensemble projections for the nearest model pixel for one location of interest, the Tweed Caldera (-28.25°S, 153.25°E), marked with a cross in all map plots in this report. There is a wide range in projected changes for this location, which is situated near the east coast (Figure 3.14).

The QFC RCP4.5 experiments generally project an increase in cloud base heights for all future periods. For the QFC RCP8.5 experiments the cloud base height changes are mixed, with the median of the models increasing by 2050, although projected changes by 2070 range from slight decreases to slight increases. The NARCliM experiments predict a rise in cloud base heights by 2030, but generally predict a decline in cloud base heights at this location by 2070.

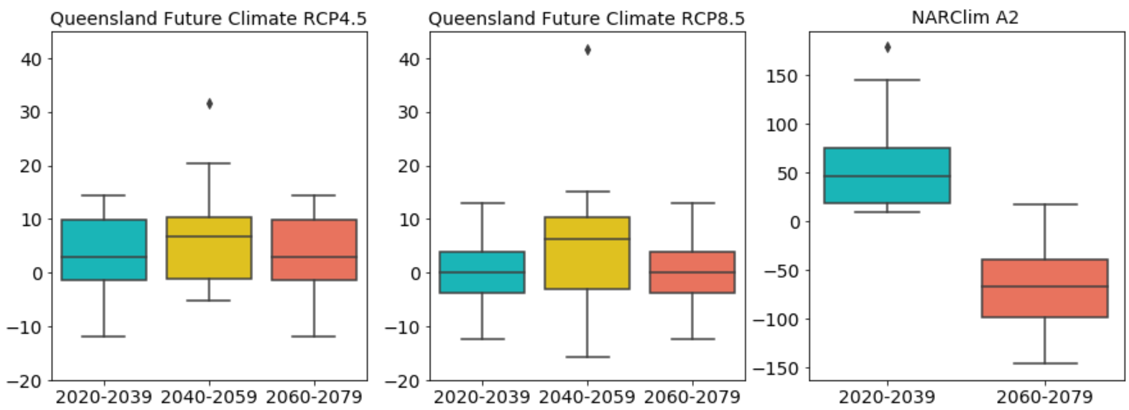

Figure 3.14: September lifting condensation level (LCL) changes for each of the ensembles and future scenarios investigated in the present study, for the Tweed Caldera location (-28.25°S, 153.25°E), marked with a cross in all previous map plots. The y-axis is change in cloud base height in metres. The boxes represent the model interquartile range, while the line through the middle is the median change of the models. The whiskers show the rest of the distribution except for the outliers, which are marked as diamonds. Changes are calculated by comparing the average LCL for the future periods against the 1990–2009 average conditions, for each model. Note that the NARCliM experiments did not include a 2040–2059 time slice, and the y-axis is different for the NARCliM panel (right).

In considering the differences between the NARCliM results and the QFC results, , it is worth noting that the NARCliM experiments are based on just four global climate model experiments, while the QFC experiments are based on 11 global model experiments. Additionally, the QFC projected LCL changes are qualitatively similar to those obtained from the full suite of CMIP5 models (see Appendix 4) for the broad Eastern Australian region and for the region of the Tweed Caldera. While some CMIP5 models do predict decreases in LCL in the future, the majority, in fact, predict increases by late 21st century in all seasons. It is unclear why the NARCLiM results present a reduction in LCL in the later scenario.

Note that the NARCliM results suggest that the driving GCM is the key uncertainty in determining the direction of future changes in LCL (at least within the range represented by the WRF downscaling model). Different variants of the downscaling model show only very modest impact on the pattern or direction of the changes. This means that having only four GCMs downscaled is a significant limitation, as there are only four 'realisations' of the future from the ensemble, not the 12 possible futures represented by the number of GCMs times the number of downscaling models.

An additional factor is that the NARCliM models are from an earlier generation than from QFC (CMIP3 versus CMIP5). Although these are essentially similar ensembles, on large scales the later generation does display slightly higher skill than the earlier in the overall representation of surface pressure, temperature and rainfall (IPCC 2013).

A final point (see Section 4.3) is that although NARCliM biases in the representation of current cloud base height are smaller than those of QFC compared to the 2019 Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia (BARRA) (see Appendix 1), the QFC results for cloud base is closer to that typically observed in the region by managers and researchers. In particular NARCliM mean values for cloud base currently extend beyond the height of the ranges in the study region, whereas clouds are commonly observed on the mountains. Reanalysis values may not be reliable for LCL, given limitations in the observational network particularly of humidity in the region, and may be affected by limitations in the host GCM.

For these reasons we suggest that the NARCliM ensemble probably does not adequately sample the future projections from global models. Therefore, it is our assessment that increases in LCL for the Gondwana Rainforests are likely in a warmer future climate.

3.5 Challenges, caveats and future work

The projections presented here are a first step towards applying information from state-of-the-art climate change experiments for understanding the future climate of the Gondwana Rainforests reserves. It is a significant improvement upon having no information or using general information available on projected changes to the region, such as GCM results for a large region of Australia's east coast. Some caveats apply to the results presented here and should be taken into consideration when making plans for future studies and for informing decision making processes.

In the present report we have focused on presenting changes for the month of September, which is typically the driest month of the year. We do so as this is the month where moisture stress is largest in the current climate, and so the future change in the height of clouds and other variables may have a large impact. However, other months may have significantly different changes to those presented here. To further investigate the changes for other times of the year, the dataset produced in the present study will be publicly available for non-commercial use (Narsey 2020).

While care has been taken to evaluate the models used here, further investigation and more detailed analysis would be required to understand how realistic the projected changes are, and how much confidence we can place in them. From this limited sample, we conclude that both ensembles represent plausible futures; however, more weighting should be placed on the QFC ensemble, given the limited sampling of GCMs in NARCliM. A broader ensemble of both GCMs and downscaling models would be required to make more definitive statements.

The downscaled projections presented here are based on global climate model simulations, but the resources required to downscale all available GCM experiments are prohibitive. As a result, neither the NARCliM nor QFC ensembles encompass the full suite of global model simulations available. The choice of global model experiments to downscale will therefore have an influence on the spread in downscaled projections. We make no comment here on those selections, however more information can be found in the documentation for each ensemble.

Indeed, the projected changes presented here do differ, at least for the QFC ensemble when compared to global model ensemble projections, especially for the cloud base heights. In the CMIP5 ensemble the cloud base heights generally rise with future warming, while the downscaled projection changes to cloud base height are mixed for the east coast of Australia. This may be due to model selection, or indeed it may be due to physical processes that are better resolved, or differently resolved, in the downscaling experiments (e.g. coastal sea breeze circulations, local processes associated with topography, and land-atmosphere interactions such as evapotranspiration). Further investigation would be required to understand these differences. Physical understanding of future LCL changes would suggest that LCL heights would be expected to rise over continental regions generally, as relative humidity decreases are a robust prediction under global warming. The reason for this is that land temperatures are expected to increase faster than ocean temperatures, and the source of moisture is predominantly from seas surrounding continental areas. Local topographic effects may be significant meaning that near coastal regions such as examined here are more uncertain.

A future downscaled ensemble should also be based on the latest generation of global climate models, CMIP6 (Eyring et al. 2016), with simulations completed during 2019-20. This would allow sampling of global models which are generally not only at higher resolution to the previous generations, but also include representations of the most recent advances in understanding of physical processes.

Nevertheless, the downscaled projections presented here represent our current best estimate, at the highest available spatial resolution, for how the physical climate of the Gondwana Rainforests reserves may change in a warmer world.

4. Detecting biodiversity changes along climatic gradients

The response of subtropical and temperate rainforests to climate change has been monitored on the northern flanks of the Tweed Caldera (Figure 4.1) within Lamington National Park since 2006 (Kitching et al. 2011). In an international collaboration known as the IBISCA Queensland Project, a transect of 20 survey plots was established between 300 m and 1100 m elevation, allowing biodiversity responses to steep climatic gradients to be studied, incorporating at least a 21% change in rainfall and a 7°C temperature range (Strong et al. 2011).

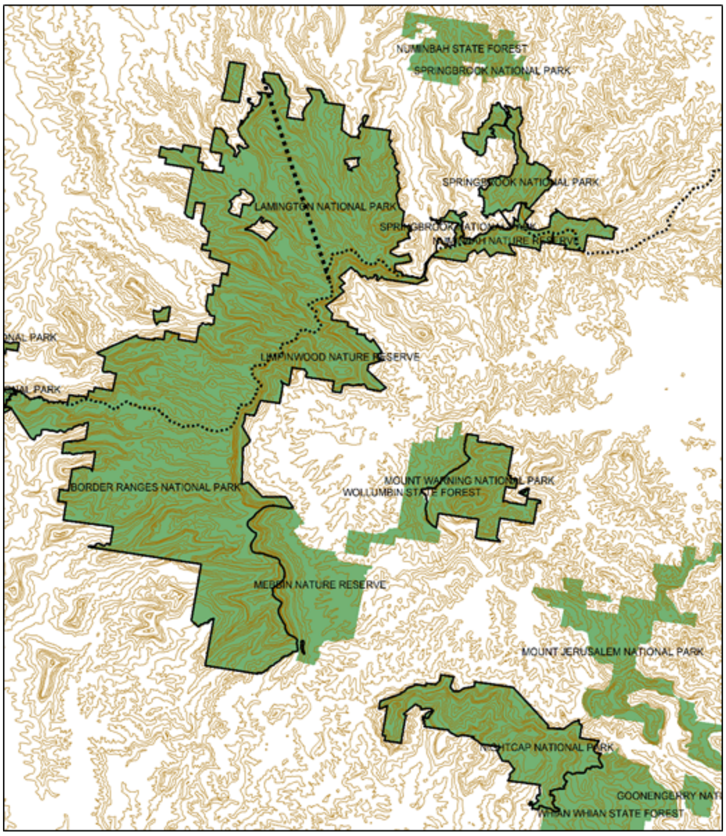

Figure 4.1: The IBISCA transect is located on the northern flanks of the Tweed Caldera within Lamington National Park

A study of tree community floristics and structure along the transect identified a transition zone in tree recruitment patterns between 700 m and 900 m elevation (Laidlaw et al. 2011). At high elevations of 900 m and above, the recruiting tree community closely resembled the species composition of the canopy, while at 700 m and below, the recruiting plant community differed to that in the canopy, regardless of elevation (Figure 4.2). Because of the distinct breakpoint and mid-slope elevation of this change, the role of cloud was highlighted for further investigation (Laidlaw et al. 2011).

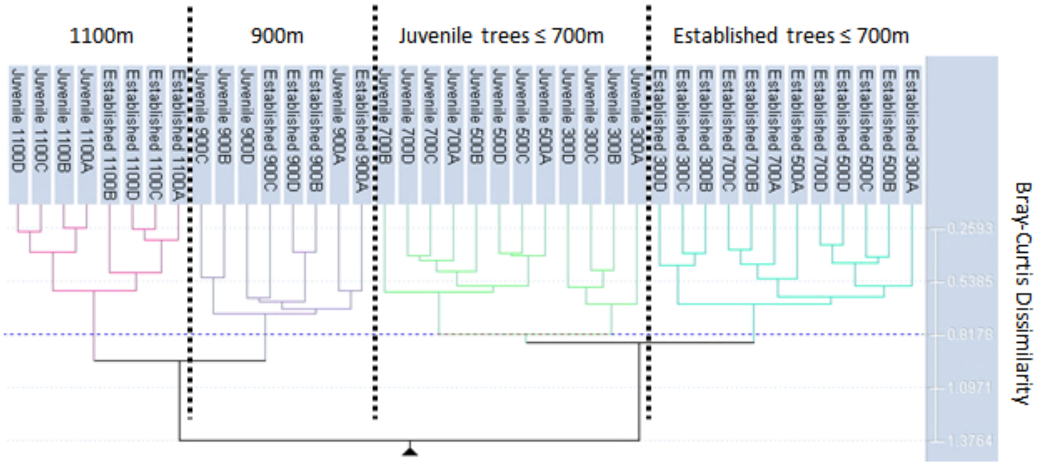

Figure 4.2: Dendrogram of established and recruiting tree community composition recorded from 20 plots at Lamington National Park, south-east Queensland, showing membership of sites to altitudinal groups (from Laidlaw et al. 2011).

Detailed data on cloud base height was not available for Lamington National Park, however various attempts were made to extrapolate from nearby airport records and from cloud water condensers deployed along the transect between 700 m and 1100 m (Figure 4.3). While these data sources can show that local cloud water inputs change with elevation, a new way to understand the influence of cloud water at a regional scale both now and into the future was required.

Figure 4.3: Cloud water condensers deployed along the IBISCA transect

Modelling of lifting condensation level (LCL) and other climate variables under multiple emission scenarios for historic and projected future climates has for the first time allowed key gaps in our knowledge to be addressed, including:

1. Can seasonal patterns in lifting condensation level be detected?
2. Can lifting condensation level help explain observed patterns in tree community recruitment?
3. Is lifting condensation level likely to change into the future?

4.1 Detecting seasonal patterns in lifting condensation level

Detecting seasonal patterns in LCL in relation to rainfall is vital to understanding the impact of moisture stress on rainforest community composition and change. Long-term rainfall records collected at 916 m elevation along the IBISCA research transect show that annual mean rainfall is strongly seasonal, with September being the driest month averaging at just 57 mm (Figure 4.4). The preceding two months are also generally dry, with an average of 86 mm and 63 mm falling in July and August, respectively. Only those species and individuals able to tolerate considerable periods of seasonal moisture stress are likely to persist at a site long-term. Tolerance to moisture stress is further tested during times of drought, including during El Niño events. While the long-term annual mean rainfall recorded at the Green Mountains weather station is 1590 mm (SE ± 62.2 mm) per year, in dry years, less than half of this amount may be received (e.g. 785.5 mm in 2019).

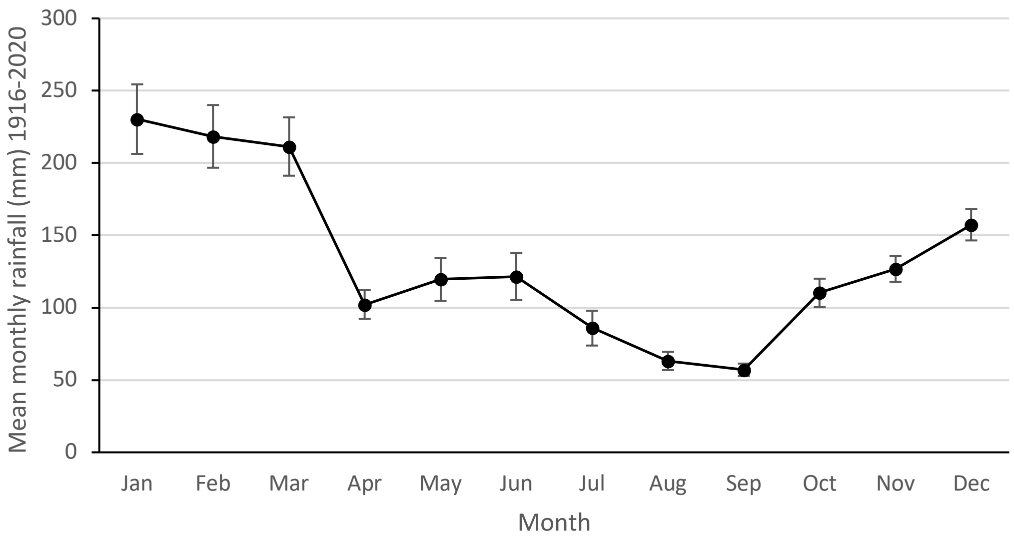

Figure 4.4: Mean monthly rainfall (mm) 1916–2020 Green Mountains (Station 40182), 916 m ASL Lamington National Park

Downscaled historic (1990–2009) QFC data for the IBISCA transect predicts seasonal LCL change between a mean low of 570 m ASL (above sea level) in June and a mean high of 653 m ASL in October, an average vertical change of 83 m (Figure 4.5). As previously discussed, variation between individual models in the QFC ensemble was considerable, with some models predicting relatively little seasonal change, while others varied considerably throughout the year.

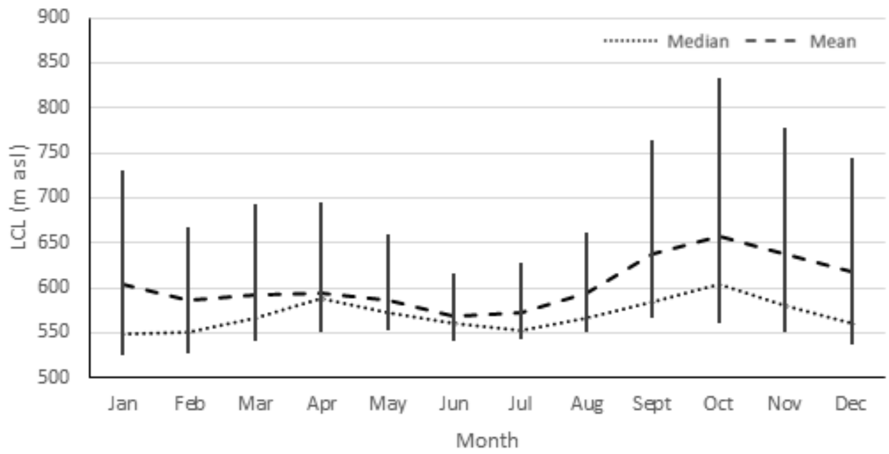

Figure 4.5: Downscaled historic (1990–2009) QFC data for the IBISCA transect. Mean (dashed line) and median (dotted line) LCL values derived from 11 CMIP5 models. Bars show the range.

Equivalent historic NARCliM data for the IBISCA transect suggests that LCL moves between a mean low of 863m ASL in March and a mean high of 1270m ASL in August, an average vertical change of 407 m (Figure 4.6). While there was greater agreement within the NARCliM ensemble regarding seasonality, minimum LCL values predicted for each month are consistently higher than those produced by QFC. NARCliM models predicting even the lowest monthly LCL values exceed field observations, as cloud is regularly sighted below 800 m.

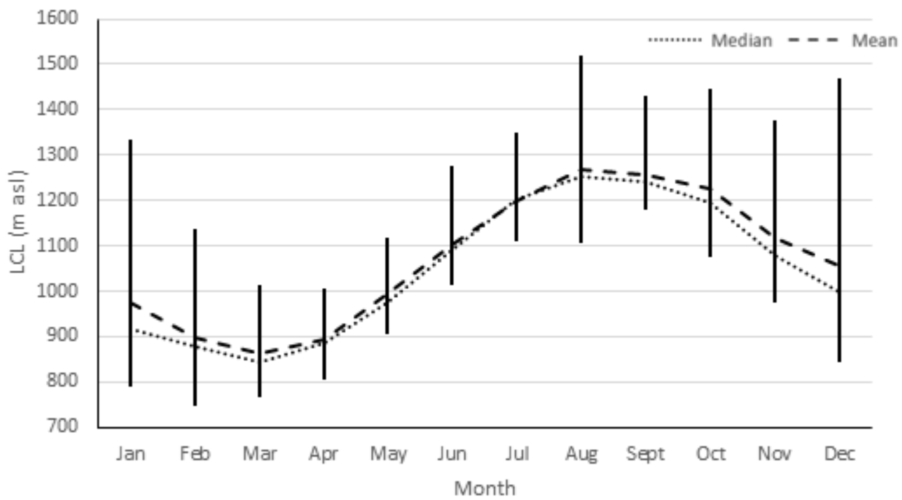

Figure 4.6: Downscaled historic (1990–2009) NARCliM data for the IBISCA transect. Mean (dashed line) and median (dotted line) LCL values derived from four CMIP3 models run using three configurations. Bars show the range.

While downscaled QFC and NARCliM data varied in terms of monthly LCL values, patterns can be detected in the degree of seasonal change and the months when the lowest and highest LCL values are likely. Data from both projects suggests that late winter and spring are times when LCL may be higher than at other times of the year. In seasons where low rainfall and high LCL coincide, the resulting moisture stress may exceed the tolerances of some tree species.

4.2 Explaining observed patterns in tree community recruitment

The mean historic NARCliM (A2) LCL along the IBISCA transect in September, the driest month, is 1257 m ASL (range 1184–1427 m) (Figure 4.6). This mean exceeds the height of the Caldera and is inconsistent with frequent anecdotal sightings of low cloud at 800–900 m (Figure 4.7; Hutley et al. 1997). This suggests that the NARCliM ensemble may be overestimating LCL along the IBISCA transect.

Historic QFC (RCP8.5) data for the IBISCA transect predicts a much lower mean September LCL of 631 m ASL (range 566–742 m) (Figure 4.5). This mid-slope mean may suggest that cloud water is available to supplement dry season rainfall at higher elevations along the transect.

While it appears that there is some preliminary evidence for the mid-slope dry season influence of LCL on tree community recruitment, further investigation of the differences between the QFC and NARCliM ensembles is being undertaken.

Figure 4.7. Low-level cloud is frequently observed on the Tweed Caldera (Photo: W McDonald)

4.3 Understanding future changes in lifting condensation level

In addition to understanding current seasonal variation in LCL and the impact on rainforest biodiversity, understanding future trends in LCL is vital for the future management of rainforest communities within the Gondwana Rainforests.

LCL projections for the IBISCA transect downscaled via the QFC project varied between models but increased to 2070 on average. Figures 4.8 (RCP4.5) and 4.9 (RCP8.5) show mean projected LCL values for September–October between 2030 and 2070 along the IBISCA transect.

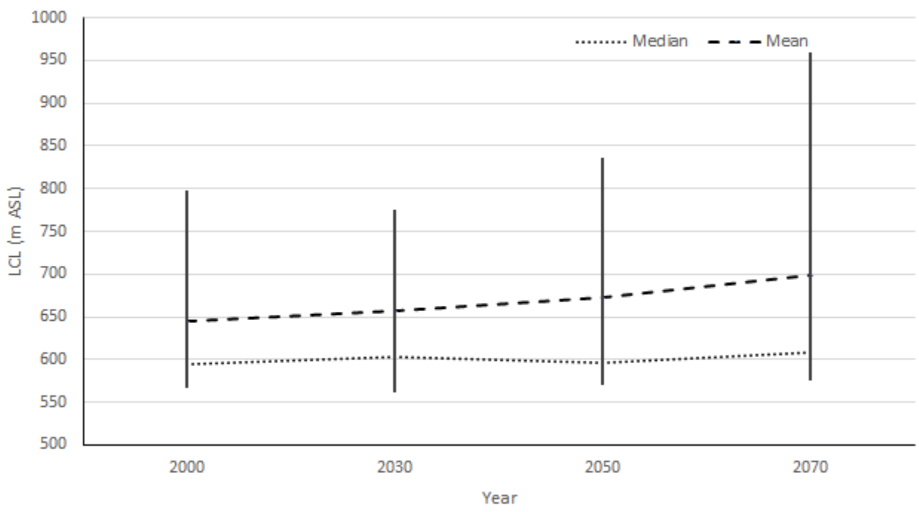

Figure 4.8: LCL projections from QFC data for the IBISCA transect under a medium emissions scenario (RCP4.5). Mean (dashed) and median (dotted) values derived from 11 CMIP5 models. Bars show the range.

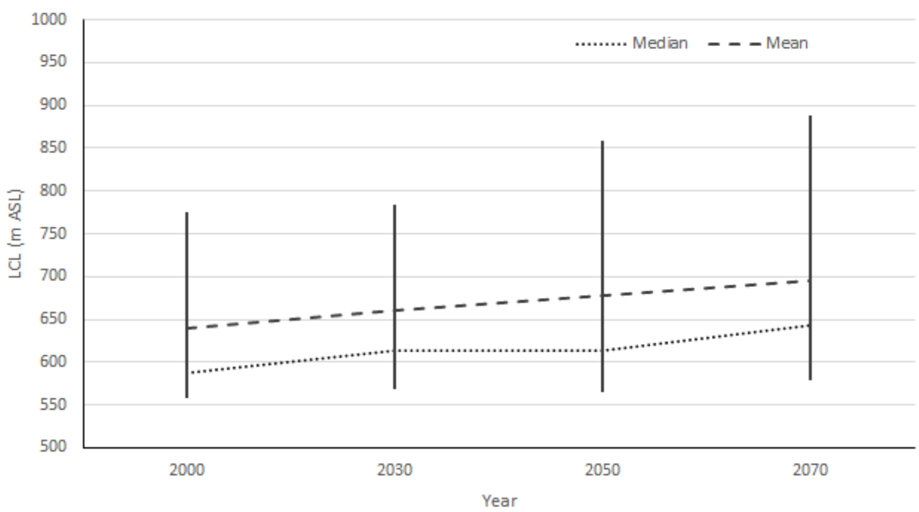

Figure 4.9: LCL projections from the QFC data for the IBISCA transect under a high emissions scenario (RCP8.5). Mean (dashed) and median (dotted) values derived from 11 CMIP5 models. Bars show the range.

NARCliM LCL projections for the IBISCA transect also varied. While mean September–October LCL is initially predicted to rise slightly to 2030, beyond 2030 NARCliM models predict a lower LCL (Figure 4.10). Given the discussion in the previous section, and in particular the smaller sample size of global climate models in NARCliM (four models) compared to QFC (11 models), while the projected decrease in LCL by 2070 found in the NARCliM high emissions scenario (A2) experiments is plausible, the increase in LCL by 2070 in the QFC high emissions scenario (RCP8.5) experiments is more likely.

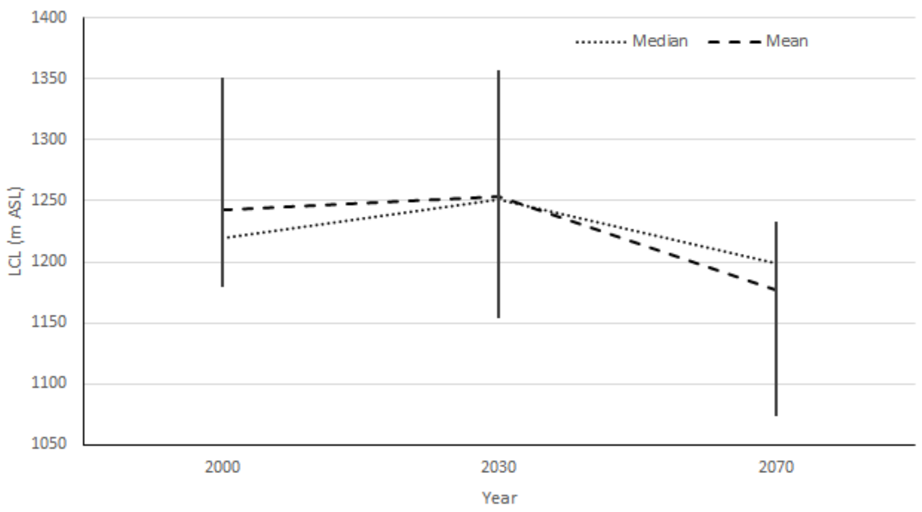

Figure 4.10: LCL projections from the NARCliM data for the IBISCA transect under a high emissions scenario (A2). Mean (dashed) and median (dotted) values derived from four CMIP3 models run using three configurations. Bars show the range.

QFC projections of increasing LCL along the IBISCA transect may have significant implications for cloud-water dependent species, especially those located at elevations adjacent to the current cloud base. Reduced cloud water inputs may increase dry-season moisture stress beyond the tolerance of some species, resulting in community change. Observed patterns in canopy species recruitment along the IBISCA transect (Figure 4.1) may already be an indicator of this change (Laidlaw et al. 2011).

5. Implications for climate change adaptation planning

5.1 Informing adaptation planning

5.1.1 Gondwana Rainforests of Australia World Heritage Area

Climate projections suggest that increased temperatures, variable rainfall and declines in relative humidity are likely to result in reduced moisture availability. While models vary, initial results from this study also suggest that cloud base height may rise over coming decades, further exacerbating drying trends.

While the elevated topography and moist microclimates of the Gondwana Rainforests have long provided a stable refuge for rainforest flora and fauna, locating and managing areas likely to provide ongoing refuge under future climates is important for their persistence. Downscaled projections developed during this study can assist with the identification of climatically stable areas or fire refuges.

Downscaled projections can also improve community and species level modelling for the World Heritage Area. Generalised dissimilarity modelling (GDM) (Ferrier et al. 2006; Laidlaw et al. 2016) is currently used to map vegetation changes in response to environmental gradients such as temperature and rainfall. GDM can also predict turnover in vegetation community composition in response to changes in climate.

Species distribution modelling can similarly be refined using downscaled projections. An improved knowledge of projected moisture availability will assist in identifying species and community resilience under future climates. By improving our ability to model likely habitat changes and key species thresholds, trigger points for interventions including monitoring, captive breeding and ex-situ conservation can also be planned.

Fire incursion

While rainforests can endure seasonal moisture stress and periodic drought, long-term drying trends may result in gradual changes to the distribution of plant and animal communities and the potential for species loss. A more acute risk, however, is the threat of fire incursion.

The humid microclimate maintained beneath rainforests generally provide some protection from fire incursion, however this defence is greatly compromised during times of drought, high temperatures and low humidity. The 2019/20 fire season saw unprecedented Forest Fire Danger Index values across much of the Gondwana Rainforests, including the study region (Figures 5.1 and 5.2; Dowdy et al. 2018) and between September 2019 and January 2020 fire impacted more than 50% of the land area of the property, including extensive areas of rainforest.

Wildfire incursion had previously been identified as a *future* risk to rainforests, however the 2019/20 fire season has demonstrated that the Gondwana Rainforests are *flammable under the current climate* and should now be managed as such.

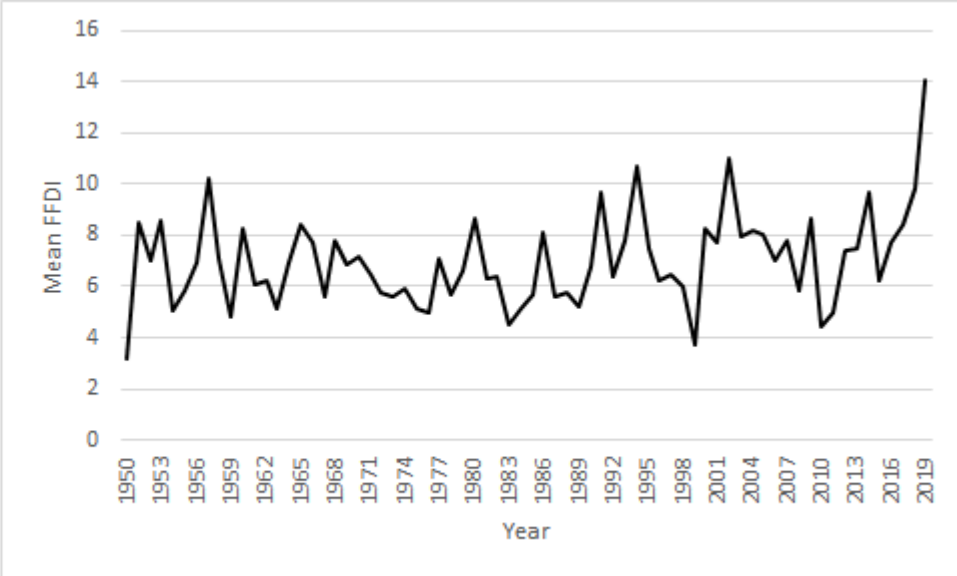

Figure 5.1: Time series of annual averaged Forest Fire Danger Index for south-east Queensland (28–29°S, 152–153.5°E). Data provided by A. Dowdy, Bureau of Meteorology, February 2020.

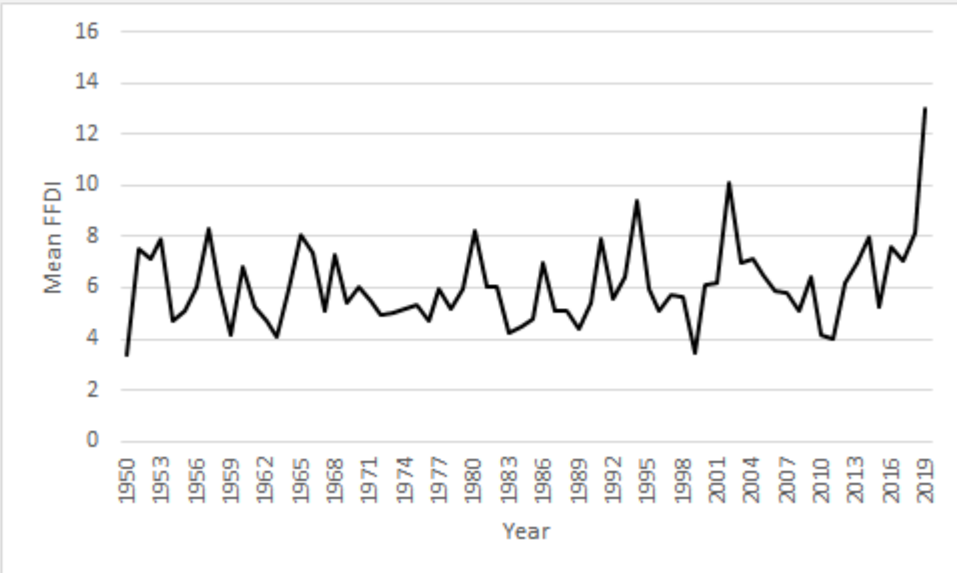

Figure 5.2: Time series of annual averaged Forest Fire Danger Index for north-east New South Wales (29–31.5°S, 151.8–153°E). Data provided by A. Dowdy, Bureau of Meteorology, February 2020.

5.1.2 Other World Heritage properties

The process used in this assessment (see Section 1.2) offers a framework for identifying climate change projections for key climate variables and incorporating these into risk assessments of climate change impacts on systems and areas of interest, including World Heritage properties.

Complex interactions of the climate with any area or subject matter of interest requires a range of expertise and perspectives that can only be achieved by including climate and subject specialist researchers, practitioners and managers. This process, with its emphasis on collaboration and co-design, provides a mechanism for including contributions from a range of World Heritage property stakeholders, ensuring the development of more useful information to inform management, risk assessment and adaptation responses on each property.

The process can be used to complete a rapid impact scan and/or to supply preliminary information about possible climate change impacts for a geographic location or a natural or built element of a World Heritage property. It can also feed into risk or vulnerability assessment frameworks, ensuring that climate change science underpins risk management decisions.

5.2 Limitations of this assessment

There are several important limitations and caveats on this work.

Downscaling results are presented for only two ensembles. Although those ensembles broadly agree on projected change in LCL in the coming decade, and physical understanding backs up this conclusion, there is significant disagreement between them later this century. The reasons for the differences in these projections is not understood, and such understanding would require much more detailed evaluation and assessment.

The downscaling ensembles are based on limited sampling of host GCMs, which limits confidence in the projections especially for the NARCliM ensemble.

These ensembles are based on previous generation GCMs (CMIP3 and CMIP5 for NARCliM and QFC respectively), so do not sample the latest generation of international models (CMIP6).

Although the GCMs and downscaled simulations show reasonable skill in representing broadscale features in the current climate (such as seasonality of temperatures and rainfall), remaining biases and errors in the downscaled models’ representation of the current climate can limit confidence in projected results. For example, the NARCliM ensemble shows cloud bases in the current climate sitting above the level of the mountains. Biases of this nature do not alone necessarily mean that the NARCliM ensemble is not useful in assessing future trends in LCL – *changes* over future decades may still be physically meaningful in the model – but should be considered in assessing overall confidence.

This assessment only considers mean values of meteorological variables, not changes in variability or extremes. These latter changes may be expected to have significant ecological impact. Other extremes such as drought, heatwaves and fire weather are also not considered here.

5.3 Recommendations for future work

Despite limitations in the number of available downscaling studies, the results presented here represent the best available information on changes in climate, including changes to cloud base heights over coming decades.

The following further work would allow a decrease in the uncertainties of the conclusions presented here and permit higher confidence statements about future climate change.

Better understanding of the reasons for the differences in projections of LCL between the two downscaling ensembles, and of associated variables such as rainfall and relative humidity. This could permit stronger confidence statements regarding projections from the two ensembles, based on understanding of the physical processes driving those changes.

Consideration of the latest generation of GCMs. Models in the CMIP6 ensemble are not only generally at higher resolution to previous generations, but also include the most up-to-date representations of key physical processes and consider a broader range of socio-economic pathways of future greenhouse gas emissions (Eyring et al. 2016). CMIP6 climate models also project higher rates of warming for given emission scenarios (Grose et al. 2020), so their impact on climate variables such as LCL should be considered.

Consideration of other possible downscaling ensembles. While the two ensembles considered here remain the only ones presently available for the region, future downscaling should be considered when they are generated and upcoming CORDEX (Giorgi and Gutowski 2015) regional downscaling ensembles could be examined.

Consideration of the optimum way of combining GCM and downscaled results in deriving a range of future climate change, and in assessing confidence in that range. Results shown here are derived from downscaling alone, whereas combining downscaled results with the broader (non-downscaled) GCM ensemble could provide further insights and potentially increase confidence in projected changes.

Consideration of possible changes in variability. Studies in the Australian deep tropics find that variability of rainfall may be expected to increase on all time scales, ranging from daily to decadal in a warmer climate (Brown et al. 2017). It is important to understand if such changes also apply in the Gondwana Rainforests region, as increases in variability in an already extremely variable climate may create additional ecological stresses.

Consideration of changes in extremes. Extremes such as droughts, heatwaves and heavy rainfall are expected to have very significant ecological impacts and further information about these would assist with risk assessment and management of these biodiversity hotspots.

Better understanding of changes in fire regimes. Possible important changes to fire that are important for management of the Gondwana Rainforests include changes in the length of the fire season and changes in the frequency or intensity of wildfire. Increases in the frequency and intensity of fire weather has already been observed broadly throughout eastern Australia (BoM and CSIRO 2018).

Better understanding of the physical processes leading to changes in LCL (and through it cloud base height), as well as changes in relative humidity and rainfall. This could include consideration of changes in the observed record, respond to changes in large-scale drivers such as ENSO, and from interannual or inter-seasonal variability.

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Appendix 1: Evaluation of regional climate models used in this assessment

Here we present evaluation metrics we employed to quantify the ability of the regional climate models used in this assessment to replicate features of the real world.

We focus first on monthly mean daily maximum temperature at the surface (Tmax) and monthly mean rainfall because they are important climate variables and are readily compared to the high-resolution observation-based dataset from the Australian Water Availability Project (AWAP, Jones et al. 2009). We compare the models and observations separately for each month of the year, using the average for each month during the period 1990 to 2009. For brevity we only show the maps for September, selected since it is typically the time of year when moisture stress is greatest in the Gondwana Rainforest reserves. It is important to note that the biases presented here are only relevant for September, and that the biases vary throughout the year. More detailed evaluation of these experiments can be found in Olson et al. (2014) and Syktus et al. (2020).

In general, the NARCliM experiments have a cool 'bias' (i.e. difference from the average) in September, and this tends to be fairly uniform throughout the eastern coast of Australia (Figure A1.1).

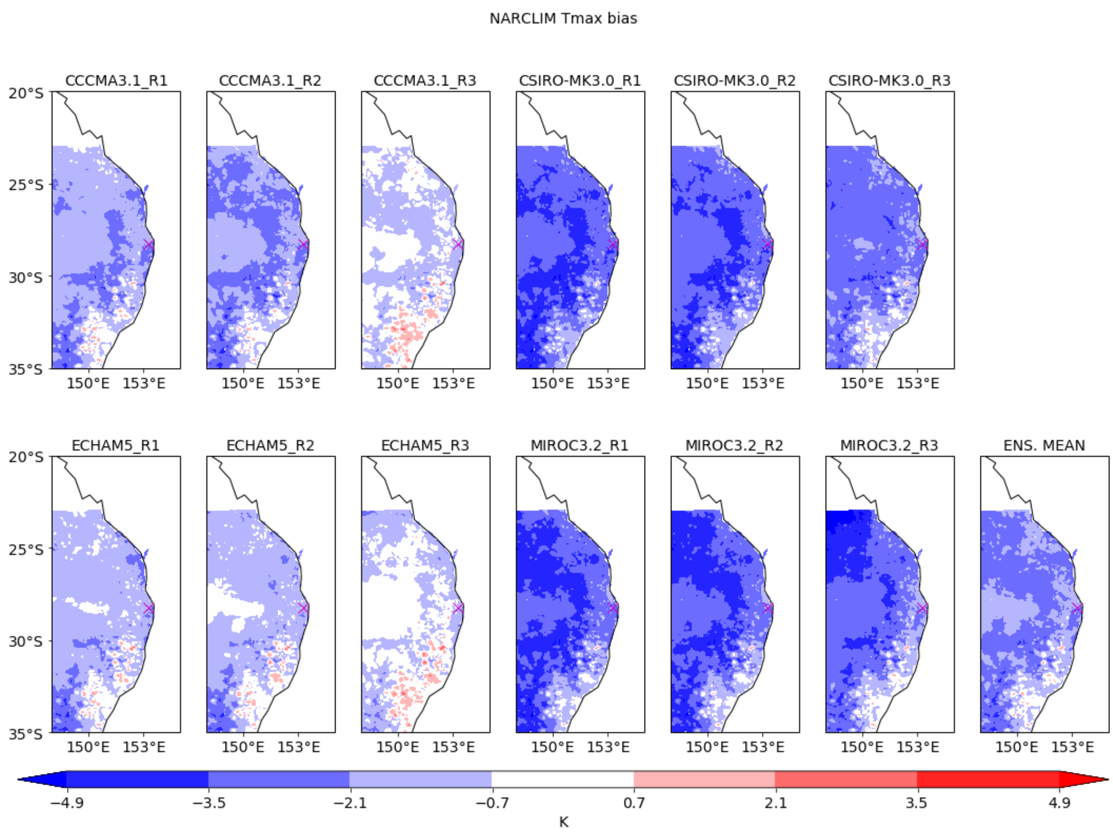

Figure A1.1: September average daily maximum temperature bias for the NARCliM model experiments. Bias is calculated by comparing the 1990–2009 average conditions for each model against the AWAP observation-based gridded dataset. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

The rainfall biases along the east coast of Australia in the NARCliM experiments are generally smaller than that from the QFC ensemble, although spatially heterogeneous. Two of the four downscaled models (CSIRO-Mk3.0 and MIROC3.2) have larger rainfall biases, particularly in the vicinity of the Great Dividing Range on the east coast of Australia (Figure A1.2).

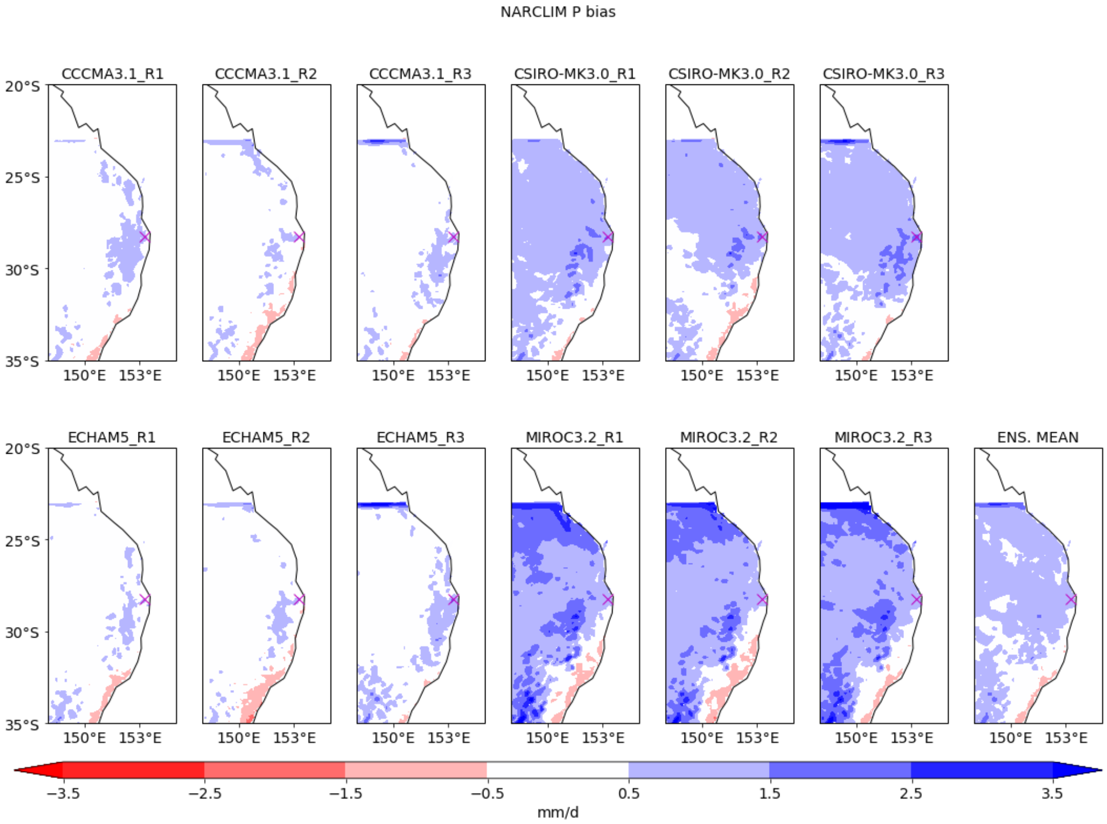

Figure A1.2: September rainfall bias for the NARCliM model experiments. Bias is calculated by comparing the 1990–2009 average conditions for each model against the AWAP observation-based gridded dataset. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

The Queensland Future Climate (QFC) simulations each have different September temperature bias patterns, although they generally are warmer than observations. However, near the coast many of the models have low, or negative temperature biases (Figure A1.3). In general, the QFC simulations have very small rainfall biases, although to a varying degree, they all have positive rainfall biases along the east coast (Figure A1.4).

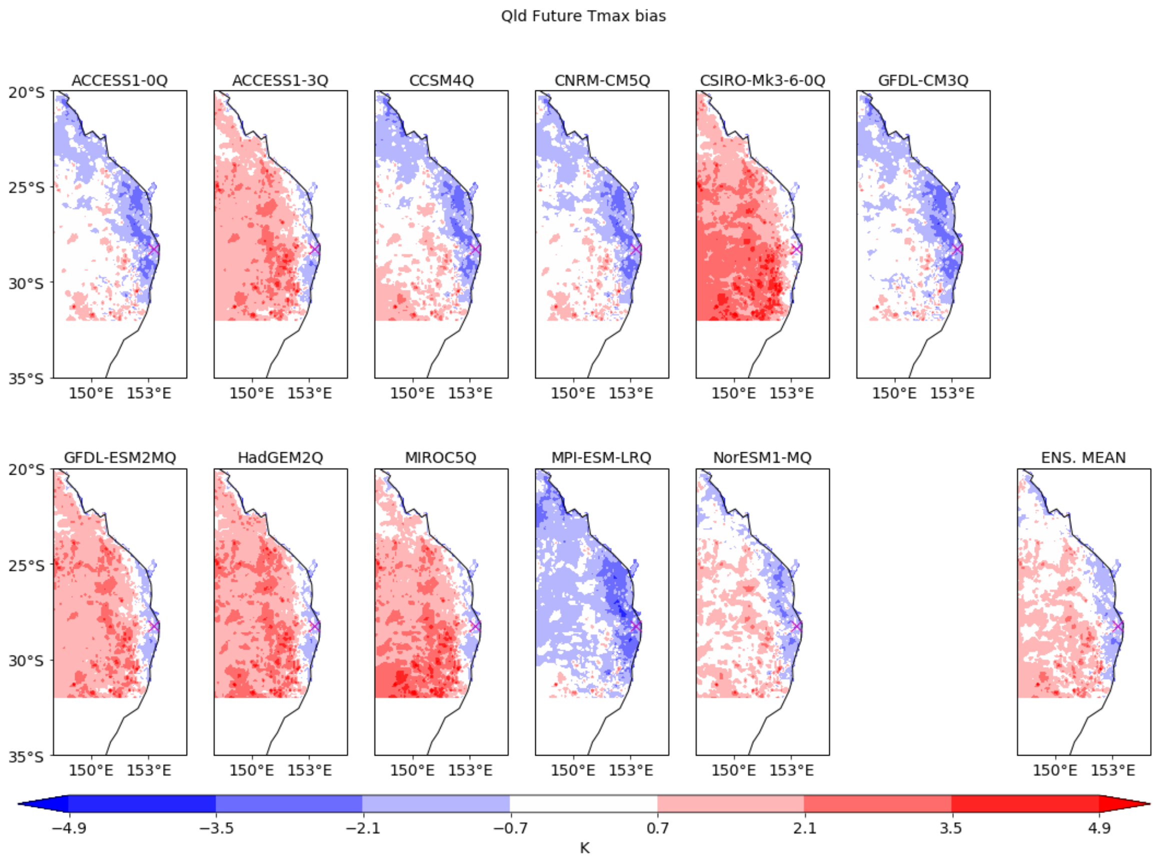

Figure A1.3: September average daily maximum temperature bias for the QFC model experiments. Bias is calculated by comparing the 1990–2009 average conditions for each model against the AWAP observation-based gridded dataset. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

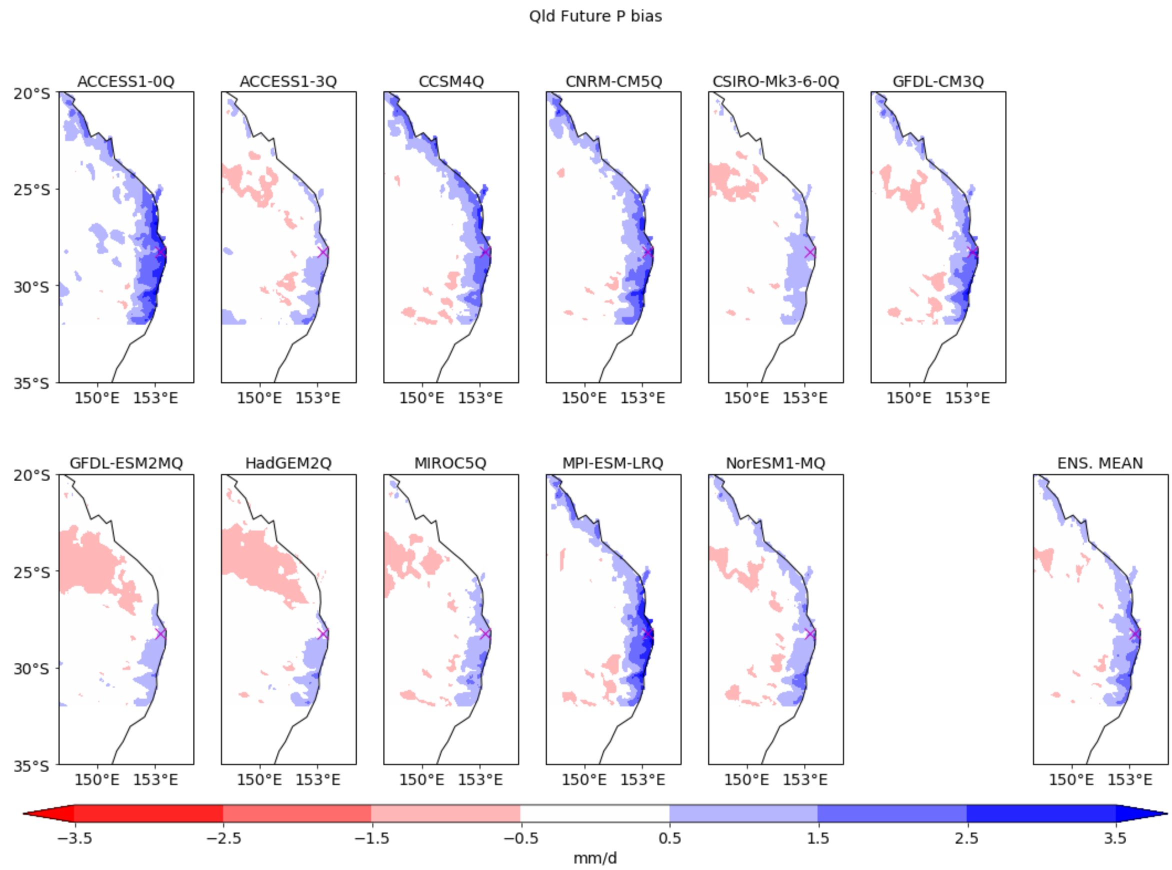

Figure A1.4: September rainfall bias for the QFC model experiments. Bias is calculated by comparing the 1990–2009 average conditions for each model against the AWAP observation-based gridded dataset. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

Investigating the model fidelity to observations more broadly, we now consider the root mean square error (RMSE) and the spatial correlation when compared to observations, calculated for a coastal east Australia region roughly covering the Gondwana Rainforests reserves (-32.3°S to -27.5°S, 149.6°E to 153.8°E). The RMSE is measure of absolute error, while the spatial correlation is a measure of spatial pattern reproduction (how well the simulated patterns of a field 'match' the patterns in the observations – i.e. irrespective of whether the fields themselves differ, by a constant amount). A perfect simulation would therefore have an RMSE of zero, and a spatial correlation of one.

Both the NARCliM and QFC simulations show a wide range in Tmax RMSE for each month of the year (Figure A1.5). It is notable here that the NARCliM experiments have larger Tmax RMSE in general for the month of September when compared to the QFC experiments. Conversely, the spatial correlation with observations for the NARCliM simulations is better in all months when compared to QFC simulations (Figure A1.6). The reason for this is that while the NARCliM simulations have larger absolute biases, those biases are relatively uniform in space. For the QFC simulations, the biases are spatially inconsistent (e.g. positive biases inland and negative biases near the coast).

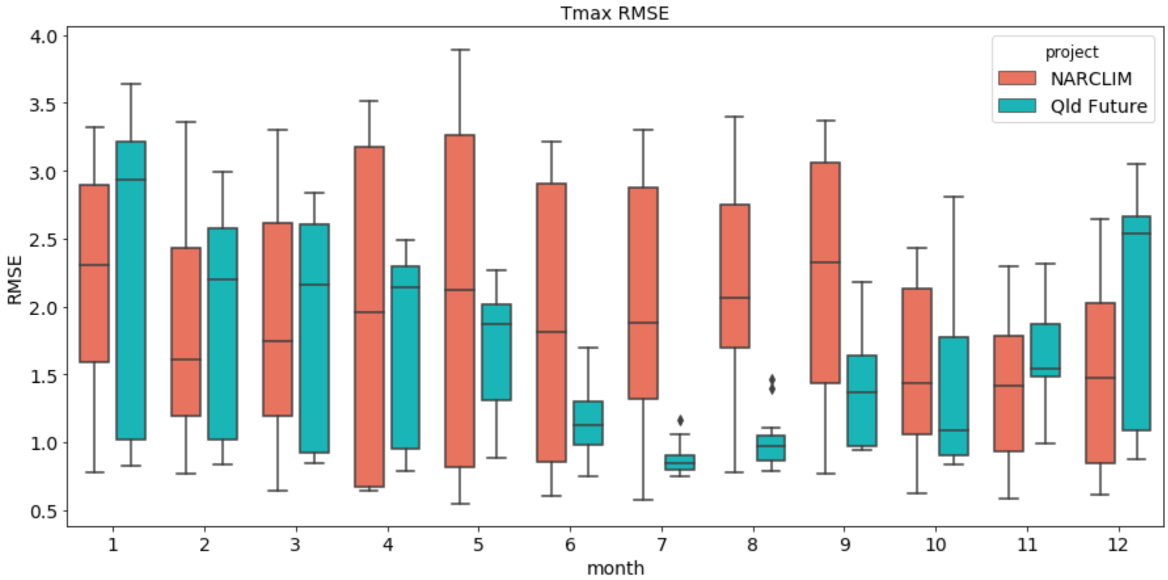

Figure A1.5: Average daily maximum temperature root mean square error (RMSE) for the NARCliM and QFC model experiments, for each month of the year. RMSE is calculated by comparing the 1990–2009 average conditions for each model against the AWAP observation-based gridded dataset for a coastal east Australia region (-32.3°S to -27.5°S, 149.6°E to 153.8°E).

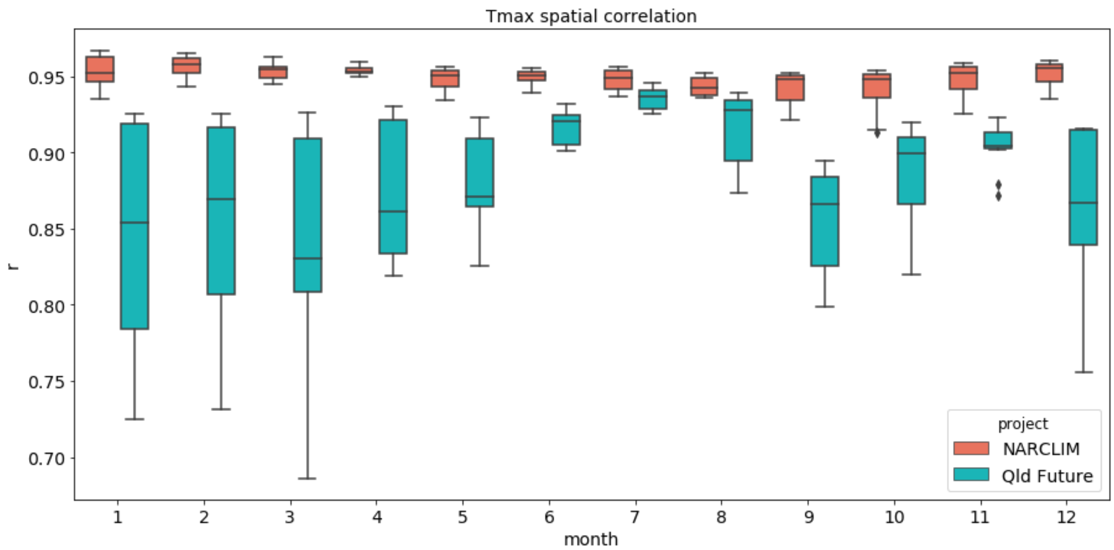

Figure A1.6: Average daily maximum temperature spatial correlation for the NARCliM and QFC model experiments, for each month of the year. Spatial correlation is calculated by comparing the 1990–2009 average conditions for each model against the AWAP observation-based gridded dataset for a coastal east Australia region (-32.3°S to -27.5°S, 149.6°E to 153.8°E).

The rainfall RMSE is similar between the two ensembles, with larger errors in the warmer months compared to the cooler months (Figure A1.7). This is possibly due to the seasonal cycle in rainfall, since lower rainfall may lead to lower RMSE in general. The rainfall spatial correlation is also similar between the NARCliM and QFC simulations, although the spread for the NARCliM simulations tends to be larger (Figure A1.8).

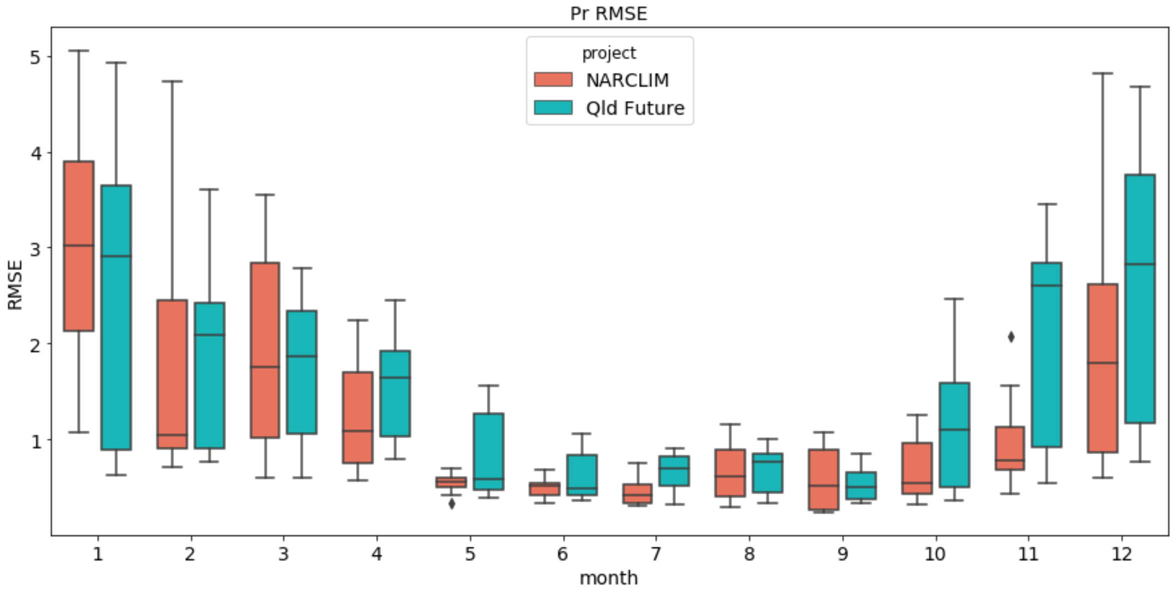

Figure A1.7: Rainfall root mean square error (RMSE) for the NARCliM and QFC model experiments, for each month of the year. RMSE is calculated by comparing the 1990–2009 average conditions for each model against the AWAP observation-based gridded dataset for a coastal east Australia region (-32.3°S to -27.5°S, 149.6°E to 153.8°E).

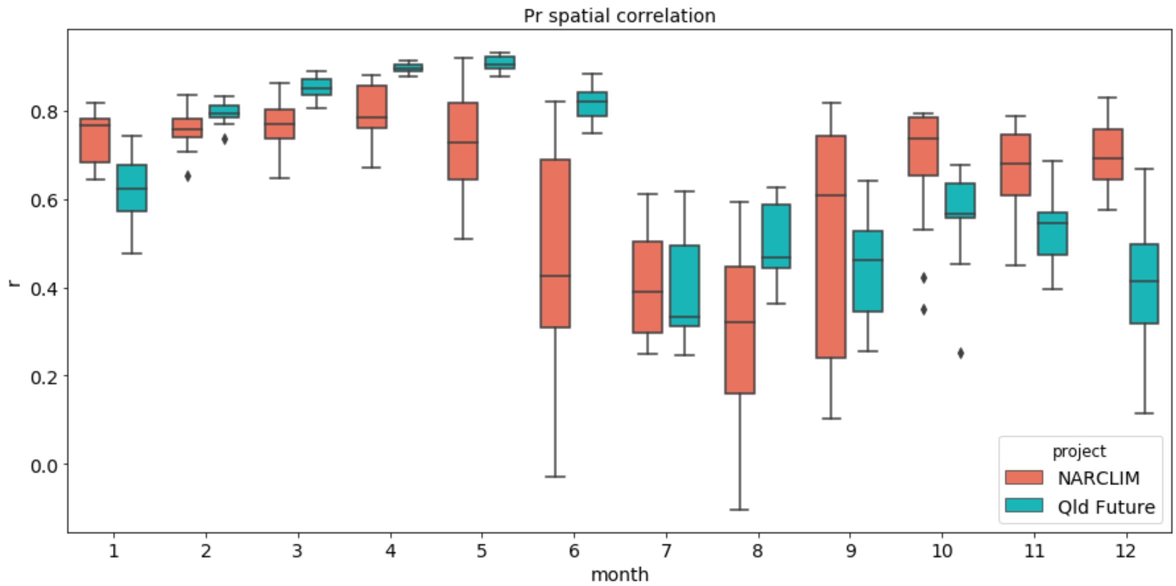

Figure A1.8: Rainfall spatial correlation for the NARCliM and QFC model experiments, for each month of the year. Spatial correlation is calculated by comparing the 1990–2009 average conditions for each model against the AWAP observation-based gridded dataset for a coastal east Australia region (-32.3°S to -27.5°S, 149.6°E to 153.8°E).

A key innovation in the present study is the application of cloud base height information for the purpose of understanding the ecology of the Gondwana Rainforests reserves. Low clouds are known to play an important role in delivering moisture to these elevated environments and are particularly critical in the driest months of the year.

Since cloud base heights are not well recorded, and are not generally specified in model output in an unambiguous manner, we apply a proxy for cloud base height. Here we use an empirical formula (Lawrence 2005) to estimate the lifting condensation level (LCL), which is the height at which we expect clouds may form when a moist airstream encounters topography. Physically the LCL represents the height that a surface 'parcel' of air must be raised to until that parcel is cool enough for the water vapour to condense into droplets – i.e. cloud droplets. Studies comparing observed cloud base heights and LCL-derived values show that in most situations LCL provides an excellent proxy (Craven et al. 2002), increasing our confidence in its use here.

The LCL is estimated using the surface temperature and dewpoint temperature. To evaluate the LCL estimates from models, we use the same quantity estimated from the Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia (BARRA) (Su et al. 2019). A reanalysis is produced by running a weather model and constraining it with as many observations as possible. This gives us the most realistic estimate of the state of the atmosphere and is particularly useful for locations where there may be insufficient observations as the model will, in a sense, 'fill in' the gaps in a way that is physically consistent with nearby observations. It is important, however, to note that reanalyses, while useful, are not the same as observations and may still suffer from some biases introduced in the modelling and data assimilation process.

With those caveats in mind, we now compare the models LCL with that from the BARRA reanalysis. The NARCliM ensemble are more spatially varied in their biases, as well as between models within the ensemble (Figure A1.9). The QFC ensemble generally show larger biases, consistently underestimating the LCL (Figure A1.10). The biases in the models don't mean that those models are not useful for examining projections of change in cloud base height, merely that there is a caveat that the models tend to identify cloud formation at a level that is systematically lower or higher than observations. This does not preclude extracting useful information from *differences* in LCL between current climate and projected climate.

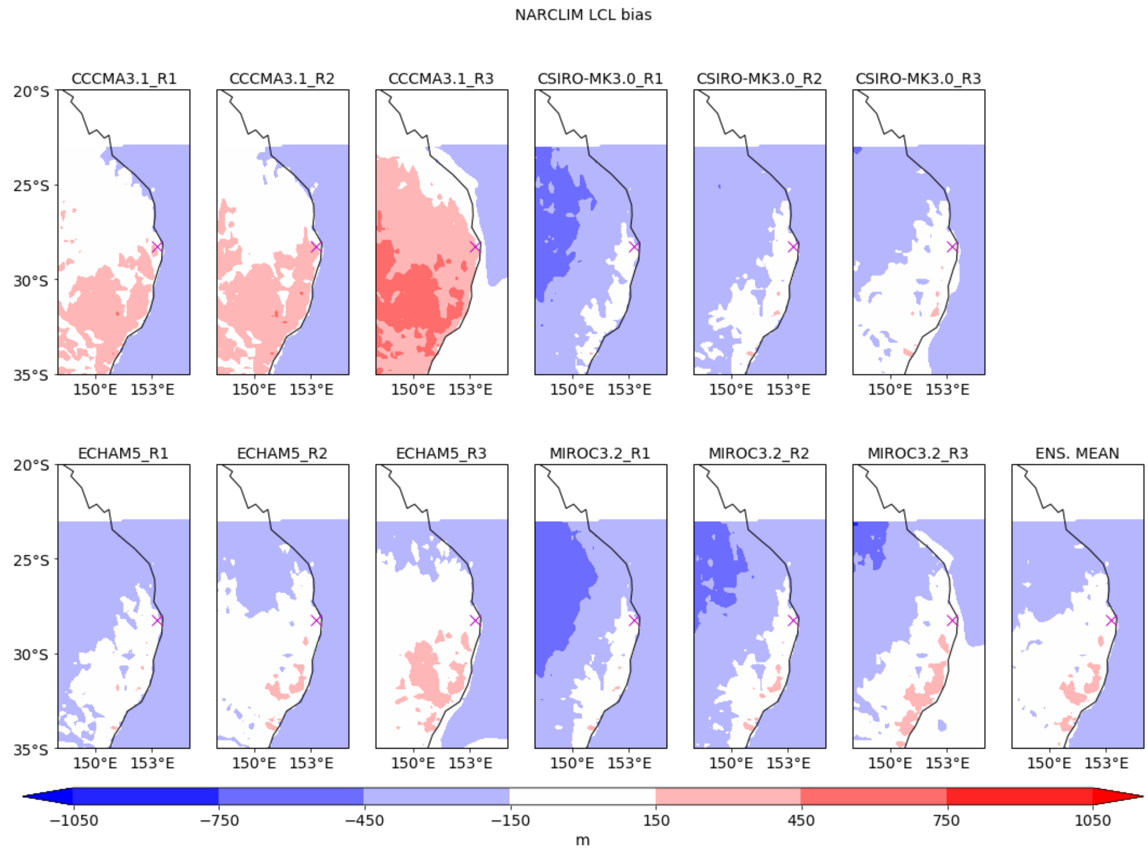

Figure A1.9: September lifting condensation level (LCL) bias for the NARCliM model experiments. Bias is calculated by comparing the 1990–2009 average conditions for each model against the BARRA reanalysis gridded dataset. Positive values denote model LCLs that are higher than BARRA values (i.e. models are forming clouds higher than our best observational estimates). The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

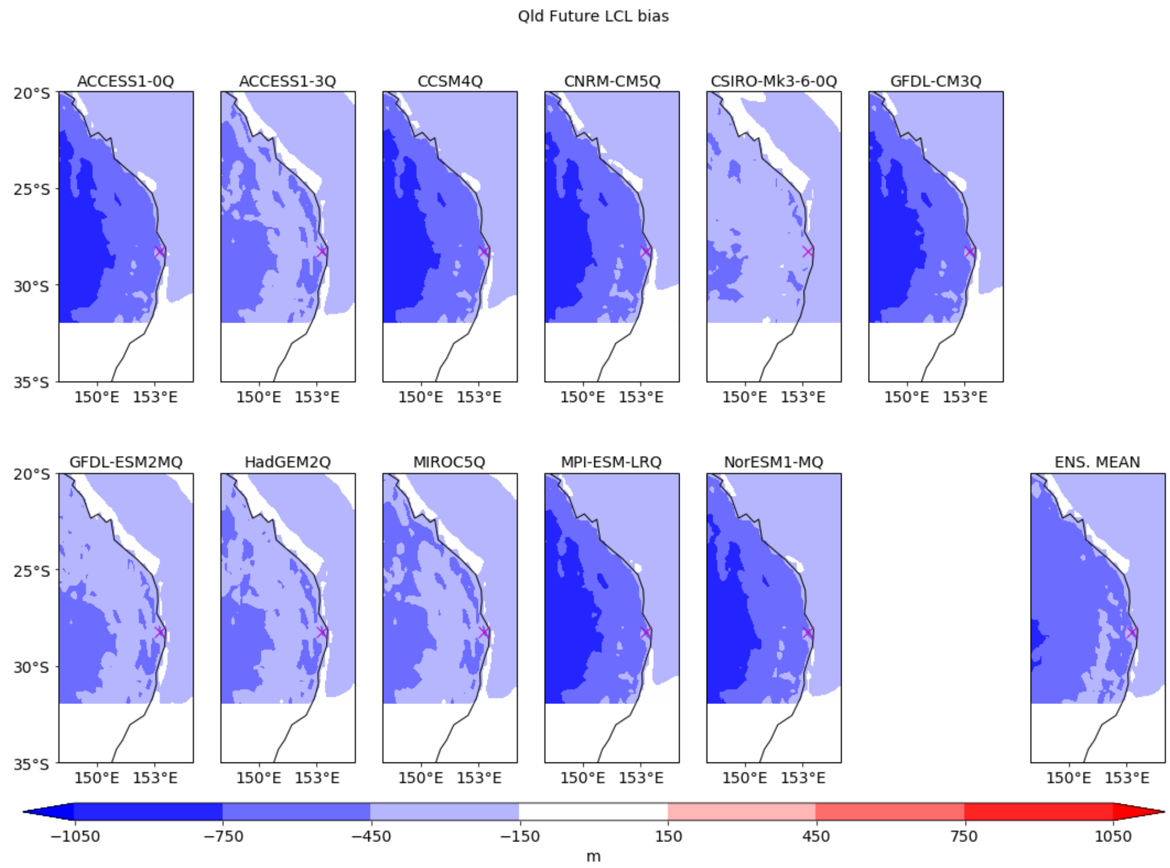

Figure A1.10: September lifting condensation level (LCL) bias for the QFC model experiments. Bias is calculated by comparing the 1990–2009 average conditions for each model against the BARRA reanalysis gridded dataset. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

While the difference in RMSE between the ensembles may seem striking (Figure A1.11), it is important to note that since the reanalysis may also contain biases it is not immediately clear which ensemble is more accurate. Nevertheless, it is interesting that they are so different, and further investigation may be warranted in future.

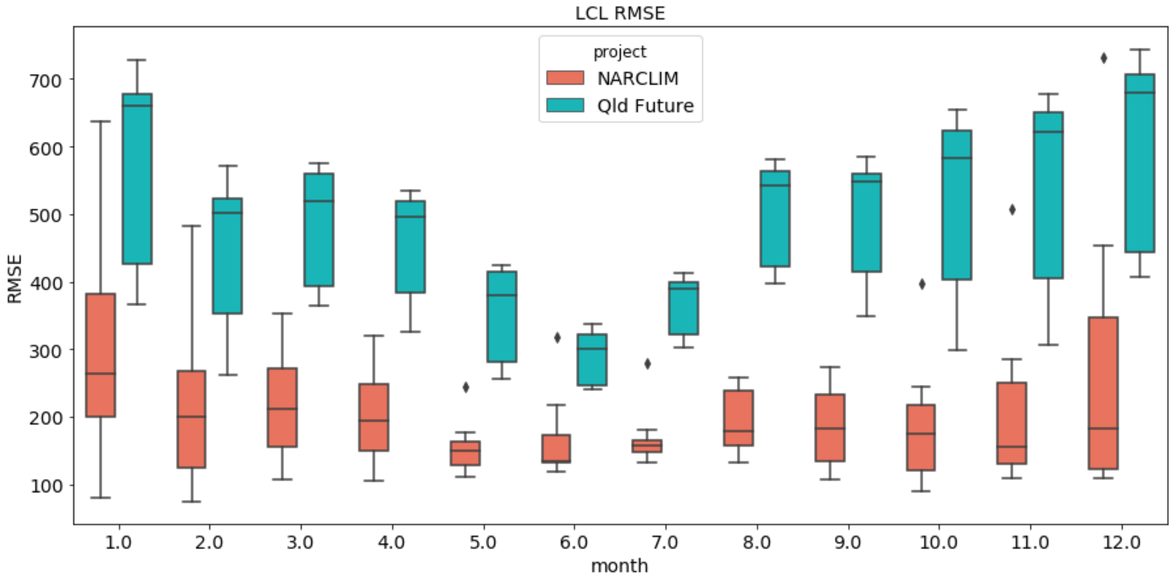

Figure A1.11: Lifting condensation level (LCL) root mean square error (RMSE) for the NARCliM and QFC model experiments, for each month of the year. RMSE is calculated by comparing the 1990–2009 average conditions for each model against the BARRA reanalysis gridded dataset for a coastal east Australia region (-32.3°S to -27.5°S, 149.6°E to 153.8°E).

The spatial patterns in both ensembles are well aligned with the BARRA reanalysis, with the QFC ensemble generally reproducing the spatial patterns of LCL from reanalysis better than the NARCliM ensemble (Figure A1.12). Note that both sets of downscaling correlate very well with the BARRA values, with pattern correlations in all seasons greater than 0.80. Pattern correlations are lowest for NARCLIM in the dry season, when we may expect cloud cover to be less. Interestingly, this is not the case with QFC.

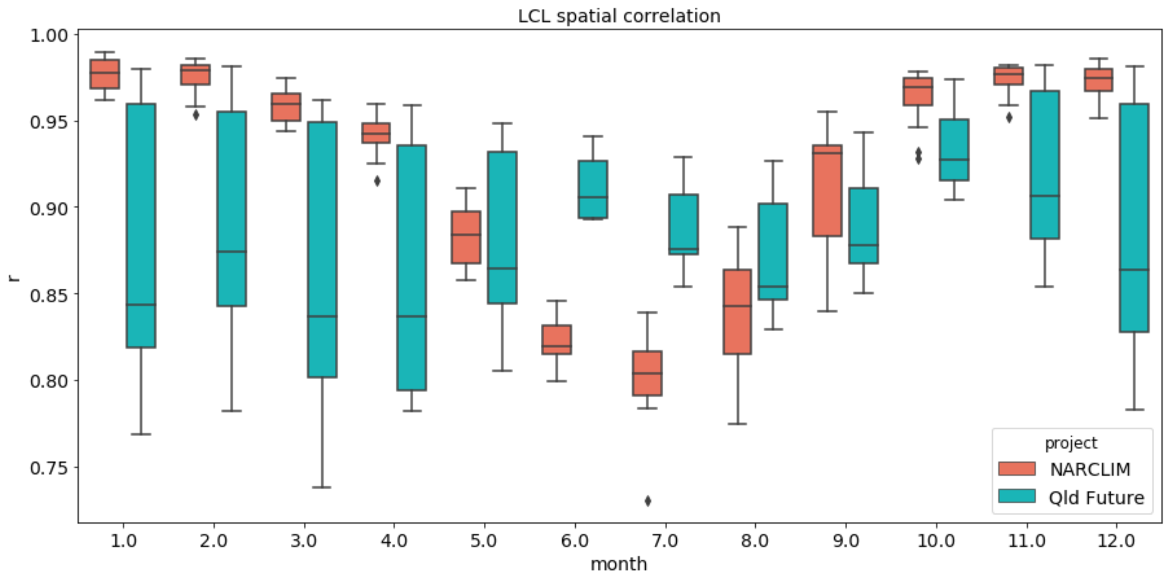

Figure A1.12: Lifting condensation level (LCL) spatial correlation for the NARCliM and QFC model experiments, for each month of the year. Spatial correlation is calculated by comparing the 1990–2009 average conditions for each model against the BARRA reanalysis gridded dataset for a coastal east Australia region (-32.3°S to -27.5°S, 149.6°E to 153.8°E).

This evaluation considered some important aspects of the downscaled simulations from the NARCliM and QFC projects. Each ensemble performs better in some metrics than the other, particularly for Tmax and rainfall simulation. While we have evaluated the estimated LCL from the models against the estimated LCL from BARRA reanalysis, it is important to note that the reanalysis itself may not adequately represent the true cloud base height. Nevertheless, it provides a standard against which to compare the ensembles. From our evaluation we note that the two ensembles have quite different cloud base heights, with NARCliM being closer to the reanalysis. The spatial patterns of LCL in each ensemble though are almost equally similar to reanalysis.

From the limited evaluation conducted within this project we conclude that while significant biases and uncertainties may exist, both the NARCliM and QFC ensembles adequately reproduce historical features of the climate in the vicinity of the Gondwana Rainforest reserves.

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Syktus J, Toombs N, Wong K, Trancoso R and Ahrens D. 2020: Queensland Future Climate Dataset – Downscaled CMIP5 climate projections for RCP8.5 and RCP4.5. Version 1.0.2. Terrestrial Ecosystem Research Network (TERN) dataset. https://doi.org/10.25901/5e3ba30f141b7

Appendix 2: Projected changes in temperature, relative humidity and rainfall by 2030

The following maps are for the projected September change in temperature, relative humidity and rainfall by 2030 (2020–2039). The changes are calculated by subtracting the corresponding monthly climatologies from the period 1990–2009. The periods analysed here were chosen to maximise the concurrent times between the NARCliM and Queensland Future Climate ensembles.

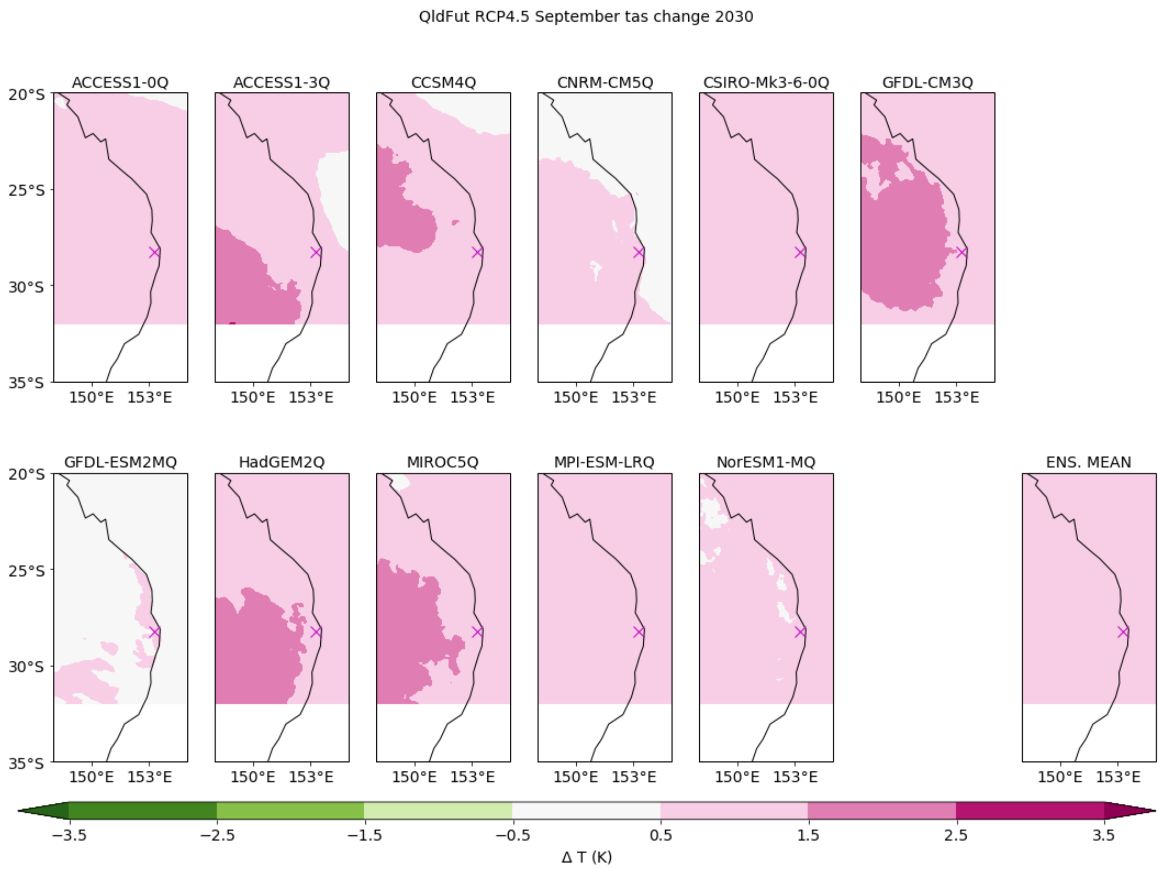

Figure A2.1: September surface air temperature change by 2030 for the Queensland Future Climate RCP4.5 (medium emissions) experiments. Changes are calculated by comparing the 2020–2039 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

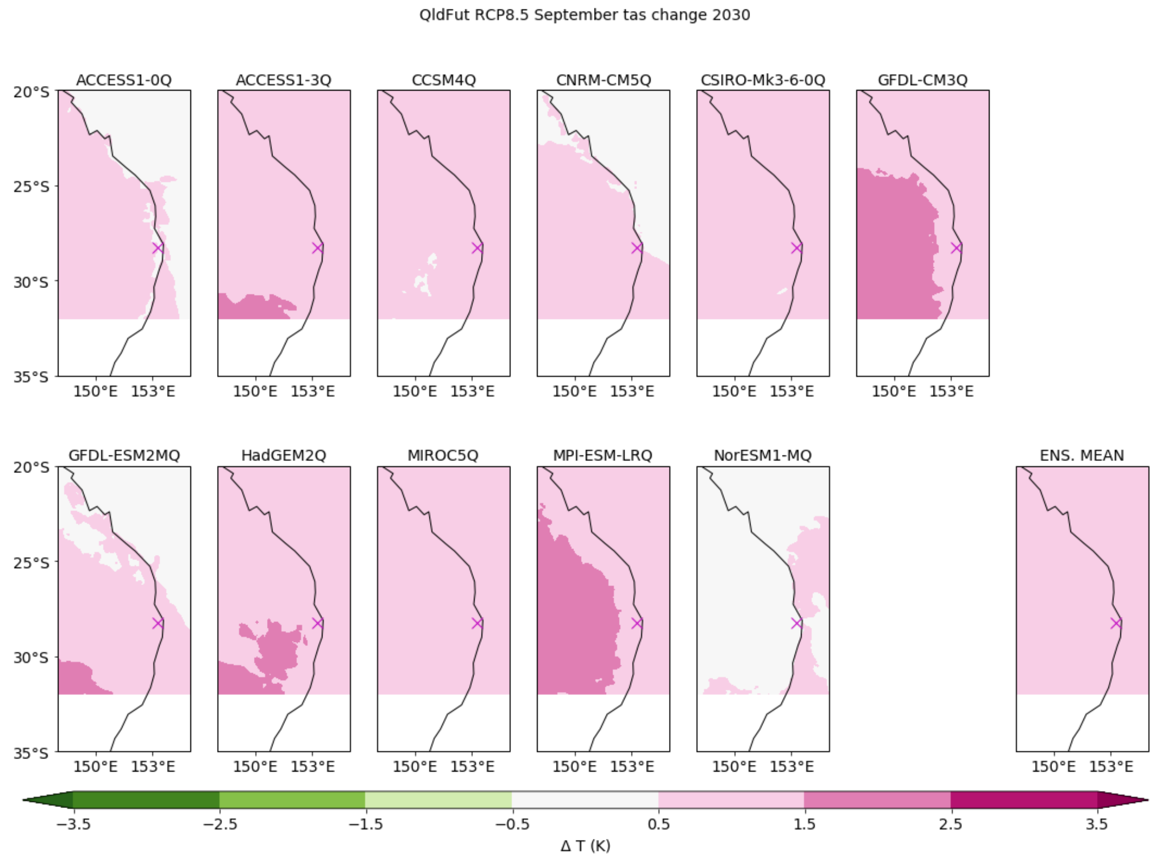

Figure A2.2: September surface air temperature change by 2030 for the Queensland Future Climate RCP8.5 (high emissions) experiments. Changes are calculated by comparing the 2020–2039 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

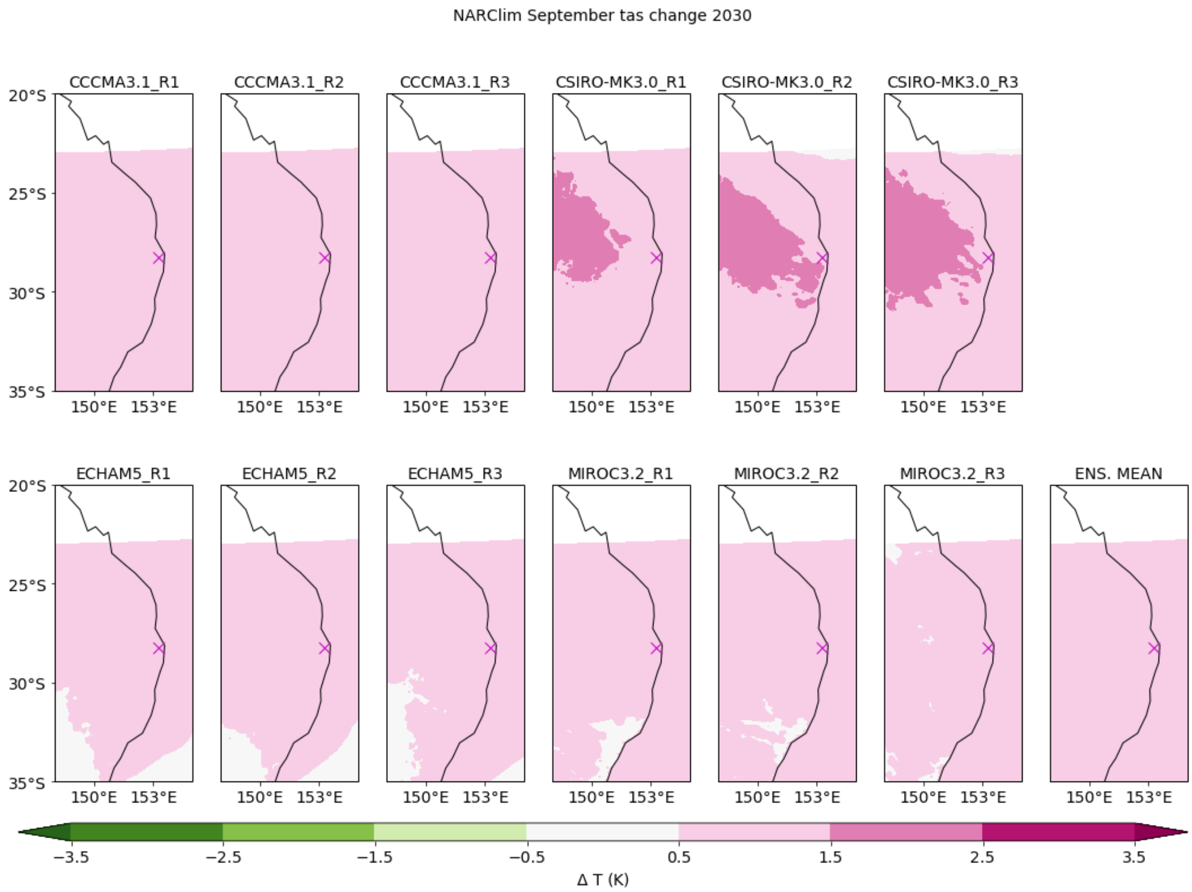

Figure A2.3: September surface air temperature change by 2030 for the NARCliM A2 (high emissions) experiments. Changes are calculated by comparing the 2020–2039 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

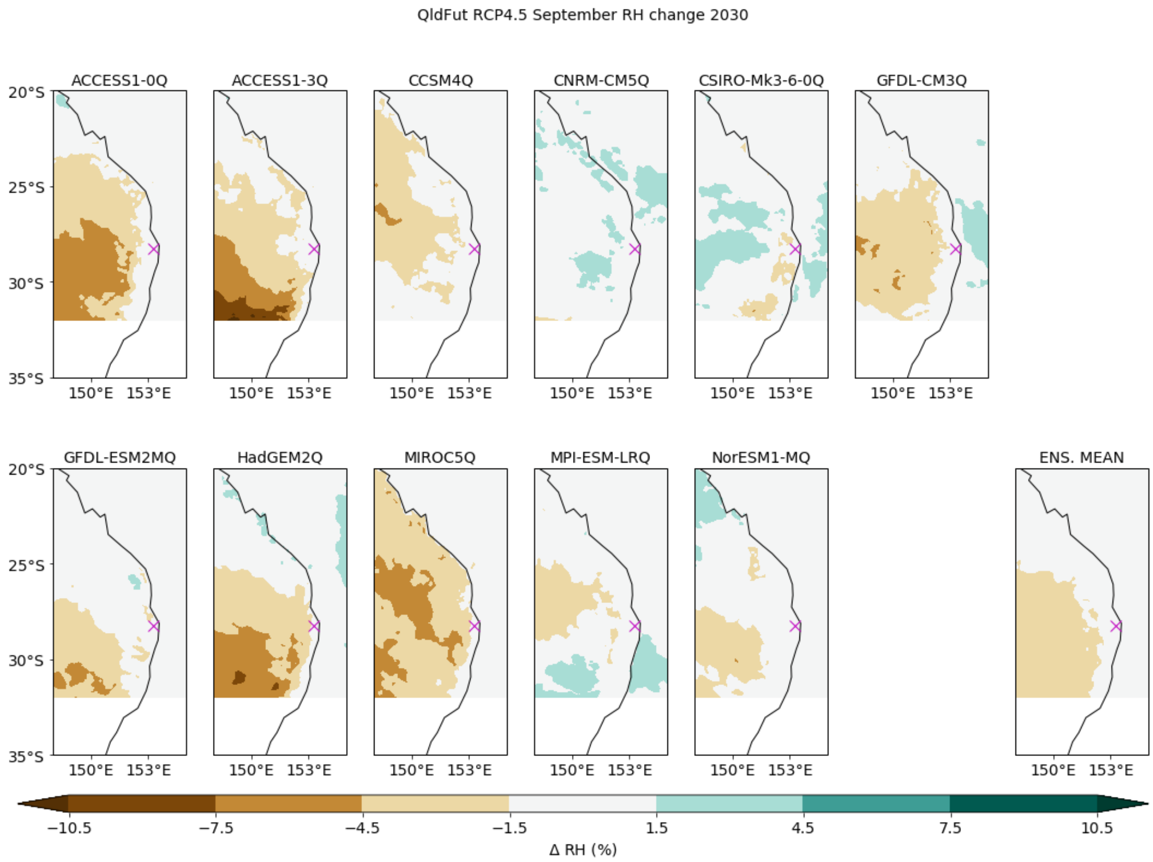

Figure A2.4: September relative humidity change by 2030 for the Queensland Future Climate RCP4.5 (medium emissions) experiments. Changes are calculated by comparing the 2020–2039 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

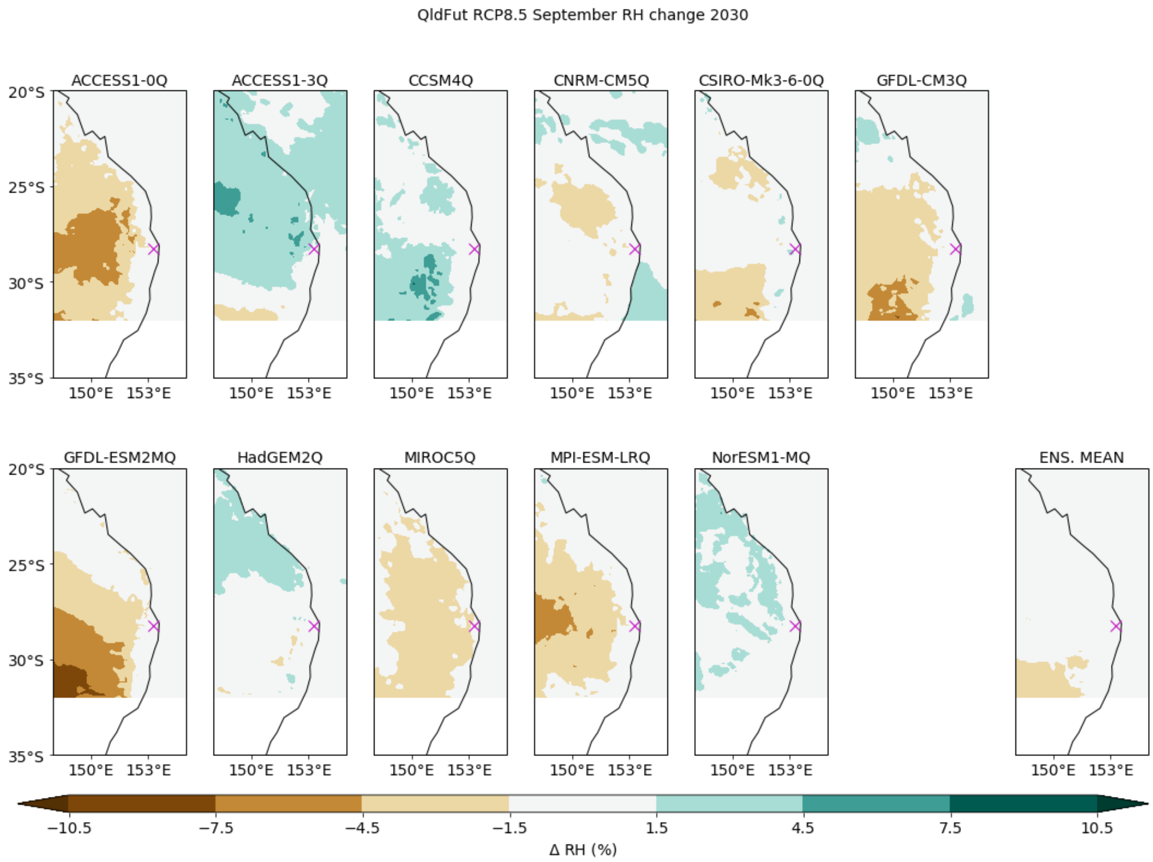

Figure A2.5: September relative humidity change by 2030 for the Queensland Future Climate RCP8.5 (high emissions) experiments. Changes are calculated by comparing the 2020–2039 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

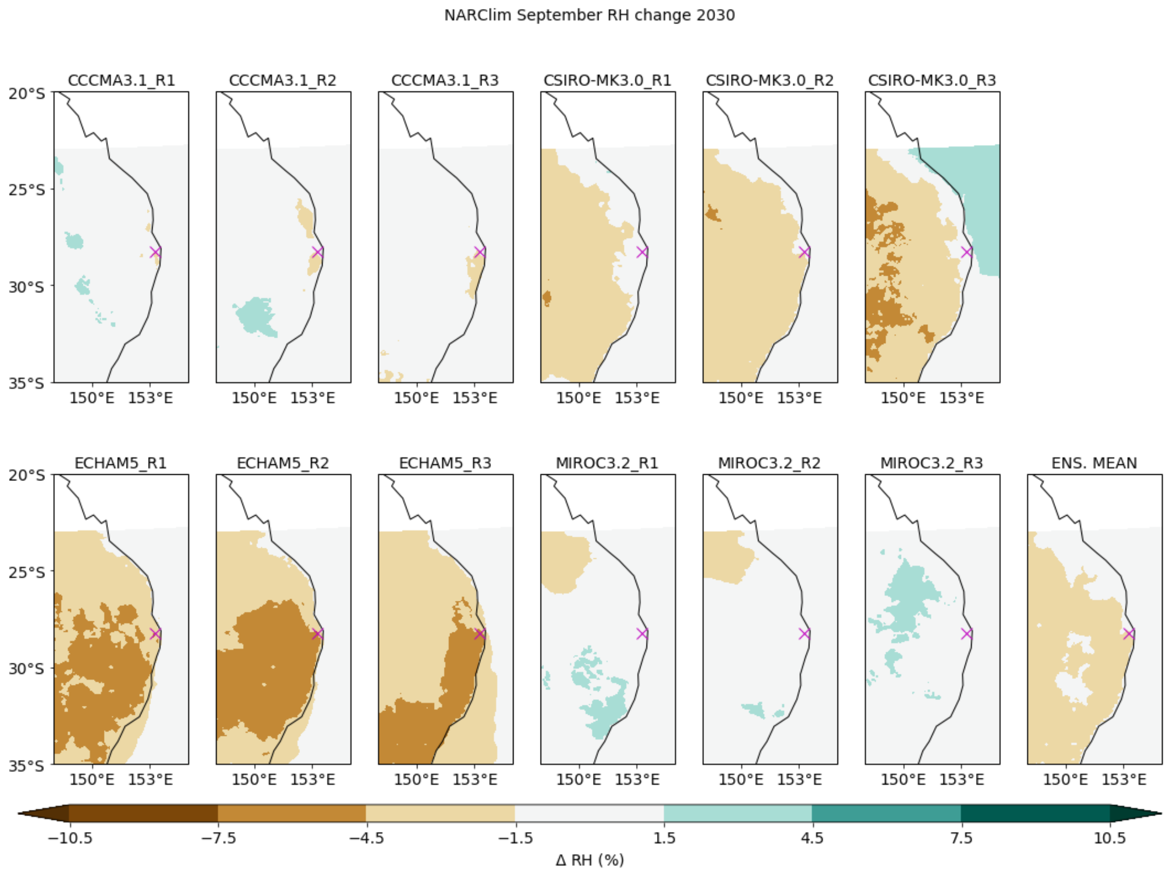

Figure A2.6: September relative humidity change by 2030 for the NARCliM A2 (high emissions) experiments. Changes are calculated by comparing the 2020–2039 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

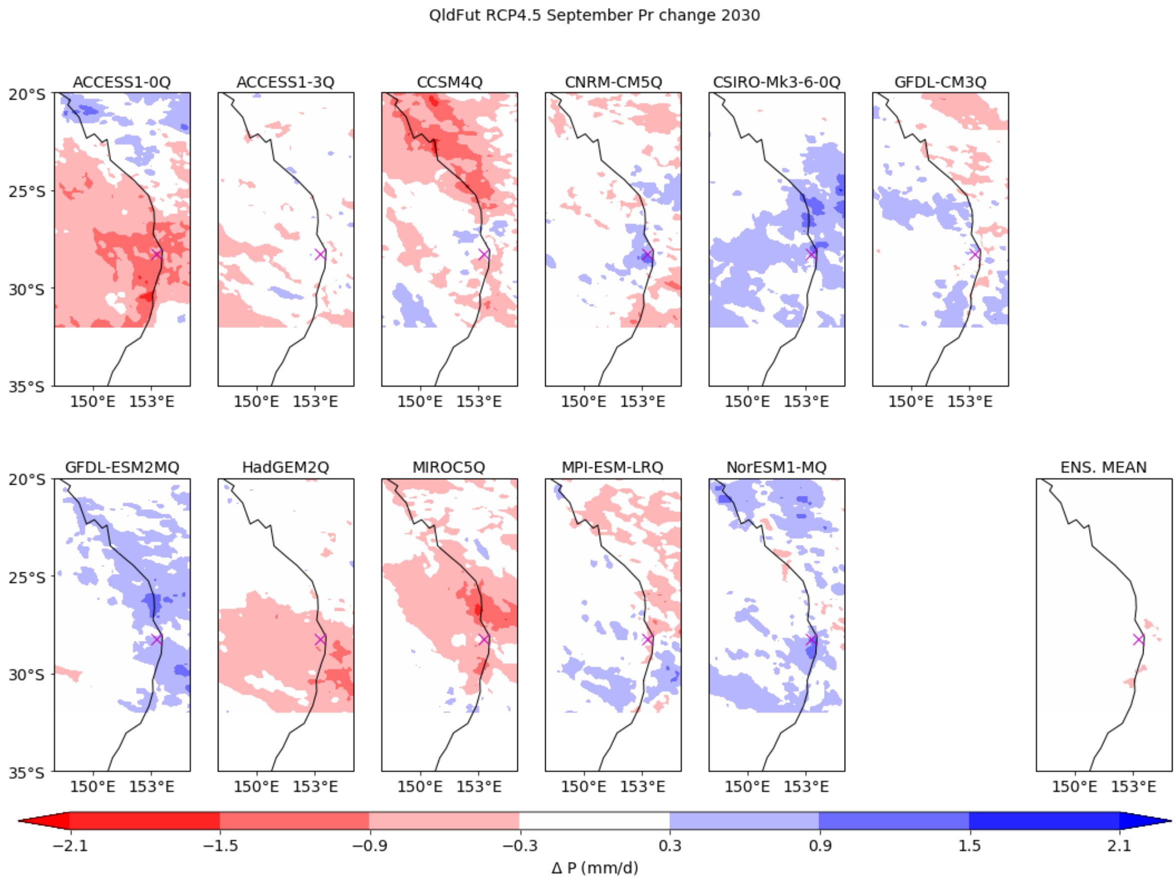

Figure A2.7: September rainfall change by 2030 for the Queensland Future Climate RCP4.5 (medium emissions) experiments. Changes are calculated by comparing the 2020–2039 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

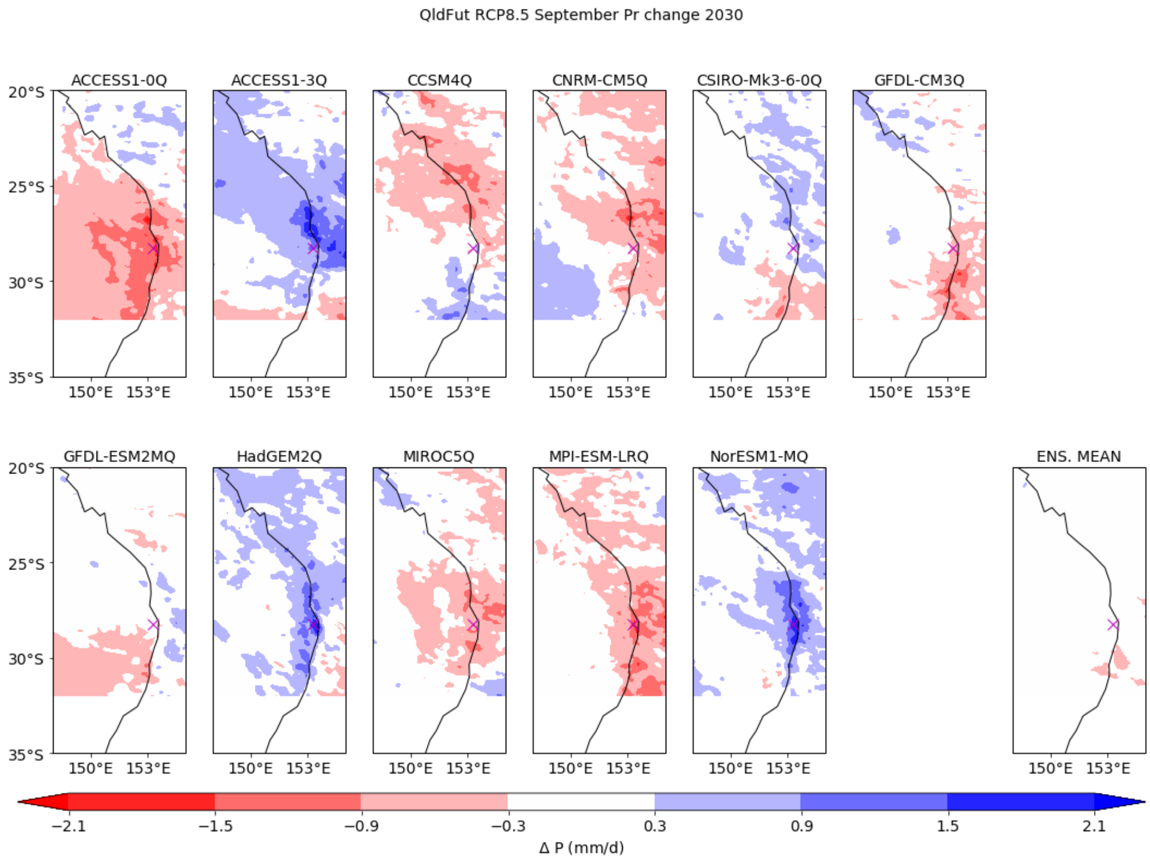

Figure A2.8: September rainfall change by 2030 for the Queensland Future Climate RCP8.5 (high emissions) experiments. Changes are calculated by comparing the 2020–2039 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

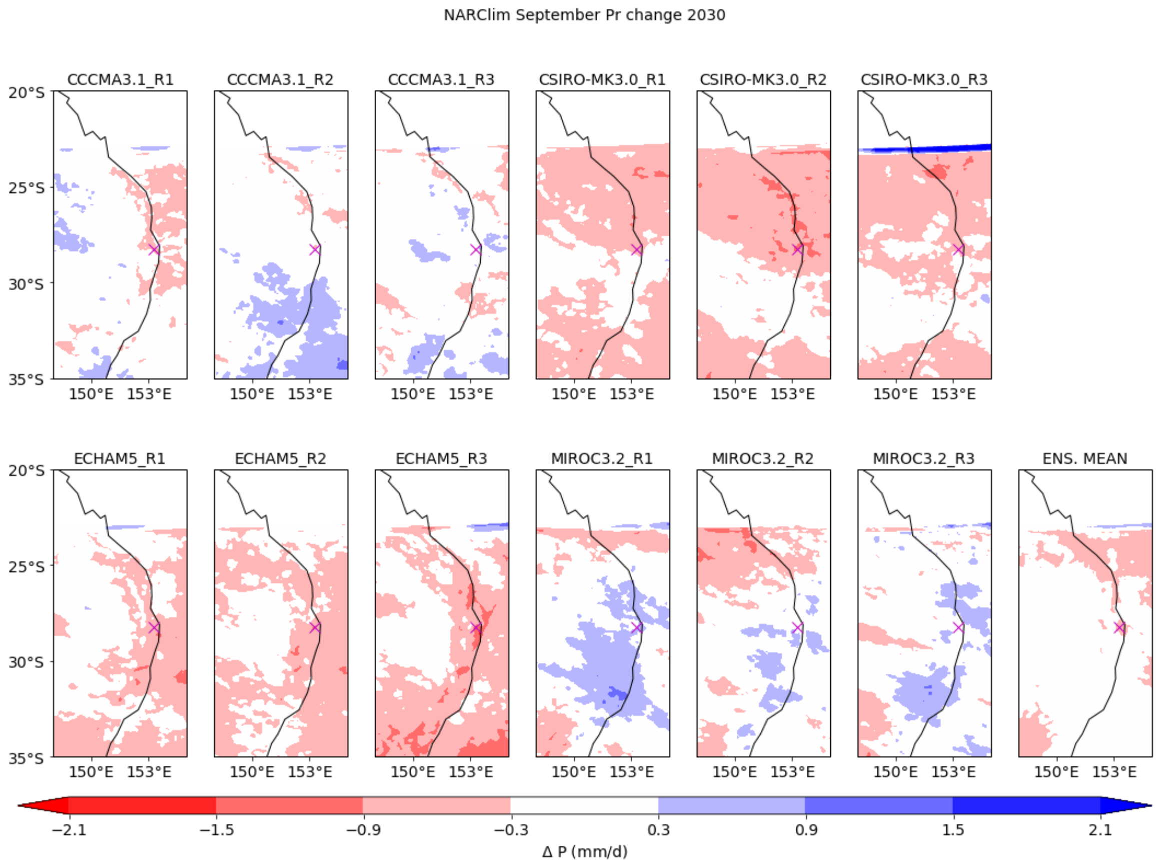

Figure A2.9: September rainfall change by 2030 for the NARCliM A2 (high emissions) experiments. Changes are calculated by comparing the 2020–2039 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

Appendix 3: Projected changes in temperature, relative humidity and rainfall by 2050

The following maps are for the projected September change in temperature, relative humidity and rainfall by 2050 (2040–2069). The changes are calculated by subtracting the corresponding monthly climatologies from the period 1990–2009. Only projections from the Queensland Future Climate ensembles are presented, as there are no NARCliM experiments for this period.

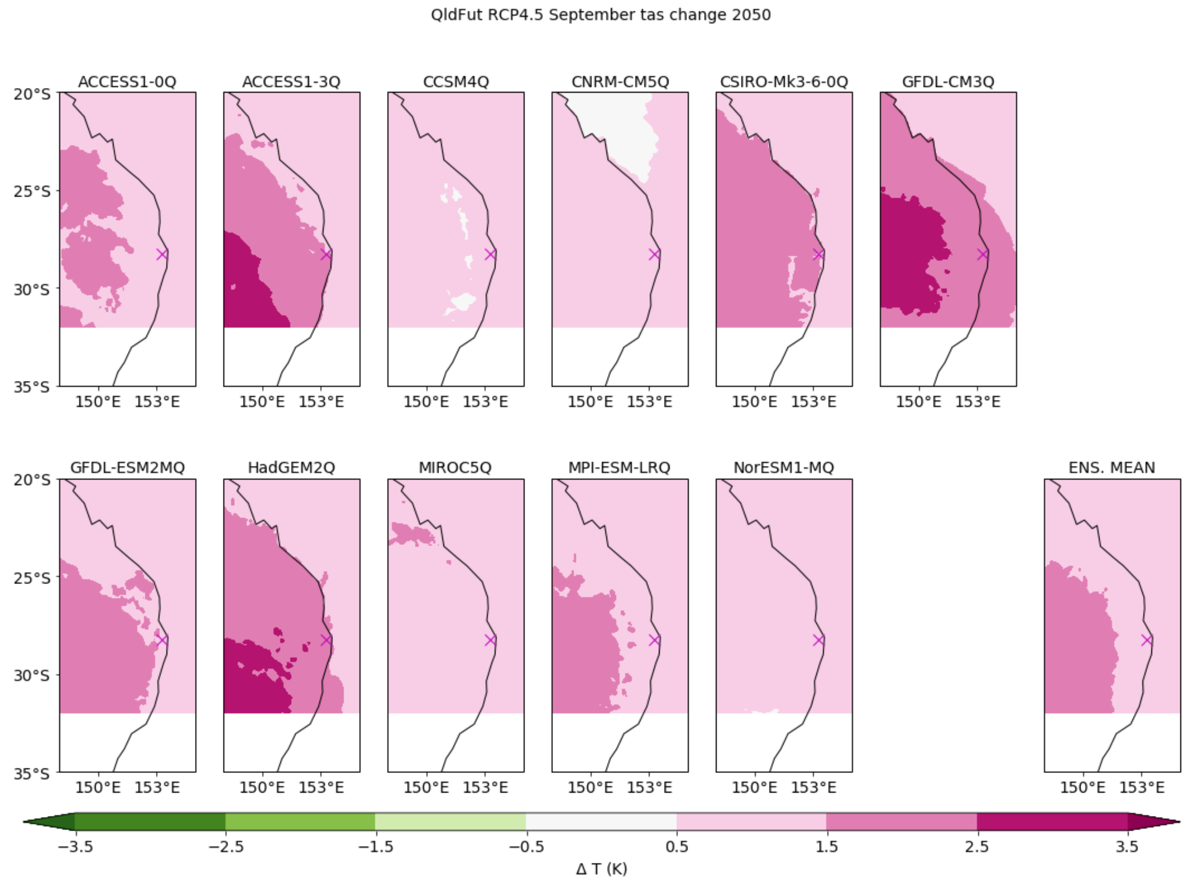

Figure A3.1: September surface air temperature change by 2050 for the Queensland Future Climate RCP4.5 (medium emissions) experiments. Changes are calculated by comparing the 2040–2059 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

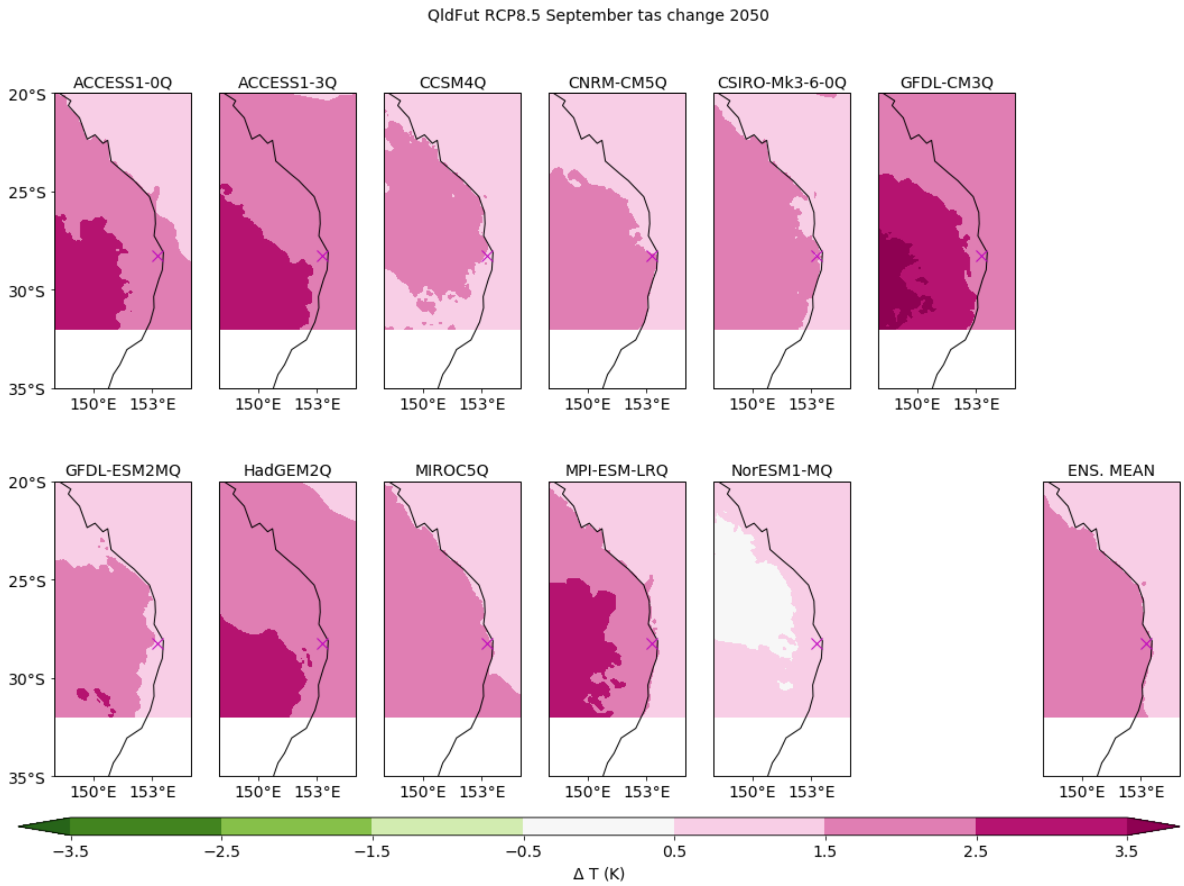

Figure A3.2: September surface air temperature change by 2050 for the Queensland Future Climate RCP8.5 (high emissions) experiments. Changes are calculated by comparing the 2040–2059 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

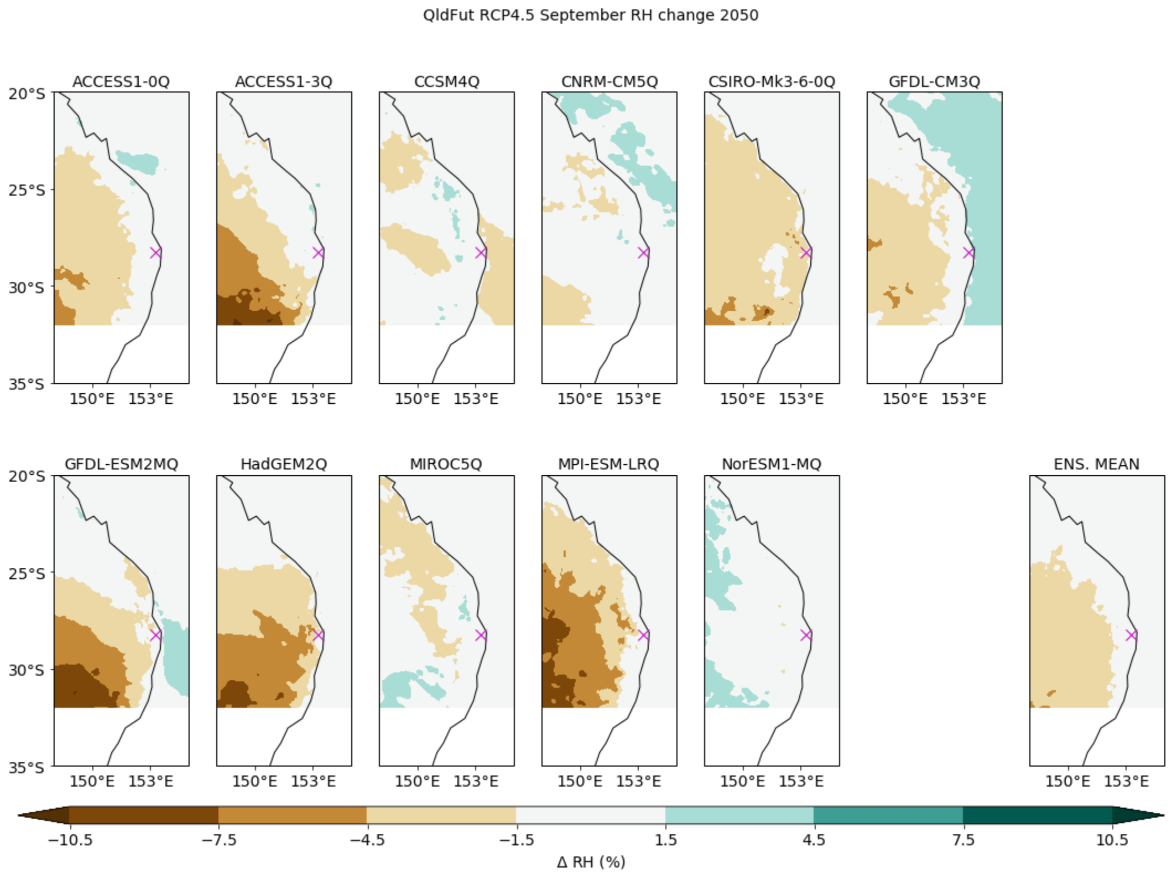

Figure A3.3: September relative humidity change by 2050 for the Queensland Future Climate RCP4.5 (medium emissions) experiments. Changes are calculated by comparing the 2040–2059 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

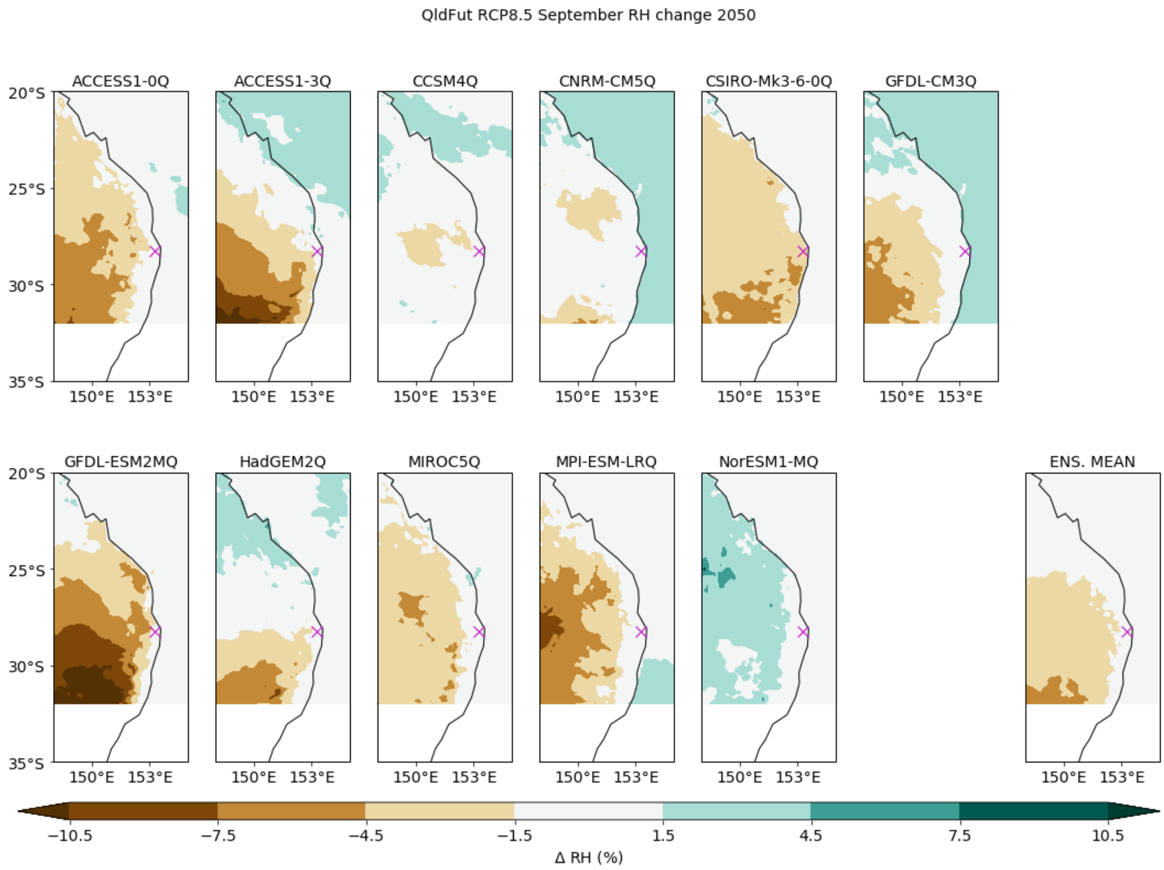

Figure A3.4: September relative humidity change by 2050 for the Queensland Future Climate RCP8.5 (high emissions) experiments. Changes are calculated by comparing the 2040–2059 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

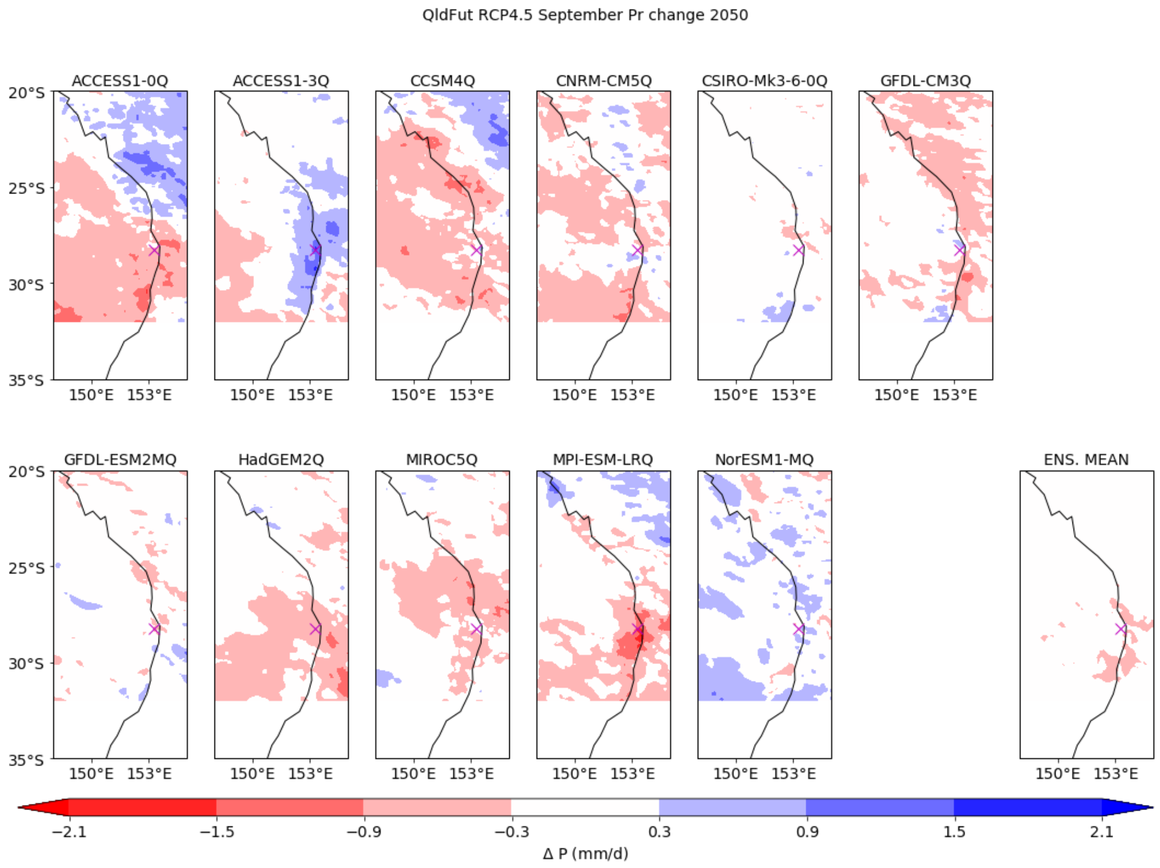

Figure A3.5: September rainfall change by 2050 for the Queensland Future Climate RCP4.5 (medium emissions) experiments. Changes are calculated by comparing the 2040–2059 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

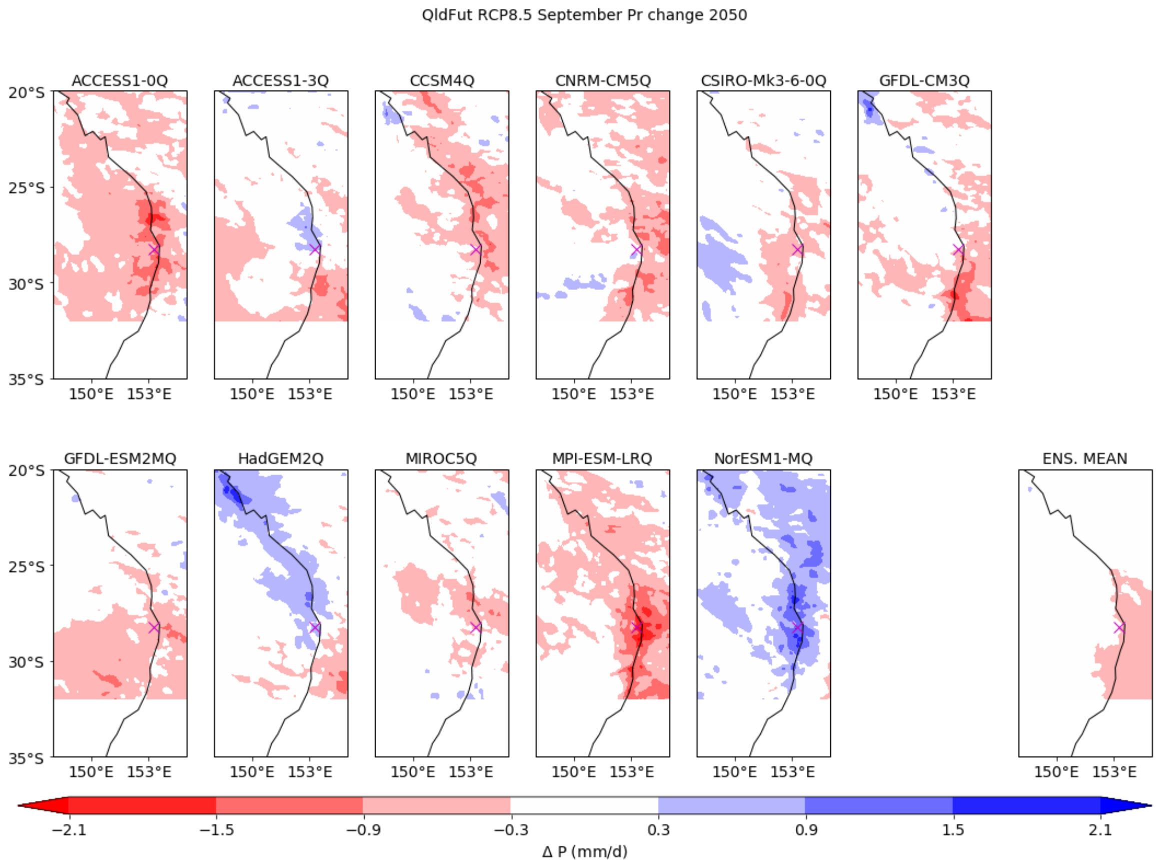

Figure A3.6: September rainfall change by 2050 for the Queensland Future Climate RCP8.5 (high emissions) experiments. Changes are calculated by comparing the 2040–2059 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

Appendix 4: Projected changes in temperature, relative humidity and rainfall by 2070

The following maps are for the projected September change in temperature, relative humidity and rainfall by 2070 (2060–2079). The changes are calculated by subtracting the corresponding monthly climatologies from the period 1990–2009. The periods analysed here were chosen to maximise the concurrent times between the NARCliM and Queensland Future Climate ensembles.

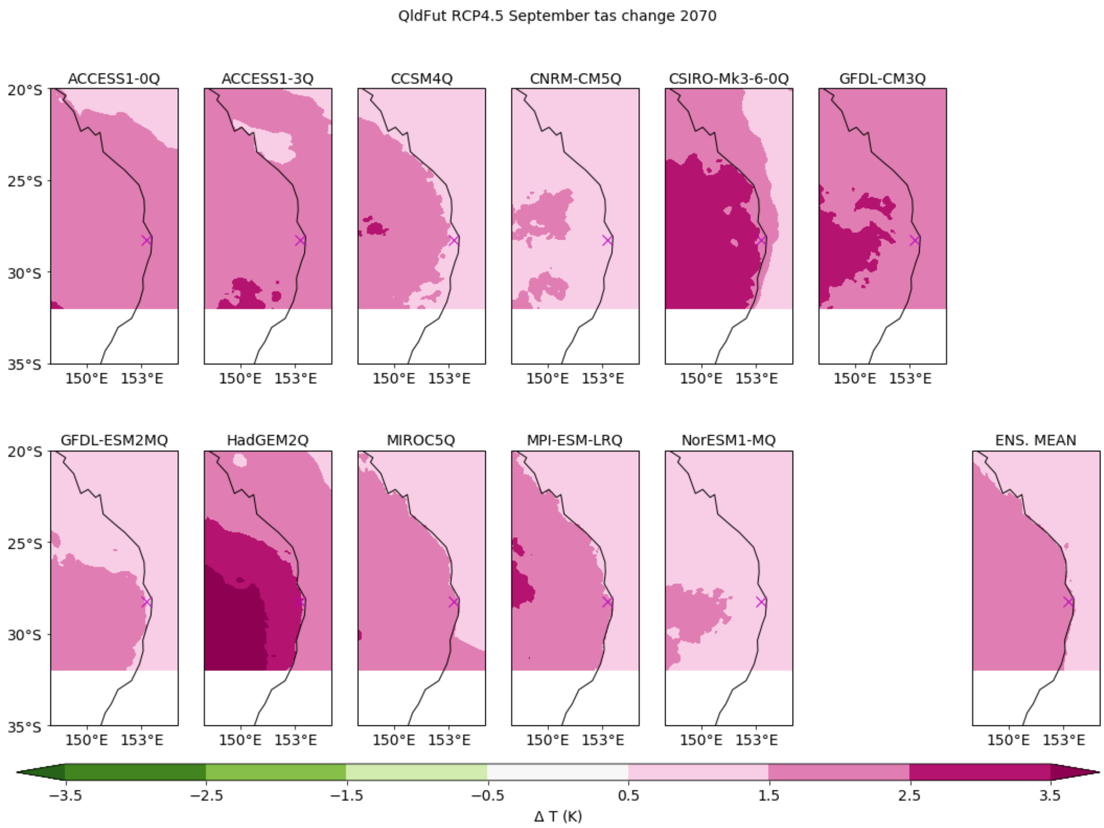

Figure A4.1: September surface air temperature change by 2070 for the Queensland Future Climate RCP4.5 (medium emissions) experiments. Changes are calculated by comparing the 2060–2079 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

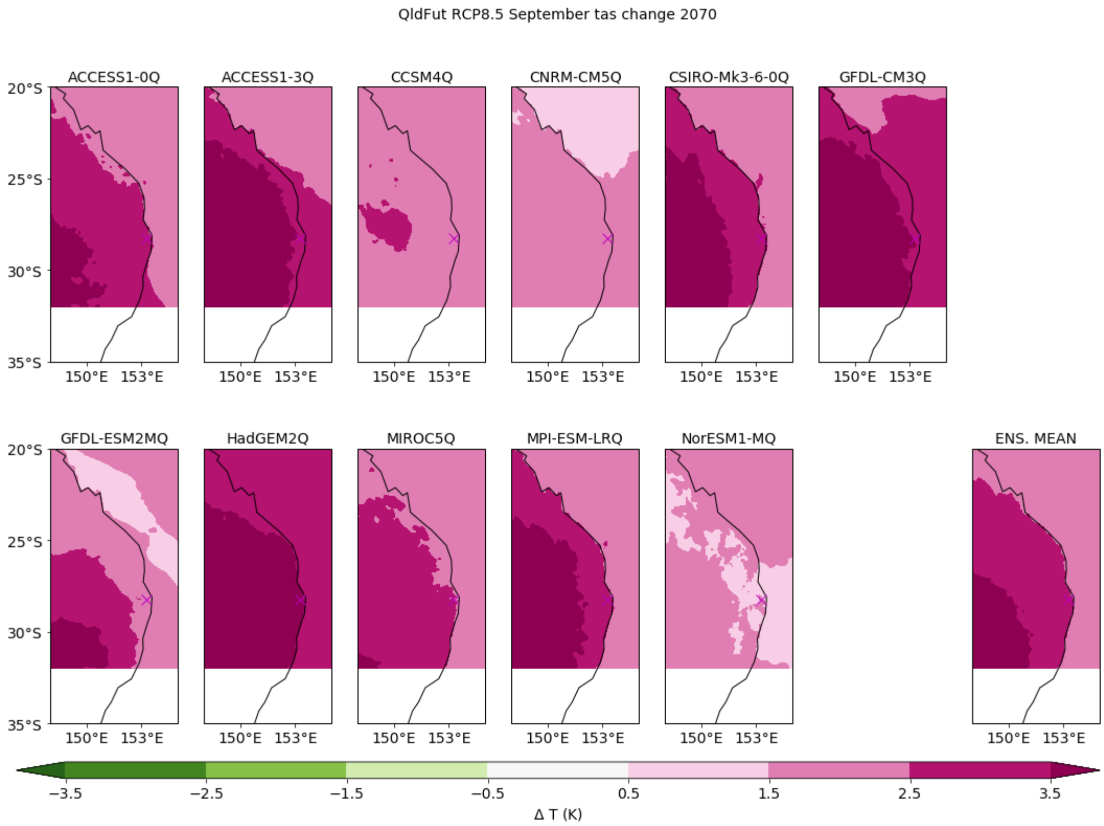

Figure A4.2: September surface air temperature change by 2070 for the Queensland Future Climate RCP8.5 (high emissions) experiments. Changes are calculated by comparing the 2060–2079 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

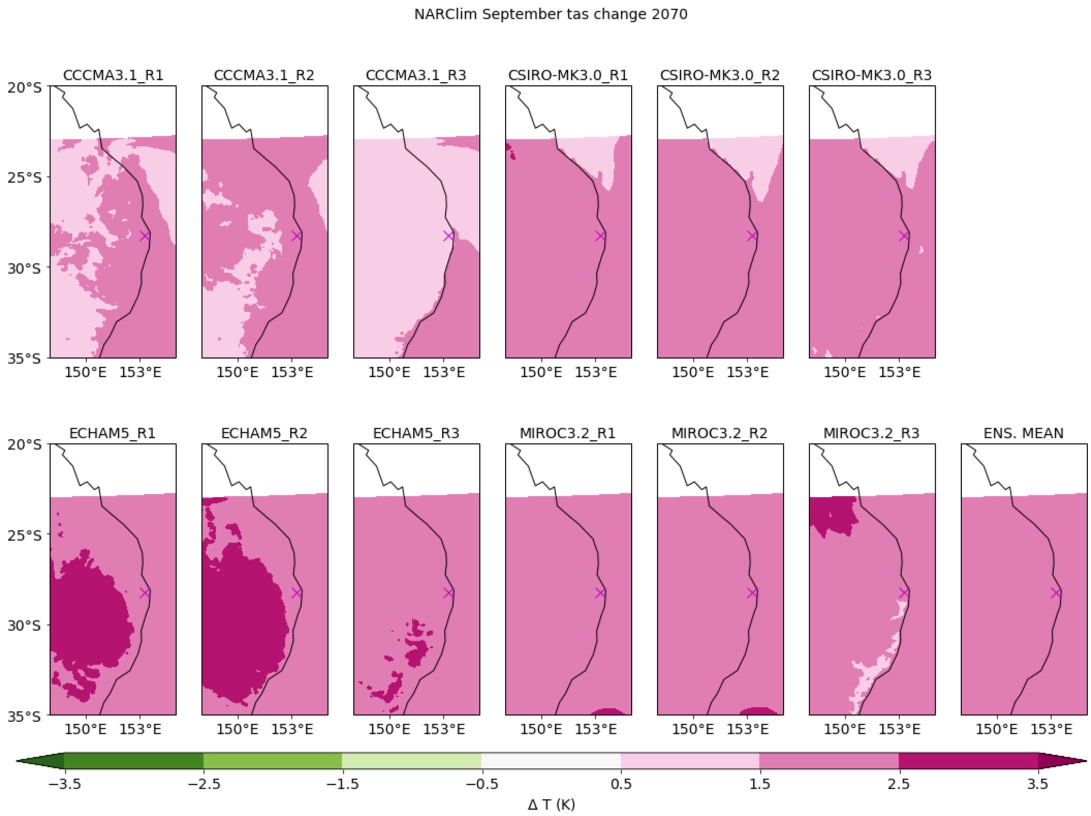

Figure A4.3: September surface air temperature change by 2070 for the NARCliM A2 (high emissions) experiments. Changes are calculated by comparing the 2060–2079 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

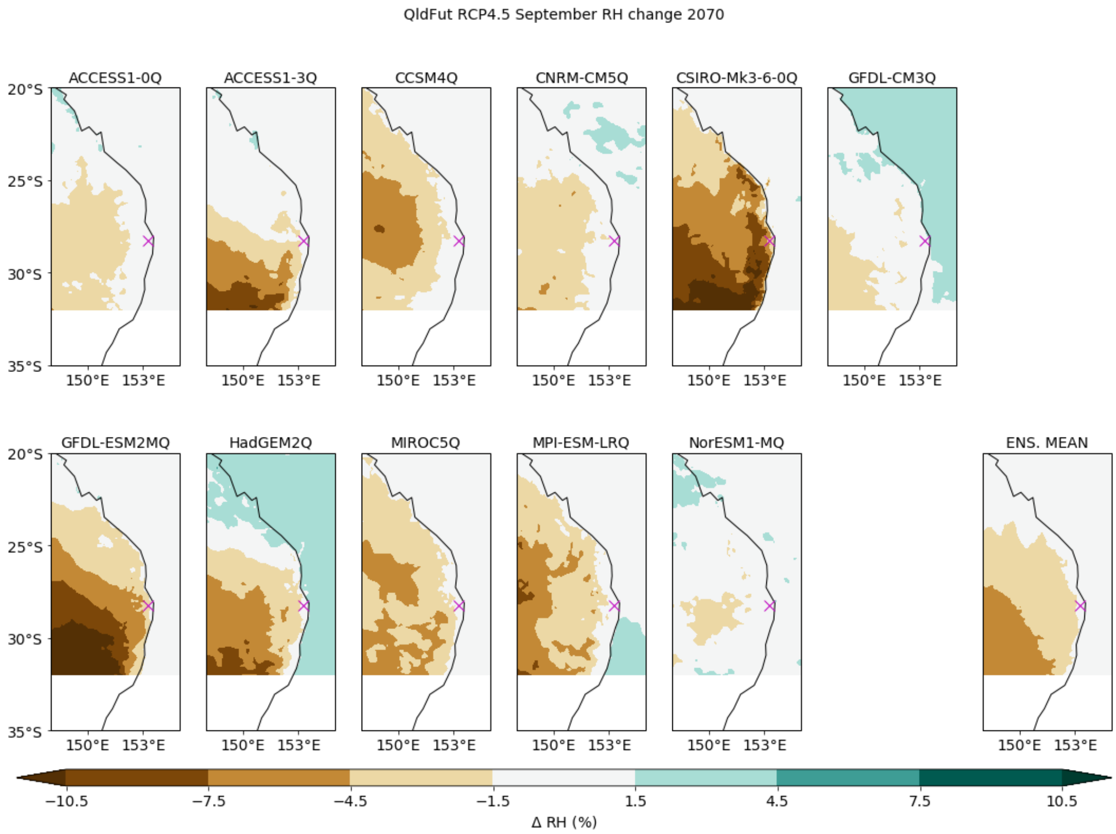

Figure A4.4: September relative humidity change by 2070 for the Queensland Future Climate RCP4.5 (medium emissions) experiments. Changes are calculated by comparing the 2060–2079 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

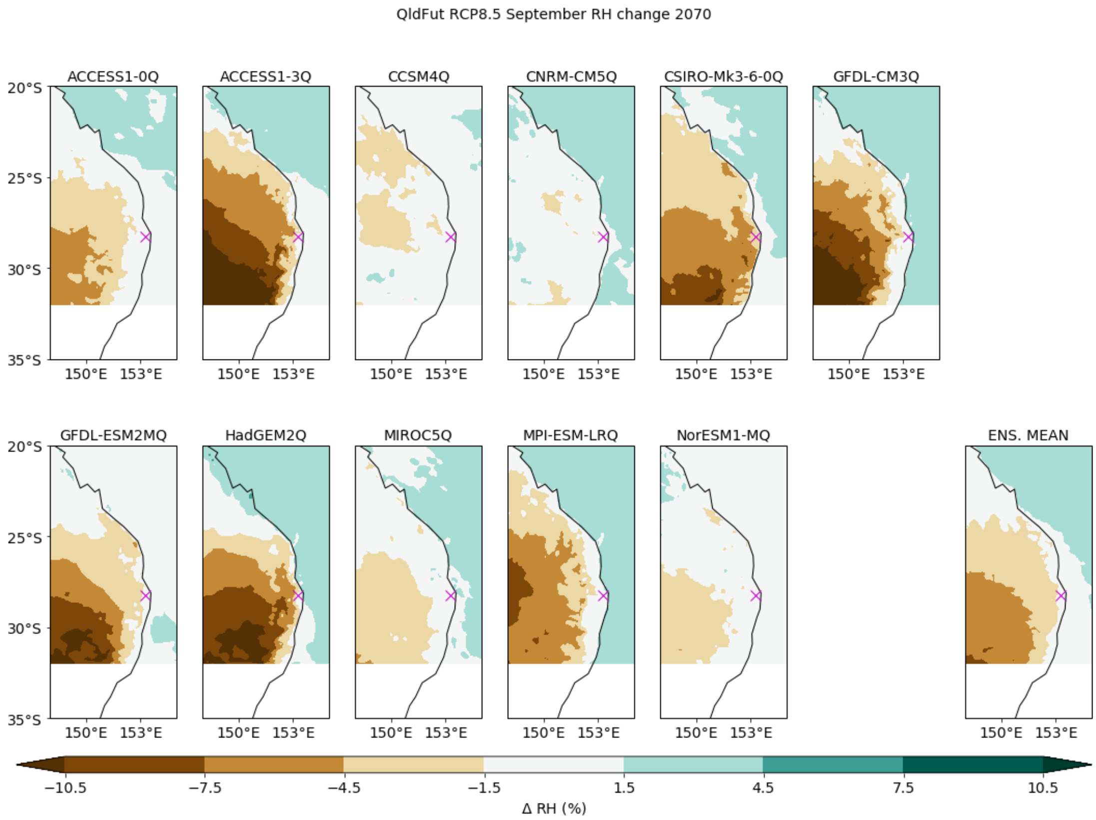

Figure A4.5: September relative humidity change by 2070 for the Queensland Future Climate RCP8.5 (high emissions) experiments. Changes are calculated by comparing the 2060–2079 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

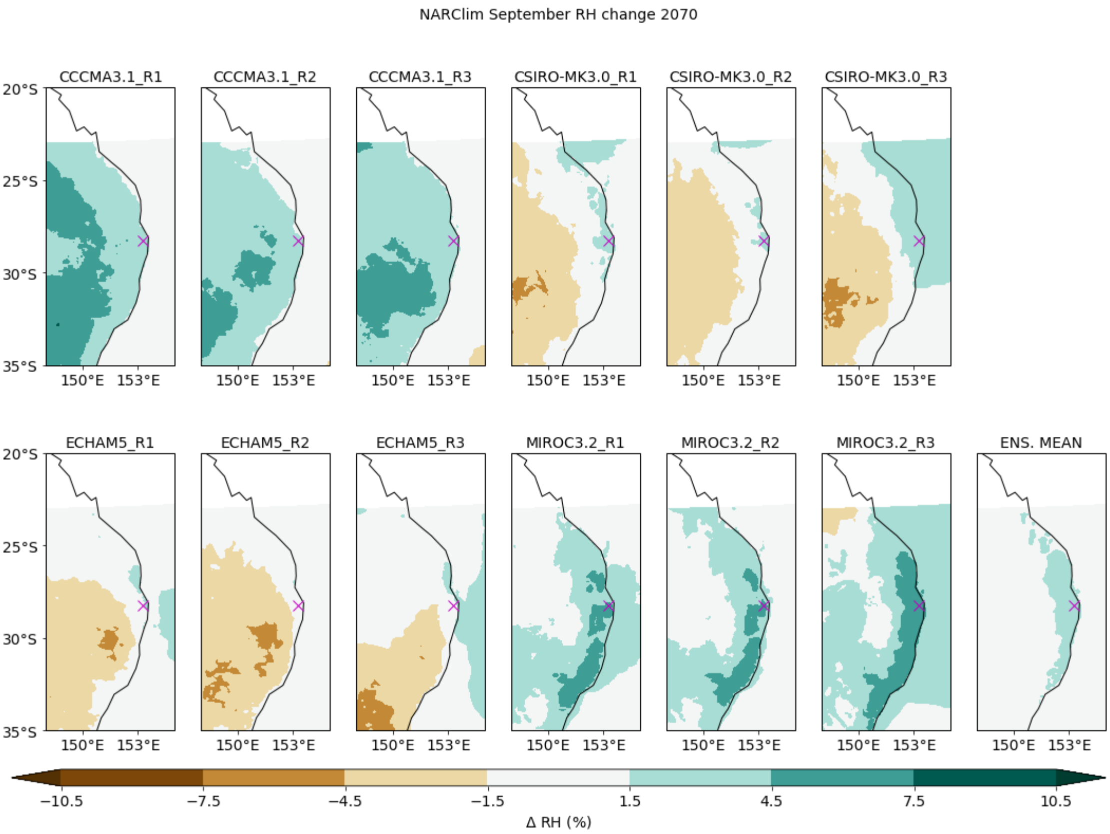

Figure A4.6: September relative humidity change by 2070 for the NARCliM A2 (high emissions) experiments. Changes are calculated by comparing the 2060-2079 and 1990-2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

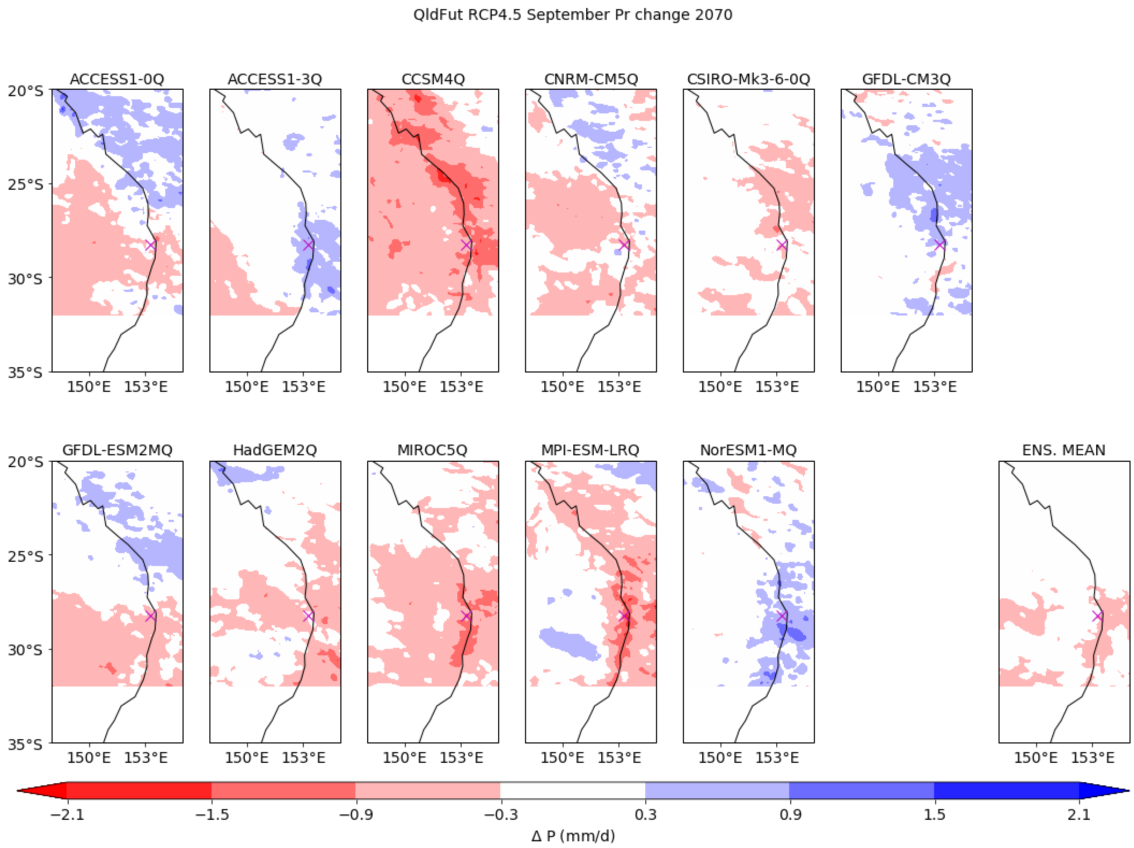

Figure A4.7: September rainfall change by 2070 for the Queensland Future Climate RCP4.5 (medium emissions) experiments. Changes are calculated by comparing the 2060–2079 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

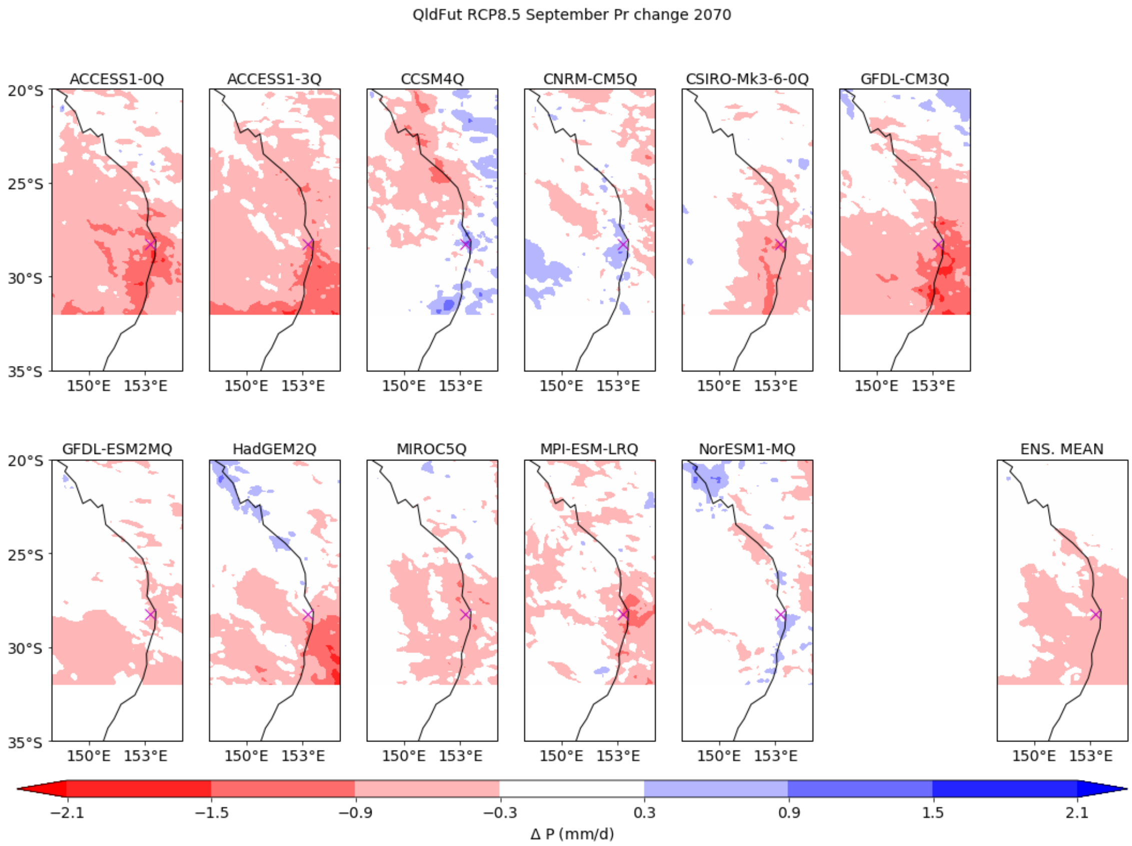

Figure A4.8: September rainfall change by 2070 for the Queensland Future Climate RCP8.5 (high emissions) experiments. Changes are calculated by comparing the 2060–2079 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

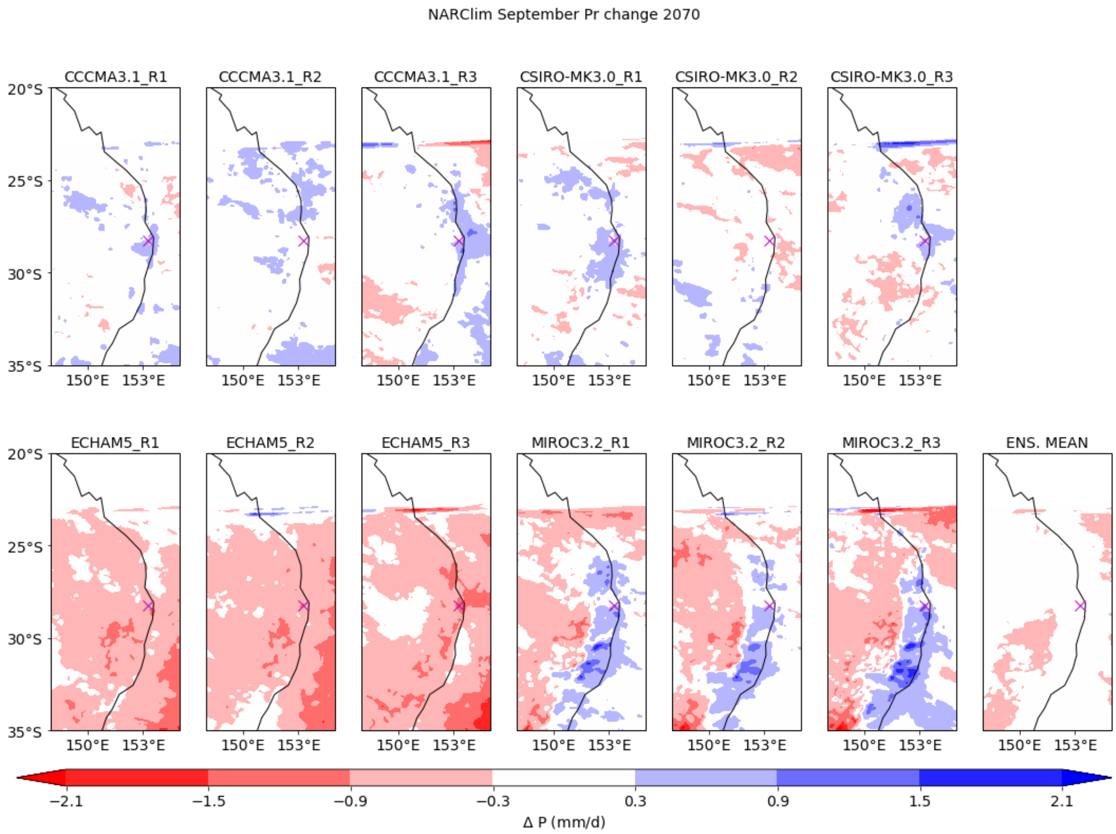

Figure A4.9: September rainfall change by 2070 for the NARCliM A2 (high emissions) experiments. Changes are calculated by comparing the 2060–2079 and 1990–2009 average conditions for each model. The ensemble mean is also shown (bottom right panel). The magenta cross marks the location of the Tweed Caldera.

Appendix 5: Projected changes in LCL from CMIP5 GCMs

The projected changes in LCL are calculated using CMIP5 global models. Note that this samples a larger number of CMIP5 models than those currently available in the QFC project. The methodology applied for this analysis differs slightly to that presented elsewhere in this report, for example longer time periods have been used to calculate the changes.

Here we use the period 1950 to 1999 as a historical baseline, and 2050 to 2099 as the future period. Instead of calculated LCL using an empirical relationship we instead apply an exact solution (Romps 2017). Elsewhere in the report we presented change quantities for the month of September, whereas here we use the September to November season. All of these differences amount to a broader sampling technique, some of which was not possible with the available QFC and NARCliM datasets. Therefore, the results presented here are a useful test of the robustness of the downscaled projections presented in the main body of this report.

Here we show that the majority of CMIP5 models project an increase in September to November cloud base height along the eastern coast of Australia by the late 21st century. This is found for both the medium emissions and high emissions scenarios.

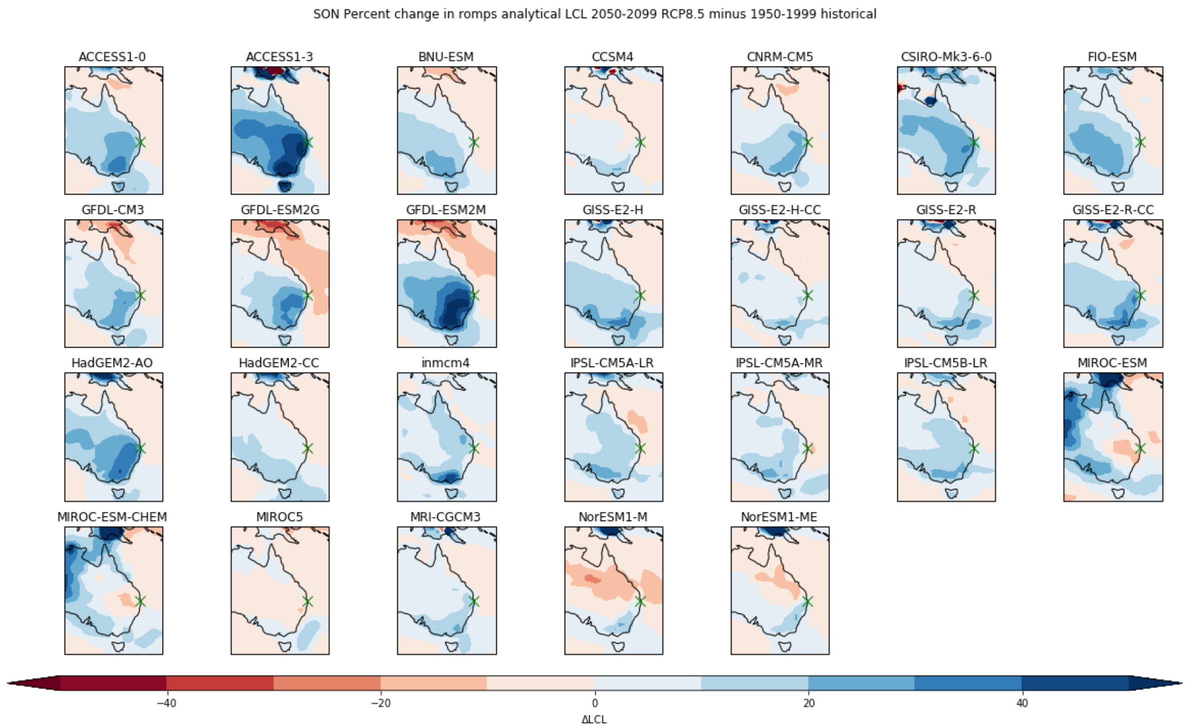

Figure A5.1: Change in LCL for September–November, calculated for models from the CMIP5 RCP8.5 ensemble. Changes are calculated as the difference between the 2050–2099 period minus the 1950–1999 period. The LCL here is calculated using an analytical solution (Romps 2017).

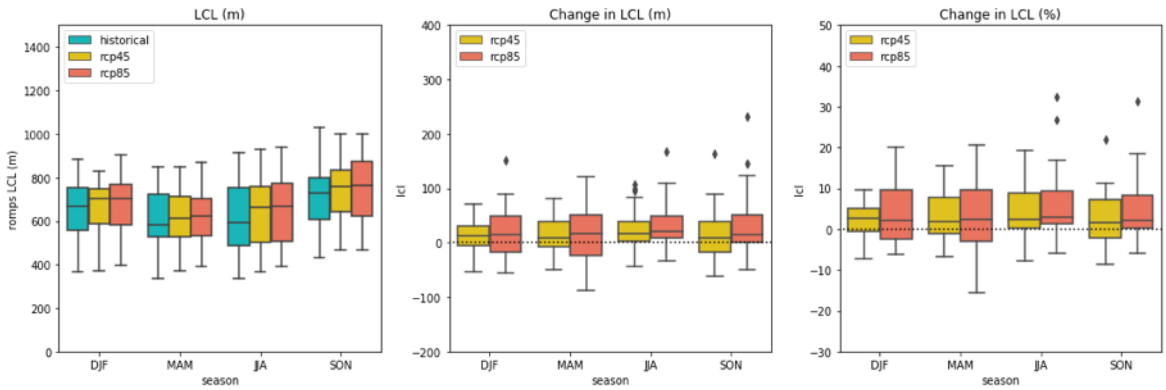

Figure A5.2: Calculated LCL (left), the change in LCL (2050–2099 minus 1950–1999) (centre), and the change in LCL expressed as a percentage change (right), for the grid point nearest to the Tweed Caldera (-28.25°S, 153.25°E). LCL is presented for the historical, medium emissions (RCP4.5) and high emissions (RCP8.5) scenarios.

Reference

Romps DM. 2017. Exact expression for the lifting condensation level. *Journal of the Atmospheric Sciences*, 74(12), 3891–3900.

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