High-resolution climate change projections of atmospheric rivers over the South Pacific

Felix W. Goddard¹, Peter B Gibson², and Neelesh Rampal³

¹National Institute of Water and Atmospheric Research
²NIWA
³National Institute of Water and Atmospheric Research (NIWA)

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Abstract

Atmospheric rivers (ARs) play a critical role in moisture transport across the Southern Hemisphere mid-latitudes and often produce extreme rainfall events across New Zealand. Here we examine ARs in a new set of high-resolution (12km) dynamically downscaled simulations from select CMIP6 models. We begin with a historical evaluation of AR properties from this model ensemble followed by future projections. We demonstrate that by end-of-century, the maximum integrated vapour transport associated with ARs will robustly increase by as much as 20% in some regions of the South Pacific, and ARs contribute a larger proportion (up to 20% more) of the annual precipitation climatology in certain regions of New Zealand. The spatial structure and seasonality of these changes indicate the role of a poleward shift and intensification of the westerly jet. This is further quantified through a decomposition into dynamic and thermodynamic components. While the thermodynamic change dominates the increase in AR frequency, the additional positive dynamical change is notable over the mid-latitudes and southern New Zealand. Separating events using an AR categorisation scale shows that higher category (longer duration, more intense) events more than double in frequency, underscoring the increasing role that ARs will play in extreme weather events in the future in this region.
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Felix W. Goddard¹,², Peter B. Gibson¹, Neelesh Rampal³

¹National Institute of Water and Atmospheric Research, Wellington, New Zealand
²School of Physical and Chemical Sciences, University of Canterbury, Christchurch, New Zealand
³National Institute of Water and Atmospheric Research, Auckland, New Zealand

Key Points:

• Properties of atmospheric rivers are examined in high-resolution simulations over the South Pacific under a high emissions future scenario.
• Atmospheric rivers robustly increase in frequency and intensity, with the most intense events nearly doubling in frequency.
• Frequency changes are mostly thermodynamic in origin; dynamical changes are linked to a poleward shift and intensification of the jet.

Corresponding author: Peter Gibson, Peter.Gibson@niwa.co.nz
Abstract

Atmospheric rivers (ARs) play a critical role in moisture transport across the Southern Hemisphere mid-latitudes and often produce extreme rainfall events across New Zealand. Here we examine ARs in a new set of high-resolution (12km) dynamically downscaled simulations from select CMIP6 models. We begin with a historical evaluation of AR properties from this model ensemble followed by future projections. We demonstrate that by end-of-century, the maximum integrated vapour transport associated with ARs will robustly increase by as much as 20% in some regions of the South Pacific, and ARs contribute a larger proportion (up to 20% more) of the annual precipitation climatology in certain regions of New Zealand. The spatial structure and seasonality of these changes indicate the role of a poleward shift and intensification of the westerly jet. This is further quantified through a decomposition into dynamic and thermodynamic components. While the thermodynamic change dominates the increase in AR frequency, the additional positive dynamical change is notable over the mid-latitudes and southern New Zealand. Separating events using an AR categorisation scale shows that higher category (longer duration, more intense) events more than double in frequency, underscoring the increasing role that ARs will play in extreme weather events in the future in this region.

Plain Language Summary

Atmospheric rivers (ARs) transport considerable amounts of water vapour and their interaction with New Zealand’s mountainous terrain can produce extremely large rainfall totals. The coarse spatial resolution of today’s global climate models makes capturing AR properties and their interaction with terrain difficult, adding to uncertainty around future impacts from ARs. Focusing on the South Pacific, here we present the first regional study examining future projections of ARs from high-resolution model simulations. We find that ARs increase in frequency (up to +5 ARs per year) and in intensity (up to 20% stronger) across the study domain, and also contribute up to 20% more of annual rainfall totals over New Zealand in the future. Both the background warming and changes to atmospheric circulation in this region play an important role in these increases. Overall, our findings underscore the increasing role that ARs will play in extreme weather events in the future in this region.

1 Introduction

Atmospheric rivers (ARs) are narrow filamentary structures of enhanced horizontal water vapour transport in the lower troposphere (Newell et al., 1992; Zhu & Newell, 1994). These structures account for over 90% of poleward vapour transport in the mid-latitudes despite occupying less than 10% of a given latitudinal band, emphasising their importance in the global water cycle (Zhu & Newell, 1998). In recent decades, understanding has grown of ARs and the important roles, both harmful and beneficial, that they play in rainfall and snowfall events (Leung & Qian, 2009; Guan et al., 2010; Little et al., 2019; Guan et al., 2023), precipitation extremes (Stohl et al., 2008; Nayak & Villarini, 2017; Neiman et al., 2016; Ralph et al., 2016), runoff and flooding (Guan et al., 2016; Ralph et al., 2006; Neiman et al., 2013, 2011), extreme winds (Waliser & Guan, 2017), water resources (Dettinger et al., 2011), and ending drought events (Dettinger, 2013; DeFlorio et al., 2024).

A number of studies have produced regional AR climatologies for the present day climate (e.g. Neiman et al. (2008); Mundhenk et al. (2016); Debbage et al. (2017); Kamae et al. (2017); Wu et al. (2020); Viale et al. (2018)). These studies demonstrate consistent patterns in AR occurrence, notably a close association of AR tracks with the position of the westerly jet and a seasonality reflective of seasonal shifts in the jet position. The contribution of ARs to precipitation varies substantially by region and season, but may exceed 30% of annual precipitation totals in parts of Western Europe, North and
South America, Australia, New Zealand, the Middle East, and South Asia (Neiman et al., 2008; Lavers & Villarini, 2015; Guan & Waliser, 2015; Nash et al., 2022). In areas where landfalling ARs interact with steep terrain, orographically-forced uplift results in significantly higher precipitation amounts.

Other studies have indicated the South Pacific as a region of interest for ARs. This includes the historical frequency and general impact of ARs, as well as studies noting the potential for large ‘hotspot’ AR changes in this region under climate change (e.g. Espinoza et al. (2018)). However, only in recent years have more comprehensive regional studies focused on AR impacts in New Zealand. The Southern Alps lie northwest–southeast along the west coast of New Zealand’s South Island, providing a topographic barrier that, through orographic forcing, generates the country’s highest annual rainfall totals (Henderson & Thompson, 1999; Wratt et al., 1996). The synoptic conditions that lead to AR landfall in New Zealand favour this rainfall generation, with > 90% of extreme rainfall measured at stations in the central Southern Alps being attributable to ARs (Prince et al., 2021).

The most extreme flood and snowfall events for locations in the Southern Alps are associated with ARs (Kingston et al., 2022; Cullen et al., 2019), and ARs contribute substantially to glacier mass balance in the Alps (Little et al., 2019).

A detailed climatology of ARs for New Zealand was presented by Prince et al. (2021), showing a reduction in winter AR frequency consistent with findings of other studies for the western side of an ocean basin. However, the wintertime separation of the subtropical and eddy-driven jets, a unique circulation feature of the Southern Hemisphere (Bals-Elsholz et al., 2001), allows AR frequency to remain high in the North Island even while the eddy-driven jet seasonally shifts south away from New Zealand.

It is expected that ARs will increase in frequency and intensity in a warming climate due to basic thermodynamic considerations. A Clausius-Clapeyron rate of increase in the moisture capacity of the atmosphere at 7% K$^{-1}$ leads to approximately a 9.5% K$^{-1}$ increase in column-integrated water vapour and hence a similar change in IVT (Payne et al., 2020). The change in IVT due to dynamical processes is far less certain due to the many competing factors, including the position and intensity of changes to the jets. For example, Shields and Kiehl (2016) and Payne and Magnusdottir (2015) each find an equatorward shift in the landfall locations of ARs on the west coast of the United States associated with a strengthening of the subtropical jet. However, Gao et al. (2015) reports a pole- and westward shift in AR frequency in the North Pacific due to dynamical changes associated with expansion of the Hadley cell, and Ma et al. (2020) find a poleward shift in AR frequency in the Southern Hemisphere due to a shift in the position of the jet. Responses of AR precipitation to future warming are expected to be smaller than the rate of IVT increase. For example, Hagos et al. (2016) found a 28% increase in the frequency of extreme AR precipitation in contrast to a 35% increase in landfalling AR frequency over the west coast of North America, owing to increases in static stability in a warmer future. However, the importance of orographic forcing to AR precipitation in many regions further complicates this, with orographic precipitation increasing at potentially super-Clausius-Clapeyron rates (Shi & Durran, 2014). At present, no detailed studies at a regional scale have examined how the properties of ARs impacting New Zealand are projected to differ under climate change.

This work expands on a number of research gaps identified above by providing projections of ARs for New Zealand and the South Pacific from a new set of high-resolution downscaled simulations. This differs from previous AR projections which have used low-resolution models at a global scale. The improved representation of New Zealand’s mountainous terrain afforded by this increased resolution allows for more accurate determination of the interaction between ARs and topography and hence the changes to orographic forcing in the future period. We also use the system of AR categorisation developed by Ralph et al. (2019) to specifically examine the most extreme AR events. New Zealand’s unique position as a mountainous island in the Southern Hemisphere mid-latitudes,
central to where future changes to the jet are projected (Gibson, Rampal, et al., 2024), provides an internationally significant region for comprehensively studying changes in ARs. The remainder of the work is organised as follows. Section 2 describes the data sources and AR tracking methodology implemented. We present and discuss the results of our analysis in section 3. First, we evaluate the skill of high-resolution simulations in representing ARs relative to reanalysis. Then we consider how AR frequency and intensity are projected to change under a high emissions scenario and break down the frequency of ARs into categories of increasing severity (see Section 2.3). Finally we decompose the AR changes into thermodynamic and dynamic contributions.

2 Methodology

2.1 Data sources

We examine six models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) which have been dynamically downscaled from their native resolutions to a resolution of 12 km over New Zealand and 12–35 km over the South Pacific. These models were selected for downscaling on the basis of their performance over the historical period, including evaluation against processes-based metrics focused on large-scale atmospheric circulation. Model independence and spread in warming rate across models were also considered when selecting a balanced ensemble of GCMs to downscale. Further details of the experiment design and historical evaluation are presented in (Gibson, Stuart, et al., 2024). Additionally, while not part of CMIP6, the NZESM (Williams et al., 2016) has been downscaled through the same approach, and is also included here.

Downscaling was performed using the Conformal Cubic Atmosphere Model (CCAM) (McGregor & Dix, 2008), a global non-hydrostatic atmosphere model that implements a variable-resolution conformal cubic grid to enhance resolution in the region of interest relative to the rest of the globe. CCAM was run with 35 vertical levels in the atmosphere and a 4-minute dynamical timestep. Four host models (ACCESS-CM2, EC-Earth3, NorESM2-MM, and NZESM) were downscaled by spectrally nudging CCAM to the host model atmospheric conditions, sea surface temperatures (SSTs), and sea ice concentrations (SICs). Atmospheric spectral nudging was applied to 6-hourly surface pressure, winds, and air temperature for levels between 850 hPa and 10 hPa. Three other host models (AWI-CM-1-1-MR, CNRM-CM6-1, and GFDL-ESM4) were downscaled by driving CCAM only from the host model SSTs and SICs after bias-correction was applied. Downscaled model fields used in this study were output at 6-hourly temporal resolution on a regular latitude/longitude grid with a horizontal resolution of 0.3125°×0.3125° and 16 pressure levels between 1000 hPa and 10 hPa.

For model evaluation purposes, we compare the downscaled simulations against ERA5 reanalysis (Hersbach et al., 2020) at 0.25°×0.25° horizontal and 6 hourly temporal resolution. We consider two time periods in our analysis: the historical (1986–2005) and future period (2080–2099). The historical period was used primarily for model evaluation. For the future period, we considered a relatively high emissions scenario from SSP370.

2.2 AR tracking

ARs were identified using a combination of criteria based on the tracking schemes of Guan and Waliser (2015) and Ullrich et al. (2021). Primarily, we used the Tempes-tExtremes tracking framework (Ullrich & Zarzycki, 2017; Ullrich et al., 2021) to identify candidate AR grid cells based on the Laplacian of the magnitude of the vertically-integrated water vapour transport (IVT) field. To identify a candidate AR point, the Laplacian was required to be less than \(-2 \times 10^4 \, \text{kg} \, \text{m}^{-1} \, \text{s}^{-1}\). Instantaneous contiguous regions of candidate AR points were required to cover a total area greater than 4×
$10^5 \text{ km}^2$ and points within $15^\circ$ latitude of the equator were discarded. AR objects were then identified as contiguous regions of candidate points that overlapped by at least 20% at adjacent 6 hourly time steps and thereby assigned unique identifiers.

The IVT field was calculated from CCAM output as

$$\overrightarrow{\text{IVT}} = \frac{1}{g} \int q\vec{v} \, dp$$

(1)

where $g$ is the gravitational acceleration, $q$ is the specific humidity, $\vec{v} = (u, v)$ is the horizontal wind vector, and the integration is carried out from surface pressure to the model top.

The choice of the TempestExtremes framework was motivated by the application of the detection algorithm to examine future projections of ARs. Other AR detection techniques include fixed thresholds of anomalous IVT (e.g. 140 kg m$^{-1}$ s$^{-1}$ (Kamae et al., 2017); 250 kg m$^{-1}$ s$^{-1}$ (Mundhenk et al., 2016)), location-specific thresholds based on the IVT distribution (e.g. the 85th percentile (Guan & Waliser, 2015); the 99th percentile (Warner & Mass, 2017)), or thresholds based on vertically-integrated water vapour (IWV; e.g. IWV > 2 cm (Dettinger et al., 2011; Neiman et al., 2008)). Methods based on a fixed threshold were deemed less appropriate for studying future changes due to changes in the background IVT field which would yield a high false detection rate. Methods based on an IVT percentile calculated over the whole period of data would also suffer from a changing background IVT. In contrast, the method used here, based on the Laplacian of IVT, is relative to the background IVT field and hence scales more appropriately with changes to the background climatological IVT.

The AR objects identified by the TempestExtremes algorithm were subjected to three further filtering criteria: (1) the mean direction of IVT weighted by the IVT magnitude evaluated across the whole object is poleward; (2) the aspect ratio of the object is > 2 for at least half the object’s lifetime; (3) the length of the object is > 1000 km for at least half the object’s lifetime. The length of the AR object is calculated as the largest great circle distance between any pair of points in the object. The aspect ratio is calculated as the object length/width, where the width is an effective width such that the product of the object’s length and width gives its total area.

The thresholds for these additional criteria were informed by previous work on AR detection. A great diversity of AR tracking algorithms exist in the literature and it has been shown that this diversity can impact measured properties of ARs (O’Brien et al., 2022). Enabled by the flexibility of the TempestExtremes tracking algorithm, we further carried out extensive sensitivity testing to these tracking criteria. The impact of these criteria on the distribution of tracked ARs is generally relatively small and spatially isolated. In the subtropics, particularly the Coral Sea, the TempestExtremes algorithm is likely to erroneously detect cyclones that are then excluded by criteria (1) and (2). Around the borders of the domain, objects crossing the domain boundary are abruptly permitted or excluded by the length and area thresholds. Importantly, the impact of these different filters is minimal (i.e. spatially restricted) when considering the climate change signal of ARs. Within the center of the domain, and around New Zealand, which is the focus here, our results are robust to these somewhat subjective decisions in the tracking algorithm. Various results for different tracking scheme configurations are shown in Figure S1.

### 2.3 AR frequency & intensity measures

We investigate AR properties from an Eulerian viewpoint, i.e. measures such as frequency and intensity are calculated based on the properties of each continuous period of AR conditions on a grid point basis. “AR event frequency” is given by the number of these AR periods.
Ralph et al. (2019) define a scale for categorising ARs (Figure 1) based on duration and intensity, intended to describe how beneficial or destructive they may be. This scale was designed based on the properties of ARs landfalling on the west coast of North America, however Guan et al. (2023) extend this to classify ARs globally. They found that, while the socioeconomic impacts of ARs vary regionally in ways the scale cannot fully account for, it remains valuable for providing consistent approach to communicating AR impact. Prince et al. (2021) applied the scale in constructing a climatology of ARs for New Zealand, demonstrating that, as expected, lower frequency high category ARs generate larger precipitation totals across the country.

We categorise ARs following the Ralph et al. (2019) scale from an Eulerian viewpoint, assigning a category to each continuous period of AR conditions for each grid cell.

### 2.4 Dynamic & thermodynamic components

Following Gao et al. (2015) and Ma et al. (2020), we further construct an alternative set of IVT data for each model in which the seasonal mean humidity is scaled according to the climatological mean humidity for each season. In particular, the humidity is multiplied by a factor $q_c/q_m$ where $q_c$ is the climatological mean humidity for each grid cell and season (evaluated over the entire period of the data, i.e. 1986–2099) and $q_m$ is the mean humidity for each grid cell and season of that year. The IVT calculated from this scaled humidity field is then used to track ARs following the same procedure described above. This effectively serves to de-trend the humidity field, removing the component of change in IVT due to thermodynamic increases in the water vapor carrying capacity of the atmosphere. From this, the dynamical and thermodynamic contributions can then be decomposed.
3 Results and discussion

3.1 Model Evaluation

We begin by evaluating historical properties of ARs in the downscaled models over the historical period. Figure 2 shows the frequency of AR events in austral summer (December–January–February) and winter (June–July–August) for ERA5 reanalysis alongside each of the seven dynamically-downscaled simulations. There is good qualitative and quantitative agreement between the reanalysis and models, which successfully reproduce the pronounced seasonal cycle observed in ERA5. The domain-average RMSE relative to ERA5 is $< 1.6$ year$^{-1}$ for all models (Figure S2), with a multimodel mean RMSE of 0.87 year$^{-1}$ in austral summer and 1.1 year$^{-1}$ in austral winter. Pattern correlations between each model and ERA5 are strong ($> 0.93$ in summer, > 0.85 in winter).

In terms of biases, the three models driven only by SSTs/SICs (GFDL-ESM4, AWICM-1-1-MR, and CNRM-CM6-1) tend to exhibit slightly increased AR frequencies relative to the other models and ERA5 in the vicinity of the westerly jet (approx. 50°S). This difference is strongest in summer, but also evident in the polar branch of the jet in winter to a lesser extent. Other studies have noted a tendency for CCAM to produce an overly strong jet in this region, though mostly confined to winter (Gibson et al., 2023). This suggests that both thermodynamic and dynamic contributions make up the differences in AR frequency shown here.

Each model appears to successfully capture the main pattern of austral summer AR frequency shown in ERA5. There is a strong influence of the midlatitude jet, with a relatively uniform zonal structure through 35°–60°S and a meridional structure peaking around 50°S, reflecting the jet position. We also note that each model is able to capture the localised reduction in AR frequency over and east of New Zealand, which is observed in ERA5. This reflects the role of New Zealand’s orography in depleting atmospheric moisture and terminating ARs as they pass over the country. A similar reduction in AR frequency is seen east of Australia due to the dryness of air originating from over the continent. In the subtropics, AR frequency tends to increase east of New Zealand, however model agreement is weaker in this region. Each model is similarly successful in capturing the austral winter distribution of AR frequency. This reflects the southern hemisphere split jet, displaying two localised peaks in AR frequency, one south and west and another north and east of New Zealand. The peak value of AR frequency is comparable between austral summer ($12.4 \pm 1.2$ year$^{-1}$; uncertainty is half the model spread) and winter ($12.2 \pm 0.7$ year$^{-1}$), however the location of the peak shifts dramatically.

As an indicator of intensity we next evaluate the proportion of total annual precipitation attributed to ARs (Figure 3). Again there is good agreement both qualitatively and quantitatively between models and reanalysis in capturing spatial patterns and interseasonal variability. As with AR frequency, the models driven only by SSTs/SICs see slightly higher fractions of total precipitation due to ARs across the subtropics in summer ($+9 \pm 2\%$ north of 35°S). This difference is largely constrained to summer, though other regional differences are apparent between models in winter (e.g. ACCESS-CM2).

In both seasons each model is able to broadly capture the contribution of ARs to total precipitation. The average peak contribution from ARs across models is 70–80\% and occurs in the subtropics. The contribution over New Zealand is 20–40\% in austral summer and 0–20\% in winter, similar to that reported for other important AR regions globally (Neiman et al., 2008; Lavers & Villarini, 2015; Guan & Waliser, 2015; Nash et al., 2022).

The mean bias in AR precipitation fraction relative to ERA5 is greatest in winter for all models, with the largest biases (both positive and negative) occurring over Australia (Figure S3). However, this region has relatively very few ARs annually and large parts of inland Australia receive very low annual rainfall (Figure 2). As such, relatively
small differences in the number and precipitation intensity of modelled AR events can produce seemingly large changes in the modelled precipitation fraction.

As a measure of AR intensity, we also evaluate the climatology of maximum intensity of IVT during ARs (Figure 4). As shown, the models capture well the AR intensity from ERA5. Each model has an RMSE in mean maximum IVT relative to ERA5 between 70 and 160 kg m$^{-1}$ s$^{-1}$. Generally, biases are greater in the subtropics and in summer (Figure S4). Pattern correlations for each model with ERA5 are strong (> 0.75 in summer, > 0.83 in winter). As shown earlier for AR frequency, the three models driven only by SSTs/SICs see slightly larger positive biases in AR intensity.

While certain biases have been described above, these comparisons suggest that overall the CCAM downscaled models are capable of reproducing the main aspects of AR frequency, intensity and related precipitation, as well as their seasonal variability. This suggests the physical processes governing AR properties and behaviour are well represented, providing a degree of confidence in the related future projections.

### 3.2 Future projections

Figure 5a shows the change in AR frequency between the historical and future periods in austral summer and winter for each model. The multimodel mean is shown in the upper left of Figure 5a for each season, where stippling indicates regions where fewer than six of seven models agreed (i.e. less than 86% model ensemble agreement) on the sign of the change. Previously, in the historical evaluation, differences were identified between the models driven only by SST/SIC and those with full atmospheric nudging. However, these differences are not evident in the changes in AR frequency between the historical and future periods.

The models show a robust increase in the frequency of ARs at latitudes between approximately 30°S and 70°S and peaking at a zonal mean change of around +5 year$^{-1}$ (+4 year$^{-1}$) at 50°S for austral summer (winter). This band of increasing AR frequency, also evident in the zonal mean (Figure 5b), is co-located with the position of the westerly jet. In winter, this band of AR frequency change is distributed over a wider range of latitudes and has a lower peak value, potentially associated with the splitting and weakening of the climatological polar branch of the jet (Bals-Elsholz et al., 2001). Note that the values shown in Figure 5 are absolute differences. In terms of the relative change in AR frequency, it is noteworthy that over the South Island of New Zealand in winter, and further towards the pole, this equates to a more than doubling of AR frequency in the future.

In the subtropics, model agreement is weaker but shows a slight decrease in AR frequency, up to a peak reduction of −4 year$^{-1}$. In austral summer, the reduction in zonal mean AR frequency is seen only in the lower ECS models GFDL-ESM4 and AWI-CM-1-1-MR, whereas in austral winter it occurs in all models except for EC-Earth3. The wintertime reduction is co-located with the subtropical branch of the split jet. The projected change in AR frequency in this region has a meridional structure suggestive of a poleward shift in the position of the subtropical jet. This is consistent with findings from both observations (Fu & Lin, 2011; Fu et al., 2006) and model studies (Kushner et al., 2001; Lorenz & DeWeaver, 2007) of a climate change-induced poleward shift in the location of the subtropical jet.

Models with a higher ECS generally show greater increases in AR frequency, as illustrated in Figure 5c. This is expected from a thermodynamic standpoint, with ‘warmer’ models experiencing a greater increase in atmospheric moisture content. The linear correlation between spatial-mean frequency change and ECS is strong in the mid-latitudes ($r = 0.92$ in summer, $r = 0.77$ in winter over 35–66.5°S) but weaker in the subtrop-
ics ($r = 0.47$ in summer, $r = 0.20$ in winter over 0–35°S). How model ECS modulates the dynamic controls on AR frequency are considered further in Section 3.4.

The change in the proportion of precipitation related to ARs is shown in Figure 6 for each model and the multimodel mean. As earlier, stippling on the multimodel mean indicates regions where fewer than six of seven models agree on the sign of the change. In general, there is a relatively large increase in the fraction of precipitation associated with ARs. In the multimodel mean there is good agreement across the Southern Ocean, with a summer (winter) average absolute increase of $+7.0 \pm 3.7\%$ ($+6.3 \pm 3.3\%$) from 35 to 66.5°S and a peak value of $+20\%$ occurring in winter over New Zealand’s Southern Alps. These increases indicate that ARs will play a larger role in the precipitation climatology of these regions in the future. However, it is noteworthy that the spatial pattern of this projected precipitation change differs more across models compared to the AR frequency change reported earlier. Model agreement is generally smallest in the subtropics, where the spatial correlation between models in summer (winter) is $r = 0.07 \pm 0.08$ ($r = 0.07 \pm 0.13$).

The change in AR precipitation fraction can be attributed to changes in the number of ARs, the precipitation delivered by each AR, and the total precipitation including non-AR sources:

$$\frac{\Delta[\text{AR precip. fraction}]}{\text{[AR precip. fraction]}} \approx \frac{\Delta[\text{AR count}]}{\text{[AR count]}} + \frac{\Delta[\text{per-AR precip.}]}{\text{[per-AR precip.]}} - \frac{\Delta[\text{total precip.}]}{\text{[total precip.]}},$$

(2)

By considering the relative magnitudes of these terms we can evaluate the relative importance of each term to the overall change in AR precipitation fraction.

Over the mid-latitudes, the change in AR precipitation fraction is dominated by the increase in AR frequency (Figure S5). There are modest increases in per-AR precipitation and total precipitation that largely compensate each other. Over the subtropics, these factors each contribute a comparable amount to the change in AR precipitation fraction. As increases in total precipitation (holding other factors constant) act to reduce the fraction of precipitation due to ARs, this acts against increases in AR frequency and per-AR precipitation. The result is therefore a balance of large terms over the subtropics, which is thus one potential source of the model disagreement on the change signal shown earlier.

Figure 7 shows the change in mean maximum IVT intensity of ARs between the historical and future periods for each model and the multimodel mean. There is a notable increase in the mean maximum IVT intensity across the majority of the domain. This increase in AR intensity is generally more robust across models compared to projections of AR frequency and AR-related precipitation described earlier. Only in a few regions and models do localized reductions in AR intensity occur. For AR intensity, somewhat lower agreement on the sign of the change is seen in the subtropics and over Antarctica and the Ross Sea for both seasons.

Larger increases in mean maximum IVT are generally seen in austral summer compared to winter, particularly for the models with higher ECS values (e.g. NZESM and CNRM-CM6-1). Greater variability in IVT magnitude can be seen in austral summer with its broader distribution of AR-associated IVT values (Figure 7b). In both seasons and for all models, the density function shifts toward higher IVT intensity in the future. This highlights that increases in AR intensity will be evident broadly across all categories of ARs, from the weakest to the strongest, which is investigated further in the following section.
3.3 AR categories

Figure 8 shows the decomposition of the multimodel mean AR frequency and change signal into the AR category system described earlier. As before, stippling on the change plots indicate regions where fewer than six of seven models agree on the sign of the change. The most damaging higher category ARs (e.g. AR4 and AR5) occur in more spatially restricted areas including New Zealand (particularly along the West Coast) as reported in previous studies Guan et al. (2023) and Prince et al. (2021).

As expected from the positive shift in the distribution of IVT magnitude, domain-mean AR frequency increases in the future for all categories. This increase is centered around 50°S, with large increases spanning 40 to 60°S, particularly for events in the AR2 to AR4 categories. Lower category (AR1 and AR2) events see slight reductions in frequency in the subtropics, whereas higher category (AR4 and particularly AR5) events see increases in frequency in these regions. This distinct difference in the change pattern may be indicative of a different set of mechanisms controlling the frequency of ARs at either end of the category spectrum.

The largest relative increases in frequency occur for the most damaging AR categories (Figure 8b). These increases have the potential to carry large societal and economic costs for New Zealand, which is centered on the ‘hotspot’ of these changes. For example, the frequency of AR5 events is projected to more than double, with large increases over the West Coast of New Zealand. This is a region where historical AR events (including AR4 and AR5 events) have caused extensive damage to major highways and destruction of critical bridges (Prince et al., 2021). Further more detailed investigation into the nature of these most intense AR changes, such as AR orientation, mesoscale dynamics, and interaction with topography will be the focus of future work. While less pronounced than for New Zealand, the south of Australia and Tasmania are other populated regions where these increases in higher category ARs are also notable and warrant further consideration.

3.4 Dynamic & thermodynamic components of the change

Turning now to the decomposition of the change in AR days into dynamic and thermodynamic components, the annual- and zonal-mean change for each model along with the multimodel mean is shown in Figure 9a. The dynamic component of the change for all models shows a clear dipole structure, indicative of a general poleward shift in the tracks of ARs. All models exhibit approximately the same dynamic change (at least over the mid-latitudes), such that ECS does not appear to be a strong determinant of the latitude or amplitude of the peak change. This is broadly consistent with Gibson, Rampal, et al. (2024), who reported a lack of a clear relationship between ECS and mid-latitude circulation changes in this region in the wider CMIP6 ensemble.

Compared to the dynamic change, the thermodynamic change component of the AR frequency change is generally greater in amplitude, in agreement with findings from other model studies (Payne & Magnusdottir, 2015; Ma et al., 2020). However the model spread is greater for the thermodynamic component than the dynamic component. This likely stems from the differences in ECS between models. Evidence for this is shown where NZESM (red coloured line in Figure 9a) has the largest ECS and shows the largest thermodynamic change component for AR frequency changes. Similarly, the very low ECS models (e.g. NorESM2-MM, blue coloured line) show the smallest change. In all cases the overall spatial pattern of the thermodynamic change is quite consistent between models (Figure S6), with a 2–5% decade$^{-1}$ contribution over much of the mid-latitudes and subtropics and a steep increase in amplitude moving toward higher latitudes. This poleward increase in the thermodynamic change likely reflects the higher rate of regional warming seen at the poles.
Figure 9b shows the multimodel mean decomposition of the change for each season. It can be seen that the dynamic change has a similar amplitude for each season (∼±2% decade⁻¹). However, most notably, in austral summer and autumn (DJF and MAM) the peak change shifts to higher latitudes, with the greatest difference of about 8° latitude between the spring (MAM) and autumn (SON) peaks. This is consistent with the greater summertime poleward shift of the jet seen in CMIP5 and CMIP6 projections (Gibson, Rampal, et al., 2024; Goyal et al., 2021). In contrast, the thermodynamic change component has less readily interpretable seasonal variability (Figure 9a). In austral winter (JJA) the thermodynamic change is slightly stronger over the mid-latitudes and toward the pole and weaker over the subtropics. This is potentially related to the stronger rate of polar warming in austral winter and spring (Smith & Polvani, 2017; Nicolas & Bromwich, 2014). While previous studies have decomposed AR changes into thermodynamic and dynamic contributions for the Southern Hemisphere (e.g. (Ma et al., 2020)), they have done so on an annual basis without seasonal consideration. Our results add to this understanding, showing the importance of seasonality in the dynamic component related to seasonal differences in how the jet is projected to change.

We employ a similar method to Gao et al. (2015) to separate the dynamic and thermodynamic responses of ARs. As noted by those authors, one caveat of the technique is the assumption that the rate of increase of the moisture content within ARs can be approximated by the rate of increase of the mean moisture content for that period. The authors estimate that this approximation leads to an error of at most around 10%. As suggested by Ma et al. (2020), we scale the moisture field for each grid point and level independently, rather than scaling using the whole-domain mean (e.g. Gao et al. (2015)). This is done to better account for horizontal and vertical variation in the moisture field.

4 Conclusions

In this study, we have examined the properties of ARs over New Zealand and the South Pacific region in a new set of high-resolution regional climate simulations (∼12km), and how these are projected to change under a high emissions forcing scenario. This model ensemble provides the highest-resolution projections of ARs to date for this region. Over the historical period, we generally find good agreement between models and reanalysis in both the spatial pattern and magnitude of climatological AR frequency and intensity (Figures 2, 3, and 4), providing a degree of confidence in the associated future projections.

In general, all downscaled models project a notable increase in AR frequency and intensity in the future period for this region. The change in AR frequency shows a strong meridional structure associated with changes in the strength and position of the westerly jet (Figure 5), consistent with previous findings of a poleward shift and intensification in the Southern Hemisphere jet (Fu & Lin, 2011; Fu et al., 2006; Kushner et al., 2001; Lorenz & DeWeaver, 2007; Goyal et al., 2021). The intensity of ARs (measured by maximum IVT) increases across the whole domain, reflecting a general shift in the distribution of AR IVT intensity toward higher values (Figure 7). ARs also contribute a larger fraction of total annual precipitation in the future period: a multimodel average +7.0% across the mid-latitudes, with some models/regions showing increases as large as 20%. This increase is mostly driven by the increase in AR frequency (Figure 6).

Model agreement on the change signal is generally most robust across the mid-latitudes, where the influence of the westerly jet is dominant and its associated change is captured relatively consistently across models. Across the subtropics, model agreement is reduced on all measures (i.e. frequency, intensity, AR-related precipitation) driven by more spatially inhomogeneous change signals across models. Understanding the different sources of model uncertainty between the mid-latitudes and subtropics would be a useful topic for future research.
When considering ARs by category (Ralph et al., 2019) higher category events (i.e. those most destructive) show the largest relative increases in frequency into the future. In some regions, these most destructive AR events may more than double in frequency, which could carry profound societal consequences. Given its latitude, the west coast of the South Island of New Zealand is likely to be most strongly impacted, with large changes to the most destructive events in both summer and winter. Given their similar latitudes, Tasmania and southern Australia are other regions that warrant further focused investigation.

Decomposing the change of AR frequency into thermodynamic and dynamic components shows that the thermodynamic component is the dominant component of the change, as shown previously in studies analyzing raw GCM output (Payne & Magnusdottir, 2015; Ma et al., 2020). Since the thermodynamic component dominates, the spread in ECS across models remains a major contributor to model uncertainty in AR frequency projections. The dynamic change shows a clear dipole structure indicating a poleward shift and intensification in the tracks of ARs. This poleward shift is largest in austral summer and autumn, consistent with the seasonality in the poleward shift of the westerly jet reported previously from CMIP5 and CMIP6.

This study has significantly contributed to our understanding of how ARs in the South Pacific region will respond to climate change. Previous studies on projections of ARs have relied on the raw coarse resolution of CMIP5/CMIP6 GCMs (typically 100-200km) (Espinoza et al., 2018; Massoud et al., 2019). The coarse resolution of these GCMs is known to underestimate the intensity of ARs and associated precipitation, casting further uncertainty in the projections (Rhoades et al., 2020; Payne et al., 2020). Furthermore, previous studies have not considered the historical performance when selecting models for future projections (Espinoza et al., 2018), or when performance is considered, it is done so globally without regional considerations or refinement (Massoud et al., 2019). As such, in this study, the use of high-resolution (12km) downscaled simulations selected from the top-performing (regionally defined) CMIP6 models has lead to highly refined understanding of the projected changes for this region. While dynamical downscaling projects (such as CORDEX) often report projected changes in extreme indices more generally, very few studies have analyzed downscaled projections of ARs. In our experience, this likely stems from data availability in the output of downscaled simulations. We suggest this could be remedied by the CORDEX community through including IVT as a ‘CORE’ or ‘TIER1’ output variable.

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Data Availability Statement

CMIP6 data used in this study is available from the Earth System Grid Federation (ESGF) archive: https://esgf-node.llnl.gov/projects/cmip6/. ERA5 data (Hersbach et al., 2020) used in this study is available from https://doi.org/10.24381/cds.bd0915c6. Access to core variable output from the CCAM ensemble can be obtained through a free NeSI account https://www.nesi.org.nz/services/applyforaccess.
Code Availability

The CCAM model used here is fully open source and made available by CSIRO:
https://confluence.csiro.au/display/CCAM/CCAM. The TempestExtremes package v2.1 used for the detection of atmospheric rivers is available from: https://github.com/ClimateGlobalChange/tempestextremes.

Figure captions

Figure 2. Spatial distribution of annual AR frequency for ERA5 reanalysis and each host model following downscaling with CCAM for austral summer (December–January–February) and winter (June–July–August).
Figure 3. Spatial distribution of the fraction of total precipitation associated with ARs for austral summer and winter for ERA5 reanalysis and each host model following downscaling with CCAM.
Figure 4. Spatial distribution of mean maximum AR IVT magnitude for austral summer and winter for ERA5 reanalysis and each host model following downscaling with CCAM.
Figure 5. (a) Change in the frequency of ARs between the historical (1986–2005) and future (2080–2099) periods in austral summer and winter for each host model following downscaling with CCAM and the multimodel mean. Stippling on the multimodel mean marks regions where fewer than six of seven models agree on the sign of the change. (b) Zonal mean change in AR frequency for each host model following downscaling with CCAM and the multimodel mean. Each host model’s line is coloured from blue to red in order of increasing ECS. (c) Area-weighted mean change in austral summer and winter AR frequency as a function of model ECS for the mid-latitudes (35 to 66.5°S) and the subtropics (15 to 35°S). Shown are the coefficients of determination and slopes for the linear regressions of each frequency change against ECS. Linear slope units are year⁻¹ °C⁻¹.
Figure 6. Absolute change in the fraction of total annual precipitation associated with ARs between the historical (1986–2005) and future (2080–2099) periods for each host model following downscaling with CCAM and the multimodel mean. Stippling on the multimodel mean marks regions where fewer than six of seven models agree on the sign of the change.
Figure 7. (a) Change in the mean per AR maximum IVT intensity between the historical (1986–2005) and future (2080–2099) periods for each host model following downscaling with CCAM and the multimodel mean. Stippling on the multimodel mean marks regions where fewer than six of seven models agree on the sign of the change. (b) Multimodel mean probability density function for the magnitude of IVT associated with ARs in the historical and future periods. The shaded area indicates one standard deviation of the model spread.
Figure 8. (a) Multimodel mean AR frequency by category for the historical and future periods and their difference. Means were taken prior to differencing. Stippling on the difference plots indicate regions where fewer than six of seven models agree on the sign of the change. (b) Whole-domain average change in AR frequency by category.
Figure 9. (a) Zonal mean dynamic and thermodynamic components of the change in number of annual AR days for each host model following downscaling with CCAM. Each host model’s line is coloured from blue to red in order of increasing ECS. (b) Multimodel mean zonal mean dynamic and thermodynamic components of the change in annual AR days for each season. The shaded area indicates one standard deviation of the model spread.

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