A Climatology of Atmospheric Rivers in New Zealand

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ABSTRACT: The occurrence of extreme precipitation events in New Zealand regularly results in devastating impacts to the local society and environment. An automated atmospheric river (AR) detection technique (ARDT) is applied to construct a climatology (1979–2019) of extreme midlatitude moisture fluxes conducive to extreme precipitation. A distinct seasonality exists in AR occurrence aligning with seasonal variations in the midlatitude jet streams. The formation of the Southern Hemisphere winter split jet enables AR occurrence to persist through all seasons in northern regions of New Zealand, while southern regions of the country exhibit a substantial (50%) reduction in AR occurrence as the polar jet shifts southward during the cold season. ARs making landfall on the western coast of New Zealand (90% of all events) are characterized by a dominant northwesterly moisture flux associated with a distinct dipole pressure anomaly, with low pressure to the southwest and high pressure to the northeast of New Zealand. Precipitation totals during AR events increase with AR rank (five-point scale) throughout the country, with the most substantial increase on the windward side of the Southern Alps (South Island). The largest events (rank 5 ARs) produce 3-day precipitation totals exceeding 1000 mm. ARs account for up to 78% of total precipitation and up to 94% of extreme precipitation on the west coast of the South Island. Assessment of the multiscale atmospheric processes associated with AR events governing extreme precipitation in the Southern Alps of New Zealand should remain a priority given their hydrological significance and impact on people and infrastructure.

KEYWORDS: Atmosphere; South Pacific Ocean; Fluxes; Mass fluxes/transport; Water vapor; Precipitation; Atmospheric river; Extreme events; Climatology; Ranking methods; Seasonal variability; Flood events; Orographic effects

1. Introduction

Atmospheric rivers (ARs) are long, transient synoptic-scale plumes of generally poleward moving water vapor that often originate from tropical moisture sources (Neiman et al. 2009). From these source regions, moisture is generally transported to higher latitudes by atmospheric processes associated with a low-level jet stream ahead of a cold front of an extratropical cyclone (Gimeno et al. 2016; Ralph et al. 2018). On average, there are approximately three to five ARs present in each hemisphere at any given point, occupying 10% of the globe's midlatitude circumference while accounting for 90% of the moisture transport in the mid-latitudes (Zhu and Newell 1994; Guan and Waliser 2015). Enhanced precipitation is commonly documented when ARs encounter land and interact with topography (Neiman et al. 2008; Ralph and Dettinger 2011; Ralph et al. 2018).

The weather of New Zealand is broadly governed by the procession of midlatitude cyclonic systems embedded within the westerly wind belt (Sinclair 1994). The exposed maritime position of New Zealand in the midlatitudes (Fig. 1) allows ARs to regularly make landfall. Indeed, estimates from global studies indicate New Zealand ARs occur on average during 9% of days annually, subsequently accounting for 50% of extreme precipitation events (98th

percentile; Waliser and Guan 2017) and 80% of annual runoff (Paltan et al. 2017). A small number of New Zealand-based studies have further demonstrated the critical role of ARs: Kingston et al. (2016) found that the largest floods in a major river draining the Southern Alps were all associated with AR events, as were the largest snow accumulation and glacier ablation events for a Southern Alps glacier (Cullen et al. 2019; Little et al. 2019). Notwithstanding the apparent high importance of ARs for New Zealand climate and hydrology, there have been no national-scale systematic assessments of AR occurrence, frequency, and magnitude.

Automated detection of atmospheric phenomena such as ARs provides a highly useful approach for developing and analyzing large datasets that would otherwise be impractical through manual classification. For ARs, automated detection of events through historical datasets facilitates an understanding of the physical processes determining their occurrence along with the attribution of impacts. Multiple AR detection techniques (ARDTs) have been utilized to study ARs at a global scale using various global atmospheric reanalyses (e.g., Wick et al. 2013; Rutz et al. 2014; Guan and Waliser 2015; Mundhenk et al. 2016). The majority of studies that use ARDTs at the regional scale focus on the United States (Guan and Waliser 2015; Mahoney et al. 2016; Gershunov et al. 2017) and Europe (Lavers et al. 2012; Eiras-Barca et al. 2018; Ramos et al. 2018). Notable applications of ARDTs outside of these two locations have been in Antarctica (Gorodetskaya et al. 2014), the Arctic (Mattingly et al. 2018; Nash et al. 2018), India (Yang et al. 2018; Lakshmi et al. 2019), Iran (Esfandiari and Lashkari 2020), and South Africa (Ramos et al. 2019).

The various detection algorithms that have been presented over the past decade have led to the formation of the Atmospheric

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FIG. 1. Map of key locations discussed in the text. Key weather stations are located with yellow circles, and the blue boxes represent the extent of the corresponding grid cell in ERA-Interim (0.75° resolution) used to develop the AR climatologies. The landmass of New Zealand is shown in gray, and elevations exceeding 1000 m are shown in red. The Southern Alps are clearly identified as the axial mountain range running the length of the South Island. All weather stations are within 100 m of sea level apart from stations adjacent to Hokitika (labeled in the bottom right inset).

Rivers Tracking Method Intercomparison Project (ARTMIP), an international effort to quantify uncertainties and reveal insights in AR science such as algorithmic and regional variabilities through the use and comparison of detection algorithms (Shields et al. 2018, 2019; Ralph et al. 2019b). Early findings from the ARTMIP indicate that AR characteristics can vary considerably based on the technique and location of the study domain (Shields et al. 2018; Ralph et al. 2019b; Guan and Waliser 2019). Thus, the individual nuances of running ARDTs in various locations must be understood for the development of such algorithms to be globally beneficial.

There has currently been no focused application of an ARDT in the southwest region of the Pacific Ocean (including New Zealand). The specific characteristics of New Zealand make this an important

omission. For instance, unlike the western coasts of the United States and Europe, New Zealand is a relatively small landmass situated in the midlatitudes (34° – 48° S) surrounded by ocean and can thus receive high moisture fluxes (and in theory, ARs) from any direction. Additionally, the position of New Zealand allows for both extratropical and tropical cyclonic systems to influence the country (Lorrey et al. 2014), and thus the spatial structure of ARs may have additional complexities. Finally, as previous global impact studies were based on reanalysis data known to have biases in their representation of precipitation and cloudiness (e.g., Naud et al. 2014; Gibson et al. 2019) and at coarse spatial scales relative to the size and topographic complexity of New Zealand, further quantification of the importance of ARs is needed.

Given the presumed (but unquantified) importance of ARs across New Zealand, the aim of this research is to provide a detailed and systematic assessment of ARs for New Zealand over a 40-yr period. Correspondingly, the Guan and Waliser (2015) ARDT (hereafter GW15) is used to identify AR objects, which provides a framework to assess their spatial and temporal variability across the New Zealand region. Additionally, ARs are ranked based on a scale proposed by Ralph et al. (2019a; the scale is hereafter referred to as R19) to investigate the spatial and temporal distribution of AR magnitude in New Zealand, with a focus on the north–south distribution of events. Finally, this research examines the contribution of detected ARs to precipitation recorded at a variety of locations around in New Zealand, addressing the suitability of R19 rankings. The AR climatology developed herein provides an opportunity to examine the large-scale atmospheric drivers responsible for AR landfall on different coasts in New Zealand.

2. Methods

The GW15 ARDT [developed by Guan and Waliser (2015) and documented at <https://ucla.box.com/ARcatalog> (retrieved January 2019)] is employed to identify ARs. GW15 is one of the most widely used global ARDTs (e.g., Debbage et al. 2017; Eiras-Barca et al. 2018; Yang et al. 2018) and has been shown to perform strongly against ARs manually identified from satellite imagery (Neiman et al. 2008) and hourly atmospheric profiling (Ralph et al. 2013).

Atmospheric data of $0.75^\circ \times 0.75^\circ$ horizontal resolution were retrieved from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim; Dee et al. 2011) at 6-hourly time steps (0000, 0600, 1200, 1800 UTC) for 40 hydrological years (1 April 1979–31 March 2019). ERA-Interim vertically integrated water vapor transport (IVT) and vertically integrated water vapor (IWV) are retrieved to evaluate the regional hydroclimatology of New Zealand. ERA-Interim IVT data are generated internally through integration across all model levels, from the surface to the top of the atmosphere (Berrisford et al. 2011). The 300-hPa geopotential height along with zonal and meridional wind speeds are retrieved to examine wind speed and pressure anomalies during landfalling ARs.

The GW15 detection algorithm produces spatial outlines of all AR events (referred to herein as AR objects) at each 6-h time step. The identification algorithm [described within Guan and Waliser (2015)] applies five distinct geometric and magnitude classifications to global plots of ERA-Interim IVT. Grid points included in an AR object must have IVT exceeding the 85th grid cell percentile for a given 5-month window with a lower fixed threshold of $100 \text{ kg m}^{-1} \text{ s}^{-1}$. The IVT direction must be coherent (the direction of IVT in over half the grid cells within the AR object must be within 45° of object-mean IVT direction), poleward (object-mean IVT must have a poleward flux $> 50 \text{ kg m}^{-1} \text{ s}^{-1}$), and consistent (object-mean IVT direction must be within 45° of the primary axis). The final classification is based on the commonly cited length/width ratio, where the object length must be over twice the effective

width of the object (the surface area of the object divided by the length).

In addition to identifying AR objects in each time step, GW15 determines the location of landfalling ARs using a binary land–sea mask. The landfalling location is determined as the location of maximum IVT within an AR object that intersects a coastline, provided the object-mean IVT direction is landward and the length of the AR remaining upwind of the landfalling location is greater than 1000 km (Guan and Waliser 2015). A single landfall location is selected for each intersecting AR and characterized by the IVT magnitude and direction at the point of detected landfall. A landfalling AR cannot encounter a landmass in the upwind direction and importantly, the algorithm also restricts a single AR from making landfall twice in one time step. Both outputs (AR objects and AR landfall location) from Guan and Waliser (2015) are employed in this study.

Following the GW15 AR detection, a newly developed AR ranking scheme proposed by Ralph et al. (2019a) is applied to the 40-yr catalogue of AR objects detected by Guan and Waliser (2015). Ralph et al. (2019a) introduce a rank scale (weak AR and AR1–AR5) for ARs based on storm intensity (maximum IVT) and duration over the location of interest, established from historical impacts of landfalling ARs on the U.S. west coast (Fig. 2). The “Weak AR” rank is proposed by Ralph et al. (2019a) for events with the same maximum moisture flux as an AR1 (between 250 and $500 \text{ kg m}^{-1} \text{ s}^{-1}$) but persists for less than 24 h, a naming convention that is maintained herein. In contrast, GW15 enables ARs with IVT values less than $250 \text{ kg m}^{-1} \text{ s}^{-1}$ to be identified due to the relative IVT threshold (85th percentile of grid cell IVT), with a lower threshold of $100 \text{ kg m}^{-1} \text{ s}^{-1}$ (Guan and Waliser 2015). Ralph et al. (2019a) (see their Table 2) define sub- $250 \text{ kg m}^{-1} \text{ s}^{-1}$ conditions as “not an AR.”

The initial application of the R19 ranking scheme considers AR events as any IVT grid cell that exceeds $250 \text{ kg m}^{-1} \text{ s}^{-1}$. While this Eulerian approach does not provide an assessment of the spatial structure of an event it does resolve the temporal progression of the moisture fluxes over a single grid cell. Since high moisture transport can occur due to a range of different dynamical processes aside from AR events in the New Zealand region, the R19 ranking scheme is only applied to AR objects detected by GW15. This modified approach is novel and ensures that storm intensity (maximum IVT) identified using the ranking scale is restricted to spatially coherent AR objects.

From this new dataset, the validity of the thresholds and descriptors of this ranking scheme is discussed for New Zealand, one of the first applications of R19 in the Southern Hemisphere. To determine latitudinal variation in AR occurrence and to examine the influence of the topographic barrier of the Southern Alps on AR characteristics, six grid cells spanning the length of New Zealand are selected for further analysis (Fig. 1). These locations form a latitudinal transect along the length of New Zealand, with Dunedin providing a South Island east–west contrast to Doubtful Sound. Precipitation data from eight weather stations located within the six grid cells used for landfall analysis are employed to explore the impacts of ARs in New Zealand (Table 1; Fig. 1). Data are sourced from

FIG. 2. The scale of AR ranks as proposed by R19 based on maximum AR IVT and the duration of the event at a given point [adapted from Ralph et al. (2019a)].

weather stations operated by the National Institute of Water and Atmospheric Research (NIWA), MetService, and the West Coast Regional Council.

The proportion of total precipitation associated with ARs over the entire precipitation recording period is calculated as the total amount of precipitation that has occurred during (and within 12 h either side) a detected AR (i.e., all AR events ranked by R19 for a given grid cell) divided by the total precipitation at each site. In addition to total precipitation, the proportion of extreme (98th percentile) 6-hourly precipitation that occurs during and within 12 h of a detected AR is also calculated. The 12-h window for detected ARs is applied to

account for precipitation that occurs immediately prior to or following a detected AR, similar to attribution techniques used by Mahoney et al. (2016) and Ralph et al. (2019a). The final temporal buffer applied is the 3-day total precipitation following AR initiation, a common value for comparing individual storm-total precipitation (Ralph et al. 2019a). The 3-day temporal window remains uniform for all rankings, allowing for suitable comparison between precipitation totals over the same temporal period for ARs of various magnitude.

To illustrate the detection of a GW15 AR object and landfall location, an extreme AR event on 25 March 2019 (UTC) is shown (Fig. 3). While the GW15 landfall location is on the west coast of the South Island, the AR object (and associated high IVT values) clearly covers the entire South Island. As such, the R19 ranking (using GW15 AR object data) considers locations covered by the AR object and provides an enhanced method for assessing the full spatial extent of AR event impacts. To study the differences in occurrence, magnitude, and direction of landfalling ARs at different locations, New Zealand is divided into three sectors (western, northern, and eastern coasts) based on coastline direction and position. IVT and 300-hPa wind vector and geopotential height fields are further examined during landfalling ARs along these three distinct coastlines of New Zealand to understand the synoptic-scale controls on landfalling ARs.

3. Results

a. New Zealand hydroclimatology and AR occurrence

The climatology of IWV and IVT percentiles are presented to provide an understanding of the seasonal variability of atmospheric moisture in the New Zealand region (Fig. 4). There is a notable annual cycle in both IWV and IVT, reaching a maximum during the Southern Hemisphere summer (February) and a minimum during winter (August). The seasonal variability in IWV remains relatively consistent throughout all percentile levels examined. The variability across IVT percentiles, however, does not remain consistent, with the upper percentiles (95th and 99th) experiencing greater seasonality than the lower percentiles. The lower IVT percentiles have a decreasing seasonal variability indicating that the background moisture fluxes remain relatively consistent throughout the year, while the occurrence of extreme IVT is concentrated in summer. Seasonal variations in the 300-hPa wind speeds are examined to provide further context of the climatology of New Zealand (Fig. 5). Similar to results published in Kidston et al. (2009), the Southern Hemisphere upper-level jet exhibits substantial modulation between warm and cold seasons. In the warm season [October–March (ONDJFM)], the polar frontal jet situated at 50°S is prominent, while in the cold season [April–September (AMJJAS)], the climatological jet stream splits, with the subtropical jet situated at 30°S becoming the dominant upper-level wind. The seasonal movement of the Southern Hemisphere jet stream maximums has been associated with the broad seasonal distribution of cyclonic systems and storm tracks that influence New Zealand (Trenberth 1991; Kidston et al. 2009).

TABLE 1. Locations and associated weather stations used to calculate AR-related precipitation and assess the performance of the R19 ranking. Mean annual precipitation and median nonoverlapping 3-day precipitation totals (nonzero) are calculated for each location.

Location	Station name	ID No.	Operational dates	Mean annual precipitation (mm yr ⁻¹)	Median 3-day precipitation (mm)
Kaitaia	Kaitaia Aero EWS	530206	16 Jun 2000–26 Dec 2018	1291	7
Auckland	Auckland Aero	740802	31 Dec 1979–29 May 2010	1136	6
Nelson	Nelson AWS	133202	28 Nov 1991–5 Nov 2018	930	5
Hokitika	Hokitika at Rapid Creek	310010	1 Apr 1979–31 Mar 2019	7630	49
Cropp River	Cropp at Waterfall	311015	12 Jun 1982–31 Mar 2019	10 453	63
Ivory Glacier	Ivory at Ripplerock	90102	2 Feb 2009–30 Mar 2019	7682	34
Doubtful Sound	Secretary Island	562800	1 Jan 1995–13 Apr 2018	3629	30
Dunedin	Dunedin Aero AWS	509202	7 Nov 1991–29 Jul 2018	717	3

The mean annual occurrence of AR days in New Zealand as detected by GW15 is presented in Fig. 6. Over the landmass of New Zealand, AR objects are present on 30–40 days annually (up to 11% of annual time steps). AR days are most frequent to the southwest of New Zealand, with the lowest AR occurrence to the northeast of the study domain. AR days are more common in the warm season with over 20 AR days occurring over the landmass of New Zealand. Notably, AR occurrence increases in the poleward direction during the warm season reaching a maximum at approximately 50°S. Northern regions of the country experience approximately five fewer warm season AR days annually than the southern regions. During the cold season, peak AR occurrence splits, with a peak region of occurrence situated at 30°S and another maximum farther south of New Zealand, toward 60°S. AR occurrence in New Zealand reduces in the cold season down to approximately 15 days. The IVT associated with detected ARs (mean AR IVT calculated only from IVT vectors associated with an AR object) is directed in a broad northwesterly direction and is generally higher on the western (windward) side of New Zealand than the eastern (leeward) side, likely indicative of

drying of the atmosphere due to orographic rainfall in the Southern Alps. Warm season ARs have a notably higher IVT with a substantial meridional component in the north of the region, whereas cold season AR IVT magnitude is reduced and in a predominant northwesterly flow throughout the domain. Interestingly, the landmass of New Zealand experiences slightly more ARs than the immediately adjacent ocean, while also experiencing a lower mean AR IVT, which is attributable to the variable IVT detection threshold within GW15.

b. Application of the R19 AR scale to the New Zealand region

As expected, higher rank ARs (based on R19) occur less frequently than lower rank ARs in the New Zealand domain (Fig. 7). The occurrence of weak and AR1–AR2 events increases in a poleward direction. Weak ARs occur at rates greater than 20 per year across New Zealand, while AR1s occur between 7 and 15 times a year across New Zealand. There is no clear region where ARs from all rankings are more frequent around New Zealand. The highest two rankings, AR4 and AR5 events, occur more frequently to the northeast of

FIG. 3. An example of a landfalling AR in New Zealand as detected by GW15 (25 Mar 2019). The AR outline is shown with the green line, and the landfall location is identified with a gray cross. IVT vector magnitudes exceeding $200 \text{ kg m}^{-1} \text{ s}^{-1}$ are shown, and the vectors associated with the AR are in bold. The height of the 850-hPa pressure level is shown with contours at 25-m intervals. Time stamp is in UTC.

FIG. 4. Seasonal variability of IWV and IVT by percentile (50th, 75th, 90th, 95th, and 99th percentiles) for New Zealand, calculated from the spatial domain as shown in Fig. 6 (20° – 55° S, 150° – 175° E).

New Zealand, with a small region of increased occurrence immediately southwest of New Zealand. The frequency of all ranks, except for weak ARs, reduces over the landmass of New Zealand and leeward of the Southern Alps. It should be noted that the sum of all ranks in Fig. 7 is less than the annual occurrence value in Fig. 6a as not all ARs identified by GW15 exceed the required classification proposed by R19 (i.e., maximum $IVT < 250 \text{ kg m}^{-1} \text{ s}^{-1}$ is not classed as an AR). For example, during the 40-yr study period, a total of 1953 AR objects were detected at the Hokitika grid cell, with 830 (42%) of these being classified as AR1–AR5, 951 (49%) as weak ARs, and 172 (9%) being excluded by R19.

To accommodate such low IVT ARs that are detected by GW15, an additional rank is proposed (named “Low IVT ARs”) that contains ARs detected by GW15 that do not contain a maximum IVT that exceeds $250 \text{ kg m}^{-1} \text{ s}^{-1}$ (Fig. 8). The occurrence and spatial distribution of Low IVT ARs are controlled by the seasonality of the 85th percentile IVT (within a 5-month moving window; Guan and Waliser 2015). Low IVT ARs are restricted to regions in the lee of elevated terrain, particularly in the lee of the Southern Alps in the South Island with an annual occurrence reaching 12.5 per year.

The seasonality of AR occurrence in each rank (excluding weak and low IVT ARs) is assessed at the six study locations

(Fig. 9). Dunedin and Doubtful Sound both experience a large seasonality in the occurrence of ARs, with approximately two-thirds of events (66%) occurring in the warm season (ONDJFM) and only one-third of events (33%) during the cold season (AMJJAS). The rank of event also exhibits a strong seasonality, with the AR3, AR4, and the very few AR5 events occurring in the warmer season, typically between November and April. Neither Dunedin and Doubtful Sound have experienced an AR4 or AR5 event between May and September. Hokitika and Nelson experience a similar seasonality, with 62% and 61% of AR1–AR5 events occurring in the warm season, respectively. It is noteworthy that over the last 40 hydrological years, Hokitika (7 events) and Nelson (8 events) received a much larger number of AR5 events compared to Doubtful Sound (3 events) and Dunedin (1 event).

The two northern sites of interest (Auckland and Kaitia) exhibit a more subdued seasonal cycle in AR occurrence compared to the four other locations (Fig. 9). Kaitia experiences AR4 and AR5 events throughout the year along with a limited seasonality in occurrence of all ranked ARs. The peak in AR occurrence in the middle of summer observed in the southern locations does not occur at Kaitia and Auckland, with October being the peak for AR activity at the top of the North Island. The winter minimum in AR occurrence

FIG. 5. Seasonal 300-hPa mean wind speed magnitude (colored) with the seasonal mean zonal and meridional components plotted as vectors. The polar jet dominates the upper-level flow during the warm season (ONDJFM), while the jet stream splits in the cold season (AMJJAS). The subtropical jet reaches a maximum to the north of New Zealand, and the polar jet diverts southward.

FIG. 6. (left) Mean annual count of all AR objects detected in the domain and (right) mean AR IVT calculated from IVT only contained within AR objects detected by GW15 for (a) all ARs, (b) warm season ARs, and (c) cold season ARs. The annual plot of AR occurrence uses a different color scale to the seasonal plots; the sum of the two seasonal AR annual occurrences [at left in (b) and (c)] is equal to the annual AR occurrence [at left in (a)].

experienced at southern locations is not experienced in Auckland and Kaitiaia, with 43% and 46% of events occurring in the cold season, respectively. Over the last 40 years, Auckland received 18 AR5s, while Kaitiaia received 25.

For all study locations except Dunedin, between 58% and 78% of total precipitation occurs within 12 h of a detected AR,

with the largest proportions in the central west coast, windward of the Southern Alps (Fig. 10). Three precipitation records from the central west coast (Hokitika, Cropp River, and Ivory Glacier) are assessed to test the validity of the highest recorded proportions, with similar results observed at the three sites (72%, 73%, and 78% of total precipitation, respectively).

FIG. 7. Average annual number of weak AR and AR rank 1–5 events according to R19 over 40 hydrological years (1979–2019). The Ralph rankings are applied to the AR events that have been detected by GW15.

FIG. 8. Average annual number of Low IVT ARs as detected by GW15 that are not accommodated by the R19 ranking technique. Regions in gray indicating locations that did not receive any Low IVT ARs during the 40-yr period.

Doubtful Sound and Nelson, situated at the two extremities of the South Island, receive a reduced 60% and 69% of total precipitation within 12 h of an AR. Importantly, these results demonstrate that the western regions of the central South Island, windward of the Southern Alps, are most susceptible to the impacts of ARs. In contrast, 35% of total precipitation at Dunedin, located in the lee of the Southern Alps, occurs within 12 h of an AR. The two northern sites, located far from any elevated topography, receive moderate precipitation proportions of 62% and 58% at Kaitaia and Auckland, respectively.

The occurrence of extreme precipitation (98th percentile) within ARs varies similarly to total precipitation (Table 2). In the central west coast (Hokitika, Cropp River, and Ivory Glacier) between 92% and 94% of extreme 6-hourly precipitation occurs within 12 h of an AR. Doubtful Sound receives the second highest proportion of extreme precipitation at 82%. Nelson, Auckland, and Kaitaia receive lower proportions of 73%, 64% and 73%, while Dunedin receives a substantially lower 40% of extreme precipitation within 12 h of an AR.

The distribution of 3-day precipitation totals associated with ARs defined by R19 shows that precipitation broadly increases with AR rank (Fig. 11). Increases in AR rank precipitation is greatest on the central west coast of the South Island. Median 3-day precipitation (averaged between the three adjacent sites) is approximately 71 mm for Low IVT ARs and 85 mm for Weak ARs, with the remaining ranks demonstrating increasing differences: 153, 238, 306, 357, and 695 mm for AR1–AR5, respectively. The eight AR5s that have been detected at Hokitika have all produced storm total rainfalls in excess of 400 mm (Table 3). Similar increases in 3-day precipitation are seen in Doubtful Sound, Auckland, and Kaitaia, with expected varying precipitation amounts between locations due to

variable precipitation regimes (Table 1). At Dunedin and Nelson, 3-day precipitation only slightly increases with AR rank, with the exception of AR5s at Nelson producing considerably greater precipitation. At all locations considered, lower AR ranks can produce anomalous precipitation comparable to higher ranked ARs, which becomes especially notable in Dunedin, Auckland, and Kaitaia, where the highest outliers are all associated with lower AR ranks (especially Weak ARs along with AR1 and AR2 events). The newly introduced Low IVT AR rank exhibits an expected lower median 3-day precipitation compared to all other ranks, providing a suitable empirical validation.

c. Large-scale atmospheric controls on AR landfall

The vast majority (90%) of landfalling ARs occur on the western coasts of New Zealand (Fig. 12). Out of all landfalling AR events, 17% are centered on the western most grid cell in Fiordland (extreme southwest), with 39% across Fiordland as a whole. The two northernmost grid cells in the North Island receive 15%. Very few landfalling ARs are detected on the east coasts of both islands, with only 79 events (<1% of total events).

Figure 13 shows the large-scale atmospheric conditions associated with landfalling AR events in the three sectors defined in Fig. 12 (western coast, northern coast, and eastern coast). Since a large proportion of ARs make landfall on the western coast (90%), the composite for the western coast is very similar to that for all landfalling ARs. The subtropical and polar jets are both identifiable by 300-hPa wind speed maximums at 30° and 55°S, respectively. Wind vectors are consistently westerly, with a northwest component over southern New Zealand. However, the composite for northern coast landfalling ARs demonstrates a substantial meridional component in the subtropical jet, producing a more northerly airflow directed toward New Zealand. The composite for eastern coast landfalling AR events demonstrates a clear split jet stream over New Zealand, with weak upper-level winds over New Zealand and an enhanced westerly jet at higher latitudes to the south.

The relative position of the largest pressure gradients appears to be the primary control on the location of landfall as shown by the geopotential height anomalies (Fig. 13). ARs that make landfall on the western coast of New Zealand are associated with a dipole pattern of lower pressure to the southwest of the country and higher pressure to the northeast, producing geostrophic winds directed toward the western coast of New Zealand. For northern coast ARs, the low pressure in the Tasman Sea is positioned farther north than in western coast events, and with high pressure located farther southward, resulting in northerly geostrophic winds that originate from the subtropics. Pressure composites during eastern coast landfalling ARs are particularly notable for a large area of high pressure to the south of New Zealand and a smaller lower pressure region to the north of the country. These anomalies disrupt the dominant westerly wind flow, enabling the conditions required for an eastern coast landfalling AR to occur.

Composites of IVT during landfalling events show that western coast landfalling ARs are typically associated with enhanced northwest moisture fluxes extending across the Tasman

FIG. 9. Seasonality of total R19 ranked AR events at six different locations throughout New Zealand over 40 hydrological years (1979–2019).

Sea from eastern Australia to New Zealand (Fig. 14). Regions of reduced IVT extend either side of this enhanced northwest moisture flux, which align with the centers of the dipole pressure anomalies present during these events (Fig. 13). Elevated

moisture fluxes associated with northern coast ARs are positioned farther north than western coast ARs, similarly, with associated reduced IVT either side of this moisture flux plume in the center of the pressure anomalies. Eastern coast ARs present the

FIG. 10. Proportion of total precipitation that has occurred at each location during and within 12 h of ARs detected using GW15. The three weather stations in close proximity located at the center of the West Coast of the South Island are highlighted in gray.

greatest disparity compared to the other IVT anomalies, with enhanced moisture flows extending northeast of New Zealand. Notably, during eastern coast ARs there is a substantial westerly moisture flux to the south of New Zealand, which is congruent with an enhanced high-latitude upper-level wind associated with the southern edge of the prominent high pressure region.

4. Discussion

a. Atmospheric river climatology and controlling dynamics for the New Zealand region

The defining feature of the New Zealand (34°–48°S) AR climatology is the peak occurrence between November and March, during the austral warm season (October–March; Fig. 9). AR occurrence increases by approximately 61% in the warm months (ONDJFM) compared to the cold months (AMJJAS) on the west coast of the South Island (Fig. 9). Peak AR activity occurs in conjunction with elevated summer atmospheric moisture (IWV) associated with higher temperatures and enhanced horizontal moisture flux (IVT; Fig. 4). This shows there is a clear relationship between AR occurrence and thermal and moisture variability of the atmosphere.

Cyclone track density and, by association, meridional advection are closely linked to the position of the upper-level jet streams due to the thermal gradients associated with the jet formation themselves and the rapid transportation of synoptic-scale features embedded within these jets (Trenberth 1991;

TABLE 2. Proportion of extreme (98th percentile) 6-hourly precipitation that has occurred during and within 12 h of a detected AR (GW15, all ranking). Cropp River and Ivory Glacier are considered to validate the anomalous values from Hokitika.

Location	AR	AR $\pm$ 12h
Kaitaia	0.57	0.73
Auckland	0.51	0.64
Nelson	0.59	0.73
Hokitika	0.81	0.92
Cropp River	0.83	0.93
Ivory Glacier	0.84	0.94
Dunedin	0.22	0.40
Doubtful Sound	0.68	0.82

Sinclair 1994). The position of cyclone tracks over southern New Zealand follows the broad seasonal latitudinal variability in the polar jet stream, situated at 50°S during summer and shifting poleward, to approximately 60°S during winter (Fig. 5; Sinclair 1994). Crucially, the equatorward position of the storm tracks during summer results in peak meridional transport over New Zealand between November and April, an indicator of the poleward advection of moist air masses (Howarth 1983; Trenberth 1991). As the vast majority of ARs are associated with extratropical cyclones, it is reasonable to associate the broad seasonality in AR occurrence in New Zealand to variances in these described cyclone tracks (Zhang et al. 2019). The observed peak in AR occurrence and elevated AR rank during summer can be attributed to these discussed aspects of Southern Hemisphere dynamics, specifically the equatorward position of the polar jet and associated cyclones tracks (50°S) paired with thermally driven elevated atmospheric moisture and moisture transport. During winter, the broad poleward shift of extratropical cyclones and associated frontal features (in alignment with the polar jet) paired with the reduced atmospheric moisture results in a reduction in the magnitude of the poleward moisture fluxes over New Zealand and therefore fewer ARs.

In addition to the described poleward shift in the winter polar jet is the development of the thermally driven wintertime subtropical jet (Fig. 5) that produces a region of enhanced subtropical cyclonic activity and meridional transport equatorward of 40°S (Trenberth 1991; Sinclair 1994). The enhanced cyclone activity at these lower latitudes during winter may explain the relatively persistent AR occurrence in the northern most regions studied: Auckland (37°S) and Kaitaia (35°S; a 32% and 17% reduction in winter AR occurrence, respectively; Figs. 6 and 9). These observations present an apparent link between AR occurrence and seasonal jet stream position, allowing for the persistence of regular AR occurrence through the year in northern regions of New Zealand. The development of a separate climatological subtropical jet is a unique feature of the Southern Hemisphere, producing an apparent split jet centered over New Zealand that results in reduced upper-level wind speeds over New Zealand (Kidston et al. 2009; Bals-Elsholz et al. 2001; Babian et al. 2018). The split jet has been linked to anomalous meteorological conditions over the Southern Alps previously (Cullen et al. 2019) and is typically

FIG. 11. Distribution of 3-day precipitation totals associated with ARs of different rank following initiation of an AR in the respective grid cell for each study location. Note that the y axes have considerably different scales due to varying precipitation regimes as noted in Table 1. Auckland and Kaitia did not receive any Low IVT ARs during the 40-yr period, and no AR5 events were observed during the Doubtful Sound precipitation record.

associated with reduced southerlies and anomalously warm conditions in the South Pacific (Bals-Elsholz et al. 2001). Thus, the split jet is consistent with warm, moist northerly airflow favorable for AR development.

Eastern coast landfalling ARs demonstrate the most distinct split jet structure (Fig. 13). The resultant wind fields are remarkably similar to those associated with positive phases of the

southern annular mode (SAM), the primary mode of climate variability in the Southern Hemisphere (Kidston et al. 2009). Indeed, a larger majority of eastern coast landfalling ARs (66%) occur during positive SAM anomalies (sourced from the NCEP–NCAR Climate Prediction Center) compared to northern coast (60%) and western coast (55%) landfalling ARs. A positive relationship between SAM and precipitation

TABLE 3. AR5 events detected at Hokitika during the 40 hydrological years between 1979 and 2019. Storm total precipitation is the summed precipitation from the Cropp River record that has occurred while the AR5 event has been detected at the Hokitika grid cell. Date (UTC) is recorded as the day during each AR5 event when IVT was at a maximum.

Date	Max IVT ($\text{kg m}^{-1} \text{s}^{-1}$)	Storm total IVT (10^7 kg m^{-1})	Max IWV (kg m^{-2})	Direction of max IVT	Duration (h)	Precipitation (storm total; mm)
15 Dec 1989	1049	11.7	35.1	NW (310°)	48	866
8 Jan 1994	1052	15.9	36.7	NW (318°)	72	843
12 Dec 1995	1106	14.7	36.5	NW (339°)	60	1120
24 Jan 2008	1126	10.7	40.4	NW (358°)	48	843
21 Dec 2010	1276	14.2	44.0	NW (342°)	84	861
18 Jan 2017	1062	9.0	34.6	NW (318°)	48	422
8 Nov 2018	1108	11.4	37.6	NW (313°)	48	785
26 Mar 2019	1018	13.7	42.6	NW (316°)	60	1108

FIG. 12. Count and landfall location of landfalling ARs detected by GW15 from 1979 to 2019. The gridded outline of New Zealand is the coastline of the country as represented in ERA-Interim with a $0.75^\circ \times 0.75^\circ$ grid resolution. No grid cells received AR counts between 1600 and 2301, with the most westerly grid cell receiving the maximum count of 2302. The combined IVT rose includes detected landfalling ARs from the entire country.

FIG. 13. (left) Composite of geopotential height and wind vectors at 300 hPa during landfalling ARs as detected by GW15 at (a)–(d) various locations on the coastline of New Zealand as described in Fig. 12. Mean wind vectors with magnitudes less than 8 m s^{-1} are not shown. Contours spaced at 150-m intervals. (right) Standardized anomalies of geopotential height at 300 hPa during landfalling ARs as detected by GW15.

on the east coast of the North Island was reported by Kidston et al. (2009). Thus, the split-jet structure and weakened upper-level wind speed over New Zealand may facilitate landfalling ARs on the eastern coast and be associated with increased precipitation. The drivers of this apparent relationship between the jet stream and ARs require further examination, in particular, whether warm, moist air advected poleward forces the enhanced polar frontal jet stream southward (below 60°S), producing conditions conducive to AR development.

The dipole pressure anomalies associated with New Zealand ARs resemble the typical synoptic setup of ARs making landfall in the United States, where the position of the cyclonic center and associated pressure gradient controls the landfall location of the AR (Neiman et al. 2008; Zhang et al. 2019). The seasonal occurrence of ARs described here, however, differs

substantially from the United States. Peak AR occurrence on the U.S. west coast occurs between November and March, during the Northern Hemisphere winter associated with elevated tropical moisture exports along the “Pineapple Express” through enhanced cyclogenesis, more intense storms, and substantial meridional flows in the North Pacific cool season (Neiman et al. 2008; Knippertz and Wernli 2010). While atmospheric moisture reaches a maximum in summer on the U.S. west coast, cyclogenesis is at a minimum resulting in reduced moisture fluxes and reduced AR occurrence (Knippertz and Wernli 2010; Mahoney et al. 2016). South America provides a suitable Southern Hemisphere location to compare the newly present New Zealand AR seasonality (Viale et al. 2018). Similar to New Zealand, AR occurrence peaks in the summer to the south of the continent (43°S), a comparable location to

FIG. 14. (left) IVT magnitude and vector composites and (right) standardized anomalies (IVT magnitude and vector anomaly) during landfalling ARs as detected by GW15 at various locations on the coastline of New Zealand as defined in Fig. 12.

New Zealand peak summer AR occurrence (Fig. 6; 50°S). Peak AR occurrence in South America then shifts northward during winter, with southern regions experiencing the largest interannual variability, similar to results presented in Fig. 9, which is explained primarily by the position of cyclonic centers (Viale et al. 2018). The seasonal variability of large-scale transport of atmospheric moisture is complex at a global scale and understanding regional atmospheric circulation, dynamics, and thermal effects is crucial in controlling AR occurrence.

Ex-tropical cyclones may also play a role in forming ARs over New Zealand. Peak AR occurrence in January occurs close to the February peak of the southwest Pacific tropical cyclone season (Sinclair 2002). The warmer and more moist atmosphere and higher ocean temperature allows, on average, three tropical cyclones to undergo extratropical transition and migrate south of 35°S into the New Zealand domain annually (Sinclair 1994, 2002). Indeed, 29 out of the 31 named tropical

cyclones (94%) that migrated south between 1979 and 1998 [as compiled by Sinclair (2004)] had AR objects detected concurrently, ranging from weak to AR 5 events. Identification of the dynamics associated with concurrent ex-tropical cyclones and ARs is beyond the scope of this study, so direct attribution to tropical cyclones is not possible. However, the composite pressure anomalies during north and east coast landfalling ARs (Fig. 11) suggest depressions of tropical origin, with comparatively small low pressure anomalies that are centered equatorward of 40°S.

While GW15 is designed to exclude moisture fluxes associated with tropical cyclones through geometric and directional constraints (Guan and Waliser 2015), IVT fields associated with such storms can satisfy the algorithmic requirements to be classified as an AR. Guan and Waliser (2019) have since noted that while the moisture advected by such storms is of interest, the detection of the core of tropical cyclones (extreme circular

moisture fluxes) in GW15 is an unintended consequence of the algorithm. The AR definition, however, does not restrict ARs to the dynamics of midlatitude cyclones, as discussed by [Ralph et al. \(2017, 2018\)](#) and [Ramos et al. \(2019\)](#), and in practice, AR occurrence has previously been associated with tropical cyclones and other storms of tropical origin ([Sodemann and Stohl 2013](#); [Gimeno et al. 2016](#); [Mahoney et al. 2016](#); [Mundhenk et al. 2016](#)). Crucially, it appears that tropical dynamics, particularly extratropical transitioning of tropical cyclones, play an important role in enhancing midlatitude moisture fluxes that lead to identifiable AR features in the New Zealand region.

b. Orographic controls on ARs

Orographically forced convection along the Southern Alps associated with northwesterly oriented weather systems is a prominent driver of precipitation on the western part of the South Island of New Zealand ([Wratt et al. 1996](#); [McCauley and Sturman 1999](#)). These barrier-normal, maritime flows lead to large storm precipitation and annual precipitation values exceeding $10\,000\text{ mm yr}^{-1}$ on the windward side of the topographic barrier ([McCauley and Sturman 1999](#); [Henderson and Thompson 1999](#)). Similar precipitation mechanisms are observed in the Andes in South America ([Viale and Nuñez 2011](#)), and the Cascades in the United States ([Smith et al. 2005](#)). The orographic precipitation in the Southern Alps occurs in conjunction with an approaching midlatitude cyclone in the southern part of the Tasman Sea and a blocking anticyclone to the east of New Zealand ([Wratt et al. 1996](#)). The resultant synoptic pressure gradients and associated cold fronts produce corridors of warm, moist atmospheric flow from subtropical regions that are subsequently uplifted as they encounter the Southern Alps. An identical synoptic setup is observed for ARs making landfall on the west coast of New Zealand ([Figs. 13 and 14](#)), indicating that orographically forced precipitation is a common outcome of these ARs. Furthermore, the frequency of ARs on the west coast of the South Island ([Figs. 6, 7, and 9](#)) indicates that ARs are the primary synoptic feature that governs the occurrence of orographic precipitation in this region.

The influence of orographic uplift on extreme precipitation due to ARs is seen on the west coast of the South Island, where topography exceeds 2000 m within 50 km of the coast and ARs account for the vast majority of extreme precipitation (92%–94% within 12 h of an AR; [Table 2](#)). This mirrors findings for the U.S. west coast, with ARs frequently producing extreme precipitation through forced ascent ([Neiman et al. 2008](#); [Ralph and Dettinger 2011](#); [Ralph et al. 2018, 2019a](#)). Doubtful Sound, also situated on the west coast of the South Island, receives a lower proportion of extreme precipitation from ARs (82%). Both Hokitika and Doubtful Sound are windward of the Southern Alps; however, the position of the rain gauges may account for the observed differences in AR precipitation regime. The Doubtful Sound rain gauge (situated at Secretary Island) is situated adjacent to the ocean at 19-m elevation, while the lowest Hokitika rain gauge (at Rapid Creek) is at 150 m with intervening topography exceeding 900 m. The higher elevation and surrounding topography would be expected to increase orographically forced precipitation at Hokitika, following the known precipitation gradient on the windward side of the Southern Alps ([Wratt et al. 1996](#)).

The reduced proportion of total precipitation from ARs in Dunedin (35%, in the lee of the alpine barrier) aligns with the clear reduction in AR precipitation inland on the U.S. west coast in the lee of substantial mountain ranges such as the Sierra Nevada ([Ralph et al. 2019a](#)). The influence of ARs on precipitation in other regions of New Zealand presents some peculiar findings with ARs accounting for comparable amounts of total precipitation in Auckland (58%) and Kaitiaki (62%) compared to Doubtful Sound (60%), locations with vastly different topography. The lack of substantial topography in northern regions of the country would suggest less forced uplift, the primary driver known for initiating AR precipitation ([Neiman et al. 2008](#)). The well-documented orographic uplift on the west coast of New Zealand provides a suitable mechanism for elevated AR precipitation; however, the lack of forced ascent in northern regions of the country suggests that other mechanisms of thermodynamic ascent may be as important in generating AR precipitation. The orientation of the AR to topographic features at landfall is also an important consideration. While orientation has not been considered herein, numerous studies have demonstrated that the orientation of moisture fluxes with respect to topography has an important role in determining precipitation intensity ([Hecht and Cordeira 2017](#); [Guirguis et al. 2018](#)). In coastal Wales, AR orientation is even proposed as the main driver for whether an AR will be impactful and so further examination of AR impacts in alpine terrain must consider AR orientation ([Griffith et al. 2020](#)).

c. Application of the combined ARDT and ranking approach

To further explore the impacts associated with the R19 descriptive rankings, the most extreme events on the west coast of the South Island (AR5 events for Hokitika) were identified. All eight of these AR5 events resulted in storm-total precipitation exceeding 400 mm, with four of these events exceeding 800 mm and the largest two AR5 events bringing over 1000 mm across 60 h ([Table 3](#)). These values are well in excess of the precipitation totals experienced on the U.S. west coast, with maximum 72-h precipitation values for AR5s only reaching 600 mm ([Ralph et al. 2019a](#)), highlighting the potential for larger storm total precipitation on the west coast of New Zealand.

To demonstrate the societal impact of one of these AR5 or “primarily hazardous/extreme” events, the AR that hit the west coast of the South Island on 25 March 2019 can be further examined ([Fig. 3](#)). While the maximum IVT associated with this event ($1018\text{ kg m}^{-1}\text{ s}^{-1}$) did not exceed the IVT threshold for AR5, the event persisted for 60 h satisfying the duration threshold for AR5 (exceeding $1000\text{ kg m}^{-1}\text{ s}^{-1}$). During this event, a new national 48-h precipitation record of 1086 mm was set at the Cropp River site ([NIWA 2019](#)). The resultant flooding caused extensive damage: most notable was the collapse of the Waiho Bridge, isolating the northern and southern regions of the west coast. The impacts on the local community were estimated at USD \$2.35 million ([ICNZ 2019](#)). Furthermore, out of all AR5s that have occurred at Hokitika, 5 out of 8 have resulted in the damage and closure of major

highways often through the destruction of bridges (e.g., the Waiho and Goat Creek bridges). While this example presents the impacts from a particularly hazardous AR5 event on the west coast of the South Island, further study is required to test the appropriateness of AR ranking magnitude/duration thresholds and the potential for beneficial (e.g., breaking drought; [Dettinger 2013](#)) or hazardous impacts—particularly on the windward side of the Southern Alps where ARs occur frequently.

A key outcome of the application of the GW15 ARDT and R19 ranking for the New Zealand region is the identification of numerous AR events (objects) by GW15 that fall below the minimum IVT threshold used by R19 and subsequently excluded from ranking and analysis of precipitation impacts. To enable full alignment between GW15 and AR ranking a new rank is introduced named “Low IVT,” encompassing ARs that are identified within a detection algorithm such as GW15 that do not meet the minimum IVT threshold requirements of the GW15 ranking. While detection of Low IVT ARs may not be particularly impactful when considering hydrological responses ([Fig. 11](#)), the spatial distribution of such events reveals valuable insights into the hydroclimatology of different regions of New Zealand. Low IVT ARs are restricted to regions in the lee of elevated terrain demonstrating the locations where the seasonal (5 month) 85th percentile IVT is below $250 \text{ kg m}^{-1} \text{ s}^{-1}$ ([Fig. 8](#)). Interestingly, Weak ARs produce some of the highest 3-day precipitation totals in Cropp River and Dunedin, while also accounting for some of the highest precipitation totals at all other locations, comparable to all other AR rankings ([Fig. 11](#)). A possible explanation is that these Weak ARs are followed by larger precipitation events that fall within the 3-day precipitation window and are therefore included in the aggregation. Weak ARs, by definition, are short duration (subdaily) and therefore the 3-day precipitation totals may be augmented by one or more different meteorological events. Additional mesoscale analysis is required to explore meteorological conditions and precipitation mechanisms for AR-related precipitation at all locations studied to unravel the primary controls on extreme precipitation.

What is clear is that the R19 ranking method (primarily focused on extreme rainfall) performs well in New Zealand, accounting for increasing AR precipitation in most regions and its use is recommended for further applications, particularly for the west coast of the South Island. At all other locations considered within this study the amount of precipitation also appears to increase with AR rank, however at a reduced magnitude, which is primarily attributed to topographic differences ([Fig. 11](#)). Such relationships demonstrate the suitability of the ranking technique for gauging the severity of AR precipitation in New Zealand, however, the relevance of the ranking descriptors is unclear. To validate the use of the “beneficial/hazardous” AR terminology, further analysis of the societal impact, possibly through the analysis of associated river flood occurrence in relation to various AR ranking, is required.

5. Conclusions

The combination of an automated atmospheric river detection algorithm and classification scheme has produced the first

detailed climatology of ARs in the New Zealand region and allowed the characteristics of ARs making landfall to be systematically evaluated. A number of key findings have arisen from this analysis.

ARs in New Zealand display a distinct seasonality that aligns with the seasonal movements of the Southern Hemisphere jet streams and consequently, the midlatitude storm tracks. The polar jet positioned at approximately 50°S and associated passage of midlatitude cyclones during the summer allow ARs to regularly make landfall throughout New Zealand. During winter, as the polar jet shifts southward, the occurrence of ARs is reduced over much of the country (a reduction of 30% at Hokitika). ARs in the southern portion of the country exhibit a strong seasonality, with peak occurrence in the warmer months between December and March (summer). The formation of the winter subtropical jet at 25°S (the split jet) is a unique feature in the Southern Hemisphere and appears to allow AR occurrence to be maintained in the north of New Zealand, providing a mechanism for the continual passage of associated midlatitude storms at these lower latitudes. As a result, ARs in the north of the country remain comparatively constant, with limited seasonality.

The maritime position of New Zealand in the southwest Pacific Ocean allows synoptic systems of tropical origin to regularly influence the country, which differs from other global locations of AR research. Pressure anomalies during ARs making landfall on the northern (equatorward) coast of New Zealand possibly indicate the influence of tropical dynamics, with cyclonic systems located at much lower latitudes and of much smaller size compared to the typical passage of midlatitude cyclones producing ARs on the western coast of New Zealand. Furthermore, 94% of named tropical cyclones between 1979 and 1998, had concurrent ARs being detected in the north of the country. Crucially, it appears that tropical dynamics, particularly extratropical transitioning of tropical cyclones, play an important role in enhancing midlatitude moisture fluxes that lead to identifiable AR features in the New Zealand region.

Atmospheric controls on AR occurrence on the west coast of the South Island strongly resemble the synoptic situation conducive to orographic precipitation. Evidence suggests that ARs are the dominant synoptic feature producing orographic precipitation on the west coast. Locations immediately windward of the central part of the Southern Alps (Hokitika) receive 72%–78% of total precipitation and 92%–94% of extreme precipitation within 12 h of an AR, with the largest AR5s exceeding 1000 mm of storm total precipitation over 3 days, much larger precipitation amounts than AR events on the U.S. west coast. Study locations outside of the central west coast of the South Island receive 58%–69% of total and extreme precipitation within 12 h of an AR, with the exception of Dunedin, receiving 35% of total precipitation and 40% of extreme precipitation within 12 h of an AR. These statistics demonstrate that the occurrence of extreme precipitation at certain locations in New Zealand has a stronger relationship with ARs than previously suggested by [Waliser and Guan \(2017; i.e., 50%\)](#), who relied on a global precipitation product from reanalysis. The topographic barrier of the Southern Alps

is of critical importance for AR precipitation and there is a need for further research on the mesoscale drivers of AR-related precipitation with regards to the presence and proximity of topographic barriers in New Zealand.

To facilitate full cohesion between GW15 and R19, a new rank named Low IVT ARs is proposed, which contains ARs detected by GW15 that do not exceed the $250 \text{ kg m}^{-1} \text{ s}^{-1}$ lower threshold of R19 (approximately 9% of detected ARs within GW15 at Hokitika). The Low IVT ARs are detected by GW15 through a variable, percentile-based IVT detection that allows extreme moisture fluxes (85th percentile) to be detected in regions that experience low moisture climatologies. The GW15 ARDT provides a highly flexible algorithm that is capable of handling a variety of conditions globally. It is recommended that the Low IVT AR rank is considered to enable full coherence with the more subjective fixed threshold within R19.

The novel combination of GW15 and the R19 ranking used in this initial study provides a suitable framework for classifying precipitation intensity of ARs primarily on the west coast of the South Island. Initial results presented herein for selected weather stations indicate that R19 ranking is suitable for classifying the intensity of precipitation in New Zealand; however, the magnitude of extreme precipitation varies substantially with location. The R19 descriptors (hazardous/beneficial) and associated IVT magnitude/duration thresholds may therefore require further validation for use in New Zealand. While precipitation totals at Hokitika increase with each rank step, the societal impact and hazardous nature of these precipitation changes have not been fully explored. The case study of a hazardous AR5 event on the west coast of the South Island (Hokitika, March 2019) presented in this research clearly demonstrates how hazardous such an event can be in this region. Future research should target the multiscale interactions between moisture laden airflow and the topography of the Southern Alps to better understand how complex terrain produces extreme precipitation with the potential for considerable societal impacts.

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REFERENCES

- Babian, S., J. Grieger, and U. Cubasch, 2018: A new index for the wintertime Southern Hemispheric split jet. *Atmos. Chem. Phys.*, **18**, 6749–6760, <https://doi.org/10.5194/acp-18-6749-2018>.
- Bals-Elsholz, T. M., E. H. Atallah, L. F. Bosart, M. J. Cempa, and A. R. Lupo, 2001: The wintertime Southern Hemisphere split jet: Structure, variability, and evolution. *J. Climate*, **14**, 4191–4215, [https://doi.org/10.1175/1520-0442\(2001\)014<4191:TWSHSJ>2.0.CO;2](https://doi.org/10.1175/1520-0442(2001)014<4191:TWSHSJ>2.0.CO;2).
- Berrisford, P., and Coauthors, 2011: The ERA-Interim archive: Version 2.0. ECMWF ERA Rep. Series 1, 23 pp., <http://www.ecmwf.int/sites/default/files/elibrary/2011/8174-era-interim-archive-version-20.pdf>.
- Cullen, N. J., P. B. Gibson, T. Mölg, J. P. Conway, P. Sirguey, and D. G. Kingston, 2019: The influence of weather systems in controlling mass balance in the Southern Alps of New Zealand. *J. Geophys. Res. Atmos.*, **124**, 4514–4529, <https://doi.org/10.1029/2018JD030052>.
- Debbage, N., P. Millar, S. Poore, K. Morano, T. Mote, and J. M. Sheperd, 2017: A climatology of atmospheric river interactions with the southeastern United States coastline. *Int. J. Climatol.*, **37**, 4077–4091, <https://doi.org/10.1002/joc.5000>.
- Dee, D. P., and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **137**, 553–597, <https://doi.org/10.1002/qj.828>.
- Dettinger, M. D., 2013: Atmospheric rivers as drought busters on the U.S. West Coast. *J. Hydrometeorol.*, **14**, 1721–1732, <https://doi.org/10.1175/JHM-D-13-02.1>.
- Eiras-Barca, J., N. Lorenzo, J. Taboada, A. Robles, and G. Miguez-Macho, 2018: On the relationship between atmospheric rivers, weather types and floods in Galicia (NW Spain). *Nat. Hazards Earth Syst. Sci.*, **18**, 1633–1645, <https://doi.org/10.5194/nhess-18-1633-2018>.
- Esfandiari, N., and H. Lashkari, 2020: Identifying atmospheric river events and their paths into Iran. *Theor. Appl. Climatol.*, **140**, 1125–1137, <https://doi.org/10.1007/s00704-020-03148-w>.
- Gershunov, A., T. Shulgina, F. M. Ralph, D. A. Lavers, and J. J. Rutz, 2017: Assessing the climate-scale variability of atmospheric rivers affecting western North America. *Geophys. Res. Lett.*, **44**, 7900–7908, <https://doi.org/10.1002/2017GL074175>.
- Gibson, P. B., D. E. Waliser, H. Lee, B. Tian, and E. Massoud, 2019: Climate model evaluation in the presence of observational uncertainty: Precipitation indices over the contiguous United States. *J. Hydrometeorol.*, **20**, 1339–1357, <https://doi.org/10.1175/JHM-D-18-0230.1>.
- Gimeno, L., and Coauthors, 2016: Major mechanisms of atmospheric moisture transport and their role in extreme precipitation events. *Annu. Rev. Environ. Resour.*, **41**, 117–141, <https://doi.org/10.1146/annurev-environ-110615-085558>.
- Gorodetskaya, I. V., M. Tsukernik, K. Claes, F. M. Ralph, W. D. Neff, and N. P. M. Van Lipzig, 2014: The role of atmospheric rivers in anomalous snow accumulation in East Antarctic. *Geophys. Res. Lett.*, **41**, 6199–6206, <https://doi.org/10.1002/2014GL060881>.
- Griffith, H. V., A. J. Wade, D. A. Lavers, and G. Watts, 2020: Atmospheric river orientation determines flood occurrence. *Hydrol. Processes*, **34**, 4547–4555, <https://doi.org/10.1002/hyp.13905>.
- Guan, B., and D. E. Waliser, 2015: Detection of atmospheric rivers: Evaluation and application of an algorithm for global studies. *J. Geophys. Res. Atmos.*, **120**, 12 514–12 535, <https://doi.org/10.1002/2015JD024257>.
- , and —, 2019: Tracking atmospheric rivers globally: Spatial distributions and temporal evolution of life cycle characteristics. *J. Geophys. Res. Atmos.*, **124**, 12 523–12 552, <https://doi.org/10.1029/2019JD031205>.
- Guirguis, K., A. Gershunov, R. E. S. Clemesha, T. Shulgina, A. C. Subramanian, and F. M. Ralph, 2018: Circulation drivers of atmospheric rivers at the North American West Coast.

- Geophys. Res. Lett.*, **45**, 12 576–12 584, <https://doi.org/10.1029/2018GL079249>.
- Hecht, C. W., and J. M. Cordeira, 2017: Characterizing the influence of atmospheric river orientation and intensity on precipitation distributions over north coastal California. *Geophys. Res. Lett.*, **44**, 9048–9058, <https://doi.org/10.1002/2017GL074179>.
- Henderson, R. D., and S. M. Thompson, 1999: Extreme rainfalls in the Southern Alps of New Zealand. *J. Hydrol. N.Z.*, **38**, 309–330.
- Howarth, D. A., 1983: Seasonal variation in the vertically integrated water vapor transport field over the Southern Hemisphere. *Mon. Wea. Rev.*, **111**, 1259–1272, [https://doi.org/10.1175/1520-0493\(1983\)111<1259:SVITVI>2.0.CO;2](https://doi.org/10.1175/1520-0493(1983)111<1259:SVITVI>2.0.CO;2).
- ICNZ, 2019: Costs of natural disasters. Insurance Council of New Zealand, accessed 1 February 2020, <https://www.icnz.org.nz/natural-disasters/cost-of-natural-disasters/>.
- Kidston, J., J. A. Renwick, and J. McGregor, 2009: Hemispheric-scale seasonality of the southern annual mode and impacts on the climate of New Zealand. *J. Climate*, **22**, 4759–4770, <https://doi.org/10.1175/2009JCLI2640.1>.
- Kingston, D. G., D. A. Lavers, and D. M. Hannah, 2016: Floods in the Southern Alps of New Zealand: The importance of atmospheric rivers. *Hydrol. Processes*, **30**, 5063–5070, <https://doi.org/10.1002/hyp.10982>.
- Knippertz, P., and H. Wernli, 2010: A Lagrangian climatology of tropical moisture exports to the Northern Hemispheric extratropics. *J. Climate*, **23**, 987–1003, <https://doi.org/10.1175/2009JCLI3333.1>.
- Lakshmi, D. D., A. N. V. Satyanarayana, and A. Chakraborty, 2019: Assessment of heavy precipitation events associated with floods due to strong moisture transport during summer monsoon over India. *J. Atmos. Sol.-Terr. Phys.*, **189**, 123–140, <https://doi.org/10.1016/j.jastp.2019.04.013>.
- Lavers, D. A., D. Villarini, R. P. Allan, E. F. Wood, and A. J. Wade, 2012: The detection of atmospheric rivers in atmospheric reanalyses and their links to British winter floods and the large-scale climatic circulation. *J. Geophys. Res.*, **117**, D20106, <https://doi.org/10.1029/2012JD018027>.
- Little, K., D. G. Kingston, N. J. Cullen, and P. B. Gibson, 2019: The role of atmospheric rivers for extreme ablation and snowfall events in the Southern Alps of New Zealand. *Geophys. Res. Lett.*, **46**, 2761–2771, <https://doi.org/10.1029/2018GL081669>.
- Lorrey, A. M., G. Griffiths, N. Fauchereau, H. J. Diamond, P. R. Chappell, and J. Renwick, 2014: An ex-tropical cyclone climatology for Auckland, New Zealand. *Int. J. Climatol.*, **34**, 1157–1168, <https://doi.org/10.1002/joc.3753>.
- Mahoney, K., and Coauthors, 2016: Understanding the role of atmospheric rivers in heavy precipitation in the southeast United States. *Mon. Wea. Rev.*, **144**, 1617–1632, <https://doi.org/10.1175/MWR-D-15-0279.1>.
- Mattingly, K. S., T. L. Mote, and X. Fettweis, 2018: Atmospheric river impacts on Greenland Ice Sheet surface mass balance. *J. Geophys. Res. Atmos.*, **123**, 8538–8560, <https://doi.org/10.1029/2018JD028714>.
- McCauley, M. P., and A. P. Sturman, 1999: A study of orographic blocking and barrier wind development upstream of the Southern Alps, New Zealand. *Meteor. Atmos. Phys.*, **70**, 121–131, <https://doi.org/10.1007/s007030050029>.
- Mundhenk, B. D., E. A. Barnes, and E. D. Maloney, 2016: All-season climatology and variability of atmospheric river frequencies over the North Pacific. *J. Climate*, **29**, 4885–4903, <https://doi.org/10.1175/JCLI-D-15-0655.1>.
- Nash, D., D. Waliser, B. Guan, H. Ye, and F. M. Ralph, 2018: The role of atmospheric rivers in extratropical and polar hydro-climatology. *J. Geophys. Res. Atmos.*, **123**, 6804–6821, <https://doi.org/10.1029/2017JD028130>.
- Naud, C. M., J. F. Booth, and A. D. Del Genio, 2014: Evaluation of ERA-Interim and MERRA cloudiness in the Southern Ocean. *J. Climate*, **27**, 2109–2124, <https://doi.org/10.1175/JCLI-D-13-00432.1>.
- Neiman, P. J., F. M. Ralph, G. A. Wick, J. D. Lundquist, and M. D. Dettinger, 2008: Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the west coast of North America based on eight years of SSM/I satellite observations. *J. Hydrometeorol.*, **9**, 22–47, <https://doi.org/10.1175/2007JHM855.1>.
- , A. B. White, F. M. Ralph, D. J. Gottas, and S. I. Gutman, 2009: A water vapour flux tool for precipitation forecasting. *Water Manage.*, **162**, 83–94, <https://doi.org/10.1680/wama.2009.162.2.83>.
- NIWA, 2019: New Zealand climate summary: Autumn 2019. National Institute of Water and Atmospheric Research Tech. Rep., 15 pp., https://niwa.co.nz/sites/niwa.co.nz/files/Climate_Summary_Autumn_2019_FINAL.pdf.
- Paltan, H., D. Waliser, W. H. Lim, B. Guan, D. Yamazaki, R. Pant, and S. Dadson, 2017: Global floods and water availability driven by atmospheric rivers. *Geophys. Res. Lett.*, **44**, 10 387–10 395, <https://doi.org/10.1002/2017GL074882>.
- Ralph, F. M., and M. D. Dettinger, 2011: Storms, floods, and the science of atmospheric rivers. *Eos, Trans. Amer. Geophys. Union*, **92**, 265–266, <https://doi.org/10.1029/2011EO320001>.
- , T. Coleman, P. J. Neiman, R. J. Zamora, and M. D. Dettinger, 2013: Observed impacts of duration and seasonality of atmospheric-river landfalls on soil moisture and runoff in coastal Northern California. *J. Hydrometeorol.*, **14**, 443–459, <https://doi.org/10.1175/JHM-D-12-076.1>.
- , and Coauthors, 2017: Atmospheric rivers emerge as a global science and applications focus. *Bull. Amer. Meteor. Soc.*, **98**, 1969–1973, <https://doi.org/10.1175/BAMS-D-16-0262.1>.
- , M. D. Dettinger, M. M. Cairns, T. J. Galarneau, and J. Eylander, 2018: Defining “atmospheric river”: How the Glossary of Meteorology helped resolve a debate. *Bull. Amer. Meteor. Soc.*, **99**, 837–839, <https://doi.org/10.1175/BAMS-D-17-0157.1>.
- , J. J. Rutz, J. M. Cordeira, M. Dettinger, M. Anderson, D. Reynolds, L. J. Schick, and C. Smallcomb, 2019a: A scale to characterize the strength and impacts of atmospheric rivers. *Bull. Amer. Meteor. Soc.*, **100**, 269–289, <https://doi.org/10.1175/BAMS-D-18-0023.1>.
- , and Coauthors, 2019b: ARTMIP-early start comparison of atmospheric river detection tools: How many atmospheric rivers hit northern California’s Russian River watershed? *Climate Dyn.*, **52**, 4973–4994, <https://doi.org/10.1007/s00382-018-4427-5>.
- Ramos, A. M., R. M. Trigo, R. Tomé, and M. L. R. Liberato, 2018: Impacts of atmospheric rivers in extreme precipitation on the European Macaronesian Islands. *Atmosphere*, **9**, 325, <https://doi.org/10.3390/atmos9080325>.
- , R. C. Blamey, I. Algarra, R. Nieto, L. Gimeno, R. Tomé, C. J. C. Reason, and R. M. Trigo, 2019: From Amazonia to southern Africa: Atmospheric moisture transport through low-level jets and atmospheric rivers. *Ann. N. Y. Acad. Sci.*, **1436**, 217–230, <https://doi.org/10.1111/nyas.13960>.
- Rutz, J. J., W. J. Steenburgh, and F. M. Ralph, 2014: Climatological characteristics of atmospheric rivers and their inland penetration over the western United States. *Mon. Wea. Rev.*, **142**, 905–921, <https://doi.org/10.1175/MWR-D-13-00168.1>.
- Shields, C. A., and Coauthors, 2018: Atmospheric River Tracking Method Intercomparison Project (ARTMIP): Project goals

- and experimental design. *Geosci. Model Dev.*, **11**, 2455–2474, <https://doi.org/10.5194/gmd-11-2455-2018>.
- , J. J. Rutz, L. R. Leung, F. M. Ralph, M. Wehner, and T. O'Brien, 2019: Defining uncertainties through comparison of atmospheric river tracking methods. *Bull. Amer. Meteor. Soc.*, **100**, ES93–ES96, <https://doi.org/10.1175/BAMS-D-18-0200.1>.
- Sinclair, M. R., 1994: An objective cyclone climatology for the Southern Hemisphere. *Mon. Wea. Rev.*, **122**, 2239–2256, [https://doi.org/10.1175/1520-0493\(1994\)122<2239:AOCFT>2.0.CO;2](https://doi.org/10.1175/1520-0493(1994)122<2239:AOCFT>2.0.CO;2).
- , 2002: Extratropical transition of southwest Pacific cyclones. Part I: Climatology and mean structure changes. *Mon. Wea. Rev.*, **130**, 590–609, [https://doi.org/10.1175/1520-0493\(2002\)130<0590:ETOSPT>2.0.CO;2](https://doi.org/10.1175/1520-0493(2002)130<0590:ETOSPT>2.0.CO;2).
- , 2004: Extratropical transition of southwest Pacific cyclones. Part II: Midlatitude circulation characteristics. *Mon. Wea. Rev.*, **132**, 2145–2168, [https://doi.org/10.1175/1520-0493\(2004\)132<2145:ETOSPT>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<2145:ETOSPT>2.0.CO;2).
- Smith, R. B., I. Barstad, and L. Bonneau, 2005: Orographic precipitation and Oregon's climate transition. *J. Atmos. Sci.*, **62**, 177–191, <https://doi.org/10.1175/JAS-3376.1>.
- Sodemann, H., and A. Stohl, 2013: Moisture origin and meridional transport in atmospheric rivers and their association with multiple cyclones. *Mon. Wea. Rev.*, **141**, 2850–2868, <https://doi.org/10.1175/MWR-D-12-00256.1>.
- Trenberth, K. E., 1991: Storm tracks in the Southern Hemisphere. *J. Atmos. Sci.*, **48**, 2159–2178, [https://doi.org/10.1175/1520-0469\(1991\)048<2159:STITSH>2.0.CO;2](https://doi.org/10.1175/1520-0469(1991)048<2159:STITSH>2.0.CO;2).
- Viale, M., and M. N. Nuñez, 2011: Climatology of winter orographic precipitation over the subtropical central Andes and associated synoptic and regional characteristics. *J. Hydrometeor.*, **12**, 481–507, <https://doi.org/10.1175/2010JHM1284.1>.
- , R. Valenzuela, R. D. Garreaud, and F. M. Ralph, 2018: Impacts of atmospheric rivers on precipitation in southern South America. *J. Hydrometeor.*, **19**, 1671–1687, <https://doi.org/10.1175/JHM-D-18-0006.1>.
- Waliser, D., and B. Guan, 2017: Extreme winds and precipitation during landfall of atmospheric rivers. *Nat. Geosci.*, **10**, 179–183, <https://doi.org/10.1038/ngeo2894>.
- Wick, G. A., P. J. Neiman, and F. M. Ralph, 2013: Description and validation of an automated objective technique for identification and characterization of the integrated water vapor signature of atmospheric rivers. *IEEE Trans. Geosci. Remote Sens.*, **51**, 2166–2176, <https://doi.org/10.1109/TGRS.2012.2211024>.
- Wratt, D. S., and Coauthors, 1996: The New Zealand Southern Alps experiment. *Bull. Amer. Meteor. Soc.*, **77**, 683–692, [https://doi.org/10.1175/1520-0477\(1996\)077<0683:TNZSAE>2.0.CO;2](https://doi.org/10.1175/1520-0477(1996)077<0683:TNZSAE>2.0.CO;2).
- Yang, Y., T. Zhao, G. Ni, and T. Sun, 2018: Atmospheric rivers over the Bay of Bengal lead to northern Indian extreme rainfall. *Int. J. Climatol.*, **38**, 1010–1021, <https://doi.org/10.1002/joc.5229>.
- Zhang, Z., M. Zheng, and F. M. Ralph, 2019: The relationship between extratropical cyclone strength and atmospheric river intensity and position. *Geophys. Res. Lett.*, **46**, 1814–1823, <https://doi.org/10.1029/2018GL079071>.
- Zhu, Y., and R. E. Newell, 1994: Atmospheric rivers and bombs. *Geophys. Res. Lett.*, **21**, 1999–2002, <https://doi.org/10.1029/94GL01710>.