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Key Points:

- Atmospheric Rivers are major contributors to rain totals in high rainfall months
- Atmospheric Rivers appear to mitigate droughts or trigger floods depending on the soil moisture condition
- Atmospheric Rivers are a major contributor to the top 10% streamflow all year around

Abstract

This study is motivated by the potential improvement in water supply reliability and better forecasts of extreme rainfall and floods linked to Atmospheric rivers (ARs) in New Zealand. Results indicate that ARs generally dominate monthly rain amounts and wet and dry conditions for the western side of mountainous regions and the north part of the country. Precursor soil moisture conditions and their relationship to runoff are also evaluated. In these regions, ARs are more likely to replenish soil moisture or lead to flash floods in warm-season months but generate severe floods in cool-season months due to low soil moisture deficit. This relationship is further confirmed by the seasonality of the monthly maximum streamflow of the Whanganui River (a major river in the North Island of New Zealand). Additionally, ARs generally lead to high streamflow all year round and are responsible for most top 10% streamflow.

Plain Language Summary

Atmospheric Rivers (ARs) are strong poleward water vapour transport events in the lower troposphere. ARs are important to water resources and are responsible for most extreme rainfall events over the western side of mountainous areas and the northern part of New Zealand. We investigated the dominance of ARs in water availability in wet and dry months and the seasonal impact of ARs on the rainfall-runoff process in these regions. Generally, above (below)-average AR frequency can lead to monthly rain above (below) normal as more than 50% of rain amounts are contributed by ARs in these regions. AR's impact on streamflow is dependent on the soil moisture condition. Here we show that the top 10% of flood events are linked with ARs, and high streamflow is more likely to be linked with AR-induced rainfall events than non-AR storms. In addition, ARs tend to refill soil moisture during the warm-season months and

trigger floods during the cool-season months, indicating the potential role of ARs on drought mitigation and severe flood forecast in New Zealand.

1 Introduction

Atmospheric rivers (ARs) are filamentary channels of enhanced poleward water vapour transport in the lower troposphere, primarily occurring in the midlatitudes (Newell et al., 1992; Newell & Zhu, 1994; Ralph et al., 2004, 2005, 2018; Zhu & Newell, 1994, 1998). They are important components of the global water cycle, and their presence is often tied with frontal systems (Liu et al., 2021; Ralph et al., 2004, 2005; Zhu & Newell, 1998) and cyclones (Cordeira et al., 2013; Guo et al., 2020; Ralph et al., 2004, 2005; Sodemann & Stohl, 2013; Zhang et al., 2019; Zhou & Kim, 2019; Zhu & Newell, 1994).

Depending on soil moisture condition and season, AR-induced extreme rainfall events can cause severe floods (Dettinger et al., 2011; Lavers et al., 2011, 2012; Neiman et al., 2011; Ralph et al., 2013; Ralph et al., 2006) and/or break droughts (de Kock et al., 2021; Dettinger, 2013). Additionally, many inland floods and extreme precipitation are associated with an AR's inland penetration (Lavers & Villarini, 2013a, 2013b; Nayak & Villarini, 2017). On the other hand, ARs are major contributors to water resources where they frequently occur (Dettinger et al., 2011; Lavers & Villarini, 2015; Nayak & Villarini, 2017; Viale et al., 2018). Globally, extreme precipitation and damaging wind events are related to ARs (Waliser & Guan, 2017).

New Zealand is a long and narrow country surrounded by ocean spanning from 34°S to 47°S in the midlatitudes. Mountain ranges in the country trend southwest-northeast peaking at 3764 m. Several studies have recently investigated the orographic enhancement of AR-induced precipitation in New Zealand (Little et al., 2019; Porhemmat et al., 2020; Prince et al., 2021; Reid et al., 2021; Shu et al., 2021) as well as the spatial connection between historical flood events and ARs (Kingston et al., 2016).

Generally, ARs are the main contributor to annual rainfall and are responsible for many extreme rainfall events on the western side of mountain ranges and the northern part throughout the country (Shu et al., 2021). Considering the seasonality of elements within the rainfall-runoff process, ARs might play a role in breaking/triggering drought and lead to floods. Quantifying the hydrological impact of ARs in different seasons and understanding the role of ARs in wet and dry months can further benefit water sectors for drought and flood mitigation and water supply reliability. Therefore, it is important to understand the seasonal impact of ARs on the rainfall-runoff process and the AR's role in water availability in wet and dry months. One study found that droughts and floods in the country are likely to be caused by the absence and presence of ARs, respectively (Paltan et al., 2017). However, there is a lack of information on both the local and seasonal impact of ARs. In this regard, this study aims to evaluate the seasonal impact of ARs on soil moisture and runoff, river flow, and AR's contribution to rainfall amounts in wet and dry months in New Zealand.

2 Data and Methods

2.1 Data

AR detection is based on the integrated water vapour transport (IVT) magnitude from an Eulerian framework (Blamey et al., 2018; Lavers et al., 2012; Nayak & Villarini, 2017), which is given by:

$$IVT = \sqrt{\left(\frac{1}{g}\int_{1000hPa}^{300hPa} \mathrm{qu\ dp}\right)^2 + \left(\frac{1}{g}\int_{1000hPa}^{300hPa} \mathrm{qv\ dp}\right)^2}, \quad (1)$$

where q is specific humidity (kg kg^{-1}), u and v are zonal and meridional wind vectors (m s^{-1}) respectively, g is the gravitational acceleration (9.81 m s^{-2}), and dp is the pressure difference between two adjacent atmospheric pressure levels (hPa). To compute IVT, 20 vertical pressure levels (1000hPa-300hPa) of 6-hourly specific humidity and wind vectors were retrieved from the most recent reanalysis dataset version from Medium-Range Weather Forecasts (ECMWF), namely the ERA-5 reanalysis project (Hersbach et al., 2020) from 1950 to 2020 with a 0.25° spatial resolution over the 0-70°S and 100°E-120°W domain.

Station-based daily rainfall amounts were obtained from New Zealand's national climate database web system managed by the National Institute of Water and Atmospheric Research (NIWA). To avoid an inaccurate estimate of the spatiotemporal connection between ARs and rainfall, and consider the coverage of sites over the country, 644 stations with full daily records of at least 30 years from 1950 to 2020 were selected (Figure 1). Daily soil moisture deficit (SMD) and runoff among 496 of the 644 stations with a time length range from 10 to 39 years were also retrieved from NIWA. In New Zealand, SMD is the amount of water the soil is short of 150 mm, the full holding capacity as the single moisture for all soils. This value is also used in the national-wide drought monitoring system by NIWA (Mol et al., 2017) and based on field experiments and is commonly typical for loam soils in New Zealand (Porteous et al., 1994). Runoff is calculated as excess rainfall less evaporation when there is no SMD. To confirm the applicability of modelled SMD and runoff, one of the largest river catchments in New Zealand was selected to evaluate the seasonality of AR impact on streamflow rates. Figure 1 shows the catchment and the location of rain sties and the river gauge. The maximum daily streamflow record of the Whanganui River between 1957 to 2019 was obtained from the Horizons regional council.

2.2 AR detection

The AR detection algorithm developed by Guan and Waliser (2015) was employed in this study, which involves a set of conditions on the IVT grid cells to identify AR objects every time step within the specified domain. The AR object refers to the instantaneous area that meets the defined AR detection conditions. The detection conditions include grided IVT magnitude thresholding, the poleward direction of the AR object, IVT direction coherence within the AR object, consistency between the AR-object mean IVT direction and orientation, and the AR-object geometry. Detailed AR detection procedures and conditions are provided in Guan and Waliser (2015). Archived landfalling AR dates from this algorithm shows over 90% agreement with other regional-specific AR detection techniques (Gorodetskaya et al., 2014; Guan et al., 2018; Lavers et al., 2012; Neiman et al., 2008; Ralph et al., 2019; Shields et al., 2018) and this algorithm remains the only one to be validated from dropsonde observations for the AR intensity and geometry. Thus, this algorithm has been widely used as a benchmark in different regions for AR tracking studies (Guan & Waliser, 2019; Zhou et al., 2018; Zhou & Kim, 2019) and regional-specific AR detection algorithm development (Gershunov et al., 2017; Pan & Lu, 2019; Reid et al., 2020).

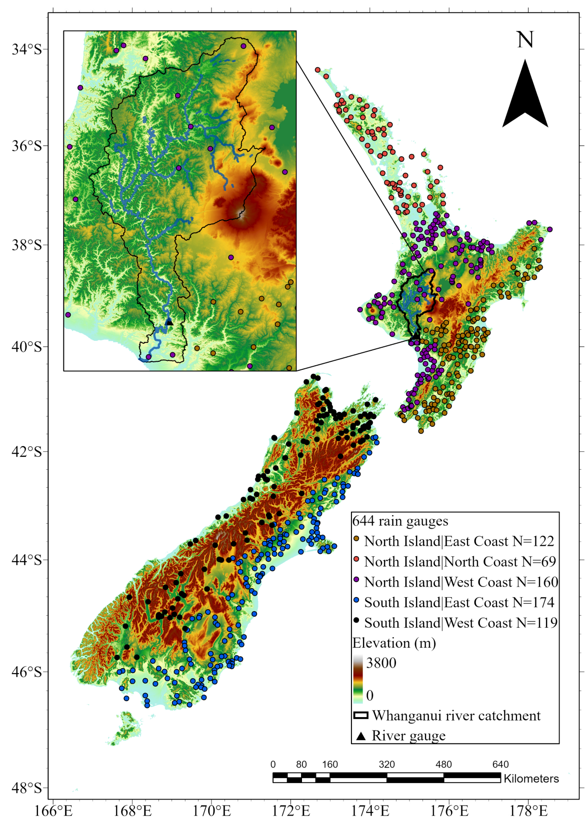

Figure 1. Map of 5 divides, 644 rain gauges, Whanganui river catchment and river gauge

2.3 AR-generated rain and streamflow

We used the method developed by Shu et al. (2021) to identify AR-induced rainfall events over rain sites. Based on the geographical coordinate of the 4 grid points enclosing a rain gauge, the date and time that all 4 points simultaneously detected AR presence were referred to as an AR event at that date and time for that rain gauge.

The day that AR events induce rainfall is referred to as an AR day. The time series of daily rainfall, SMD, runoff was then divided into AR and non-AR series. Moreover, the daily rainfall, SMD, runoff was standardised based on its mean and standard deviation over the entire series of its value greater than 0. The monthly max streamflow rates of the Whanganui River and dates were obtained, and we found that streamflow generally relates to rain within 3 days. Hence, AR-induced rain events were also checked 3 days prior to the maximum streamflow rate dates, and that streamflow would be marked as AR-generated streamflow if all rain sites within the catchment observed AR-induced rain at least 1 day within the 3-day time window.

Monthly rainfall amounts were computed and standardised based on monthly mean and standard deviation. For instance, the standardised rainfall amount for May 2000 is based on the mean and standard deviation of all rainfall amounts in May through the record. The standardised index 1 indicates 'above normal' conditions, while -1 indicates 'below normal' conditions. The monthly AR days were also standardised in the same procedure, and the index >0 indicates the 'above mean' condition while <0 indicates the 'below mean' condition. To illustrate whether the monthly rainfall is dominated by ARs, the contribution of ARs to monthly rain was calculated. The concurrence probability of AR day above (below) mean and monthly rain above (below) normal was also evaluated.

All rain sites were divided into 5 groups in terms of 'AR impact' and geographical location. Figure 1 shows the 5 categorised regions. The west coast region is where ARs contribute to more than 41% of annual rain and more than 50% of the top 10% daily rainfall events; sites that do not meet this condition are subsequently labelled as the east coast region (Figure S1). The northern north island is a long thin region and is not affected much by topography compared to other divides but is highly impacted by ARs.

3 AR's impact on monthly rain

Figure S2 shows the AR contribution to monthly rain for the five New Zealand regions. The north coast and west coast regions generally see more than 50% of rain amounts contributed to by AR events apart from winter months (JJA) or 1 month before or after winter. Conversely, monthly rain amounts in the east coast regions are more likely contributed to by non-AR storms. Figures 2a-e further shows the monthly AR-related rain fraction with respect to monthly rain conditions. For the north coast and west coast regions, AR contributions are generally more (less) than 50% when monthly rain is above (below) normal (Figures 2a-c). It should be noted that monthly rain can be below normal in some cases, even more than half of the rain produced by ARs in these regions (in December-January).

Furthermore, the likelihood of more than half of monthly rain by ARs is higher (lower) than 50% when monthly rain is above (below) normal in east coast regions (Figures 2f-h). Because ARs do not dominate rain totals for these regions, the probability of more than half rain amounts linked with ARs is lower than 50% regardless of the monthly rain condition (Figures 2d-e and 2i-j). As expected, in the north coast and west coast regions, AR days monthly frequency are generally above (below) average when monthly rain is above (below) normal (Figure 3). Interestingly, monthly AR days are generally below the mean in dry months in east coast regions, and it is evident that ARs are not a major contributor to rain (Figures 3d-e and 3h-j). Thus, dry conditions for east coast regions are not likely due to AR absence.

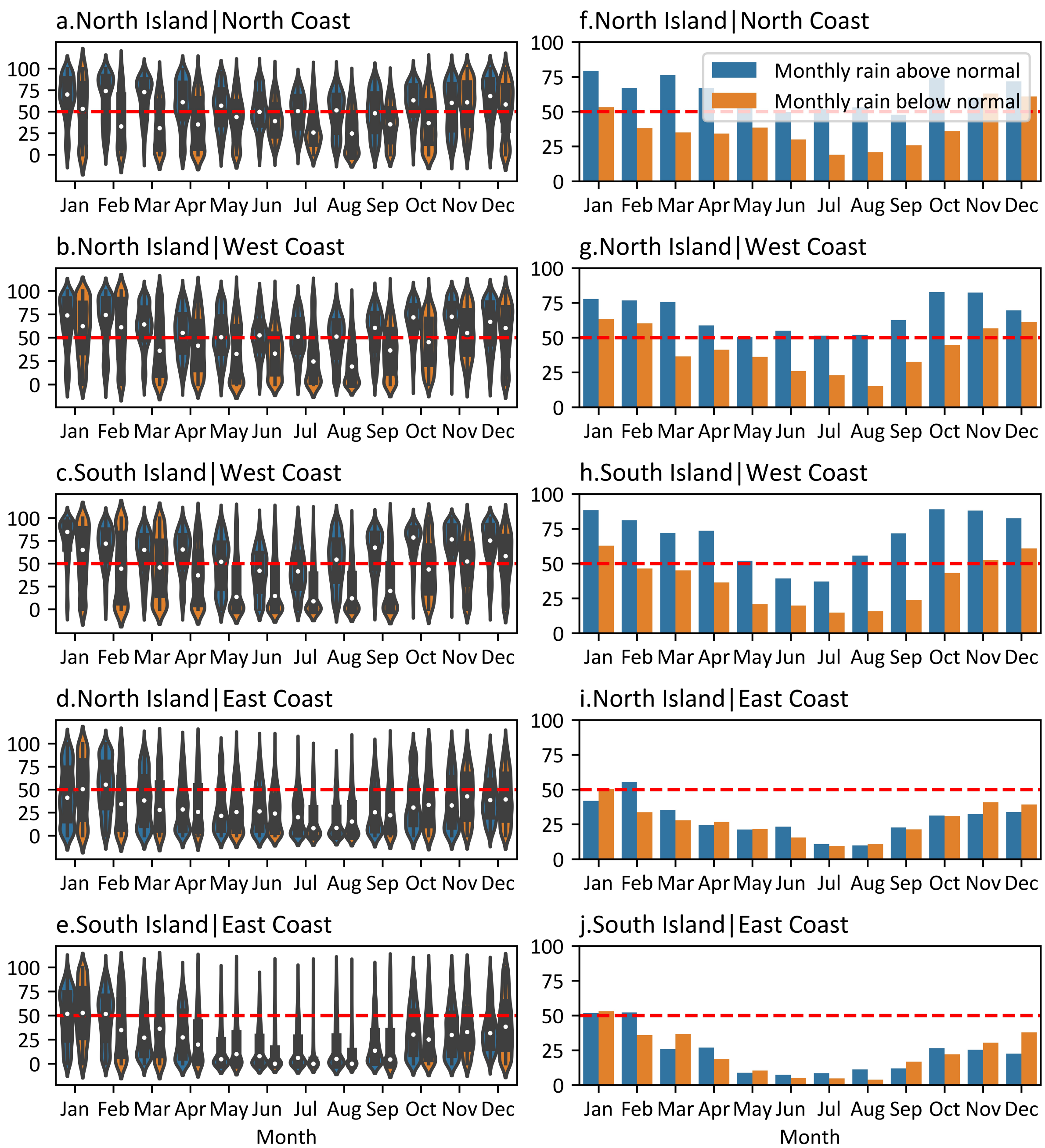

Figure 2. AR contribution to monthly rain in wet and dry months (a-e). Probability of over 50% rain contributed by ARs in wet and dry months (f-j).

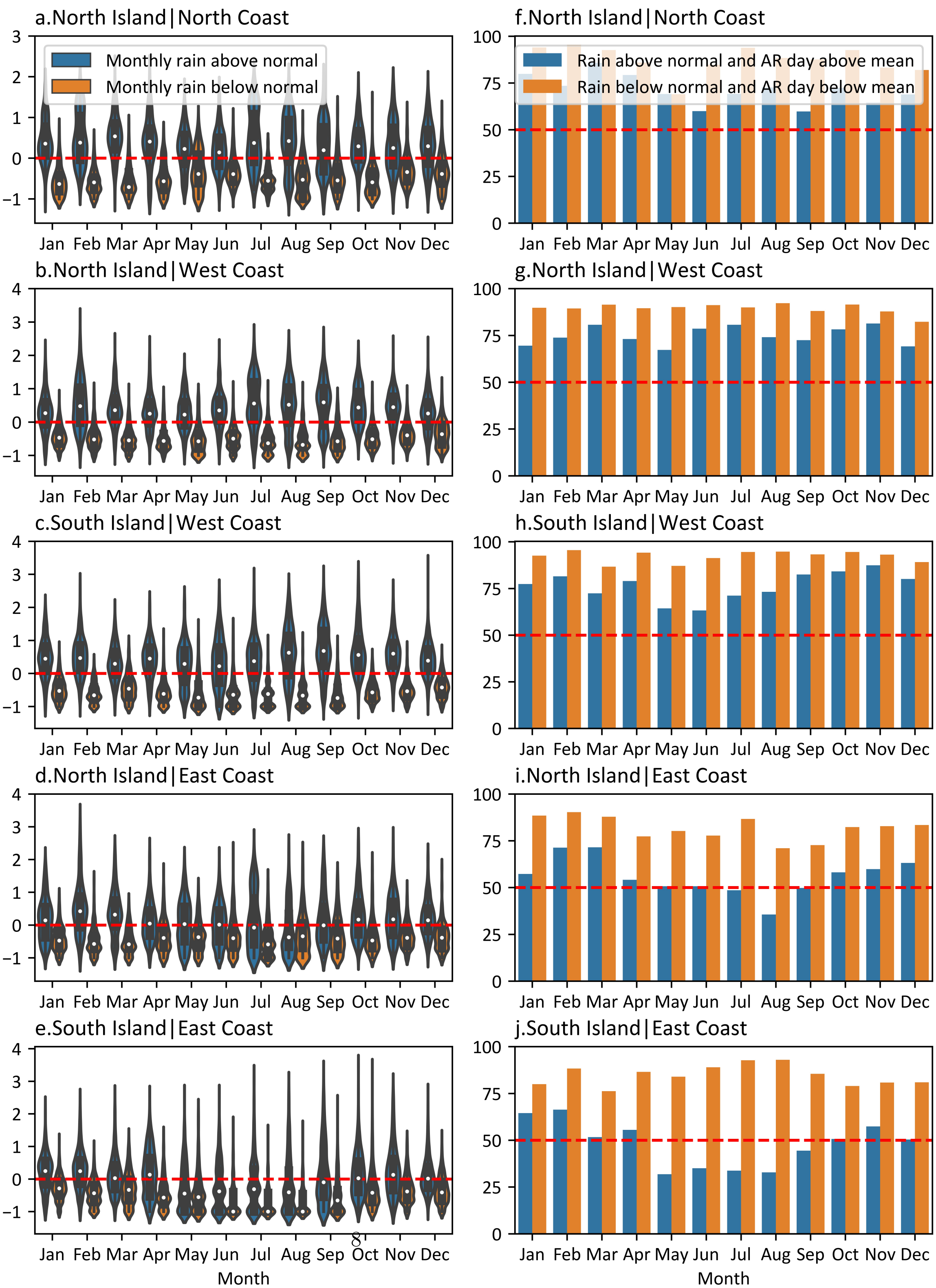
a.North Island|North Coast
Monthly rain above normal
Monthly rain below normal
b.North Island|West Coast
c.South Island|West Coast
d.North Island|East Coast
e.South Island|East Coast
f.North Island|North Coast
Rain above normal and AR day above mean
Rain below normal and AR day below mean
g.North Island|West Coast
h.South Island|West Coast
i.North Island|East Coast
j.South Island|East Coast
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Month
Month

Figure 3. Condition of standardised monthly AR day (only days that ARs lead to rainfall) frequency in wet and dry months (a-e). Probability of AR day condition in wet and dry months (f-j).

4 Seasonality of AR impact on soil moisture and runoff

Figure S3 illustrates the standardised rainfall against SMD and runoff for AR and non-AR events. For AR events, anomalously high AR-rainfall and SMD generally occur in summer (DJF) and autumn (MAM) months, while anomalously high AR-rainfall and runoff can occur each month. In some cases, ARs even cause extreme rain to saturate the soil and generate high runoff in the months of December-May.

Figure 4. Probability of concurrence of anomalously high AR-induced rain, runoff, SMD (a-e). Probability of runoff increase and SMD decrease caused by ARs (f-j).

We calculated the probability of the concurrence of anomalously high AR-rainfall and runoff and SMD, respectively. Anomalously high runoff generally resulted from AR-induced rain through the west and north coast regions as the likelihood is over 50% all year round (Figures 4a-c). Anomalously high SMD can occur, although ARs bring heavy rainfall through months of November-May. We further investigated the AR's hydrological impact in relation to runoff increase and SMD decrease, and Figures 4f-h indicate an over 50% chance that runoff increase and SMD decrease caused by AR-induced rain for the north coast and west coast regions. Therefore, in these regions, ARs are likely to mitigate droughts or generate flash floods in the months of November-May as the concurrence probability of anomalously high AR-induced rain, SMD, runoff is higher than 50%, respectively. On the other hand, ARs are likely to produce severe floods during June-October as anomalously high SMD generally does not occur, but more than 50% high runoff is caused by ARs.

Figure 5 illustrates the maximum monthly flow linked with AR events and non-AR events. Most top 10% streamflow is caused by ARs (values above the dashed red line), and AR-generated streamflow is generally higher than non-AR events related. Additionally, AR-generated streamflow is generally higher during June-October than other months, which confirms results in Figures S3 and 4.

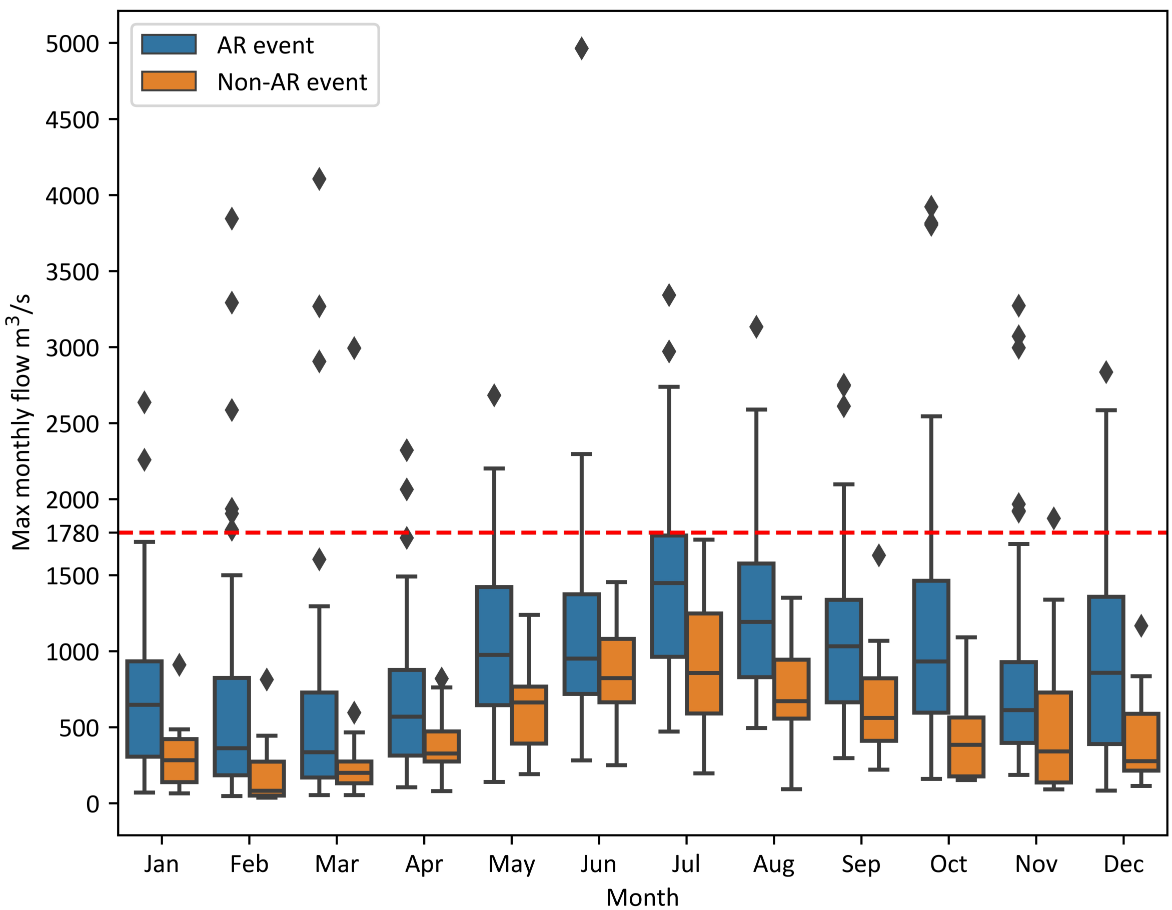

Figure 5. Wanganui river monthly maximum streamflow linked with ARs and non-AR storms. The dashed red line represents the 90th value of the maximum monthly streamflow through the entire record.

5 Conclusions

This study investigated the seasonality of AR's role in rain amounts under wet and dry month conditions, seasonal impact on soil moisture and runoff, and streamflow of one of the largest catchments in New Zealand. Overall, landfalling ARs were detected based on the widely used AR detection algorithm by Guan and Waliser (2015) and AR-induced rain events at respective rain gauges were identified by the technique of Shu et al. (2021). The country was also divided into five sectors in terms of "AR impact" based on work by Shu et al. (2021). Overall, the contribution of ARs to monthly rain and their seasonal impact on soil moisture and runoff in the five distinct regions were investigated.

It is shown that ARs can contribute to more than 50% of monthly rainfall for north and west coast regions, except for the winter months (JJA), in line with previous studies (Prince et al., 2021; Shu et al., 2021). Further, in these regions, ARs are found to generally dominate the rain amounts when monthly rain is above normal in terms of AR contribution and frequency, and vice versa. This indicates the importance of further investigation of the role of ARs in breaking and triggering meteorological droughts, of high importance given the country's largest populations and developed water supply system (including hydropower dams) occur in these regions. It should note that, in these regions, dry months sometimes can occur in the months of November-January though ARs dominate the rain amounts in these months. This is presumably due to the influence of large-scale climate patterns influences on ARs. Thus, further investigation of climate mode impacts on ARs is needed.

The seasonal AR impact on the rainfall-runoff process in these regions were also evaluated. The majority of anomalously high runoff, runoff increase, SMD decrease is caused by AR-induced rain. Considering the seasonality of anomalously high SMD, ARs are very likely to replenish soil moisture and lead to flash floods in the summer and autumn months of November-May, yet generate severe floods in the months of June-October. This varying seasonal impact of ARs is also reflected by the seasonality of AR-generated and its comparison to non-AR-related streamflow on the Whanganui River catchment. Moreover, ARs are found to co-occur with the top 10% monthly maximum river flow. Hence, there is a huge potential to employ AR information for extreme river flow forecasts.

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Data Availability Statement

Data used in this study were obtained freely online (registration required):

ERA5 hourly data on pressure levels from 1950 to 1978 (preliminary version): https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-preliminary-back-extension?tab=overview

ERA5 hourly data on pressure levels from 1979 to present:

https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview

Daily rainfall, soil moisture deficit, runoff: https://cliflo.niwa.co.nz/pls/niwp/wgenf.genform1

Whanganui river streamflow (Gauge name: Whanganui at Te Rewa; direct data request to the council staff is required for the entire record): https://envirodata.horizons.govt.nz/?siteName=Whanganui%20at%20Te%20Rewa&collectionName=Flow

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