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Characteristics and large-scale drivers of atmospheric rivers associated with extreme floods in New Zealand

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DOI: 10.1002/joc.7415

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Document Version Peer reviewed version

Citation for published version (Harvard): Kingston, DG, Lavers, DA & Hannah, DM 2021, 'Characteristics and large-scale drivers of atmospheric rivers associated with extreme floods in New Zealand', *International Journal of Climatology*. https://doi.org/10.1002/joc.7415

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- 1 Characteristics and large-scale drivers of atmospheric rivers associated with extreme floods in
- 2 New Zealand
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- 4 Short title: Atmospheric rivers and floods in New Zealand
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- 16
- 17 Re-submitted to the International Journal of Climatology
- 18 September 2021
- 19
- 20 See acknowledgements for details of data availability.

21 Abstract

The Southern Alps in the South Island of New Zealand are one of wettest places globally, making it 22 critical to understand the mechanisms for delivery of extreme precipitation and river flooding. 23 24 Atmospheric rivers (ARs) are recognised as key causes of extreme precipitation in New Zealand, but relatively little is known about their large-scale meteorological drivers. Here, we aim to investigate 25 these hydroclimatological connections for five major South Island catchments located from south-26 north along the axis of the Southern Alps: Te Anau, Matukituki, Pūkaki, Rakaia and Waiau Toa. For 27 28 each catchment, the top eight flood events over a 38-year period are characterised. Specifically, vertically integrated horizontal water vapour transport (IVT), 500 hPa geopotential and 300 hPa 29 winds are examined to quantify the large-scale atmospheric drivers of flood events. The Kidson 30 synoptic weather classification is also employed to understand better the connection of IVT to New 31 32 Zealand weather patterns. Intense IVT is associated with flood events for all five catchments and, in most instances, corresponds to AR-type events. Spatial patterns of IVT display substantial variation 33 34 between flood events and catchments; however, there are some generalizable patterns. Firstly, clear AR-type IVT patterns dominate for all catchments (except the Waiau Toa) with AR orientation 35 ranging from westerly to northwesterly. For the most northerly catchment (Waiau Toa), cyclonic 36 zones of high IVT occur instead for some events. Secondly, AR length varies from those restricted to 37 the Tasman Sea (~ 2000 km) to those extending to the west or north of Australia. Thirdly, 38 39 northwesterly ARs are associated with the passage of a depression in the general westerly circulation, characterised in particular by the Kidson 'Trough' weather type. Finally, AR orientation 40 is associated strongly with 300 hPa winds, and in many cases to the general wave characteristics of 41 Southern Hemisphere circulation, particularly the Zonal Wave 3 pattern. 42

43 Key words: Atmospheric rivers, floods, atmospheric water vapour flux, New Zealand

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47 Introduction

Extremely high rainfall along the main divide of the Southern Alps/Kā Tiritiri o te Moana in New 48 49 Zealand makes this region one of the wettest places globally, and so a location where mechanisms for delivery of extreme precipitation totals are critical to understand. These high precipitation 50 amounts mean that the Southern Alps act as 'water towers' for the much drier areas to the east 51 52 (Vivroli et al. 2007), where water from the rivers originating in the Southern Alps is used intensively for electricity generation and irrigated agriculture. Just as this multi-scale perspective is needed to 53 54 understand terrestrial hydrology, precipitation delivery is also influenced by a number of interacting 55 climate variables across different scales (Kingston et al. 2020). For New Zealand, these include 56 weather systems of tropical, temperate and sub-polar origin, themselves affected by hemispheric-57 scale atmospheric circulation patterns such as the Southern Annular Mode (SAM; Kidston et al. 58 2009) and El Nino Southern Oscillation (ENSO; Gordon 1986). Irrespective of their origin, these 59 weather systems are all subject to strong topographic modification across New Zealand's mountain 60 terrain.

A handful of global-scale studies have identified New Zealand as being strongly affected by 61 62 landfalling atmospheric rivers (ARs), which are synoptic features responsible for transporting the majority of water vapour in the warm sector of mid-latitude cyclones. Strikingly, global-scale 63 analyses have shown that up to 80% of annual river flow can be associated with ARs in some parts 64 of the country (Paltan et al. 2017). These impacts may be exacerbated in the future as New Zealand 65 66 is a hotspot for projected climate change impacts on ARs (Espinoza et al. 2018), with ARs in general expected to increase in their magnitude and duration (Douville et al. 2021). Studies focussed directly 67 on New Zealand have provided further support for the importance of ARs. Similar to the findings of 68 69 Paltan et al. (2017), Prince et al. (2021) showed that over 70% of total precipitation in locations on the west coast of the South Island/Te Waipounamu occurred during or within 12 hours of AR arrival, 70 and an even higher proportion of extreme (98th percentile) precipitation (>80%). Although their 71 importance diminishes away from the west coast and topographic forcing associated with the 72 73 Southern Alps, ARs were shown to remain critical to precipitation climatology across a series of 74 locations around New Zealand. In subsequent studies, both Reid et al. (2021) and Shu et al. (2021) 75 have found a similarly dominant role of ARs for extreme precipitation events across New Zealand. 76 Furthermore, these broad characteristics of New Zealand AR climatology are reflected in more 77 geographically focussed studies within New Zealand, and from precipitation to river flows and the cryosphere. For example, ARs have been shown to be critical for extreme high flow events in the 78 headwaters of the Waitaki river (Pūkaki catchment) that drains eastwards from the Southern Alps 79

(Kingston et al. 2016), as well as for major snowfall and ablation events at study sites within the
Southern Alps (Cullen et al. 2019; Little et al. 2019; Porhemmat et al. 2020; Porhemmat et al. 2021).
As with other locations around the world that commonly experience ARs, in New Zealand their
impact ranges from beneficial for more moderate events (i.e. providing water for irrigation and
hydroelectric storage schemes), to damaging for the most extreme events (Prince et al. 2021). Floods
are the most common cause of high-magnitude insurance losses from natural disasters in New

86 Zealand (McAneney et al. 2021).

87 Although these previous studies have firmly established the importance of ARs for the 88 hydroclimatology of New Zealand, many unanswered questions remain regarding the nature of the 89 weather systems that lead to AR occurrence, and in turn the relationship to driving features of the regional and larger scale climate system such as SAM and ENSO. Moreover, little is known about 90 91 how the importance of these climate system features vary for ARs occurring over different parts of NZ – this is important, given its topographical complexity and the extreme climatic gradients that 92 93 result (e.g. Sturman et al. 1999). Bearing in mind these research gaps, the following questions are addressed in this study: 1) how does the AR influence on floods vary spatially across the South 94 Island/Te Waipounamu; 2) how does AR magnitude and structure vary between events and 95 96 locations; and 3) what are the links between ARs across the South Island and large-scale climate 97 patterns. By answering these questions, we aim to enhance understanding of the hydroclimatological process cascade connecting to regional climate, ARs and extreme floods in New Zealand. 98

99

100 Data and Methods

The top eight river flow events from 1979-2018 are investigated for tributaries or upper reaches of 101 102 five major catchments across the South Island of New Zealand (Figure 1). These study catchments 103 include some of the major hydroelectricity power stations in New Zealand, alongside providing 104 water for large irrigation schemes and important, biodiverse habitats. From south to north, the Lake Te Anau inflow record (3100 km²) is used as representative of the larger Waiau catchment (8314 105 km²; part of the 850 MW Manapouri hydropower scheme. The Matukituki at West Wānaka (800 106 km²) is a headwater tributary of the Clutha/Mata Au, New Zealand's largest catchment (20,582 km²). 107 The Clutha includes two major hydroelectric power stations (Roxburgh and Clyde), comprising 784 108 MW generating capacity in total. The Lake Pūkaki catchment (1457 km²) forms one of the three 109 headwater lake catchments for the Waitaki (11,900 km²), draining eastwards from the central zone of 110 the Southern Alps. The Waitaki was also the study focus of Kingston et al. (2016), and is the most 111

important catchment for hydro-electricity generation nationally (1738 MW generating capacity 112 across seven power stations). The Rakaia catchment is gauged at Fighting Hill (2560 km²), covering 113 the montane runoff generating area that comprises the majority of this catchment (2800 km²). There 114 is a relatively small hydroelectric scheme on this river (34 MW). Below the gauging station the 115 Rakaia broadens into a large braided river, and also services the largest irrigation scheme in the 116 South Island (the Central Plains Water Enhancement Scheme). Finally, the 3154 km² Waiau 117 Toa/Clarence is represented by the Jollies station record (440 km²). In contrast to the other 118 catchments, the Waiau Toa largely flows through wilderness areas, with comparatively little direct 119 120 abstraction or modification of river flow. Lake inflow data were provided by Meridian Energy for Lakes Te Anau and Pūkaki; the National Institute for Water and Atmospheric Research (NIWA) 121 122 provided data for the other three study catchments.

123 The top eight absolute highest flow events were identified from mean daily discharge records from each river/lake catchment. Events were required to be independent – defined by river flow returning 124 to (approximate) monthly average values between events and a minimum seven-day separation 125 between events. Although river flow in all study catchments is modified to some extent by human 126 activity, either this predominantly influences low rather than high flows, occurs primarily in a 127 128 downstream location, or a naturalised record is used. Specifically, for the Matukituki the river flow 129 record at West Wanaka (near the river outlet to Lake Wanaka) is not substantially modified. The 130 upstream locations of the discharge records used for the Rakaia and Waiau Toa were chosen due to the occurrence of abstractions (primarily for irrigation) in the lower sections of these catchments. 131 Similarly, inflow data for Lakes Pūkaki and Te Anau are naturalised records for two catchments (the 132 Waitaki and Waiau) that are managed intensively for hydropower at the lake outlet and for irrigation 133 purposes further downstream. Correspondingly, hydroclimatological connections for extreme high 134 flows can be explored largely independently of human influence on the land surface. 135

136 The Matukituki, Pūkaki and Rakaia catchments have their lowest seasonal flows in the austral winter, with peaks in spring or summer (Figure 2). This seasonal cycle corresponds closely to the 137 138 storage and melt of seasonal snow, as the snow line moves from approximately 1000 to 2500 m 139 between winter and summer (Fitzharris et al. 1999). The Matukituki, Pūkaki and Rakaia are partly 140 fed by glacial meltwater, although snow storage and melt are proportionally far more important (e.g. 141 Jobst et al. 2018; Kerr 2013). The headwaters of these three catchments are located in the highest 142 parts of the Southern Alps (with the highest peak, Aoraki/Mount Cook at 3724 m), again indicating the dominant role of snow storage and release for the annual river flow regime. This is also reflected 143 in the highest extreme flow events occurring primarily during spring and summer. The more 144

southerly Lake Te Anau catchment has a somewhat smaller snow influence, with the seasonal regime 145 (and occurrence of extreme events) less pronounced, but still peaking in spring and summer (Figure 146 2). In addition to mid-winter low flows, the annual minimum for Lake Te Anau is actually 147 experienced in February, again reflecting the earlier cessation of snowmelt input compared to the 148 middle three catchments. In contrast to the lower four catchments, the Waiau Toa rises in the inland 149 150 Kaikōura range, a northeastern extension of the Southern Alps. The inland Kaikōura range is both 151 further from the west coast and lower in altitude than other catchments (highest elevation 2885 m, at Tapuae-o-Uenuku). Although the annual regime of the Waiau Toa peaks in spring (again, associated 152 153 with snowmelt), it maintains relatively high river flow through winter, with the annual minimum occurring during February (Figure 2). High flow extremes are distributed relatively evenly from 154 155 winter through to late spring.

156 The widely used Kidson synoptic weather classification (Kidson 2000) is applied here to characterise the meteorological situation associated with high flow events for the five study catchments. The 157 158 Kidson scheme is based on a combination of principal components analysis and cluster analysis of 1000 hPa geopotential data from the NCEP/NCAR reanalysis (Kalnay et al. 1996), with synoptic 159 types assigned twice daily, at 00 and 12 UTC. There are 12 individual synoptic types, which can be 160 161 grouped into three broad regimes: trough, westerly and blocking (Kidson 2000). These regimes are associated with distinct patterns of temperature and precipitation across New Zealand (Renwick 162 2011). 163

164 To identify the meteorological situation associated with the occurrence of extreme high river flows at 165 each study site, and in particular the role of ARs, vertically integrated horizontal water vapour 166 transport (IVT) was analysed for each instance. This was performed, at 6-hour time-steps, using the 167 ERA5 reanalysis data set (Hersbach et al. 2020): specifically the northwards and eastwards IVT fields, IVT divergence field, as well as 500 hPa geopotential and 300 hPa U- and V-components of 168 169 wind. Bearing in mind the event-based focus of this study, the presence of ARs were not formally tested using an auto-detection algorithm such as that presented by Guan and Waliser (2015). Instead, 170 IVT magnitude (> 250 kg m⁻¹ s⁻¹), spatial pattern of IVT (i.e. length/width ratio >2) and connection 171 to a low pressure system were used to manually identify IVT patterns as corresponding to ARs, 172 173 following the general definition of ARs provided by Ralph et al. (2017).

174

175 **Results and Discussion**

176 *Flood timing and magnitude*

Flood events for the four southernmost catchments (Te Anau, Matukituki, Pūkaki and Rakaia) occur 177 primarily during the austral summer half year (27 of 36 events), and in particular the peak summer 178 months of December and January (19 events; Figure 2). This concentration is particularly the case 179 for Pūkaki and Rakaia, which between them have just two events outside the November-January 180 period (March for Pūkaki, and May for Rakaia). The highest flood events also typically occur in 181 182 December-January for these four catchments. The timing of Te Anau flood events is just slightly more variable than the other three, with two floods also recorded in the mid-winter months of August 183 and June (the 5th and 7th ranked events, respectively). 184

The concentration of flood events during summer months for the four southernmost catchments
strongly indicates the augmentation of extreme rainfall totals by seasonal snowmelt for flood events,
with all having their headwaters at elevations above the seasonal snowline in the Southern Alps.
Furthermore, the catchment with the strongest concentration of flood events in peak summer, Pūkaki,
also has the highest elevation headwaters and highest contribution of snowmelt to river flow (23%;
Kerr, 2013).

In contrast to the other four catchments, Waiau Toa floods are relatively evenly spread through the 191 year (Figure 2), although with some grouping of events during the winter-early spring period (four 192 from July to September). This difference from the other four catchments reflects the location of the 193 Waiau Toa headwaters in the Inland Kaikoura range, which is both at a lower elevation and located 194 further east (and so drier) than the more central region of the Southern Alps where the other study 195 196 catchments are located. The resultant higher rain: snow ratio and lower overall precipitation totals for 197 the Waiau Toa lead to the greater occurrence of flood events year-round, and slight tendency of rain-198 on-snow flood peaks to occur more commonly in winter, rather than spring and summer.

Alongside similarities in seasonality, there are some common flood event timings between
catchments, particularly for the two more central catchments: Pūkaki (four out of eight events are
coincident with top eight floods in other catchments) and Rakaia (six coincident events). However,
there are no common events between the furthest north and south catchments (Waiau Toa and Te
Anau, respectively).

Differences in flood magnitude across the five catchments corresponds broadly to differences in catchment size – i.e. the highest magnitude floods occur for Te Anau (up to 4656 m⁻³ s⁻¹), and lowest for Waiau Toa (maximum of 263 m⁻³ s⁻¹). However, for the four southernmost catchments the proportional departure from monthly average flow is relatively consistent. Once discharges have been standardised relative to their respective monthly mean and standard deviation, the monthly zscore values for the flood discharge range between approximately 6 and 14. In contrast, flood

- 210 magnitudes for the smaller Waiau Toa are proportionally higher, with z-scores ranging from 12-22.
- 211 This may indicate that where ARs intersect with smaller catchments there is a greater likelihood of
- extreme discharge, given that more of the catchment is exposed to the AR.
- 213

214 *IVT and local circulation characteristics during flood events*

All flood events for all five study locations occur in conjunction with IVT immediately upwind of 215 the catchment above the nominal 250 kg m⁻¹ s⁻¹ threshold for AR occurrence (Gimeno et al. 2014; 216 Figures 3-7). Higher IVT values are typically present upwind of the study catchments, with a 217 218 maximum IVT of over 1800 kg m⁻¹ s⁻¹ for Pūkaki event 6/Rakaia event 3. With flux magnitudes >1250 kg m⁻¹ s⁻¹ in many instances across all five catchments, a number of systems fall into the 219 maximum AR intensity category proposed by Ralph et al. (2019) – although these values drop 220 substantially as the system reaches the catchment gauge/outlet (Table 1). Overall, the strongest IVT 221 222 systems occur for Te Anau, Pūkaki and Rakaia floods, with the Waiau Toa systems generally the 223 weakest.

Although an important precursor to floods, high IVT values in themselves are not a direct indicator 224 225 of extreme precipitation and river flow. Substantial moisture convergence is necessary for the most extreme precipitation events in the Southern Alps (Sinclair et al. 1997, Chater and Sturman 1998). 226 227 Correspondingly, ouranalysis reveals strong areas of IVT convergence immediately upwind of the study catchments associated with the top eight flood events for the lower four catchments (Figures 228 229 S1-S4), and most of the Waiau Toa events (Figure S5). Furthermore, IVT direction is close to perpendicular to the approximate northeast-southwest orientation of the Southern Alps across all 230 231 events for the Te Anau, Matukituki, Pūkaki and Rakaia catchments (Table 1). For Waiau Toa, 232 similar perpendicular IVT – topography orientations are found, but with some events from the northwest and others from the opposite southeast direction. As such, these results indicate clearly 233 that weather systems with high IVT and subsequent convergence associated with orographic forcing 234 as the primary cause of the precipitation that drives these extreme flood events. Snowmelt is likely to 235 be a contributing factor during the period from winter to early summer, bearing in mind the tendency 236 237 for AR-bearing weather systems to be associated with warmer air (e.g. Little et al. 2019).

The spatial form of the areas of high IVT for most events for the four southernmost catchments are

broadly consistent with ARs, consisting of long and relatively thin zones of IVT>250 kg m⁻¹ s⁻¹

240 (Figures 3-6). A smaller number of events have much wider zones of high IVT. In some cases these

are wide and long zones of high IVT, associated with less distinct or possibly closely following
weather systems (e.g. Matukituki events 3 and 4; Figure 4). For five Waiau Toa flood events (1-3, 5,
7), there are strongly circular high IVT patterns that are centred to the north of New Zealand (Figure
7). In contrast to the Tasman and Southern Ocean systems that dominate for the four southernmost
catchments, these Waiau Toa systems are more difficult to describe in terms of typical length: width
ratios due to their circular nature.

247 The weather systems that lead to high IVT and flood events for the four southern catchments consist 248 generally of an eastward-propagating low pressure trough passing over or to the south of New 249 Zealand, leading to a northwesterly AR orientation at landfall. Many of these high IVT systems are 250 part of a series of depressions embedded in the mid-latitude westerlies, with each depression 251 containing a northwesterly orientated AR (e.g. Te Anau events 1 and 3, Pūkaki event 6/Rakaia event 252 3: Figures 3, 5 and 6). These systems extend across the majority of the width of the Tasman Sea 253 towards the east coast of Australia, and in some cases a substantial distance into the continent (e.g. 254 Matukituki event 2 vs. Te Anau event 1: Figures 4 and 3). Irrespective of how far these northwesterly systems extend into the Australian continent, they are associated commonly with the 255 troughing regime of the Kidson synoptic classification for New Zealand (Kidson 2000), indicating 256 257 the passage of a low pressure trough over New Zealand (Figure 8). When totalled across all events for all catchments, the troughing regime occurs for 57% of the time during the rising limb of flood 258 259 hydrographs (Figure 9). The Trough weather type within the Kidson troughing regime is particularly common, occurring during 35% of the time and comprising the most common type for Pūkaki and 260 261 Rakaia flood events, and second most common type for the other three study catchments. The Trough type is associated with strong NW-W-SW airflow from the west to east of the South Island 262 (respectively) and a low pressure system centred in the Southern Ocean (Figure 8), and so matches 263 well the geopotential height and IVT fields associated with many high flow events (Figures 3-7). The 264 265 Trough type has previously been shown to be associated with increased precipitation across much of New Zealand (Renwick 2011) and ARs in the Pūkaki catchment (Kingston et al. 2016). Other 266 267 weather types associated with northwesterly airflow and the passage of a trough over the South 268 Island coincide commonly with AR events too: TNW (troughing regime, 15% of the time) and HE 269 (blocking regime, 19%).

Notwithstanding the strong connection between the majority of extreme river flow events and the
Trough weather type for the southern four catchments, a smaller number of events are instead linked
to relatively isolated cyclonic weather systems that are part of a more strongly westerly circulation

regime (e.g. Te Anau event 2/Rakaia event 4, Te Anau event 5; Figures 3 and 6). These typically

contain relatively long zones of high IVT, continuing uninterrupted across the Southern Ocean and
past the western limits of Australia. Correspondingly, these events are more commonly associated
with the Westerly type (Zonal regime; Figure 8), occurring over 13% of the time during the flood
hydrograph rising limb, but the most common type for Te Anau. The Zonal regime has been linked
to increased precipitation in the southwest of the South Island before (Renwick 2011) but not yet to
ARs.

280 In contrast to the westerly quadrant origin of high IVT and AR-producing weather systems that 281 predominate for the four southern catchment events, the five Waiau Toa events originating from 282 circular IVT patterns are instead associated with easterly moisture flux over the catchment. Although 283 these are still associated with depressions moving in a broadly westerly direction, these are centred to the north of New Zealand rather than the south (Figure 7), meaning that the Waiau Toa experiences 284 285 the easterly flow associated with the southernmost section of the (clockwise rotating) cyclonic system. As the Waiau Toa is located some way east of the Main Divide of the Southern Alps in 286 287 comparison to the other catchments, these strong easterly moisture fluxes (and associated IVT divergence) can yield substantial precipitation. For these E-NE systems, the TSW and R Kidson 288 weather types are most commonly observed, which have a low pressure centred over or to the north 289 290 of New Zealand and relatively widely spaced isobars (Figure 8), consistent with the geopotential 291 height and IVT patterns for these events.

292

293 Large-scale meteorological drivers of AR and flood events

294 Despite the importance of the mid-latitude westerlies for the occurrence of AR-producing weather systems, flood events do not occur consistently across either strong positive, negative or neutral 295 296 Southern Annular Mode (SAM) situations: the average daily SAM index value across the top eight 297 events for each catchment is within the -1 to +1 range, and each catchment has flood events that occur for index values above +1 and below -1 (Table 2). There is little evidence of consistent 298 299 differences either between AR strength, orientation and extent with the SAM. For example, Waiau 300 Toa events 1 and 2 are both associated with easterly IVT and a cyclonic weather system centred over 301 the North Island, yet the event 1 SAM index is +1.17 whereas for event 2 it is -0.94. Similarly, 302 relatively similar high IVT/AR events associated with Southern Ocean depressions and northwesterly flow over the South Island can also occur under substantially different SAM index 303 304 values: e.g. -1.83 for Te Anau event 1 vs. 1.31 for Te Anau event 7 (Figure 3). Although in each case 305 the poleward/equatorward movement of the mid-latitude westerlies can be seen between positive and

negative SAM index situations, apparently similar flood-producing weather events are still observed
from a New Zealand perspective. This situation perhaps reflects the difficulty of describing relatively
local-scale conditions using a large-scale circulation index (Kingston et al. 2006; Lavers et al. 2010).

309 Irrespective of the connection to the SAM and the strength and latitude of the mid-latitude westerlies, 310 there is strong association between the presence of high IVT values and the concurrent location of strong upper atmosphere winds (i.e. the jet stream) in the New Zealand-Tasman Sea region during 311 each flood event (Figure 8, and Figures S6-10). Ralph et al. (2004) and Cordeira et al. (2013) have 312 313 previously developed conceptual models of the connection between ARs and jet stream patterns 314 based on findings from the North Pacific (see also Ralph et al. 2017). In terms of the larger-scale 315 context for upper atmosphere winds and New Zealand climate, two jet stream configurations dominate: either the presence of both the subtropical and polar front jets (i.e. a split-jet situation), or 316 317 a just a single jet stream in the New Zealand region (Gallego et al. 2005). Previous studies have focussed primarily on the relationship of jet stream configuration to the mass balance of glaciers 318 319 Southern Alps (Clare et al. 2002; Cullen et al. 2019; Mackintosh et al. 2017; Tyson et al. 1997), but more recently Prince et al. (2021) explored the connection to the AR climatology of New Zealand. In 320 particular, the climatological position of the polar jet at 50 °S during the austral summer half year 321 322 was shown to be important for ARs on the South Island west coast, with a split jet situation more conducive to ARs on the east coast. 323

Here, distinct configurations for the two jets are shown across extreme IVT patterns (including ARs) 324 325 associated with floods for the different catchments in both summer and winter – with variation in 326 IVT patterns between events and catchments mirrored by differences in 300 hPa winds. As 327 exemplified in Figure 10 (and shown on an event-by-event basis in Figures S6-S10), the cyclonic 328 systems leading to northeasterly IVT and high river flows in the Waiau Toa are associated with a 329 clear separation of the subtropical and polar jets – following the findings of Prince et al. (2021). 330 Reflecting their origin in the Southern Ocean (rather than the sub-tropics), zonally extensive events as exemplified by Rakaia event 4 (Figure 6) are linked to a single and much stronger jet stream 331 located between 40-55 °S (Figure 10). Other events fall somewhere in between these two general 332 333 typologies, for both summer and winter season high flow events: for example, ostensibly separate 334 jets but with some overlap associated with individual weather systems (e.g. Te Anau event 7); or a predominantly Southern Ocean polar jet system with residual connection to lower latitudes (e.g. 335 336 Matukituki event 2). Irrespective of the jet configuration, peak IVT during flood events is typically spatially coincident with strong upper atmosphere winds and in particular a strong north-to-south 337 directional component (i.e. the preceding limb of the trough). Hence, these results further highlight 338

the key connection between ARs, extratropical cyclones and the jet stream configuration in the NewZealand sector.

341 Consistent with the apparent relationship between circulation troughs at both the surface (i.e. Kidson weather types) and in the upper atmosphere, there is also some connection to the presence of zonal 342 waves in the general Southern Hemisphere circulation. Although Southern Hemisphere extratropical 343 circulation is largely zonally symmetric, some zonal asymmetry is superimposed (e.g. Fogt et al. 344 345 2012; Irving and Simmonds 2015; Raphael 2004). These zonal wave patterns are quasi-stationary 346 and are dominated by a zonal wave 1 and 3 pattern (ZW1 and ZW3). As such, indices of annular 347 circulation characteristics (i.e. the SAM) can be insufficient as the sole descriptor of southern 348 hemisphere circulation. For example, Garreaud et al. (2013) found that zonal asymmetry was more important for variation in Patagonian precipitation compared to the annular mode (Patagonia is the 349 350 approximate location of one of the ZW3 ridges). Similarly, ZW3 is of particular interest in the context of New Zealand weather given that another of the three quasi stationary ridges is located at 351 352 approximately 166 °E (Raphael 2004), i.e. within the New Zealand domain. Furthermore, teleconnections have been described between New Zealand glacier mass balance and dry spells in 353 South Africa (Tyson et al. 1997), close to the approximate location of the third ZW3 ridge. 354

An index of ZW3 pattern strength can be calculated by averaging the standardised zonal 500 hPa 355 356 geopotential height anomaly at the location of the three quasi-stationary ridges of the wave (Raphael 357 2004). Here, a daily ZW3 index based on ERA-Interim 500 hPa geopotential height data was used 358 (Raphael 2004). Positive ZW3 values indicate strong wave activity across the Southern Hemisphere, 359 and thus a stronger meridional component, and vice versa (Figure S11). Although AR-driven flood 360 events occur during both positive and negative phases of the ZW3 index, the mean daily ZW3 index 361 value across the top eight flow events for all five rivers is negative: from -0.16 (Pūkaki) to -0.43 (Matukituki) (Table 3). Out of the 40 events analysed across all rivers, only nine occur under positive 362 ZW3 conditions, with only one of these more than one standard deviation away from the longer term 363 mean of zero (Pūkaki event 7). In contrast, 18 events have negative ZW3 values more than one 364 365 standard deviation away from the mean (i.e. index value of ± -0.5). Thirteen of these events are 366 coincident with a Kidson Trough weather type. The strongest individual negative value is -1 (Te 367 Anau event 4), with a highest positive value of 0.6 (Pūkaki event 7). As such, the results suggest 368 some predisposition to ARs and flood events occurring in a negative ZW3 situation. This 369 relationship becomes even more apparent from comparison of the ZW3-geopotential height correlation (Figure S11) and geopotential patterns associated with ARs and extreme flood events 370 (Figures 3-7). Specifically, ZW3 is positively correlated with geopotential height to the south and 371

southwest of New Zealand, whereas ARs and associated flood events occur frequently in associationwith an area of low pressure to the southwest of New Zealand.

374 Alongside connections to the zonality of the Southern Hemisphere mid-latitude circulation, links to tropical latitudes are evident for some flood events. In some cases these are located over the western 375 Pacific/coastal Queensland region (e.g. Pūkaki event 6). For other events, the zone of high IVT 376 extends into the tropics via the interior of the Australian landmass. In particular, a number of events 377 appear to trace back to (or close to) the Indian Ocean coastline of northwestern Australia (e.g Te 378 379 Anau events 1, 6-8). As such, these IVT patterns show some resemblance to the Australian northwest 380 cloudband weather pattern (albeit with a Tasman Sea extension) that has been shown to originate in 381 the Indian Ocean (Tapp and Barrell 1984) and can itself be associated with ARs over Australia (Chen et al. 2020). The upper atmosphere winds during these events also show some evidence of a 382 383 connection to the Indian Ocean, via a transient overlap between the subtropical and polar jet streams associated with the westerly passage of isolated mid-latitude depressions (e.g. Te Anau event 7; 384 385 Figures 3 and 10). The northwest cloudband weather pattern has been documented previously as bringing high rainfall events over a broad zone from northwest to southeast Australia (Tapp and 386 Barrell 1984, Telcik and Pattiaratchi 2014). Winter instances of this pattern appear linked to 387 388 anomalous meridional SST gradients in the Indian Ocean, with the cloud band during summer driven by low pressure anomalies over northwest and central Australia (Reid et al. 2019). Although Mullan 389 (1998) found some connection from Indian Ocean sea surface temperatures to New Zealand 390 precipitation associated with the northwest cloudband pattern, its extension towards and importance 391 of this pattern for New Zealand climate has not been widely studied. However, the apparent 392 correspondence of these high IVT/high river flow events with a northwest cloudband-type pattern 393 suggests this may be a promising direction for further study of large-scale meteorological drivers of 394 New Zealand precipitation – alongside other connections to the tropics via the Madden-Julian 395 396 Oscillation (Fauchereau et al. 2016).

397

398 Conclusions

High magnitude IVT is associated with major flood events across five major catchments along a
meridional transect across the South Island of New Zealand. In most instances, IVT fields indicate
that these flood events are the result of AR occurrence. In a few cases, IVT patterns reach AR
magnitude but do not match the conventional AR spatial pattern. In particular, these IVT patterns

403 correspond to the most northerly study catchment (the Waiau Toa), which is also located closest to
404 the east coast – and so furthest away from the Main Divide of the Southern Alps.

405 ARs vary widely in magnitude and structure between flood events and catchments, but with some general themes. AR orientation ranges from westerly to northwesterly for the four southernmost 406 catchments (Te Anau, Matukituki, Pūkaki, Rakaia); length varies from those restricted to the Tasman 407 Sea (~ 2000 km) to those extending to the west or north of Australia. For these four southern 408 catchments all flood events are also associated with northwesterly circulation in the immediate 409 410 vicinity of New Zealand, which in many situations are connected to the passage of a wave depression 411 in the general westerly circulation (i.e. the Kidson trough regime and Trough weather type). In 412 contrast, more than half of the flood events for the more northerly Waiau Toa are associated with easterly or northeasterly water vapour flux, associated with the cyclonic circulation of a low pressure 413 414 system passing over or to the north of the country. Owing to the strongly curved zone of high IVT, these systems correspond less clearly with the more typical appearance of an AR as a long and thin 415 416 filament of poleward high IVT values.

AR orientation is associated strongly with upper atmosphere (i.e. jet stream) winds, with ARs 417 occurring under both single and split-jet configurations in the New Zealand region. Wider 418 connections to Southern Hemisphere atmospheric circulation are evident, most consistently to the 419 general wave characteristics of Southern Hemisphere circulation and the ZW3 pattern. Given the 420 local importance of meridional flow (i.e. troughing) for the majority of AR events, and the 421 coincidence of one of the ZW3 ridges in the New Zealand region, the ZW3 index is most often in a 422 negative phase during the occurrence of extreme flood events in the study catchments. Further work 423 424 is required to better define this emergent ZW3-AR relationship, the possible role of tropical 425 teleconnections from Australian northwest cloudband weather systems to Tasman Sea ARs for New Zealand flood events, as well as the wider role of ENSO in modulating these systems. 426

427

428 Acknowledgements

Kathy Walter (NIWA) and Jennifer Purdie (Meridian Energy; now University of Otago) provided the
river flow and lake inflow data. Marilyn Raphael (University of California – Los Angeles) provided
the ZW3 data. James Renwick (Victoria University of Wellington) provided the Kidson Weather
Type data. Chris Garden (University of Otago) produced Figure 1. This work was initiated during the
lead author's time as a Vanguard Fellow at the University of Birmingham Institute of Advanced

- 434 Studies. The authors gratefully acknowledge the constructive comments from two anonymous435 reviewers.
- 436

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Table 1 IVT direction and magnitude over each catchment during the top eight AR events (N.B.
mean values for Waiau Toa have been calculated separately for southeasterly and northwesterly
events).

	Te Anau		Matukituki		Pukaki		Rakaia		Waiau Toa	
	Dir	Mag	Dir	Mag	Dir	Mag	Dir	Mag	Dir	Mag
1	312	722	351	316	317	566	320	388	163	195
2	320	539	360	289	345	339	329	313	136	136
3	322	502	341	281	309	454	324	650	143	160
4	337	699	340	385	331	363	318	476	324	488
5	315	282	342	128	311	452	317	537	149	213
6	326	815	323	551	320	344	332	473	296	258
7	317	383	314	544	331	406	312	432	148	240
8	329	270	333	412	334	441	330	315	332	265
Mean	322	527	338	363	325	421	323	448	148 /	189 /
									317	337

Te Anau	Matukituki	Pūkaki	Rakaia	Waiau Toa
-1.83	1.58	0.27	-1.51	1.17
-1.90	2.71	2.71	-1.58	-0.94
1.70	-1.14	1.72	-0.03	1.23
-1.03	2.19	0.66	-1.81	-1.58
0.08	-0.15	-0.23	0.65	0.31
0.18	0.27	-0.03	2.71	0.51
1.31	0.40	-1.42	-0.23	0.63
1.55	2.00	0.35	-2.02	1.63
0.01	0.98	0.5	-0.48	0.37

Table 2 SAM index values for top eight river flow events for each study catchment (mean SAM value per catchment in final row)

Te Anau	Matukituki	Pūkaki	Rakaia	Waiau Toa
-0.3	-0.5	-0.8	-0.7	0.1
0.4	-0.3	-0.3	-0.6	-0.3
-0.5	-0.7	-0.4	0.1	-0.3
-1	-0.5	-0.2	0.4	-0.6
-0.2	-0.2	-0.5	-0.8	0.1
0.3	-0.8	0.1	-0.3	-0.4
-0.3	0	0.6	-0.5	0
-0.8	-0.4	0.2	-0.6	-0.5
-0.3	-0.43	-0.16	-0.38	-0.24

Table 3 ZW3 index values for top eight river flow events for each catchment (mean ZW3 value for
each catchment given in final row).

569 Figure captions

- 570 **Figure 1** Location of the five study catchments and corresponding river gauging stations.
- 571 Figure 2 Thirty-day running mean of mean (solid line), maximum and minimum (dotted lines) daily
- river flow for 1979-2018 for the five study rivers, plus the top eight events for each catchment
- 573 (circles). Note the different y-axis scales.
- Figure 3 IVT (kg m⁻¹ s⁻¹, shading) and 500 hPa geopotential height (m, isolines) for the Te Anau top
 eight flow events.
- Figure 4 IVT (kg m⁻¹ s⁻¹, shading) and 500 hPa geopotential height (m, isolines) for the Matukituki
 top eight flow events.
- Figure 5 IVT (kg m⁻¹ s⁻¹, shading) and 500 hPa geopotential height (m, isolines) for the Pūkaki top
 eight flow events.
- Figure 6 IVT (kg m⁻¹ s⁻¹, shading) and 500 hPa geopotential height (m, isolines) for the Rakaia top
 eight flow events.
- Figure 7 IVT (kg m⁻¹ s⁻¹, shading) and 500 hPa geopotential height (m, isolines) for the Waiau Toa
 top eight flow events.
- **Figure 8** 1000 hPa geopotential height composites for the 12 Kidson Weather Types (Kidson 2000)
- Figure 9 Occurrence (number of 12-hour timesteps) of different Kidson Weather Types during the
 ascending limb of top eight flood events for each catchment (TA = Te Anau; MT = Matukituki; PK =
 Pūkaki; RK; RK = Rakaia; WT = Waiau Toa).
- **Figure 10** 300 hPa wind speed (m s⁻¹, shading) and IVT (kg m⁻¹ s⁻¹, isolines) for four exemplar high flow events.
- 590



Figure 1 Location of the five study catchments and corresponding river gauging stations.



Figure 2 Thirty-day running mean of mean (solid line), maximum and minimum (dotted lines) daily
river flow for 1979-2018 for the five study rivers, plus the top eight events for each catchment
(circles). Note the different y-axis scales.



Figure 3 IVT and 500 hPa geopotential height for the Te Anau top eight flow events.





Figure 4 IVT and 500 hPa geopotential height for the Matukituki top eight flow events.



Figure 5 IVT and 500 hPa geopotential height for the Pūkaki top eight flow events.









Figure 7 IVT and 500 hPa geopotential height for the Waiau Toa top eight flow events.

"Trough" group





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Figure 8 1000 hPa geopotential height composites for the 12 Kidson Weather Types (Kidson 2000).

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Figure 9 Occurrence (number of 12-hour timesteps) of different Kidson Weather Types during

- ascending limb of top eight flood events for each catchment (TA = Te Anau; MT = Matukituki; PK =
- 618 Pūkaki; RK; RK = Rakaia; WT = Waiau Toa).





Figure 10 300 hPa wind speed (m s⁻¹, shading) and IVT (kg m⁻¹ s⁻¹, isolines) for four exemplar high flow events.