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Floods in the Southern Alps of New Zealand: the importance of atmospheric rivers

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Abstract

Extremely high precipitation occurs in the Southern Alps of New Zealand, associated with both orographic enhancement and synoptic-scale weather processes. In this study, we test the hypothesis that atmospheric rivers (ARs) are a key driver of floods in the Southern Alps of New Zealand. Vertically-integrated water vapour and horizontal water vapour transport, and atmospheric circulation, are investigated concurrently with major floods on the Waitaki River (a major South Island river). Analysis of the largest eight annual maximum floods between 1979 and 2012 indicates that all are associated with ARs. Geopotential height fields reveal that these ARs are located in slow eastward moving extra-tropical cyclones, with high pressure to the northeast of New Zealand. The confirmation of ARs as a contributor to Waitaki flooding indicates the need for their further exploration to better understand South Island hydrometeorological extremes.

Keywords: atmospheric rivers, precipitation, flooding, New Zealand

1. Introduction

Flooding is a recurrent phenomenon in New Zealand, with flood magnitude relative to basin size close to global maximum values, particularly for the rivers draining the Southern Alps in the South Island (Pearson and Henderson, 2004). Many communities are located on floodplains and much critical infrastructure is dependent on water from rivers (in particular, hydroelectricity and irrigation). Consequently, floods have been calculated as the most costly natural hazard in New Zealand (McSaveney, 2009).

Heavy precipitation events in the Southern Alps region are associated often with cold fronts embedded within the general moist westerly circulation (Pearson and Henderson, 2004; Salinger *et al*., 2004). Precipitation associated with these fronts is enhanced typically by the orography of the Southern Alps, which rise from sea level to >3000 m within approximately 40 km of the west coast. The combination of frontal precipitation and orographic uplift can result in a 'seeder-feeder' situation, whereby the synoptic-origin precipitation scavenges moisture that has condensed at a lower level as a result of forced uplift to create extreme heavy precipitation events (Purdy and Austin, 2003; Purdy *et al.*, 2005).

In mid-latitude regions of the world, atmospheric rivers (ARs) have been identified as important meteorological drivers of floods, for example in western North America (e.g. Ralph *et al., 2006*; Neiman *et al.,* 2011) and Europe (e.g. Lavers *et al.*, 2011, 2012, Lavers and Villarini, 2013; Ramos *et al.,* 2015). A very recent global study has indicated the presence of ARs in New Zealand (Guan and Walliser, 2015), and the presence of an AR has been noted for individual floods before (Dean *et al.,* 2013; Rosier *et al.,* 2015), but ARs importance for flooding in New Zealand has not yet been investigated systematically. Herein, we hypothesise that ARs may be useful in understanding the causes of New Zealand floods given the very high proportion of precipitation originating from oceanic sources (Dirmeyer *et al.* 2009) and occurrence of very high annual precipitation totals (up to 15,000 mm) in the Southern Alps (e.g. Kerr *et al. 2011*).

The aim of this study is to determine the role of ARs for flood events on the Waitaki River in the South Island of New Zealand. The Waitaki is typical of rivers draining east from the Southern Alps and is the single most important river nationally for hydroelectricity generation. Analysis of the potential role of ARs is achieved by characterising the vertically integrated water vapour (IWV) and vertically integrated horizontal water vapour transport (IVT) concurrent with the largest annual maximum flood events for the Waitaki River for the period 1979-2012. Additionally, geopotential height fields are used to determine the connection between atmospheric circulation, IWV and IVT over the Waitaki.

2. Data and Methods

The Waitaki River (11,900 km^2) drains in a southeasterly direction from a height of 3724 m above sea level in the Aoraki/Mount Cook National Park. The river basin has very marked climatic and physiographic gradients, varying from the snow and glacier dominated alpine headwaters with high precipitation (annual totals > 15,000 mm; Kerr *et al*. (2011)), to a continental-type climate with mean annual precipitation < 500 mm. In this study, inflow data for Lake Pukaki are used as the basis for flood analysis, and were obtained from Meridian Energy, the hydroelectricity company that operate this section of the upper Waitaki basin. Pukaki (1457 km^2) is the largest of the three main headwater sub-basins in the Waitaki, and timing of high inflow events in this lake is similar to the other two sub-basins (Tekapo and Ohau; Kingston *et al.* (2016)). Owing to the aforementioned very strong precipitation gradient, and limited storage within the Waitaki basin, river flow in these sub-basins are highly correlated with downstream variation in river flow.

Daily lake inflow data were analysed for the period 1 October 1979 to 30 September 2012 (33 water years; herein we define the water year as beginning on 1 October, the month of lowest flow annually in the study period). Henceforth, 1980 refers to the water year of 1979–1980. Flood events were identified using a block maxima approach over the period 1980–2012 (Coles, 2001; Tallaksen *et al.*, 2004). This method extracts the maximum daily mean flow in a certain period (or block), and in this study two different time periods were used: (1) October to March to determine the Summer Maximum Series (SMS); and (2) April to September to determine the Winter Maximum Series (WMS). The resulting half-yearly time series were assessed to determine the seasonality of the largest floods in the Waitaki basin.

Specific humidity, and zonal and meridional winds on 20 pressure levels between 1000 and 300 hPa were retrieved from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim (ERAI) reanalysis (Dee *et al.,* 2011) at a 6-hourly resolution over the 1979–2012 period. Data were extracted on a T128 (N255) reduced Gaussian grid and converted on to a regular latitude-longitude grid of approximately 0.7°×0.7°. Following Neiman *et al.* (2008), the ERAI vertically-integrated horizontal water vapor transport (IVT) was then calculated. ERAI Geopotential at 500 hPa was retrieved for the analysis of the large-scale atmospheric circulation. Meteorological data for the basin (temperature, precipitation) were obtained for the Mount Cook weather station (located near the head of Lake Pukaki) from the National Institute of Water and Atmospheric Research (NIWA) CliFlo database.

3. Results

In Figure 1, we show the SMS and WMS floods over 1980–2012. In most years (except 2003 and 2009) the SMS is greater than the WMS, meaning that the annual maxima floods occur during the Southern Hemisphere summer (October to March). Generally, the difference between the SMS and WMS is substantial (i.e. greater than twice the magnitude). Given these findings, hereafter we focus on the summer floods and the associated large-scale atmospheric conditions.

3.1 Hydrometeorological analysis of the largest flood

To investigate the atmospheric conditions that were associated with the largest flood in the 1979-2012 analysis period (9th January 1994), maps of IVT and 500 hPa geopotential height on the day of the flood and two days preceding were evaluated (Figure 2). On the 7th of January a relatively strong and persistent IVT was present over the basin (location given by a black dot on Figure 2). An area of low geopotential height (a proxy for a low pressure region) moved eastwards from the south of Australia towards New Zealand, which was associated with strengthening IVT over the Tasman Sea. This low geopotential region became quasi-stationary on the 8th January, leading to a persistent and strong northwesterly airflow and IVT corridor in the form of an AR, with IVT values exceeding 1000 $kgm^{-1}s^{-1}$. The 'core' of the AR appears to have been located over the basin for approximately 24 hours between 8-9th January (Figure 2i-l), leading to 131% of the January mean precipitation being received over these two days, an increase in surface air temperature and a corresponding lake inflow 1162% higher than the monthly mean (Table 1).

3.2 Hydrometeorological analysis of the top eight floods

Given the key role that an AR had in the largest flood on the Waitaki River, we consider if ARs are responsible for the largest eight (approximately the top 25%) floods too (Table 1). All flood events are associated with very high precipitation totals and all-but-one with above average temperatures occurring within the timeframe of the event (Table 1). For this broader analysis, we use the 3-day time-integrated IVT, a diagnostic that has been used in previous studies to show the presence of AR conditions (e.g. *Moore et al.,* 2012; *Ralph and Dettinger,* 2012). Figure 3 presents the 3-day time-integrated IVT and 3-day average 500 hPa geopotential field for the largest eight floods. (For the 9th January 1994 event, the time average is taken from 12UTC 6 January 1994 to 06UTC 9 January 1994.) All floods have low geopotential heights to the south of New Zealand and high 3-day time-integrated IVT embedded in a northwesterly airflow near the basin, indicating that ARs are responsible for these floods. Moreover, inspection of the IVT and 500 hPa geopotential height fields for all 6-

hour time steps on the day of the flood and two days preceding the flood confirms this AR finding (not shown).

We investigate the low altitude atmospheric conditions during the largest eight floods by evaluating the total column water vapour (IWV) and 850 hPa wind (Figure 4). Around midnight on the day of the flood, the IWV fields provide further evidence for AR features, with IWV values of greater than 20mm (following Ralph *et al.,* 2004). The 850 hPa wind speeds of between 15 to 30 ms^{-1} across the events are consistent with likelihood that orographic enhancement of precipitation occurred (Wratt *et al.,* 2000).

4. Discussion

The majority of the largest floods occur in summer (Figure 1), which is generally the season of maximum precipitation in this region of New Zealand (Salinger *et al.* 2004). This result is also linked to the effects of seasonal snowmelt (meltwater is estimated to account for 47% of entire Waitaki river flow from December-February: McKerchar *et al.* (1998)). Snowmelt is thought to be particularly high during summer flood events due to both rain-on-snow processes, and prior to that, the higher temperatures due to warm air-masses advected by a northwesterly circulation (for all but one event; Table 1). Relatively high temperatures under northwesterly airflow are associated with windward saturated adiabatic cooling and leeward dry adiabatic warming immediately prior to passage of the eastward moving band of precipitation (McGowan and Sturman, 1996).

Notwithstanding snowmelt contributions to flood events, the results indicate strongly that high IVT is an important contributor to the largest floods in the Waitaki River. Analysis of the IVT and IWV fields (Figures 2-4) indicate that in the case of the most extreme Waitaki floods, the fluxes of atmospheric moisture are sufficiently large and concentrated to be classified as an AR (e.g. following the definitions of Ralph *et al.* (2004)). Furthermore, the IVT and IWV during the largest flood events are comparable in magnitude to previously studied northern hemisphere extratropical flood events (e.g. Lavers *et al*. (2011, 2012)).

The ARs contributing to extreme Waitaki floods form at the northeastern edge (along the cold front) of eastward moving low pressure systems (Figures 3 and 4), showing moisture transport within a predominantly northwesterly airflow. The eastward moving low pressure area typically occurs in combination with a high pressure system to the northeast of the country (Figures 3 and 4). The resultant strong southwest-to-northeast synoptic pressure gradient and related strong northwesterly winds over the Southern Alps indicate the forthcoming passage of a cold front; warm and moist air is drawn typically into the path of the frontal system from the northwest, resulting in high precipitation (Brenstrum, 1988). Indeed, northwesterly airflow under this situation is associated often with high precipitation over the Southern Alps (e.g. Pearson and Henderson, 2004; Salinger and Mullan, 1999), and furthermore to high upper Waitaki lake inflow at both the monthly and event scale (Kingston *et al.,* 2016; Kingston and McMecking, 2015).

The synoptic situation described in the preceding paragraph is recognisable in two prominent methods of characterising atmospheric circulation in the New Zealand region. Firstly, the Kidson synoptic weather classification (Kidson*,* 2000), and specifically the Trough regime and T synoptic type, which have been demonstrated to correspond to high precipitation in study area (Renwick*,* 2011). Secondly, the MZ1 and MZ2 ‘Trenberth Indices’ (Trenberth*,* 1976; Salinger and Mullan*,* 1999) of station-pair sea level pressure anomalies capture neatly the approximate southwest-northeast gradient across the South Island associated with high precipitation and lake inflow. As a result, it may be that the MZ1 and MZ2 indices represent a useful proxy for AR occurrence – an important area for further research, especially because both indices have previously been shown to be of some use for season-ahead prediction of Waitaki river flow (Purdie and Bardsley*,* 2010; Kingston *et al.,* 2016).

5. Conclusion

Atmospheric rivers (ARs) have been shown to be an important process associated with the largest flood events in Waitaki River, one of largest and most economically important rivers in New Zealand. AR characteristics are comparable to those in more widely studied locations (such as Western Europe). AR occurrence aligns well with previous understanding of synoptic situations associated with both high precipitation events in New Zealand, and high river flow for the Southern Alps. As such, this research adds important new understanding of the hydrometeorological processes underpinning the occurrence of extreme precipitation and river flow. Confirmation of ARs as a contributor to Waitaki flooding indicates the need for their further exploration to better understand hydrometeorological extremes in New Zealand.

Acknowledgements

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Table 1 Date and magnitude of peak inflow, and concurrent precipitation and daily maximum temperature (Tmax). Anomalies from 1981-2000 monthly means shown in brackets: % for inflow and precipitation, °C for Tmax. Also indicated are precipitation totals over course of precipitation event, and peak temperature on the preceding day.

Date	**Inflow (m^{-3} s^{-1})**	**Precip (mm)**	**Tmax (°C)**	**Event details**
25/12/1979	1847	341 (69%)	12.3	471 mm (95%) fell over three days.
	(849%)		(-0.5)	15.7 °C (+3.0) on preceding day.
12/03/1982	1869	314 (83%)	14.7	440 mm (116%) fell over three days.
	(1147%)		(+2.4)	16.5 °C (+4.2) on preceding day.
21/12/1984	1563	225 (45%)	13.8	548 mm (110%) fell over three days.
	(718%)		(+1.1)	11.1 °C (-1.6) on preceding day.
28/12/1989	1803	359 (72%)	11.4	468 mm (94%) fell over three days.
	(829%)		(-1.3)	11.5 °C (-1.2) on preceding day.
9/01/1994	2688	302	15.3	555 mm (131%) fell over two days.
	(1162%)	(72%)	(+0.7)	15.9 °C (+1.3) on preceding day.
13/12/1995	2210	275 (55%)		515 mm (104%) fell over three days.
	(1016%)		No data	13.5 °C (+0.7) on preceding day.
04/01/2002	1473	0	10.4	109% fell over three days at Franz Josef*.
	(637%)		(-4.2)	15.1 °C (+0.5) on preceding day.
28/12/2010	1762	0	12.1	49% fell over two days at Franz Josef*.
	(810%)		(-0.6)	14.2 °C (+1.5) on preceding day.

*Daily precipitation at Mt Cook <1 mm; Franz Josef is the closest station upwind of Mt Cook.

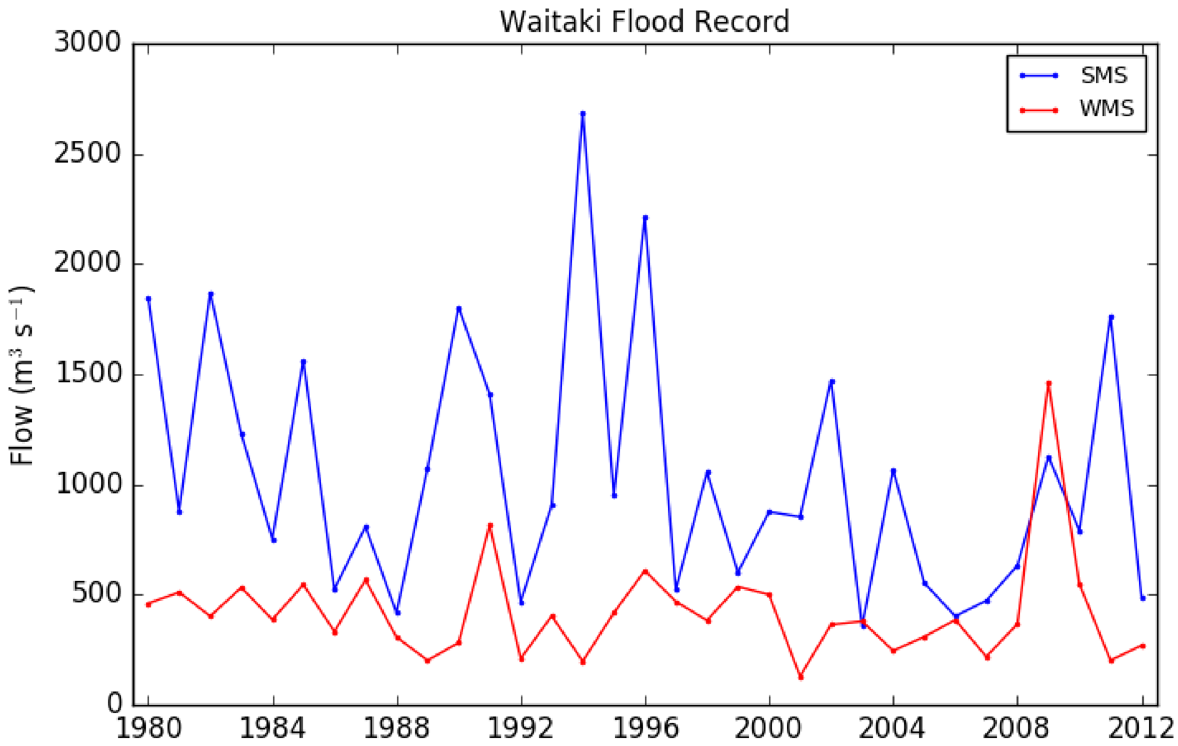

Figure 1: Time series of the Summer Maxima Series (SMS; blue line), and Winter Maxima Series (WMS; red line) over 1980–2012.

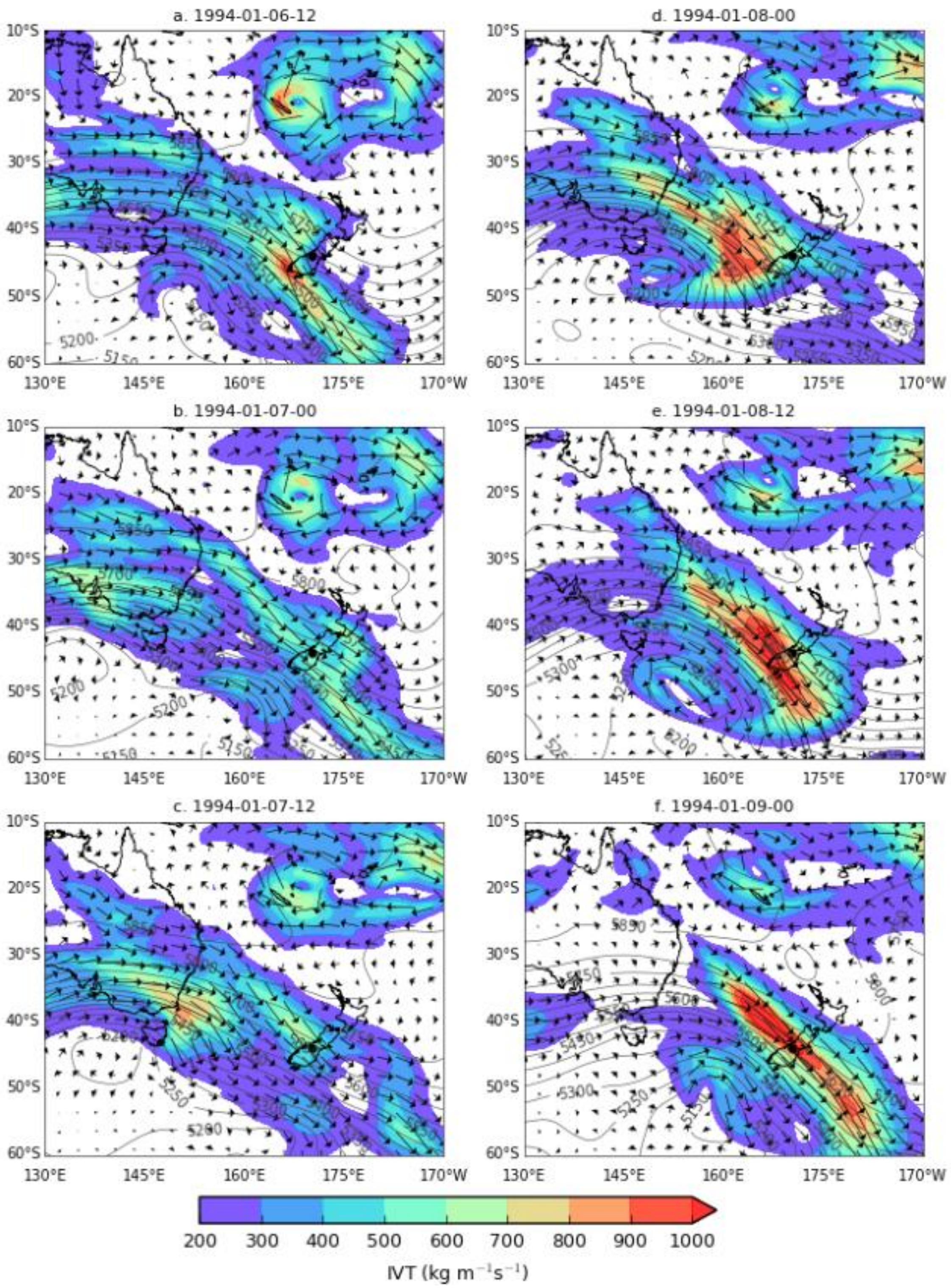

Figure 2 (a–f): The integrated water vapour transport (IVT; shading, and arrows) and 500 hPa geopotential heights (contours on a 50 meter interval) from (a) 12UTC 6th January 1994 to (f) 00UTC 9th January 1994. These times approximately correspond to 00UTC 7th January 1994 to 12UTC 9th January 1994 local time. The black dot is the location of the Waitaki River.

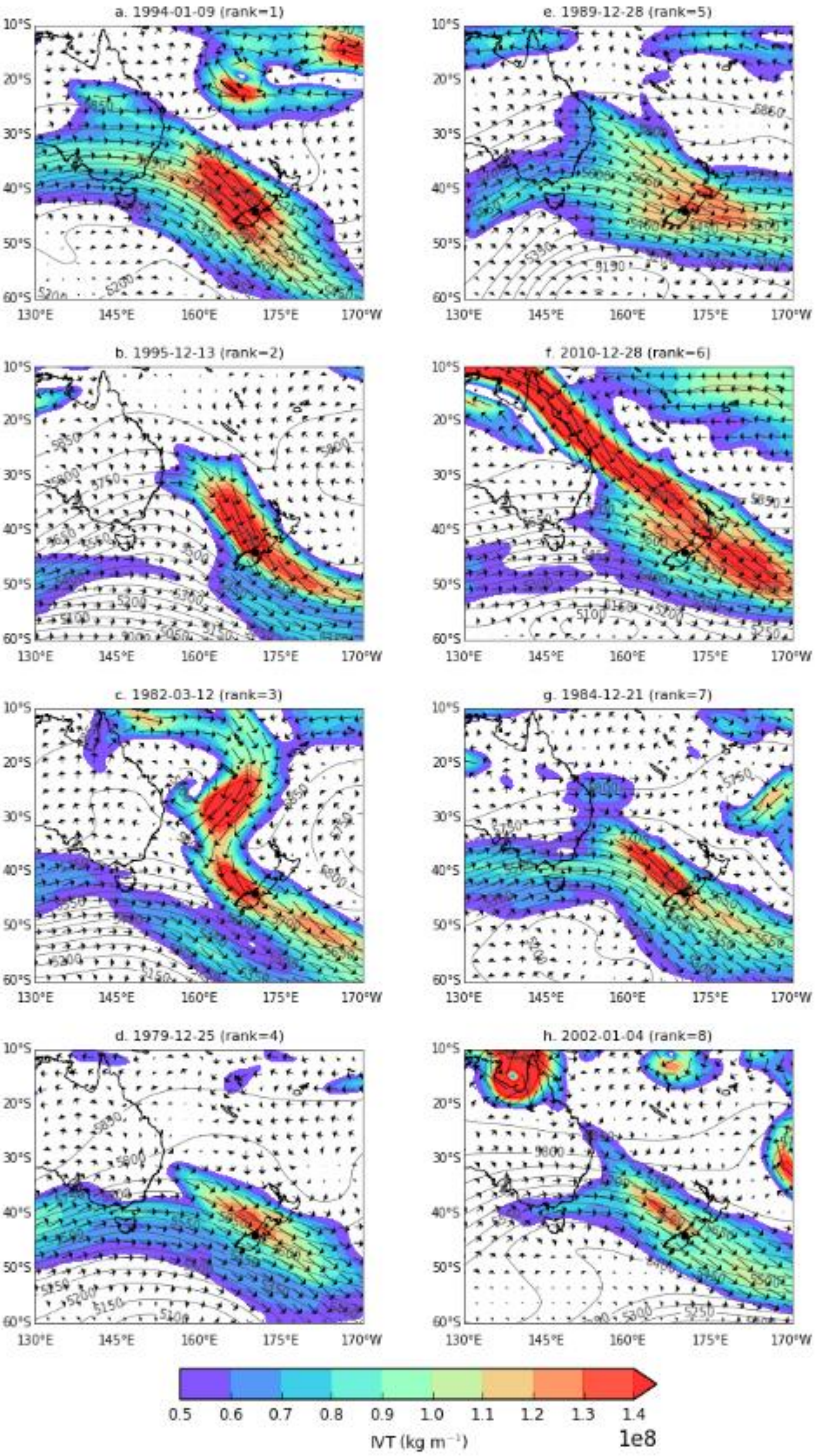

Figure 3 (a–h): The 3-day time-integrated IVT (IVT; shading, and arrows) and 3-day average 500 hPa geopotential heights (contours on a 50 meter interval) before the largest eight floods (the flood rank is given in the title of each panel). The time average is taken from 12UTC 3 days before the flood to 06UTC on the day of the flood; for example, for panel (a) the time average is taken from 12UTC 6 January 1994 to 06UTC 9 January 1994. The black dot is the location of the Waitaki River.

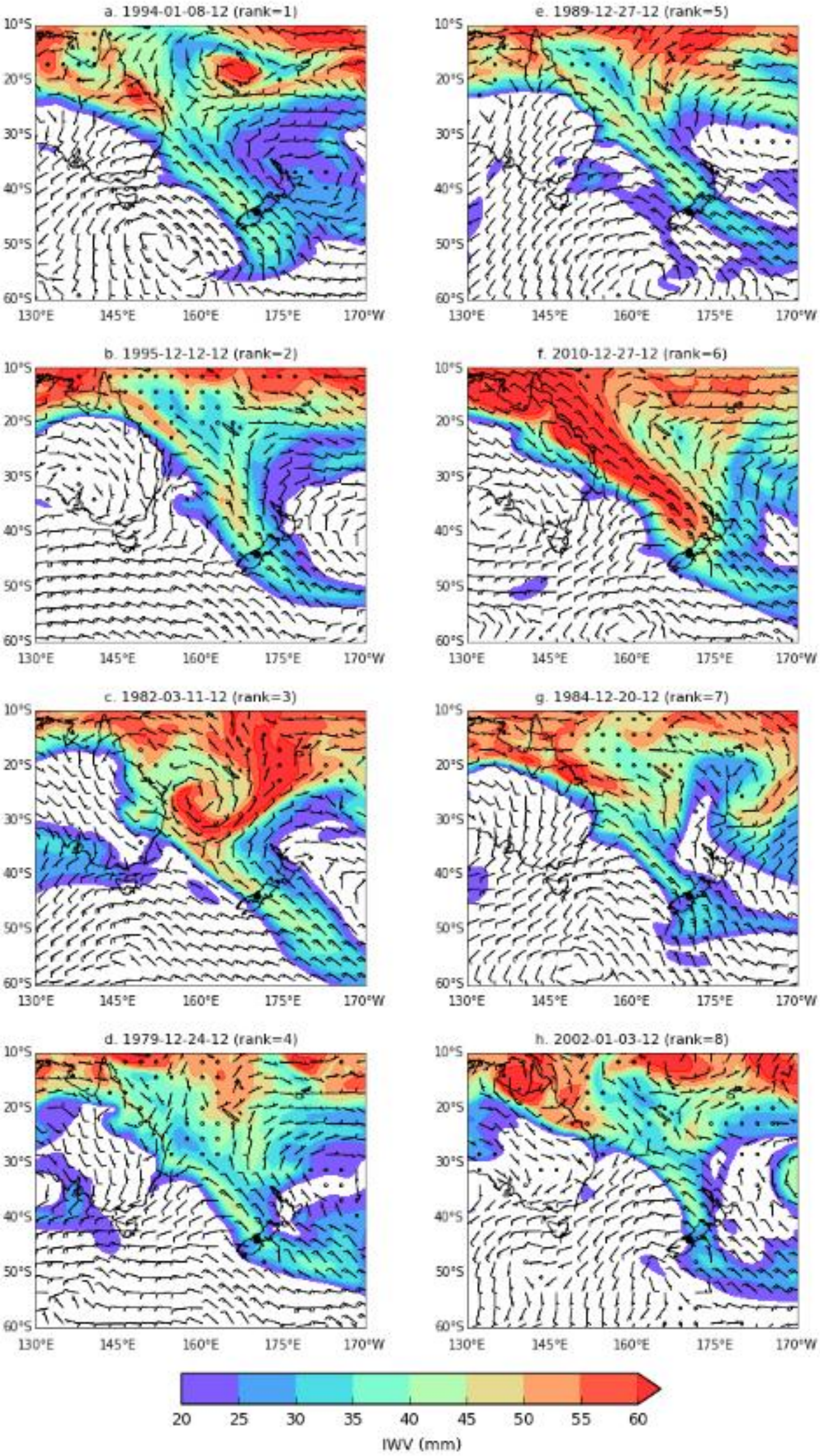

Figure 4 (a–h): The integrated water vapour (IWV shaded in mm) and 850hPa wind (barbs in ms^{-1}) at 12UTC on the day before the flood (approximately midnight local time on the day of the flood). Key for the barbs: circles are < 5 ms^{-1}, half-barbs are 5 ms^{-1}, full barbs are 10 ms^{-1}. The black dot is the location of the Waitaki River.