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Key Points:

- Investigate precipitation isotope variability in a mid-latitude alpine location
- Moisture pathway and terrain have greatest impact on isotopic variability
- Moisture pathway isotopic signatures can inform palaeoclimate reconstruction

Supporting Information:

- Readme
- Movie S1
- Movie S2
- Movie S3
- Movie S4
- Movie S5

Correspondence to:
N. Callow,
nik.callow@uwa.edu.au

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Drivers of precipitation stable oxygen isotope variability in an alpine setting, Snowy Mountains, Australia

Nik Callow[1], Hamish McGowan[2], Loredana Warren[3], and Johanna Speirs[3]

[1]Environmental Dynamics and Ecohydrology, School of Earth and Environment, University of Western Australia, Crawley, Western Australia, Australia, [2]Climate Research Group, School of Geography Planning and Environmental Management, University of Queensland, Brisbane, Queensland, Australia, [3]Snowy Hydro Limited, Sydney, New South Wales, Australia

Abstract Natural archives that preserve a stable isotopic signature are routinely used to reconstruct palaeoenvironmental conditions. Isotopic values of precipitation are known to be influenced by factors such as the amount and type of precipitation, moisture pathway, landscape and terrain factors, and processes associated with precipitation formation and deposition. This study investigates oxygen isotopic variability using real-time rain and snow precipitation data from a moderate altitude (<2250 m above sea level), Southern Hemisphere alpine environment, where the causes of isotopic variability are largely unknown. Previous research at Global Network of Isotopes in Precipitation sites skewed toward rain precipitation, low-altitude, predominantly coastal locations identified amount effects as the dominant explanation of isotopic variability in southern Australia. This study based on within- and between-event real-time sampling finds that the origin of moisture and terrain effects are the dominant cause of isotopic variability in this alpine region, with little evidence of amount effects. Rainfall that originated from similar Southern Ocean latitudes showed a consistent (moderate) isotopic signature (δ^{18}O −6.5 to −8‰). Depleted isotopic signatures are associated with prefrontal activity and intense circulation such as east coast lows. Localized thunderstorms have a more neutral isotopic signature. A windward to leeward depletion (−0.5‰ δ^{18}O) and an elevation impact (−0.5‰ δ^{18}O 100 m^{-1}) were found also. These results have significant implications for understanding atmospheric drivers of isotopic variability from which oxygen isotope-based palaeoclimate reconstruction is informed in regions with complex topography and geographically diverse moisture pathways such as the Australian Alps.

1. Introduction

Stable isotopic signatures preserved in natural archives are routinely used to reconstruct palaeoenvironmental conditions [*Rozanski et al.*, 1997; *McDermott*, 2004; *St. Amour et al.*, 2010; *Polk et al.*, 2012]. Suitable archives which preserve both hydrogen (^{2}H/^{1}H) and oxygen (^{18}O/^{16}O) stable isotope data include polar ice sheets, midlatitude and low-latitude glaciers, and groundwater [*Rozanski et al.*, 1997]. Other archives include silicate oxide diatom frustule bodies preserved in oceanic and lacustrine environments [*Leng and Marshall*, 2004; *Leng and Barker*, 2006] and speleothem calcite from karst landscapes which preserve only the stable oxygen isotope signal [*McDermott*, 2004]. Understanding the drivers of variability in stable isotopic signatures of precipitation, streamflow, and groundwater provides an exciting method for shedding new light on causes of hydrometeorological variability [*Lachniet*, 2009; *Mariethoz et al.*, 2012].

Ocean-atmosphere teleconnection cycles such as El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) are recognized as major influences on interannual variability of rainfall in the Southern Hemisphere and Pacific Basin [*Hastings*, 1990; *Murphy and Timbal*, 2008; *McGowan et al.*, 2009]. In eastern Australia including the high alpine areas, ENSO is a significant control on interannual rainfall variability [*McBride and Nicholls*, 1983; *Bundin*, 1985; *Nicholls*, 2005; *Marx et al.*, 2011], while the PDO has been shown as the major influence on multidecadal variability of precipitation and streamflow in the Australian Alps [*McGowan et al.*, 2009]. In addition, the Southern Annular Mode (SAM) has been linked to rainfall variability across southern Australia, including the Australian Alps with precipitation-bearing extratropical cyclones and associated fronts tracking further south during high phases of SAM, particularly in winter [*Hendon et al.*, 2007]. An increased tropical to midlatitude tropospheric temperature gradient due to global warming and stratospheric ozone depletion has been proposed as causing the positive trend in SAM observed over the past ≈ 25 years [*Murphy and Timbal*, 2008], which has been linked to a drying trend across southern Australia. The Indian Ocean Dipole (IOD) is also recognized as influencing rainfall over the region through tropical-extratropical contribution of moisture via northwest cloud bands which is more pronounced in winter to spring [*Murphy and Timbal*, 2008].

The Snowy Mountains in southeast Australia are a location of particular significance from which to understand drivers of annual to multidecadal variability at both a local (Australia) and regional (Pacific Basin) scale. As a modest-altitude (<2250 m above sea level (m asl)) alpine region, it is also highly susceptible to climate change [*Nicholls*, 2005] and associated impacts on water resource availability. This is also of strategic economic and environmental interest, as runoff from the region is used for hydropower generation which accounts for 32% of the renewable energy supplied to the east Australia mainland electricity grid (Snowy Hydro Limited, unpublished data, 2014, available from http://www.snowyhydro.com.au/energy/hydro/snowy-mountains-scheme). In addition, as a significant tributary of the Murray-Darling River system, runoff from the Snowy Mountains underwrites more than $3 billion of agricultural products each year by providing drought security in the southern part of the Murray-Darling River Basin (Snowy Hydro Limited, unpublished data).

While the general impacts of teleconnections on the hydrometeorology of the Australian alpine region over the past approximate 100 years can be gained from analyses of instrument records, impacts over longer time periods or of longer-period climate cycles on hydroclimate variability cannot. The presence of karst in the Snowy Mountains alpine region provides a potential to reconstruct the climate histories of the high alpine region of Australia beyond the limited instruments records. This would allow an enhanced local and regional understanding of the influence of various teleconnections on seasonal- to millennial-scale hydroclimate variability. Interpretation of any hydroclimate proxy records such as from speleothem calcite requires a detailed understanding of drivers of variability of the oxygen isotopic composition values of precipitation for the region.

Precipitation stable oxygen isotope values of a specific precipitation event or series of events preserved in a natural archive are determined by numerous factors or isotopic effects, as summarized in Table 1. The Global Network of Isotopes in Precipitation (GNIP) program [*International Atomic Energy Agency/World Meteorological Organisation* (*IAEA/WMO*), 2006] and other monthly precipitation isotopic data sets are often used to determine the factors affecting the isotopic variability of precipitation [*Rozanski et al*., 1992, 1993, 1997; *Araguás-Araguás et al*., 2000; *Liu et al*., 2010]. GNIP sites have collected data across 800 meteorological stations in 101 countries since 1961. However, *Araguás-Araguás et al*. [2000] identify that over 80% of stations collect data below 250 m asl. Of the 389 GNIP sites with sufficient data to calculate mean month isotopic characteristics, only 14% (55/389) are above 1000 m asl, 7% (29/389) are above 1500 m asl, and only 4% (14/389) are above 2000 m asl [*IAEA/WMO*, 2006]. Australia's only inland and highest GNIP site is in arid central Australia (Alice Springs) at 546 m asl, with all other sites in coastal locations at elevations ranging from Brisbane 4 m asl to Margate (Hobart) at 176 m asl. Accordingly, sites recording precipitation isotope characteristics are skewed toward low-altitude coastal sites recording precipitation falling as rainfall and in topographically simple (i.e., nonmountainous) locations. As a result, drivers of isotopic variability of precipitation in the alpine areas, and in particular the Australian Alps, are largely unknown.

Previous research on the isotopic composition of precipitation in Australia has mostly centered on the coastal GNIP sites [*Treble et al*., 2005a, 2005b; *Barras and Simmonds*, 2008; *Liu et al*., 2010], with some event-based studies surrounding Melbourne (Victoria) [*Barras and Simmonds*, 2009] and the Mount Lofty Ranges east of Adelaide in South Australia [*Guan et al*., 2009, 2013]. Studies utilizing the monthly GNIP data in Australia have found strong relationships between the isotopic variability and amount effect or the quantity of rainfall [*Treble et al*., 2005a, 2005b; *Barras and Simmonds*, 2008; *Liu et al*., 2010]. This information has informed palaeo reconstruction based on interpretation of the δ^{18}O variability from speleothem calcite being interpreted through linear regression of rainfall volume with δ^{18}O rainfall from GNIP and other monthly data [*Treble et al*., 2005a, 2005b].

Other work highlights the potential role that synoptic factors may play in southern Australia. For sites in Tasmania and Victoria, the synoptic hydroclimatology is dominated by prevailing westerly airflow, and synoptic drivers of precipitation isotopic variability are due to the proximity and intensity of midlatitude Southern Ocean low-pressure systems [*Treble et al*., 2005a] and their interaction with other moisture sources during the passage of cold fronts [*Barras and Simmonds*, 2008, 2009]. Cyclonic low-pressure systems in the Tasman Sea have also been shown to cause an easterly airflow with precipitation of depleted isotopic

Table 1. Details of Known Physical Processes or "Isotopic Effects", Detailing the Forcing Mechanisms and the Way Each "Effect" Can Impact the Isotopic Composition of Precipitation

Isotopic Effect	Description of the Forcing Mechanisms and the Impact on the Oxygen ($\delta^{18}O$) Isotopic Signature of Precipitation	References
Continental	Isotopic values become increasingly depleted across a continent or a transect from coastal to inland locations due to preferential rain out of heavier isotopes along an air parcel trajectory.	*Rozanski et al.* [1992, 1993], *Rozanski et al.* [1997], *Araguás-Araguás et al.* [2000], *Sjostrom and Welker* [2009], and *Liu et al.* [2010]
Event rain out	Isotopic values become increasingly depleted in isotopic value during an event as heavier isotopes preferentially fall earlier in a precipitation event.	*Dansgaard* [1964], *Rozanski et al.* [1997], *Araguás-Araguás et al.* [2000], *Sjostrom and Welker* [2009], and *Liu et al.* [2010]
Amount	(An) "apparent correlation between the heavy isotope composition and the amount of rainfall" *Araguás-Araguás et al.* [2000, p. 1348], most pronounced and widely reported from monthly data sets and from locations with a more pronounced seasonal climate (precipitation) regime.	*Dansgaard* [1964], *Araguás-Araguás et al.* [1998], *Araguás-Araguás et al.* [2000], and *Treble et al.* [2005a]
Convective depletion	Potential for enhanced isotopic depletion of samples due to deep convection and vertical development associated with events such as cold fronts and thunderstorms, which may also be enhanced by complex (mountainous) terrain.	*Dansgaard* [1964] and *Gat* [1996]
Type	The influence of enhanced kinetic fractionation associated with snowfall relative to rain that results in a more depleted isotopic signature from snow precipitation due to kinetic fractionation effects of snowflake formation.	*Jouzel and Merlivat* [1984] and *Araguás-Araguás et al.* [2000]
Elevation	A vertical component due to orographic forcing of adiabatic lift of moisture causing fractionation consistent with Rayleigh distillation and resulting in more depleted isotopic values at higher elevation due to preferential precipitation of heavier isotopes at lower elevations.	*Araguás-Araguás et al.* [2000], *Guan et al.* [2009], *Stevenson et al.* [2010], and *Wassenaar et al.* [2011]
Orographic terrain	A windward to leeward depletion due to the effect of the elevation effect described above, but may be also due to subcloud processes associated with evaporation on the leeward site of the barrier, with the end result of a windward to leeward trend in depletion in the isotopic value of precipitation.	*Guan et al.* [2009] and *Sinclair et al.* [2011]
Circulatory distillation	Where intense circulation of low-pressure systems (such as intense lows and tropical cyclones) act as a fractionation chamber to create highly depleted isotopic signatures of precipitation.	*Lawrence and Gedzelman* [1996], *Gedzelman et al.* [2003], and *Nott et al.* [2007]
Origin or synoptic	This is a function of numerous factors including the isotopic characteristics of the (predominantly) oceanic source for the evaporated moisture which shows a strong global variability and association with sea surface temperature (SST) and the atmospheric (synoptic) circulation patterns which control the moisture pathway to a precipitation location and result in some of the mechanisms described above due to evaporation- and condensation-related fractionation processes along the moisture pathway.	*Araguás-Araguás et al.* [2000], *Treble et al.* [2005a], *Barras and Simmonds* [2008], *Sjostrom and Welker* [2009], *St. Amour et al.* [2010], *Wassenaar et al.* [2011], *Munksgaard et al.* [2012], and *Guan et al.* [2013]

signatures onto mainland Australia [*Barras and Simmonds*, 2008]. In these locations the dominance of the westerly flow and midlatitude cyclonic systems leads to a strong relationship between changes in rain-out proportion and rainfall intensity largely explaining isotopic depletion, at single sites and across regions [*Treble et al*., 2005a, 2005b; *Barras and Simmonds*, 2008, 2009]. However, this relationship may not hold for areas with more complex topography or those that experience a larger variability in moisture origin pathways and in the synoptic drivers of precipitation.

Guan et al. [2009] showed that for the Mount Lofty Ranges (South Australia), which are more topographically complex than the coastal sites discussed above, 75% of the spatial variability in δ^{18}O values could be explained by terrain effects alone. They identified a windward/leeward difference in δ^{18}O values of 0.5‰ and an elevation δ^{18}O lapse rate of -0.25‰ 100 m^{-1}. *Guan et al*. [2013] found a significant influence of synoptic moisture pathways on precipitation stable isotope values, concluding that, in general, more depleted signatures were associated with higher rainfall volumes during winter months; they were caused by synoptic conditions (frontal systems in winter and dominant low-pressure systems and tropical moisture in summer).

Despite this work, little is known about the potential influence of various synoptic weather systems, moisture sources, and variability on the stable isotopic signatures of precipitation events in more complex mountain terrain such as the Australian Alps. Furthermore, research to date has been conducted at sites that do not record snowfall. Snowflake formation from supercooled water vapor is an additional second-order kinetic effect that can influence isotopic composition of precipitation [*Araguás-Araguás et al*., 2000] (also see Table 1). Therefore, the impacts of precipitation type are also unknown for interpreting oxygen isotopic archives in Australian alpine areas.

Chubb et al. [2011] presented a climatology of wintertime precipitation (for the period 1990–2009), identifying that cutoff lows (57% of precipitation) and embedded lows (40%) were the dominant synoptic weather patterns affecting the Australian alpine region, with east coast lows and other infrequent synoptic-scale precipitation-bearing weather systems having little impact. Their research used backward air parcel trajectory modeling to identify moisture sources of precipitation from the Tasman Sea and middle to high latitudes in the Southern Ocean. This also highlighted the influence of the Southern Annular Mode (SAM) on controlling the dominant moisture pathways at this time of the year. The synoptic characteristics of wintertime precipitation do not account for the known role that extratropical and midlatitude moisture plays on the region due to migration of the subtropical high-pressure ridge, a characteristic which is most pronounced in spring [*Murphy and Timbal*, 2008].

Given the evidence of multiple synoptic moisture pathways and the known interaction of ocean-atmosphere teleconnections such as the PDO, ENSO, SAM, and IOD, it is critical to better understand the controls on precipitation isotopic variability in the Australian Alps. The presence of speleothem records in this alpine landscape provides a unique opportunity to better understand the palaeoclimate of this region, Southern Hemisphere, and the role of ocean-atmosphere teleconnection processes in the Pacific, Southern, and Indian Oceans. The objective of this study is to determine which of the factors known to influence the oxygen stable isotopic composition of precipitation can describe a 2 year event data set from the Australian Alps. Due to the potential application of these data toward informing speleothem (calcite) palaeoclimate reconstruction, we focus explicitly on exploration of precipitation isotopic variability based on stable oxygen isotopes (^{16}O and ^{18}O) only. A significant motivation of this study is to inform interpretation of oxygen isotope archives in alpine areas of Australia for the understanding of the influence of ocean-atmosphere teleconnections such as the SAM, IOD, ENSO, and PDO on the region's hydroclimate.

2. Methods

Real-time precipitation (snowfall ($n = 24$), mixed ($n = 1$), and rainfall ($n = 19$)), snowpack ($n = 21$) and integrated snowpack ($n = 5$) samples were collected across 18 different sites in 12 field campaigns from February 2010 to March 2012 (Table 2). Sites spanned an elevation range from 950 to 2045 m asl (Figure 1). Three sites were accessed by vehicle, with the remainder only accessible by helicopter. The sampling program collected high-frequency intra-event samples from a limited number (two or three sites depending on access and personnel availability) of all weather sites that were accessible by vehicle or ski lifts before an event (with sampling of any snow created by ski resorts from local water stores avoided). This was complimented by a limited number of more spatially distributed, opportunistic sampling of sites accessed by vehicle or helicopter. Targeted synoptic types included those identified by *Chubb et al*. [2011] (cutoff lows and embedded lows with and without cold fronts), plus inland troughs. A disturbed southwesterly event was also sampled, which was characterized by convective precipitation cells embedded within a southwesterly airstream. The synoptic meteorology of each event was determined by analysis of mean sea level charts, satellite images, rainfall/snowfall distributions, and moisture pathways. The arithmetic (δ_A) (equation (1)) and amount-weighted (δ_W) (equation (2)) mean isotopic composition were also calculated for each of the five synoptic conditions (cold front, cold front/cutoff low, cutoff low, disturbed southwesterly flow, and inland trough).

$$\overline{\delta}_A = \frac{\sum_{i=1}^{n} \delta_i P_i}{\sum_{i=1}^{n} P_i} \tag{1}$$

$$\overline{\delta}_W = \frac{\sum_{i=1}^{n} \delta_i}{n} \tag{2}$$

where δ_i is the isotopic value of an individual sample, P_i is the precipitation amount (mm) during the sample collection period, and n is the total number of samples for that particular type of synoptic system.

Table 2. Details of the Sampling Plan of Real-Time Snow and Rain Precipitation Samples and the Synoptic Conditions, Together With Integrated Snowpack and Specific Snowfall Events Sampled From the Snowpack During 12 Separate Field Campaigns Between February 2010 and March 2012

Event/Sample	No. Samples	No. Locations	Date[a]	Precipitation Type	Synoptic Type	$\bar{\delta}_A{}^{18}O$ (‰)	$\bar{\delta}_W{}^{18}O$ (‰)	$\bar{\delta}_{SL}{}^{18}O$ (‰)	$\bar{\delta}_A{}^{2}H$ (‰)	Ave. Elev (m)	Ave. Temp (°C)
Event 1	1	1	17/2/2010	Rain	Inland trough	−5.1	−5.1	−0.3	−25.7	956.1	21.6
Event 2	8	4	10/8/2010–12/8/2010	Snow	Cutoff low	−10.1	−10.8	−1.7	−59.6	1680.6	6.3
Event 3	1	1	25/8/2010	Snow	Cold front	−7.9	−7.9	1.6	−41.6	1901.1	4.3
Event 4	1	1	01/9/2010	Rain	Cold front (postfrontal)	−5.3	−5.3	2.4	−18.4	1546.6	12.4
Event 5	2	1	05/6/2011	Mixed	Cold front with cutoff low	−6.1	−6.1	1.3	−21.5	1482.0	2.0
Event 6	4	1	21/6/2011–22/6/2011	Snow	Cold front	−7.9	−12.0	−0.5	−41.8	1482.0	4.6
Event 7	5	1	4/7/2011–6/7/2011	Snow	Disturbed SW flow	−8.2	−7.9	−0.8	−47.0	1482.0	6.6
Event 8	3	3	17/8/2011	Rain	Cold front with cutoff low	−10.1	−7.8	−2.4	−71.9	1546.6	11.6
Event 9	4	1	29/9/2011	Snow	Cold front	−11.8	−11.8	−4.4	−81.0	1482.0	9.7
Event 10	1	1	24/11/2011	Rain	Inland trough	−2.1	−2.1	2.7	−2.8	956.1	12.4
Event 11	2	1	11/12/2011	Rain	Inland trough	−8.6	−8.6	−2.9	−51.7	1153.8	15.3
Event 12	11	2	28/2/2012–3/3/2012	Rain	Inland trough	−5.6	−7.6	0.2	−26.1	1153.8	19.9
Integrated snowpack	5	5	Sampled on 15/8/2011	Integrated snow Pack		N/A—multiple events					
Snow layers (2010)	9	3	Sampled on 31/8/2010	Snow layer		N/A—multiple events					
Snow layers (2011)	12	4	Sampled on 15/8/2011	Snow layer		N/A—multiple events					

[a]Dates are formatted as day/month/year.

To compliment real-time rain and snow sampling, in situ sampling of the integrated snowpack was done using a Mount Rose snow sampler at five sites (Sites SMO1, 4, 18, 19, and 22). By sampling locations at the time of peak depth in the snowpack and at the end of winter, we minimize the potential for isotopic fractionation of the snowpack, and sampled across multiple events preserved in the snowpack, based on logging of snowfall events and the snowpack across the field sites. Based on this data set, we calculate a relationship of the mean oxygen isotope composition from the cool-bath melted-out integrated snowpack sample against elevation of the sites of −0.5 (−0.498) ‰ $\delta^{18}O$ 100 m^{-1} ($R^2 = 0.88$), also see section 3. We then use this value to also account for the potential elevation bias in our sampling of specific events where certain sites were accessed during specific conditions of each event. We calculate a corrected to sea level equivalent (δ_{SL}), according to equation (3):

$$\bar{\delta}_{SL}{}^{18}O = \delta^{18}O - \left(\delta^{18}O * \left(0.5 * \frac{Elev(m)}{100}\right)\right) \quad (3)$$

where $\delta^{18}O$ is the raw oxygen isotope value, $\delta_{SL}{}^{18}O$ is the isotope value adjusted to sea level equivalence, and Elev(m) is the height of the location in meters above sea level.

Due to the inaccessibility of the sites and difficulty in accessing field sites during protracted snowfall events with a helicopter, selected snow pit layers were also sampled, where specific and large layers could be attributed to known snowfall events using proximal snow course and heated pluviometer data. These data from specific layers are not presented at length in this paper, aside from one sample collected from the snowpack at SMO1 ($\delta^{18}O$ −15.5‰) on 31 August 2010 from an east coast low event on 12 August 2010.

Snow samples were sealed in ultraclean plastic sample bags and kept frozen until they were melted in a cool water bath. All rain and thawed snow samples were filtered with a 0.45 μm in-line syringe filter and stored at 3°C in a completely filled (i.e., no air void or bubbles), sealed McCartney bottle prior to analysis. The

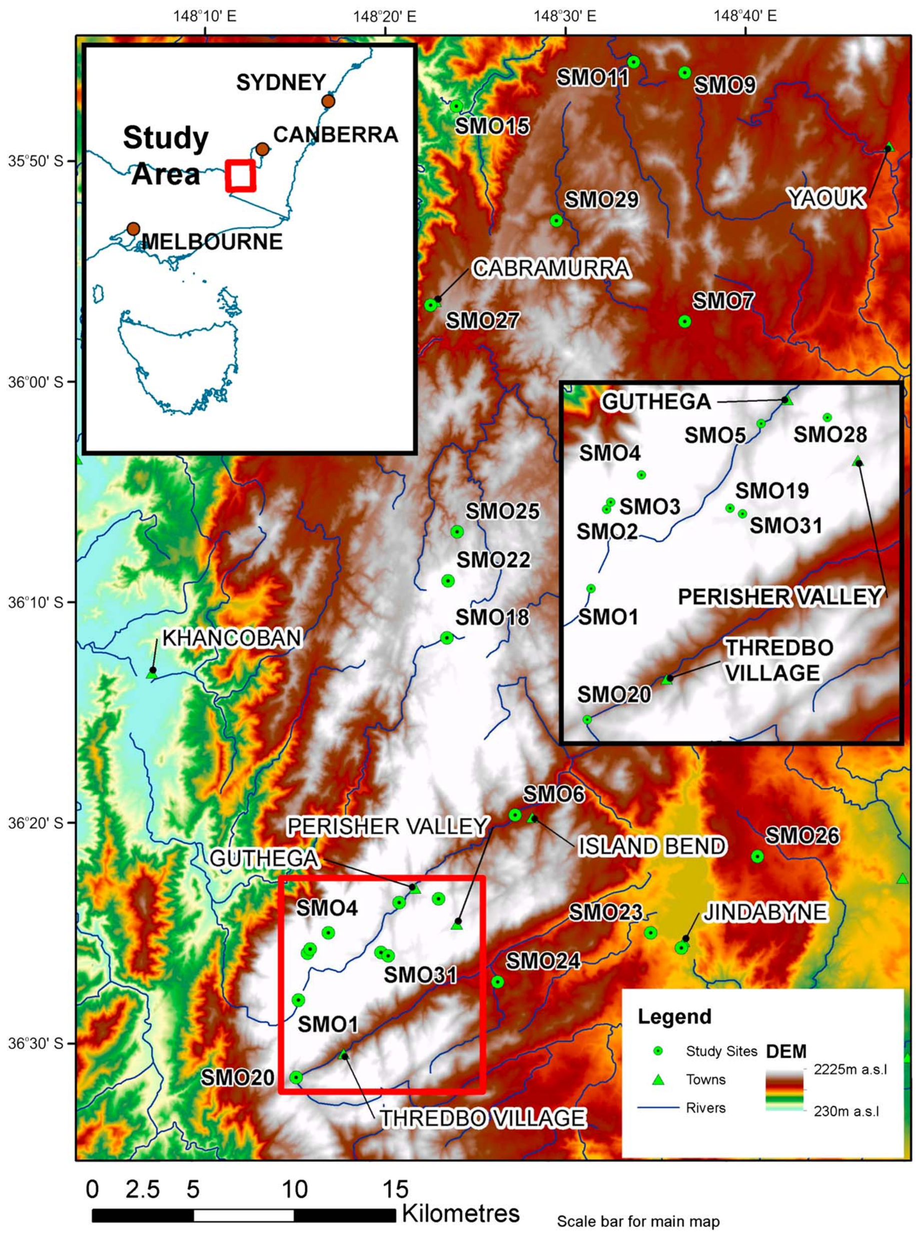

Figure 1. Sampling locations in the study region, Snowy Mountains, Australia.

oxygen isotope signatures were analyzed using an Isoprime Dual Inlet Mass Spectrometer and a Los Gatos Laboratories off-axis integrated cavity output spectroscope. Duplicate samples were used across the two machines to ensure that both delivered sample accuracy of better than δ^2H 0.3‰ and δ^{18}O 0.1‰. Data are reported herein as the per mil (‰) deviations in the ^{16}O/^{18}O ratio from the Vienna standard mean ocean water (VSMOW) standard, and for the sake of brevity, the notation δ^{18}O *x* ‰ is used and referred to as the isotopic value.

Similar to *Chubb et al.* [2011], event backward precipitation pathways were constructed using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (HYSPLIT is available from http://ready.arl.noaa.gov/HYSPLIT.php, Draxler, R. R., and G. D. Rolph (2012), HYSPLIT-Hybrid Single-Particle Lagrangian Integrated Trajectory model, edited, NOAA Air Resources Laboratory, Silver Spring, USA.). An end elevation of 500 m above ground level (agl) was used. The National Centers for Environmental Prediction/National Center for Atmospheric Research Global Reanalysis (for 2010–2011 events) and Global Data Assimilation System (2012 events) data sets were used to construct vapor vertical and geographic pathways for every hour over the period of time that the real-time samples were collected. Back trajectories were calculated for a period of 72 h, for the five events with four or more within-event precipitation isotopic samples (Events 2, 6, 7, 9, and 12). The mean temperature (°C) and mean elevation (m) were determined for the period of 2, 6, 12, 24, and 48 h before the precipitation event along the air parcel pathway, calculated from the reanalysis data. Ground-based precipitation data were used from a network of heated pluviometer stations operated by Snowy Hydro Ltd., along with snow course data provided by Snowy Hydro Ltd. from Spencer's Creek (36.428°S, 148.341°E, Elev 1882 m asl).

Rainfall total along the air parcel back trajectories were extracted from the reanalysis data sets. Back trajectory and ground-based rainfall data (Snowy Hydro Ltd. sites) were both analyzed, but data from reanalysis data sets were found to have a stronger relationship to isotopic values and are presented in Table 4. This is most likely due to the fact that the event rain-out effect along the air parcel has a greater influence on the isotopic value, rather than rainfall volume (leading up to an event) recorded at the point where the event precipitation sample is collected. Analysis of the relationships between temperature, elevation, and rainfall against the raw isotope value of all real-time precipitation (rain, snow, and mixed) data sets was examined via linear regression, with the R2 statistic reported as the measure of correlation.

3. Results

Real-time precipitation samples that included rainfall, snowfall, and mixed precipitation types in the Snowy Mountains conformed more closely to the global meteoric water line (GMWL) of *Craig* [1961] than the local meteoric water line (LWML) for Australia presented by *Liu et al*. [2010] from Australian GNIP sites (Figure 2). A local meteoric water line (LMWL) (δ^2H = 8.16 δ^{18}O + 18.38, $n = 47$, $R^2 = 0.947$) was constructed from real-time all snow, rain, and mixed precipitation samples. The slope of our LMWL (slope = 8.16) plots close to the GMWL (slope = 8) and is above the minimum Rayleigh condensation equilibrium value for a temperature range of $20 > t > -20$°C (LMWL slope > 7.5) [*Liu et al*., 2010]. The closer grouping of our LMWL to the GMWL and Rayleigh condensation equilibrium value is consistent with a cooler, more temperate, and moist moderate-altitude location, less affected by subcloud evaporative processes which may influence the Australian GNIP data presented by *Liu et al*. [2010].

Based on the 12 real-time precipitation events sampled, some broad relationship between synoptic conditions and oxygen isotope values emerge (Table 3). Arithmetic mean oxygen isotopic values were most depleted (most negative oxygen isotope values) for cutoff low events such as Event 2 (Cutoff low, August snowfall event, $\bar{\delta}_A{}^{18}$O −10.1‰), and Event 8 (cutoff low with cold front, August rain event, $\bar{\delta}_A{}^{18}$O −10.1‰). Inland trough events such as Event 1 ($\bar{\delta}_A{}^{18}$O −5.1‰), Event 10 ($\bar{\delta}_A{}^{18}$O −5.1‰), and Event 12 ($\bar{\delta}_A{}^{18}$O −5.6‰) had the least depleted mean isotopic values. Some results do not fit with such a simple synoptic explanation for the variability. The single sample for Event 4, which was a sample of postfrontal rainfall from a cold front, was also less depleted (δ^{18}O −5.1‰). The values for the inland trough Event 2 ($\bar{\delta}_A{}^{18}$O −8.6‰) were more depleted than the other inland trough rainfall events and had a mean isotopic value that was more depleted than many of the cold front events.

Few events showed significant bias based on the variability of the mean arithmetic isotopic values ($\bar{\delta}_A{}^{18}$O) in comparison to sampled weighted for the influence of rainfall volume ($\bar{\delta}_W{}^{18}$O) or sampling biased toward high- or low-elevation locations ($\bar{\delta}_{SL}{}^{18}$O). Based on the 12 events (Table 2), only Event 6 (snow, cold front, $\bar{\delta}_A{}^{18}$O −7.9‰, and $\bar{\delta}_W{}^{18}$O −12.0‰), Event 8 (rain, cold front with cutoff low, $\bar{\delta}_A{}^{18}$O −10.1‰, and $\bar{\delta}_W{}^{18}$O −7.8‰), and Event 12 (rain, inland trough, $\bar{\delta}_A{}^{18}$O −5.6‰, and $\bar{\delta}_W{}^{18}$O −7.6‰) had significant variability for the arithmetic and rainfall-weighted mean isotopic values. *Dansgaard* [1964] proposes that precipitation is more depleted in oxygen isotope values under higher rainfall conditions. Events 6 and 12 show more depleted isotopic values associated with the rainfall-weighted measure and are consistent with Rayleigh distillation amount effects proposed by *Dansgaard* [1964], with more enriched mean isotopic values for the rainfall-weighted measure. Event 8 has a less depleted isotopic values associated with the rainfall-weighted measure. This result is at odds with the amount effect explanation but could be explained by factors such as enhanced convective activity during precipitation events such as cold fronts and thunderstorms, consistent with the synoptic conditions of these two events [*Gat*, 1996].

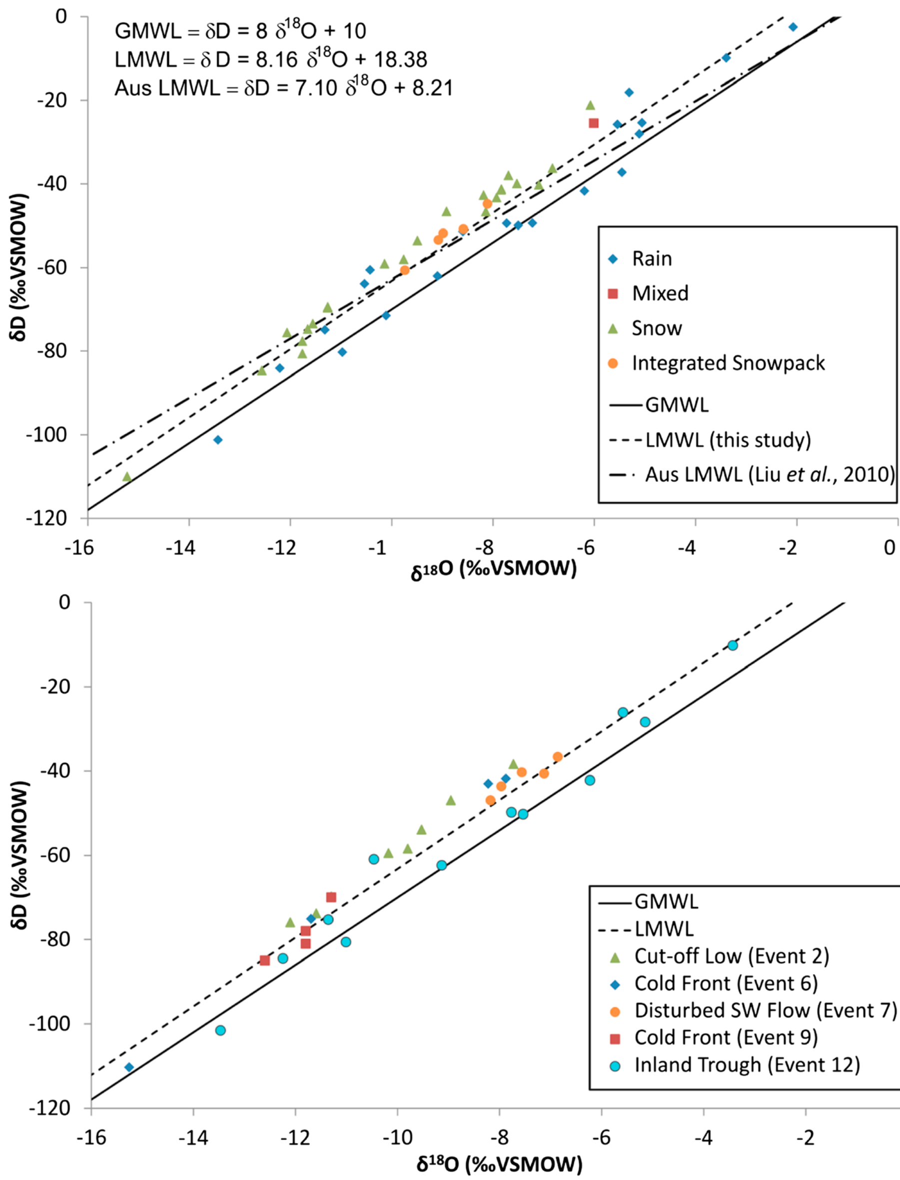

Figure 2. The data set of 47 real-time samples collected across 12 separate events and five integrated snowpack samples, stratified by (top) precipitation type collected across the period (bottom) February 2010 to March 2012. The local meteoric water line (LMWL) calculated from all real-time samples is plotted against the GMWL [*Craig*, 1961] and LMWL for Australian GNIP sites [*Liu et al*., 2010] (Figure 2, top). A subset of data for the five selected events is presented against the LWML (this study) and GMWL, showing kinetic fractionation for snow precipitation-dominated events (Events 2, 6, 7, and 9; see Table 1) relative to the rain precipitation Event 12.

The overall results for each synoptic type show that cold front events (Events 3, 4, 6, and 9) had the most depleted mean isotopic values ($\overline{\delta}_A{}^{18}$O −10.4‰, $\overline{\delta}_W{}^{18}$O −11.8‰, and $\overline{\delta}_{SL}{}^{18}$O −0.2‰) (Table 3). Event 2, the cutoff low which collected eight samples across four sites, has the second most depleted signature ($\overline{\delta}_A{}^{18}$O −10.1‰, $\overline{\delta}_W{}^{18}$O −10.8‰, and $\overline{\delta}_{SL}{}^{18}$O −1.7‰), though when the potential sampling bias is removed by adjusting values to an equivalent isotopic value at sea level, Event 2 has a more depleted signature than for cold front events. Data for the cold front and cutoff low, disturbed southwesterly, and inland trough events have similar mean isotopic values across arithmetic, rainfall-weighted, and sea level equivalent measures.

Elevation terrain effects were investigated by analysis of the seasonal alpine snowpack samples from five sites (ranging from 1752 to 2044 m asl) at the time of maximum snowpack depth along the middle of the

Table 3. Arithmetic Means for the Precipitation Stable Isotope Values (δ^{18}O VSMOW‰ and δD VSMOW‰) for the Different Synoptic Events Sampled in the Study

Event Meteorology	n	Events	Season[b]				Precipitation Type		δ^{18}O (‰)				δ^{2}H (‰)			Mean	Mean Temp
			DJF	MAM	JJA	SON	Rain	Snow	$\bar{\delta}A$	$\bar{\delta}W$	$\bar{\delta}SL$	σ	$\bar{\delta}A$	$\bar{\delta}W$	σ	Elev (m)	(°C)
Cold front	10	3, 4, 6, and 9	0	0	4	6	1	9	−10.4	−11.8	−0.225	2.94	−64.4	−77.7	27.36	1630.2	7.75
Cold front/cutoff low	5	5 and 8	0	0	2	3	3[a]	1[a]	−7.0	−7.0	−0.55	1.87	−41.3	−40.8	20.30	1689.3	6.8
Cutoff low	8	2	0	0	0	8	0	8	−10.1	−10.8	−1.7	1.46	−59.6	−65.2	13.19	1689.3	6.3
Disturbed SW flow	5	7	0	0	5	0	0	5	−7.1	−7.9	−0.8	1.11	−39.0	−43.9	7.37	1647.4	6.6
Trough	16	1, 10, 11, and 12	1	7	0	8	16	0	−8.1	−7.6	−0.075	3.30	−51.0	−45.5	27.55	1656.1	17.3

[a]Plus one mixed phase sample (3 × rain, 1 × snow, 1 × mixed phase, total of five samples).
[b]DJF, December-January-February; MAM, March-April-May; JJA, June-July-August; SON, September-October-November.

main range (Sites SMO1, 4, 18, 19, and 22). Snow pits were used to identify event layers and relate these to heated snow pluviometer and temperature data to ensure that all sites had preserved the same sequence of major snowfall events. Sites below 1750 m were deemed as not preserving a reliable and comparable snowpack to the higher sites (i.e., snow fell as rain at these lower elevations and snow precipitation events were not preserved in the snowpack). Regression through the five points found a relationship of −0.50‰ δ^{18}O 100 m^{-1} ($R^2 = 0.88$). This value is higher than the value of −0.25‰ δ^{18}O 100 m^{-1} reported by *Guan et al*. [2009] for the lower altitude and less topographically complex Mount Lofty Ranges in coastal South Australia, a data set that only included rain. Our results do correspond to results from *Vogel et al*. [1975] in the Argentinian Andes who reported values ranging with elevation from −0.1 to −0.6‰ δ^{18}O 100 m^{-1} and around −0.5‰ δ^{18}O 100 m^{-1} for an elevation of roughly 2000 m asl. Our results are also consistent with the typical range of observed altitude effects discussed by *Araguás-Araguás et al*. [2000].

Guan et al. [2009] reported a windward to leeward effect of −0.5‰ δ^{18}O 100 m^{-1} was evident (i.e., leeward side was more depleted in δ^{18}O) for the Mount Lofty Ranges. Using a limited data set of two paired integrated snowpack samples taken at similar elevations but at locations from the windward side of the top of the main range and at a leeward location at the margin of the snow line, we investigated for evidence of orographic terrain effect. Paired samples at SMO18 (windward, 1752 m asl, δ^{18}O −8.1‰, $\bar{\delta}_{SL}{}^{18}$O 0.66‰) and SMO19 (leeward, 1882 m asl, δ^{18}O −8.6‰, $\bar{\delta}_{SL}{}^{18}$O 0.81‰), together with SMO22 (windward, 2001 m asl, δ^{18}O −9.0‰, $\bar{\delta}_{SL}{}^{18}$O 1.01‰) paired to both SMO1 (leeward, 2044 m asl, δ^{18}O −9.8‰, $\bar{\delta}_{SL}{}^{18}$O 0.42‰) and SMO4 (leeward, 1950 m asl, δ^{18}O −9.1‰, $\bar{\delta}_{SL}{}^{18}$O 0.65‰), yielded a windward to leeward depletion of 0.45‰ δ^{18}O 100 m^{-1}. Adjusting the isotope values to an equivalent sea level value to account for any elevation effect in the sampling (see above and equation (3)), we found a value of 0.54‰ δ^{18}O 100 m^{-1} for windward to leeward depletion. We therefore report an orographic terrain effect for this region of −0.5‰ δ^{18}O 100 m^{-1} .

Analysis of the within-event variability of isotopic values for the five events analyzed in detail (Events 2, 6, 7, 9, and 12; see Figure 2, bottom) revealed further insight into the factors controlling isotopic variability. Some events such as the disturbed southwesterly (Event 7) and the cold front (Event 9) show relatively small within-event variability, whereas the other cold front (Event 6) showed higher within-event variability. The greatest variability within our data set was associated with the inland trough (Event 12) having oxygen isotope values varying from δ^{18}O −3.4 to −13.5‰ within the same event.

The HYSPLIT model was used to determine air temperature, air parcel elevation, and rainfall along the backward trajectory of the air parcel that resulted in precipitation reported in this study. Temperature data are likely to describe the influence of kinetic fractionation through air parcels such as low or below-zero mean temperatures representing the likelihood of ice and snow formation either along the air parcel or immediately preceding precipitation. Elevation data are a measure for enhanced convective activity, particularly using the data for shorter

Table 4. Results for Regression Analysis (R^2) of the Stable Isotope Results (δ^{18}OVSMOW‰ and δDVSMOW‰) Against the Environmental Variables, Temperature, Elevation, and Rainfall, Along the Backward Trajectory of the Vapor Pathway for the Period of 2 h, 6 h, 12 h, 24 h, and 48 h Preceding the Precipitation Event

	Temperature (°C)					Elevation (m agl)					Rainfall Total (mm)				
	2 h	6 h	12 h	24 h	48 h	2 h	6 h	12 h	24 h	48 h	2 h	6 h	12 h	24 h	48 h
δ^{18}OVSMOW‰	0.05	0.03	0.03	0.01	0.00	0.08	0.09	0.08	0.08	0.09	0.07	0.07	0.11	0.14	0.13
δDVSMOW‰	0.01	0.00	0.00	0.00	0.01	0.06	0.10	0.12	0.14	0.13	0.11	0.11	0.16	0.18	0.16

periods (i.e., the 2 h) immediately preceding precipitation recorded at the ground sites. Rainfall data are a direct measure of event rain-out depletion along the moisture pathway.

Linear regression of the temperature and mean air parcel elevation along the air parcel trajectory modeled using HYSPLIT had very poor and almost no relationship to observed variation in the precipitation oxygen stable isotope composition (Table 4). Rainfall along the air parcel trajectory (HYSPLIT rainfall data) over the 24 h preceding deposition (R^2: $\delta^{18}O = 0.14$, R^2 $\delta^2H = 0.18$) had the strongest relationship to variability of the raw isotope values (Table 4). However, this was still a poor fit and explained only 14% of the total observable variance in oxygen stable isotope values recorded in ground precipitation sampled.

Synoptic pathways may play a significant role in stable isotope signatures of precipitation [*Munksgaard et al.*, 2012]. To further investigate the potential influence of synoptic conditions on isotopic values, we analyzed the air parcel tracks. Our five-event detailed data set included a cutoff low (Event 2), cold front (Events 6 and 9), a disturbed southwesterly (Event 7), and an inland trough (Event 12) and represents the major precipitation-bearing synoptic types for the region (aside from east coast lows) identified by *Chubb et al.* [2011]. The plan view moisture pathway origin (Figure 3) and vertical pathway (see supporting information) suggest that aspects of the within- and between-event variability (or lack thereof) appear to bear a strong relationship to the variability in the geographic moisture origin and pathway.

The isotopic signature is relatively consistent for the disturbed southwesterly (Event 7) and also for the cold front (Event 9), where moisture was sourced from the Southern Ocean, between 31°S and 49° (though most north of 43°S) in latitude. Event 6, by contrast, shows significant intra-event variability. This cannot be explained by the rainfall amount, which is relatively consistent for the four within-event samples (all samples recorded between 11.4 and 15.7 mm, Figure 3). The most depleted samples are the prefrontal rainfall samples (Event 6—samples E6-1 and E6-2) which have a more northern, continental origin. There is no evidence in the vertical pathway of enhanced convection for this event (see supporting information). The air parcel track suggests continental depletion of the early samples, before progressive enrichment in the isotopic value later in the event, as the moisture source switched to a localized source as the most plausible explanation of factors causing within-event isotopic variability for Event 6. For Event 2 (cutoff low), the precipitation early in the event does not have a depleted isotopic signature but, in general, becomes progressively depleted during the event. While this is consistent with the event rain-out effect [*Araguás-Araguás et al.*, 2000; *Munksgaard et al.*, 2012], the later event samples (E2-5 to E2-8) are associated with a shift of the moisture source from the Pacific Basin to the Southern Ocean. These data suggest that a more depleted stable isotope signature is generally associated with prefrontal and early event samples particularly with a continental or moderate latitude oceanic (i.e., north of 35°S to 40°S) moisture pathway. Moisture sources from between 40°S and 55°S across the events show a relatively consistent signature at around δ^{18}O −6.5 to −8.5‰.

The inland trough (Event 12) showed significant within-event variability in moisture origin and isotopic signature. Pathways shift from the onshore flow of moisture from the Pacific Ocean east of New South Wales and Queensland through the Tasman Sea to the Southern Ocean during the event (e.g., Figure 3, Event 12, and supporting information). This is atypical of most inland trough events that have a predominantly tropical moisture origin. Other real-time samples collected by this study for localized thunderstorm activity and other inland troughs had consistently less depleted isotopic values, e.g., −5.1 δ^{18}O ‰ (17 February 2010), −5.3 δ^{18}O ‰ (1 September 2010), and −5.5 δ^{18}O ‰ (17 August 2011). The results for Event 12 further support the finding that events that source moisture from geographically diverse regions have high within-event variability. However, there is no single, clear explanation for the results of isotopic variability from this event that can adequately explain the variability within the samples sourced from the Southern Ocean and Tasman Sea to the southeast of Tasmania (E12-3 to E12-12).

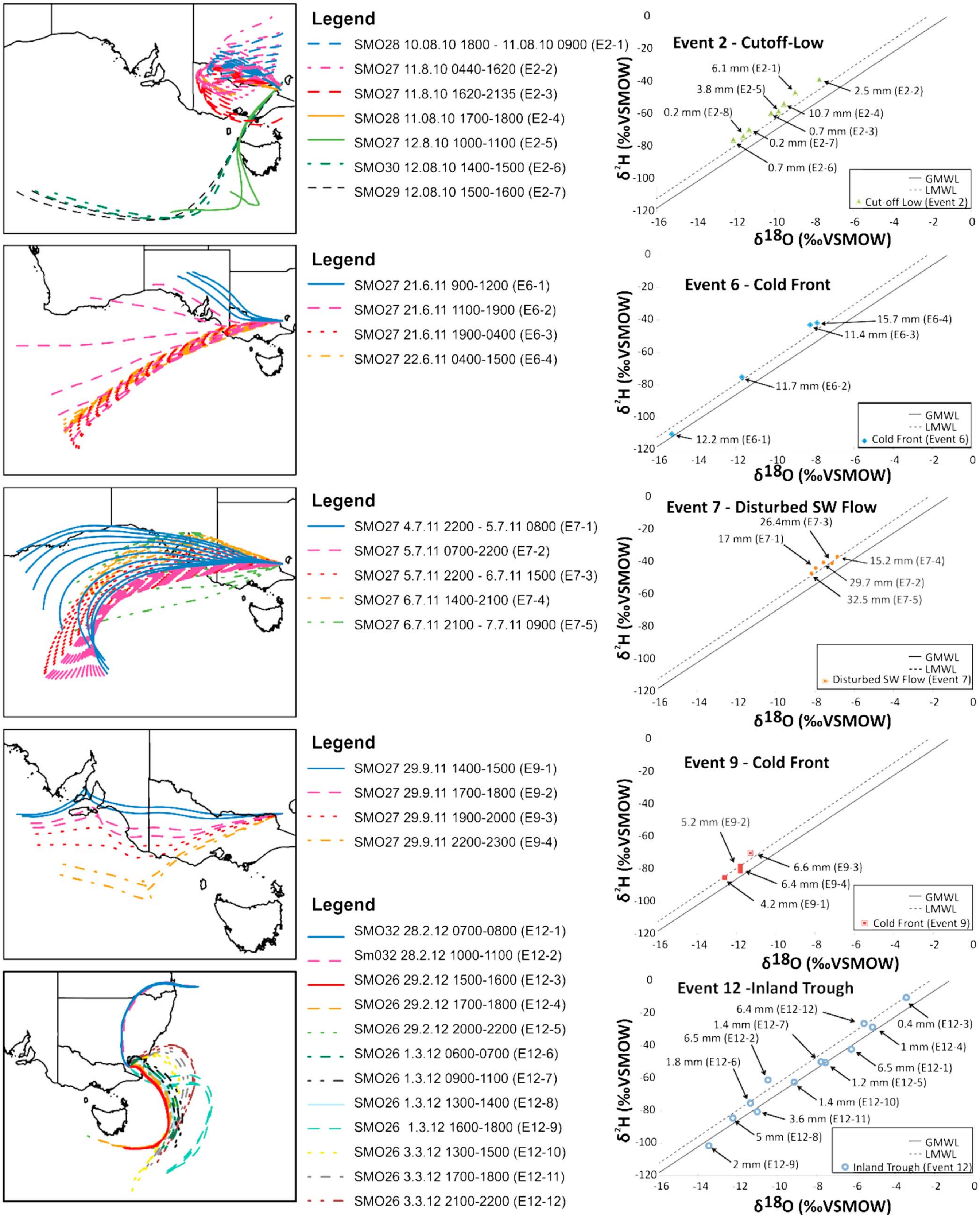
Legend
SMO28 10.08.10 1800 - 11.08.10 0900 (E2-1)
SMO27 11.8.10 0440-1620 (E2-2)
SMO27 11.8.10 1620-2135 (E2-3)
SMO28 11.08.10 1700-1800 (E2-4)
SMO27 12.8.10 1000-1100 (E2-5)
SMO30 12.08.10 1400-1500 (E2-6)
SMO29 12.08.10 1500-1600 (E2-7)
Event 2 - Cutoff-Low
6.1 mm (E2-1)
3.8 mm (E2-5)
0.2 mm (E2-8)
2.5 mm (E2-2)
10.7 mm (E2-4)
0.7 mm (E2-3)
0.2 mm (E2-7)
0.7 mm (E2-6)
GMWL
LMWL
Cut off Low (Event 2)
δ²H (‰VSMOW)
δ¹⁸O (‰VSMOW)
Legend
SMO27 21.6.11 900-1200 (E6-1)
SMO27 21.6.11 1100-1900 (E6-2)
SMO27 21.6.11 1900-0400 (E6-3)
SMO27 22.6.11 0400-1500 (E6-4)
Event 6 - Cold Front
15.7 mm (E6-4)
11.4 mm (E6-3)
11.7 mm (E6-2)
12.2 mm (E6-1)
GMWL
LMWL
Cold Front (Event 6)
Legend
SMO27 4.7.11 2200 - 5.7.11 0800 (E7-1)
SMO27 5.7.11 0700-2200 (E7-2)
SMO27 5.7.11 2200 - 6.7.11 1500 (E7-3)
SMO27 6.7.11 1400-2100 (E7-4)
SMO27 6.7.11 2100 - 7.7.11 0900 (E7-5)
Event 7 - Disturbed SW Flow
26.4mm (E7-3)
17 mm (E7-1)
15.2 mm (E7-4)
29.7 mm (E7-2)
32.5 mm (E7-5)
GMWL
LMWL
Disturbed SW Flow (Event 7)
Legend
SMO27 29.9.11 1400-1500 (E9-1)
SMO27 29.9.11 1700-1800 (E9-2)
SMO27 29.9.11 1900-2000 (E9-3)
SMO27 29.9.11 2200-2300 (E9-4)
Event 9 - Cold Front
5.2 mm (E9-2)
6.6 mm (E9-3)
6.4 mm (E9-4)
4.2 mm (E9-1)
GMWL
LMWL
Cold Front (Event 9)
Legend
SMO32 28.2.12 0700-0800 (E12-1)
Sm032 28.2.12 1000-1100 (E12-2)
SMO26 29.2.12 1500-1600 (E12-3)
SMO26 29.2.12 1700-1800 (E12-4)
SMO26 29.2.12 2000-2200 (E12-5)
SMO26 1.3.12 0600-0700 (E12-6)
SMO26 1.3.12 0900-1100 (E12-7)
SMO26 1.3.12 1300-1400 (E12-8)
SMO26 1.3.12 1600-1800 (E12-9)
SMO26 3.3.12 1300-1500 (E12-10)
SMO26 3.3.12 1700-1800 (E12-11)
SMO26 3.3.12 2100-2200 (E12-12)
Event 12 -Inland Trough
6.4 mm (E12-12)
1.4 mm (E12-7)
6.5 mm (E12-2)
1.8 mm (E12-6)
0.4 mm (E12-3)
1 mm (E12-4)
6.5 mm (E12-1)
1.2 mm (E12-5)
1.4 mm (E12-10)
3.6 mm (E12-11)
5 mm (E12-8)
2 mm (E12-9)
GMWL
LMWL
Inland Trough (Event 12)

Figure 3

4. Discussion

This study has sought to understand the factors that cause variability in the stable oxygen isotope signature of precipitation for the Australian Alpine region. This area is recognized as acutely susceptible to impacts of anthropogenic climate change [*Nicholls*, 2005; *Chubb et al*., 2011]. Furthermore, teleconnections from both the Pacific Basin and Indian Oceans and their variability are known to significantly impact precipitation and runoff processes in this region [*McGowan et al*., 2009, 2010]. Speleothems in this region contain a potentially rich archive of the oxygen isotope record for a region with significance for palaeoenvironmental research and climate variability but which require a robust understanding of the drivers of isotopic variability for their interpretation. This study has sought to investigate evidence for known drivers of isotopic variability in precipitation, which includes continental, event rain out, amount, convective depletion, type, elevation, orographic terrain, circulatory distillation, and origin (or synoptic) effects from an event data set collected over a 2 year period.

Previous research on precipitation oxygen stable isotope variability in southern Australia has investigated variability using monthly GNIP data from low-altitude coastal, southern Australian sites [*Treble et al*., 2005a, 2005b; *Barras and Simmonds*, 2008; *Liu et al*., 2010]. Much of this research has attributed isotopic variability to an amount and event rain-out effects [*Treble et al*., 2005a; *Barras and Simmonds*, 2008], and interpreted speleothem isotopic variability as indicative of changed rainfall volume [e.g., *Treble et al*., 2005b]. *Treble et al*. [2005a] and *Barras and Simmonds* [2008], in identifying that amount and event rain-out effects were the dominant control on isotopic variability of monthly precipitation data in Tasmania, noted that there was a consistent geographic origin of moisture in their study areas. Rain bands are embedded in prevailing westerly airflows, consistently originating from middle to high Southern Ocean latitudes delivering rainfall to Tasmania and southern Victoria [*Treble et al*., 2005a; *Barras and Simmonds*, 2008].

Data from this and other recent event-based studies in Australia suggest that drivers of precipitation isotopic variability are poorly explained by amount effects, as is found for monthly data sets [*Treble et al*., 2005a, 2005b; *Barras and Simmonds*, 2008; *Liu et al*., 2010]. *Araguás-Araguás et al*. [2000, p. 1348] describe the effect as an "apparent correlation between the heavy isotope composition and the amount of rainfall," and the results of this study do not explain the amount effect as a robust model of isotopic variability observed in event data over the Snowy Mountains.

Guan et al. [2013] used daily, event-stratified data to study subannual variability in precipitation isotope signature. While monthly to subannual variability in mean isotopic values corresponded to a change in rainfall amount, they found they were physically driven by changes in factors such as sea surface temperatures and relative humidity of the source moisture and shifts in the synoptic conditions that altered the dominant moisture pathway. In regions such as the Snowy Mountains with a more complex topography and geographically diverse moisture sources, the combination of moisture origin (and associated sea surface temperatures of the moisture sources), pathways (continental or oceanic and the potential for continental depletion), localized terrain, and precipitation-type effects are all likely to be significant causes of isotopic variability.

Work in complex terrain settings identifies the role of Rayleigh distillation in causing orographic effects, and the results of this study are consistent with this work [*Guan et al*., 2009; *Sjostrom and Welker*, 2009; *Stevenson et al*., 2010; *Sinclair et al*., 2011]. This study finds evidence of an upwind to downwind effect of $-0.5‰\ \delta^{18}O\ 100\ m^{-1}$ (i.e., leeward side was more depleted in $\delta^{18}O$). *Guan et al*. [2009] found a $+0.5‰\ \delta^{18}O\ 100\ m^{-1}$ result in the more warm and humid Mount Lofty Ranges, attributing their windward to leeward depletion as due to subcloud evaporation on the leeward side and the altitudinal effect (through adiabatic process) on the windward side. In this colder, more topographically complex and higher-elevation site (with limited potential for subcloud processes), we attribute our results to altitudinal effect through adiabatic/orographic forcing of rain out that is consistent with the processes described extensively for depletion of isotopic signatures in more complex terrain [*Rozanski et al*., 1993; *Araguás-Araguás et al*., 2000; *St. Amour et al*., 2010; *Sinclair et al*., 2011].

Figure 3. Detailed analysis of the five selected events (Events 2, 6, 7, 9, and 12). (first column) Within each event is a plan view plot of moisture pathway trajectories calculated from the HYSPLIT model with (second column) the key for each within-event sample. Note the notation in the legend: "SMO26 3.3.12 2100-2200 (E12-12)" represents the sample location (refer Figure 1), date of sample, and time that the sample was taken (Australian Eastern Standard Time) and the sample identified—event number and sample number. (third column) The plot presents isotope values for each data point and total rainfall (during the sampling period) (mm) and the individual event sample identifier (e.g., E12-12) which allows the isotopic values to be related back to moisture pathway. Also supporting these data are the supporting information which have 3-D animation of the moisture pathway trajectories.

The orographic windward to leeward effect has implications for palaeoenvironmental reconstruction of isotope archives in this region. Occasional but intense east coast low events draw moisture from east to west across the range (against the dominant west-to-east flow) [*Chubb et al*., 2011]. The −0.5‰ δ^{18}O 100 m^{-1} windward to leeward isotopic depletion is likely to apply to this event making the interpretation more complex. The high rainfall volumes and intense circulation of these events (e.g., our snowpack sample of the lowest recorded isotopic signature at SMO1 (δ^{18}O −15.5‰) from the east coast low event on 31 August 2010) mean that large volumes of isotopically depleted precipitation can be deliver by these events. More depleted signatures (δ^{18}O −11 to −13‰) may also be associated with more intense circulation and higher wind speeds for the middle of the event (e.g., see Figure 3, Event 12—samples E12-6, E12-8, E12-9, and E12-11).

This study identifies an elevation effect, with an isotope-elevation impact of −0.5 (−0.498) ‰ δ^{18}O 100 m^{-1}. This elevation effect is significantly greater than the rates presented by *Guan et al*. [2009], though their research was conducted on the lower-altitude topography of the Mount Lofty Ranges (reporting a value of −0.25‰ δ^{18}O 100 m^{-1}). The higher value is consistent with the higher elevation and steeper terrain of the Snowy Mountains that enhances orographic lifting of airflow and any associated precipitation. As identified earlier, our value is consistent with data presented by *Vogel et al*. [1975] for mountainous alpine terrain in South America at a similar elevation range (~2000 m asl) and within theoretical limits proposed by *Araguás-Araguás et al*. [2000].

While the elevation effect is unlikely to influence the interpretation of isotope records over time periods of decades and for sites where the catchment for speleothem drip water covers a small area, it is of significance to reconstruction over longer timeframes, where shifts in temperature regime may be represented by alterations to the isotope record. While along moisture pathway, temperature was found to be a poor descriptor of isotopic variability; the elevation effect is likely to be caused by an interaction of factors such as temperature (and associated kinetic fractionation), orographic-forced convective precipitation at higher elevations, and a component of orographic-forced rain out. There is a need to further account for these factors in interpreting any temperature signal from isotope archives.

While there is poor support from our event data set for explaining precipitation isotopic variability on the basis of event rain out or amount, the moisture pathways and synoptic conditions appear to be very important. The influence of synoptic conditions and the source and pathway of moisture to the collection site are also found to show significant variability of within-event sampling. High-resolution within-event sampling by *Munksgaard et al*. [2012] in the Australian tropics (Cairns, latitude 16°55′S) found significant within-event variability of up to δ^{18}O 10.9‰ (from δ^{18}O −8.7 to −19.6‰) and was related to shifting moisture pathways during an event. *Barras and Simmonds* [2009] also found significant within-event variability in data collected for stratiform rainfall around Melbourne (southeast Australia), with variation of δ^{18}O −3 to −11‰ due to shifts in moisture source from the Pacific Ocean off Queensland to the southeast of Tasmania in the Tasman Sea.

Within our event data set there is evidence of synoptic-driven isotopic variability, caused by moisture origin (synoptic influences) and continental effects. Event 7 (disturbed southwesterly) has a relatively consistent moisture source, as does Event 9 (cold front), where moisture is sourced from the Southern Ocean at middle to moderate latitudes (40°S to 55°S). Both show little intraevent isotopic variability. Event 6, by contrast, shows significant intraevent isotopic variability, despite very consistent rainfall amounts within the four event samples (11.4–15.7 mm). For Event 6, the most depleted samples are the prefrontal rainfall samples (Event 6—samples E6-1 and E6-2) which have a more northern, continental origin. It is also possible that these early event samples are associated with convective uplift. The postfrontal rainfall switches to a potentially more local oceanic source and may result in a less depleted signature later in a cold front event, with similar values and geographic origin of the moisture to Event 4.

The reconstruction of palaeoenvironmental conditions based on precipitation stable isotopes from archives such as speleothems and diatoms relies only on the stable oxygen isotope record preserved in calcite or the diatom frustule. The isotopic kinetics associated with Deuterium excess, while not relevant to this work, may be of significance to other studies and are therefore briefly discussed below. The vertical displacement of snow samples relative to rain samples (refer to the sample data and the LMWL in Figure 2) is consistent with precipitation formed by kinetic fractionation during snow formation [*Jouzel and Merlivat*, 1984]. Precipitation-type variability is evident within the event data. Figure 2 (bottom) shows that snowfall in Events 2, 6, and 7 has higher Deuterium excess values (plotting above the LMWL). Event 9 (snow) conforms more closely to the

LWML. Event 12 which was a late spring/summer trough rainfall, with warm air temperatures event (mean 24 h air parcel temperature was 19.9°C), largely conforms to the GMWL. Mean temperature data along the air parcel trajectory for the 24 h preceding the recorded precipitation event suggest that there is a limited potential for kinetic fraction associated with snowflake formation away from the Snowy Mountains as temperatures remain well above freezing. Higher Deuterium excess values are associated with cooler air masses of Event 2 (6.3°C), Event 6 (4.6°C), and Event 7 (6.6°C), in comparison to Event 9 (9.7°C) and the warm spring/summer rainfall Event 12 (19.9°C).

These data suggest that the LMWL defined by this study for the Snowy Mountains is influenced by the precipitation isotopic kinetics of snowfall, and the data for this LWML are more reflective of localized cooler and wetter environmental conditions that appear to differ to those which prevail at the Australian GNIP sites represented in the LMWL of *Liu et al.* [2010].

Based on the results of this event-based study, a clearer picture of the drivers of precipitation variability observed across our 2 year study has emerged. Moisture origin and the pathway are of critical importance. This includes factors such as sea surface temperature (SST) at the moisture source, continental depletion, and circulatory distillation (for particular systems (e.g., east coast lows)) along the pathway and then orographic terrain, convective depletion, and type effects in areas immediately preceding precipitation in the complex mountainous terrain of the Snowy Mountains. Relatively consistent precipitation isotopic values are associated with moisture originating from between 45°S and 55°S in the Southern Ocean (Figure 3 E6-3 and 4 and Event 7 and supporting information) and have values of between δ^{18}O -6.5 and -8‰. Less depleted isotopic signatures appear to be linked to localized thunderstorms and moisture drawn from local sources and the tropics and subtropics, particularly where the synoptic event lacks the potential for circulatory distillation. Events that draw moisture from the Pacific Basin and interact with inland trough systems (e.g., Event 12) seem to produce a relatively complex signature. Highly depleted isotopic signatures appear associated with events such as east coast lows, and while these are irregular, they can deliver large volumes of rainfall.

Given the location of the study site and the data set collected for this region, there appears evidence to suggest that the isotope signature of precipitation may be sensitive to important components of the regional atmospheric circulation. There is a strong relationship of the PDO to the streamflow record of this region that has been found by *McGowan et al.* [2009, 2010, 2011]. While this study does not support the physical basis of a link in amount effects to the isotopic signature for event data, mechanisms such as shift in moisture source and pathway are likely to be preserved in the isotope archives and are associated with a response of annual precipitation of this region.

The variability in the isotopic values from weather systems originating to the south and west suggests that the isotopic archives of the Snowy Mountains may be sensitive to synoptic controls on rainfall such as the position and strength of the subtropical ridge over southern Australia. Not recorded within our data set, but an area of ongoing research, are the isotopic characteristics of northwest cloud bands which are recognized as significant in this region for their influence on spring rainfall and snowmelt runoff. This is especially significant in differentiating strongly depleted signatures associated with east coast lows and inland troughs, where the isotopic signatures are similar, but moisture origin and convective activity are very different.

While not the focus of this study, our findings underlie the use of other proxies such as geochemistry and carbon isotope data in undertaking complex interpretation of oxygen isotope records from geologic archives within palaeoclimate studies [*Frappier*, 2013]. This study highlights the potential of this region for informing palaeoenvironmental reconstruction of the local, regional, and Southern Hemisphere climate history. There is strong evidence of modulation of the hydroclimate by the Southern Annual Mode (SAM), El Niño–Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Indian Ocean Dipole (IOD). We establish a basis for physical mechanisms to describe the causes of isotopic variability of key weather systems which will inform analyses of isotopic records and their variability in response to changes in synoptic circulation forced by large-scale teleconnections and their interactions.

5. Conclusions

This study provides a new insight into the variability of oxygen stable isotope values for precipitation in a moderate-altitude (<2250 m asl) alpine area, the Snowy Mountains region in the Australian Alps. This region is identified as particularly susceptible to the impacts of climate change given the relatively low relief and evidence of a declining winter snowpack extent and longevity [*Nicholls*, 2005; *Chubb et al*., 2011]. There is also a recognition that climate variability impacts due to solar cycles and multidecadal ocean-climate teleconnection forcing of inflows are significant for this alpine region [*McGowan et al*., 2009, 2010, 2011]. While local natural archives exist from which palaeoclimate reconstruction can be undertaken for the Australian alpine region, the causes and physical mechanisms underlying of precipitation stable oxygen isotope variability were unknown for this region.

This study has presented a unique event data set of precipitation stable oxygen isotope samples collected across the Snowy Mountains region of the Australian Alps for the period 2010 to 2012. It represents the first precipitation isotopic data set for the alpine areas of Australia (and first LMWL derived from a data set including snow precipitation in Australia). This study establishes that in contrast to previous research in southern Australia in coastal GNIP and other locations where amount effects are the dominant control on isotopic variability, that in the Australian Alps, the moisture source, pathway and conditions at the time of precipitation, and the local terrain are the most significant determinants of precipitation stable isotope variability.

Accounting for this mechanism is particularly significant in any palaeoclimate reconstruction work for this region that aims to use stable isotopes as proxy for palaeoclimate and hydrological variability. This is particularly important given recent evidence of a poleward expansion of the subtropical belt and the apparent increasing influence of tropical and subtropical moisture on southeastern Australia [*Murphy and Timbal*, 2008] and the need to account for any such shifts in any natural archive of palaeoclimate.

This study finds that precipitation in the Australian Alps has a wide geographic range of moisture source areas and complex pathways which have a strong influence on the isotopic value of precipitation. This includes distant moisture pathways that include the midlatitude Southern Ocean-Australian continental fringe, the middle to higher latitudes of the Southern Ocean, northern Australia, Pacific Ocean, and Tasman Sea. Some grouping behavior and isotopic signatures appear related to specific types of events. For rainfall embedded in the dominant westerly airflow, moisture originating from similar latitudes (40°S to 55°S) shows similar, moderate isotopic signatures (δ^{18}O -6.5 to -8‰). Prefrontal rainfall and precipitation from convective systems have more negative signatures, with intense circulation such as during east coast lows being associated with the most negative isotopic signature observed in this study. Localized (typically summer) thunderstorms with modest convection have a less depleted isotope signal of samples analyzed in this study. Ongoing research will continue to build a more comprehensive data set to further unpack the drivers of isotopic variability from which palaeoclimate reconstruction studies for this and other regions can be informed. These results would suggest that the isotope archives are likely to be sensitive to variation in synoptic circulation caused by teleconnections such as the PDO, ENSO which control the flow of moisture from the Pacific, Southern, and Indian Oceans over the Australian continent. Not contained in this data set, but the focus of ongoing research, are data on precipitation from northwest cloud bands and the IOD and how they are manifested in the isotope record over this region.

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References

Araguás-Araguás, L., K. Froehlich, and K. Rozanski (1998), Stable isotope composition of precipitation over Southeast Asia, *J. Geophys. Res.*, *103*(D22), 28,721–28,742, doi:10.1029/98JD02582.

Araguás-Araguás, L., K. Froehlich, and K. Rozanski (2000), Deuterium and oxygen-18 isotope composition of precipitation and atmospheric moisture, *Hydrol. Processes*, *14*(8), 1341–1355, doi:10.1002/1099-1085(20000615)14:8<1341::aid-hyp983>3.0.co;2-z.

Barras, V. J. I., and I. Simmonds (2008), Synoptic controls upon ^{18}O in southern Tasmanian precipitation, *Geophys. Res. Lett.*, *35*, L02707, doi:10.1029/2007GL031835.

Barras, V., and I. Simmonds (2009), Observation and modeling of stable water isotopes as diagnostics of rainfall dynamics over southeastern Australia, *J. Geophys. Res.*, *114*, D23308, doi:10.1029/2009JD012132.

Bundin, G. R. (1985), Interannual variability of Australian snowfall, *Aust. Meteorol. Mag.*, *33*, 145–159.

Chubb, T. H., S. T. Siems, and M. J. Manton (2011), On the decline of wintertime precipitation in the Snowy Mountains of southeastern Australia, *J. Hydrometeorol.*, *12*(6), 1483–1497, doi:10.1175/jhm-d-10-05021.1.

Craig, H. (1961), Isotopic variation in meteoric waters, *Science*, *133*, 1702–1703.

Dansgaard, W. (1964), Stable isotopes in precipitation, *Tellus*, *16*(4), 436–468, doi:10.1111/j.2153-3490.1964.tb00181.x.

Frappier, A. B. (2013), Masking of inter-annual climate proxy signals by residual tropical cyclone rainwater: Evidence and challenges for low-latitude speleothem palaeoclimatology, *Geochem. Geophys. Geosyst.*, *14*, 3632–3647, doi:10.1002/ggge.20218.

Gat, J. R. (1996), Oxygen and hydrogen in the hydrologic cycle, *Annu. Rev. Earth Planet. Sci.*, *24*(1), 225–262, doi:10.1146/annurev.earth.24.1.225.

Gedzelman, S., J. Lawrence, J. Gamache, M. Black, E. Hindman, R. Black, J. Dunion, H. Willoughby, and X. Zhang (2003), Probing hurricanes with stable isotopes of rain and water vapor, *Mon. Weather Rev.*, *131*(6), 1112–1127, doi:10.1175/1520-0493(2003)131<1112:phwsio>2.0.co;2.

Guan, H., C. T. Simmons, and A. J. Love (2009), Orographic controls on rain water isotope distribution in the Mount Lofty Ranges of South Australia, *J. Hydrol.*, *374*(3–4), 255–264, doi:10.1016/j.jhydrol.2009.06.018.

Guan, H., X. Zhang, G. Skrzypek, Z. Sun, and X. Xu (2013), Deuterium excess variations of rainfall events in a coastal area of South Australia and its relationship with synoptic weather systems and atmospheric moisture sources, *J. Geophys. Res. Atmos.*, *118*, 1123–1138, doi:10.1002/jgrd.50137.

Hastings, P. A. (1990), Southern Oscillation influences on tropical cyclone activity in the Australian/South-West Pacific region, *Int. J. Climatol.*, *10*, 291–298, doi:10.1002/joc.3370100306.

Hendon, H. H., D. W. J. Thompson, and M. C. Wheeler (2007), Australian rainfall and surface temperature variations associated with the Southern Hemisphere Annular Mode, *J. Clim.*, *20*(11), 2452–2467, doi:10.1175/jcli4134.1.

IAEA/WMO (2006), Global Network of Isotopes in Precipitation. The GNIP Database, edited, IAEA-International Atomic Energy Agency and WMO-World Meteorological Organisation. [Available at http://www.iaea.org/water.]

Jouzel, J., and L. Merlivat (1984), Deuterium and oxygen 18 in precipitation: Modeling of the isotopic effects during snow formation, *J. Geophys. Res.*, *89*(D7), 11,749–11,757, doi:10.1029/JD089iD07p11749.

Lachniet, M. S. (2009), Climatic and environmental controls on speleothem oxygen-isotope values, *Quat. Sci. Rev.*, *28*(5-6), 412–432.

Lawrence, R. J., and D. S. Gedzelman (1996), Low stable isotope ratios of tropical cyclone rains, *Geophys. Res. Lett.*, *23*(5), 527–530, doi:10.1029/96GL00425.

Leng, M. J., and P. A. Barker (2006), A review of the oxygen isotope composition of lacustrine diatom silica for palaeoclimate reconstruction, *Earth Sci. Rev.*, *75*(1–4), 5–27, doi:10.1016/j.earscirev.2005.10.001.

Leng, M. J., and J. D. Marshall (2004), Palaeoclimate interpretation of stable isotope data from lake sediment archives, *Quat. Sci. Rev.*, *23*(7–8), 811–831, doi:10.1016/j.quascirev.2003.06.012.

Liu, J., G. Fu, X. Song, S. P. Charles, Y. Zhang, D. Han, and S. Wang (2010), Stable isotopic compositions in Australian precipitation, *J. Geophys. Res.*, *115*, D23307, doi:10.1029/2010JD014403.

Mariethoz, G., A. Baker, B. Sivakumar, A. Hartland, and P. Graham (2012), Chaos and irregularity in karst percolation, *Geophys. Res. Lett.*, *39*, L23305, doi:10.1029/2012GL054270.

Marx, S. K., B. S. Kamber, H. A. McGowan, and J. Denholm (2011), Holocene dust deposition rates in Australia's Murray-Darling Basin record the interplay between aridity and the position of the mid-latitude westerlies, *Quat. Sci. Rev.*, *30*(23–24), 3290–3305, doi:10.1016/j.quascirev.2011.07.015.

McBride, J. L., and N. Nicholls (1983), Seasonal relationships between Australian rainfall and the Southern Oscillation, *Mon. Weather Rev.*, *111*, 1998–2004, doi:10.1175/1520-0493(1983)111<1998:SRBARA>2.0.CO;2.

McDermott, F. (2004), Palaeo-climate reconstruction from stable isotope variations in speleothems: A review, *Quat. Sci. Rev.*, *23*(7–8), 901–918, doi:10.1016/j.quascirev.2003.06.021.

McGowan, H. A., S. K. Marx, J. Denholm, J. Soderholm, and B. S. Kamber (2009), Reconstructing annual inflows to the headwater catchments of the Murray River, Australia, using the Pacific Decadal Oscillation, *Geophys. Res. Lett.*, *36*, L06707, doi:10.1029/2008GL037049.

McGowan, H. A., S. K. Marx, J. Soderholm, and J. Denholm (2010), Evidence of solar and tropical-ocean forcing of hydroclimate cycles in southeastern Australia for the past 6500 years, *Geophys. Res. Lett.*, *37*, L10705, doi:10.1029/2010GL042918.

McGowan, H. A., J. N. Callow, and J. Denholm (2011), Inflow variability in the Murray & Murrumbidgee rivers, *Irrig. Res. Ext. Comm. Farmers Newsl.*, *184*(Autumn 2011), 21–23.

Munksgaard, N. C., C. M. Wurster, A. Bass, and M. I. Bird (2012), Extreme short-term stable isotope variability revealed by continuous rainwater analysis, *Hydrol. Processes*, *26*(23), 3630–3634, doi:10.1002/hyp.9505.

Murphy, B. F., and B. Timbal (2008), A review of recent climate variability and climate change in southeastern Australia, *Int. J. Climatol.*, *28*(7), 859–879, doi:10.1002/joc.1627.

Nicholls, N. (2005), Climate variability, climate change and the Australian snow season, *Aust. Meteorol. Mag.*, *54*(3), 177–185.

Nott, J., J. Haig, H. Neil, and D. Gillieson (2007), Greater frequency variability of landfalling tropical cyclones at centennial compared to seasonal and decadal scales, *Earth Planet. Sci. Lett.*, *255*(3–4), 367–372, doi:10.1016/j.epsl.2006.12.023.

Polk, J. S., P. van Beynen, and J. Wynn (2012), An isotopic calibration study of precipitation, cave drip water, and climate in west-central Florida, *Hydrol. Processes*, *26*(5), 652–662, doi:10.1002/hyp.8169.

Rozanski, K., L. Araguás-Araguás, and R. Gonfiantini (1992), Relation between long-term trends of oxygen-18 isotope composition of precipitation and climate, *Science*, *258*(5084), 981–981.

Rozanski, K., L. Araguás-Araguás, and R. Gonfiantini (1993), Isotopic patterns in modern global precipitation, in *Climate Change in Continental Isotopic Records*, *Geophys. Monogr. Ser.*, vol. 78, edited by P. K. Swart, pp. 1–36, AGU, Washington, D. C.

Rozanski, K., S. J. Johnsen, U. Schotterer, and L. G. Thompson (1997), Reconstruction of past climates from stable isotope records of palaeo-precipitation preserved in continental archives, *Hydrol. Sci. J.*, *42*(5), 725–745, doi:10.1080/02626669709492069.

Sinclair, K. E., S. J. Marshall, and T. A. Moran (2011), A Lagrangian approach to modelling stable isotopes in precipitation over mountainous terrain, *Hydrol. Processes*, *25*(16), 2481–2491, doi:10.1002/hyp.7973.

Sjostrom, D. J., and J. M. Welker (2009), The influence of air mass source on the seasonal isotopic composition of precipitation, eastern USA, *J. Geochem. Explor.*, *102*(3), 103–112, doi:10.1016/j.gexplo.2009.03.001.

St. Amour, N. A., D. A. N. Hammarlund, T. W. D. Edwards, and B. B. Wolfe (2010), New insights into Holocene atmospheric circulation dynamics in central Scandinavia inferred from oxygen-isotope records of lake-sediment cellulose, *Boreas*, *39*(4), 770–782, doi:10.1111/j.1502-3885.2010.00169.x.

Stevenson, B. A., E. F. Kelly, E. V. McDonald, and J. M. Welker (2010), Oxygen isotope ratios in Holocene carbonates across a climatic gradient, eastern Washington State, USA: Evidence for seasonal effects on pedogenic mineral isotopic composition, *Holocene*, *20*, 575–583, doi:10.1177/0959683609356588

Treble, P. C., W. F. Budd, P. K. Hope, and P. K. Rustomji (2005a), Synoptic-scale climate patterns associated with rainfall $\delta^{18}O$ in southern Australia, *J. Hydrol.*, *302*(1–4), 270–282, doi:10.1016/j.jhydrol.2004.07.003.

Treble, P. C., J. Chappell, M. K. Gagan, K. D. McKeegan, and T. M. Harrison (2005b), In situ measurement of seasonal $\delta^{18}O$ variations and analysis of isotopic trends in a modern speleothem from southwest Australia, *Earth Planet. Sci. Lett.*, *233*(1–2), 17–32, doi:10.1016/j.epsl.2005.02.013.

Vogel, J. C., J. C. Lerman, and W. G. Mook (1975), Natural isotopes in surface and groundwater from Argentina, *Hydrol. Sci. Bull.*, *2*, 203–221.

Wassenaar, L. I., P. Athanasopoulos, and M. J. Hendry (2011), Isotope hydrology of precipitation, surface and ground waters in the Okanagan Valley, British Columbia, Canada, *J. Hydrol.*, *411*(1–2), 37–48, doi:10.1016/j.jhydrol.2011.09.032.

