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Rainfall isotope variations over the Australian continent – Implications for hydrology and isoscape applications

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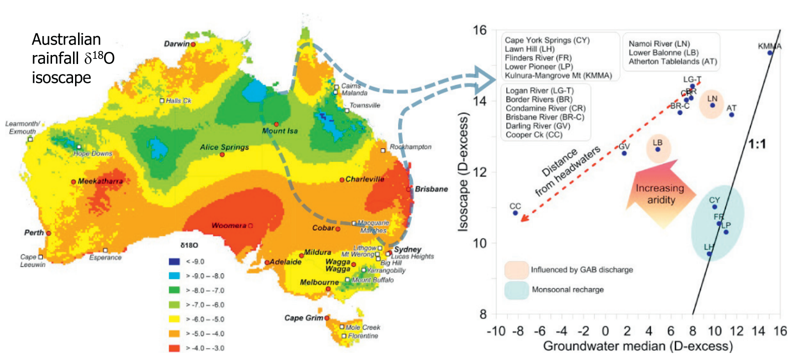
HIGHLIGHTS

- Stable isotopes in precipitation decode the hydrological cycle.
- Long term stable isotopes in Australian precipitation at 15 sites presented.
- Relationships with meteorology/geography used to develop continental isoscape.
- Rainfall isotope and groundwater connections established for NE Australia.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents a continental scale interpretation of δ^2H and $\delta^{18}O$ in Australian precipitation, incorporating historical GNIP data at seven sites (1962–2002) and 8–12 years of new monthly data from 15 sites from 2003 to 2014. The more than doubling of stations and the significant time series duration allow for an improved analysis of Australian precipitation isotopes. Local meteoric water lines were developed for each site, and for the Australian continent. When the annual precipitation weighted values were used, the Australian meteoric water line was $\delta^2H = 8.3\,\delta^{18}O + 14.1‰$.

Precipitation amount was found to be a stronger driver of precipitation isotopes than temperature at most sites, particularly those affected by tropical cyclones and the monsoon. Latitude, elevation and distance from the coast were found to be stronger drivers of spatial variability than temperature or rainfall amount.

Annual isoscapes of δ^2H, $\delta^{18}O$ and deuterium excess were developed, providing an improved tool to estimate precipitation isotope inputs to hydrological systems. Because of the complex climate, weather and oceanic moisture sources affecting Australia, regional groupings were used instead of the climate zone approach and additional data was included to improve the coverage in data poor regions. Regression equations for the isoscape were derived using latitude, altitude and distance from the coast as predictor variables.

We demonstrate how this isoscape can be used as a tool for interpreting groundwater recharge processes using examples from across Queensland and New South Wales, including the Murray Darling Basin. Groundwater isotopes at sites where direct local recharge occurs are similar to rainfall, but for inland sites, which are often arid or semi-arid, a disconnect between shallow groundwater and local rainfall is observed; the departure in deuterium excess for these sites increases with aridity and distance from the headwaters where flooding originates.

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1. Introduction

The stable isotopes of hydrogen (^{2}H, or D) and oxygen (^{18}O) are commonly used as tracers of the hydrological cycle. For example, they can be used in studies of surface water–groundwater interactions (Kalbus et al., 2006), in the estimation of evaporative loss (Skrzypek et al., 2015) and estimating groundwater recharge (Adomako et al., 2010; Cartwright et al., 2017). In addition, the relationship between stable isotopes of precipitation with temperature (and rainfall) has been used to interpret paleoclimate records (Rozanski et al., 1993; McDermott, 2004; Vachon et al., 2010; Treble et al., 2013). In a large number of cases, these relationships have been studied using the Global Network of Isotopes in Precipitation (GNIP) data (e.g. Dansgaard, 1964; Araguás-Araguás et al., 2000). More recently, efforts have been made to predict the spatial variation in isotopic composition (isoscape) of precipitation for regions where little GNIP data exists: the Online Isotopes in Precipitation Calculator (OIPC, Bowen and Wilkinson, 2002; Bowen and Revenaugh, 2003; Bowen, 2018) and the Regionalized Cluster-based Water Isotope Prediction (RCWIP, Terzer et al., 2013). As stated in Terzer et al. (2013), this was due in part to the increasing demand for spatio-temporal predictions of δ^2H and δ^{18}O values in precipitation for use in ecological, wildlife forensics (Bowen et al., 2005) and food source traceability studies after it was found that there was correlation between the δ^2H and δ^{18}O values of some plant, animal and human tissues and isotopic patterns of precipitation.

The isotopic composition of precipitation can be affected by its moisture source, followed by the condensation temperature and the precipitation history in the cloud (Dansgaard, 1964). Further, as the raindrops fall below the cloud, it can be affected by moisture exchange with the surrounding vapour and sub-cloud evaporation, which increases ^{18}O and decreases deuterium excess (defined as $d = \delta^2\text{H} - 8 \times \delta^{18}\text{O}$; Dansgaard, 1964; Froehlich et al., 2002). Thus the regional climate can have a considerable impact on the isotopic composition of precipitation at a particular site. As a result of these processes, depletion in ^{2}H and ^{18}O occurs with increasing distance from the coast (continental effect) and increasing elevation (altitude effect; e.g. Araguás-Araguás et al., 2000). A latitude effect also exists (Feng et al., 2009), with a local minimum near the equator and two maxima on either side, which coincide with the subtropical highs. These processes can have an impact on the isotopic composition of Australian regional precipitation, as a number of climate zones occur over the Australian continent, with tropical conditions in the north, sub-tropical further south and then temperate conditions in the south of the continent. Moving inland from the coast, we see the vegetation distribution changes from woodlands or rainforest, to grassland regions followed by deserts, reflecting the reduction in rainfall with distance from the coast. Liu et al. (2010), in their study of Australian GNIP data from 1962 to 2002, noted that rainfall at the single inland site in their study was isotopically more depleted than the coastal sites and interpreted this as a continental effect.

The isotopic values of precipitation are also affected by synoptic weather patterns (Barras and Simmonds, 2008; Scholl et al., 2009; Baldini et al., 2010) with some of the lowest ^{2}H and ^{18}O values recorded in rainfall from tropical cyclones (Gedzelman et al., 2003). Tropical cyclones are experienced in the northern half of the Australian continent. Continuous measurements of δ^{18}O and δ^2H in precipitation and water vapour were reported by Munksgaard et al. (2015) during the passage of the tropical cyclone Ita in north-eastern Australia. The Australian monsoon also dominates rainfall in northern Australia. Zwart et al. (2016) undertook a study in northern Australia during two monsoonal events. They found that the size and the activity of the convective envelope played a dominant role in lowering the isotopic composition of precipitation. This was supported by the significant correlation between the isotopic composition of local precipitation and the regional precipitation amount, and also with the integrated precipitation amount of the air mass before arrival at the measurement site.

Inland troughs are also common over the Australian continent, particularly during the warmer months of the year. Frontal systems dominate in the south, predominantly in winter, whilst low-pressure systems are important for coastal regions. Multiple studies investigating the impact of these synoptic weather systems, and of varying moisture sources, on the isotopic composition of precipitation in SE Australia have been undertaken in sites in Tasmania (Treble et al., 2005a; Barras and Simmonds, 2008), Melbourne (Barras and Simmonds, 2009), Adelaide (Guan et al., 2013, 2009), at four sites in the Sydney region (Hughes and Crawford, 2013; Crawford et al., 2013), at the Macquarie Marshes (Crawford et al., 2017), and at the Snowy Mountains (Callow et al., 2014).

Previous interpretations of the spatial characteristics of isotopes in precipitation across the Australian continent by Liu et al. (2010) and Terzer et al. (2013) were based on data from six coastal sites and only one inland site (Alice Springs), as recorded in the Global Network for Isotopes in Precipitation (GNIP) database (IAEA/WMO, 2017). The limited spatial distribution of data available at the time of these studies meant that the range of climatic processes affecting rainfall isotopes across the Australian continent was not fully revealed. This paper builds significantly on these earlier studies, through the presentation and interpretation of much-needed data from an expanded network of rainfall collection sites across the Australian continent, and fills a gap in these important records in the Southern Hemisphere. The expanded rainfall sampling network developed for this study included the recommencement of sampling at all seven of the original Australian GNIP sites, but more importantly included the addition of seven inland continental sites and one further coastal site to improve spatial distribution across the Australian continent (see Fig. 1a and Table 1). Additional data from this study offers improved spatial characterisation of isotopes in rainfall across the Australian continent, as well as extending the GNIP record a further 8–12 years in all stations, enabling characterisation of seasonal trends and the environmental controls on isotopes in Australian rainfall.

This paper also develops and presents the first set of rainfall isoscapes for Australia, allowing for the detailed prediction of the isotopic signature in precipitation at any point on the Australian continent. We demonstrate the predictive capability of these isoscapes and their utility in informing groundwater studies in rainfall isotope data poor regions, through the presentation of a number of case studies of groundwater systems across NE Australia. Understanding the linkage between rainfall and groundwater recharge processes in aquifers containing groundwater with residence times that span several orders of magnitude in timescale is vital for its management and sustainability. This tool will help to better estimate recharge processes and therefore incorporate more realistic predictions in groundwater models.

2. Site description and methods

2.1. Australian climate and weather

Approximately 70% of the Australian continent is classified as arid (desert, average annual rainfall <250 mm) or semi-arid (grasslands, average annual rainfall between 250 and 350 mm) and seven of the fifteen rainfall collection sites in this study fall within these categories (Fig. 1 (a), Table 1). These are areas where rainfall is low Fig. 1(b) and unpredictable, with considerable inter-annual variation.

Fig. 1(c–e) shows the typical weather patterns and related air mass distributions that occur across the Australian continent during summer and winter respectively. The monsoonal circulation and the formation of a series of low pressure cells to the north of Australia (Fig. 1(c)) brings very warm, moist and unstable air to the north and north-west of Australia, where it converges across a broad region with tropical continental (Tc) and tropical maritime (Tm) air masses, shown as the intertropical convergence zone (ITCZ) in Fig. 1(d). The rising air along this zone results in extensive convective activity and rainfall - known as the wet