5.2.4 Comparison of Mairs Cave record with tropical archives

Thirdly, we consider whether effective precipitation may be higher if the region is being watered from systems other than the westerlies. There is evidence that northern Australia and southern Indonesia were wetter during parts of the Last Termination and this has been linked to changes in the Indo-Australian Summer Monsoon (IASM) activity/Western Pacific Warm Pool (WPWP) dynamics and/or a southward shift in the ITCZ (e.g. Nott and Price, 1994; English et al., 2001; Turney et al., 2004; Denniston et al., 2013a; Ayliffe et al. 2013). A more southerly displaced ITCZ could increase the availability of tropical moisture into northern Australia; as was demonstrated in a modelling study under HS1 boundary conditions (Mohtadi et al., 2014). This could have increased the availability of tropically-sourced moisture to the mid-latitudes via continental troughs as described in Section 2.

Figure 6 shows the speleothem records from Ball Gown Cave in NW Western Australia (Denniston et al., 2013a), Cape Range in Western Australia (Denniston et al., 2013b) and Liang Luar in Flores, Indonesia (Ayliffe et al., 2013); as well as a marine record of reconstructed tropical eastern Indian Ocean salinity, from off the coast of Sumatra (Mohtadi et al., 2014) (see Fig. 1a for locations). Both the Ball Gown Cave and Liang Luar records are considered to be influenced by the intensity/location of the IASM with a more southerly-displaced IASM inferred during HS1 (Denniston et al., 2013; Ayliffe et al., 2013). While it's difficult to judge against the Ball Gown Cave record, given that the uncertainty in its chronology is approximately ±1 kyr at this point, δ^{18}O decreases at the onset of HS1 and rises again after 15 ka (Fig. 6f), which is approximately similar in timing to the period of highest recharge in the Mairs Cave record: 17.2±0.08 (or possibly ~0.4 kyr earlier, given MC-S1's earliest growth was not retrieved) until 15.8±0.07 ka. This interval also compares well with low δ^{18}O from 17.6±0.1 to 14.6±0.1 ka in the comparatively well-dated Flores record. It also agrees well, in terms of timing, with events recorded in other precisely dated archives outside of the Australasian region, interpreted as a response to HS1 e.g. Wang et al., 2001; Partin et al., 2007; Cheng et al., 2010 and others summarised in Naafs et al., (2013). Thus there is consistent evidence that the enhanced recharge recorded during ~17.2-15.8 ka at Mairs Cave coincides with a more southerly-displaced IASM during HS1.

The above offers an explanation for the period of enhanced recharge seen in the Mairs Cave record during HS1. However, in the Mairs Cave record, this period of enhanced recharge occurred within the context of an earlier shift to relatively wetter conditions at 18.9 ka, evidenced by the decrease in speleothem δ^{18}O and δ^{13}C, reduced isotopic disequilibrium, calcite fabric changes and lowered Mg/Ca. According to the above studies, the timing of the ITCZ displacement coincides

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with the onset of HS1, which is at least 1000 years later than the onset of the relatively wetter interval at Mairs Cave (18.9 ka), although consistent with the highest interval of recharge in the MC-S1 record (17.2-15.8 ka), as described above. The Cape Range speleothem δ^{18}O record contains a downward trend that indicates increased recharge from approximately 18.5-19 ka that reaches a maximum during HS1 (Fig. 6g), consistent with the Mairs Cave record. This could support that both sites were affected by a common driver. At Cape Range, the driver of δ^{18}O variability was unconstrained as this location is currently watered by moisture both from subtropical/tropical systems and mid-latitude westerlies, and these end members could not be separated isotopically (Denniston et al., 2013b). But given that both sites are receiving more recharge, and if the westerlies are further south during this interval as interpreted in the MD03-2611 record (Fig. 6b), it could be argued that a moisture source from lower latitudes is the most plausible explanation.

In the modern record, the delivery of moisture from the warm seas surrounding northern Australia to its interior is strongly governed by tropical ocean patterns associated with the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Ummenhofer et al., 2009). Variability in tropical Pacific and Indian Ocean SSTs, in particular, strongly influences southern Australian rainfall (Ummenhofer et al., 2009; Pook et al., 2014) and has been shown to display decadal variability (Ummenhofer et al., 2011). A more La Nina-like state in the glacial period has been previously invoked (e.g. Sarnthein et al., 2011; Muller et al., 2008). However, a reconstruction of tropical eastern Indian Ocean salinity, from marine sediments off the coast of Sumatra, suggests anomalously dry conditions prevailed from approximately 19-20 ka until 16 ka (Mohtadi et al., 2014; Fig. 6h). This site lies within the core of the IOD zone of upwelling, suggesting that it is unlikely that the IOD was responsible for enhanced recharge to Mairs Cave from 18.9-15.8 ka. In the study by Mohtadi et al. (2014), the strong anti-phase relationship between hydroclimate records from NW and SE Indonesia (reduced rainfall over Sumatra versus enhanced rainfall over Flores) was noted, and reproduced in their model simulation. This was argued to further support the southward position of the ITCZ during HS1. Interestingly, in the Sumatran record, this drying trend appears to begin as early as sometime between 19-20 ka (Fig. 6h).

An additional explanation is that a weaker sub-tropical ridge across Australia may have permitted deeper penetration of troughs into interior Australia. This possibility is supported by a modelling study by Sime et al. (2013) who showed that the strength of the Hadley Cell in the subsidence regions was reduced during the LGM. Thus recharge to Mairs Cave throughout the 23-15.8 ka period may

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have been favoured by a weakened sub-tropical ridge, with a further enhancement of moisture delivery by a southward displaced ITCZ during HS1.

Finally, we consider the relationship between the Mairs Cave record and regional data for the transition to drier conditions at 15.8 ka in the Mairs Cave record. As noted by Zhang et al. (2016), both the Flores and Ball Gown Cave records have low $\delta^{18}O$ troughs at 16 ka, implying wet conditions, but the trend in both records quickly reverses suggesting a weakening of the IASM followed from 16 to approximately 14.7 ka (Fig. 6f-g). The MD03-2611 marine record also suggests a northward displacement in the mid-latitude westerlies from 16 ka, implying a return of westerly airflow to the Flinders Ranges at the same time that Mairs Cave records an abrupt shift from wetter to drier conditions (Section 5.1.3). This combined evidence reinforces a tropical driver for enhanced recharge to the Flinders Ranges followed by an abrupt shift to aridity via the retraction of tropical moisture and restored westerly airflow. This is feature in the Mairs Cave record is thus further evidence for the northward shift in the ITCZ interpreted in the monsoon speleothem records at the onset of the Bølling-Allerød (Ayliffe et al., 2013; Denniston et al., 2013a)

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