Southern African Climate Dynamics and Archaeology During the Last Glacial Maximum

by

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A thesis submitted in conformity with the requirements for the degree of Master of Science

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Abstract

There is little consensus on what forced the climate of southern Africa to change during the Last Glacial Maximum (LGM). Because of southern Africa's latitudinal position, changes in seasonal precipitation can help resolve the influence of internal climate factors such as groundwater and external climate forcers such as large scale atmospheric circulation patterns. This paper presents a simple model of groundwater discharge based on permeability and topography in comparison with general circulation model precipitation results and paleoenvironmental proxy records. Results show that during the LGM the Intertropical Convergence Zone (ITCZ) likely weakened and moved slightly further south while the westerlies likely expanded slightly northward, with no significant change in strength. The climate and groundwater results were compared to the distribution of LGM and pre-LGM archaeological sites. Results show that the Later Stone Age peoples of southern Africa were likely inhabiting a relatively wet environment rather than an arid one.

Acknowledgements

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Chapter 1 Introduction

1. Introduction

1.1 Southern African Climate

It is clear that large temperature changes occurred in southern Africa between glacial-interglacial transitions (Talma & Vogel, 1992 Holmgren et al., 2003; Kulongoski et al., 2004; Wu et al., 2007), however, there is little consensus on the changes in regional climate and in large-scale moisture bearing atmospheric circulation patterns. The controversy mainly concerns the relative influence of the region's two major atmospheric circulation patterns: the Intertropical Convergence Zone (ITCZ) and the Southern Hemisphere westerly winds.

The ITCZ is a zone of converging and rising air at the approximate latitudinal band of maximum insolation. Intense convection between the northern and southern Hadley Cells at this location produces large amounts of precipitation through rising air. The dry descending air of the Hadley Cells produces deserts such as the Kalahari and the Sahara at ~30°N and ~30°S. In southern Africa, the ITCZ dominates the summer rainfall zone (SRZ) (Figure 1), the geographic area located in the northwestern section of the subcontinent that receives predominantly summer rainfall (Chase & Meadows, 2007). The ITCZ, and its associated rainfall, move north and south annually with the position of the sun. The location of the ITCZ also varies during glacial cycles. Climate models generally show a southward shift of the average position of the ITCZ during the Last Glacial Maximum (LGM), taken here as 24-18 thousand years ago (ka) (Clark and Mix, 2002). This shift in the ITCZ has been attributed to changes in atmospheric heat exchange between the tropics and mid-latitudes due to the different interhemispheric thermal contrasts between the LGM and present (Broccoli et al., 2006; Kang et al., 2008). The southward displacement of the ITCZ causes changes in the trade winds as well as an expansion of the northern Hadley Cell and contraction of the southern Hadley Cell

(Broccoli et al., 2006). General Circulation Models (GCMs) achieve a glacial interhemispheric thermal contrast by warming the Southern Hemisphere and cooling the Northern Hemisphere. Another modeling experiment, the second phase of the Paleoclimate Intercomparison Modeling Project (PMIP2) uses a set of several coupled ocean-atmosphere and ocean-atmosphere-vegetation simulations to model LGM and mid-Holocene climate. They found that most of the models showed a southward shift in the boreal summer position of the ITCZ. However, there was a difference in the degree of the latitudinal shift (Braconnot et al., 2007a). The ocean-atmosphere-vegetation model (HadCM3M2) showed the greatest southward shift. Braconnot et al. (2007a) did not address the position of the austral summer ITCZ in the discussion of this paper, so presumably it either did not shift its position during the LGM, resulting in a narrowed ITCZ range or it moved southwards as well. Conversely, it has also been suggested that the position of the ITCZ did not change during the LGM. Instead, the Hadley Cells contracted relative to late Holocene and contemporary conditions (Collins et al., 2010).

The amount of precipitation in the summer rainfall region is not only controlled by the position of the ITCZ, but also the ability of the convective cells to deliver moisture. The amount of moisture in the cells is largely a result of temperature contrast between the continent and surrounding oceans, evaporation, and the convective strength of the Hadley Cells (Kutzbach at al., 2008).

The westerlies are the other dominant atmospheric circulation pattern in southern Africa. The westerlies are high altitude winds that blow west to east in the mid-latitude belt and produce rainfall. The westerlies control the precipitation patterns in what is generally known as the winter rainfall zone (WRZ), the geographic area that receives most of its precipitation during the austral winter (Chase & Meadows, 2007). The position and strength of the westerlies is thought to be controlled by the thermal contrast in the middle of the atmosphere (Toggweiler & Russell, 2008). Observations have shown that a poleward shift and intensification of the westerlies has occurred during the past 40 years, as CO_2-levels have increased (Hurrell and van Loon, 1994; Toggweiler and Russell, 2008). The poleward shift of the westerlies has been attributed to a CO_2-induced increase in the thermal contrast in the middle atmosphere (Schindell and Schmidt, 2004). Presumably, this implies that a decreased thermal contrast during the LGM, due to a decrease in CO_2, would produce a weaker westerly system closer to the equator (Toggweiler et al., 2006; Toggweiler and Russell, 2008). It is also thought that the expanded Antarctic sea-ice (Bard and Rickaby, 2009) and a smaller and weaker ITCZ (Williams & Byan, 2006) would additionally contribute to the equatorward shift of the westerlies.

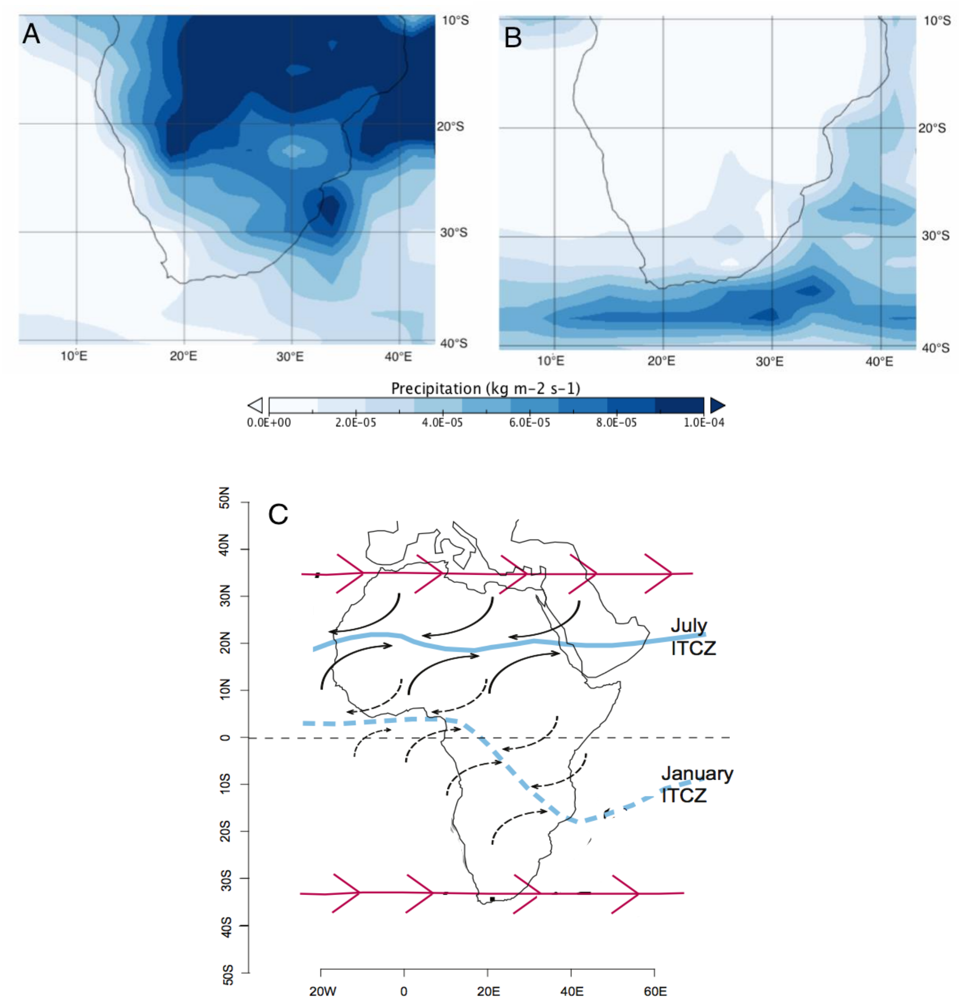

Figure 1: Major contemporary climate features of southern Africa. (a) 0 ka HadCM3M2 modeled precipitation for the month of January. (b) 0 ka HadCM3M2 modeled precipitation for the month of July. (c) The idealized position of the January and July ITCZ (blue) and the idealized annual average position of the westerly wind system (red) modified from Blome et al., (2012).

However, the response of the westerlies is still poorly understood. None of the PMIP2 suite of models simulate a latitudinal shift in the position of the westerly jet stream, but most do show a reduction in near surface and middle atmosphere wind strength that in turn translates into weaker westerlies (Rojas et al., 2008). A recent paleo-proxy synthesis for the entire Southern Hemisphere shows that either an overall strengthening of the westerly winds, an equatorward movement of the winds, or no change at all in strength and position during the LGM would be consistent with the paleo-proxy data (Kohfeld et al., 2013).

A comprehensive review by Chase and Meadows (2007) of the proxies in southern Africa tentatively suggests a northward shift of the WRZ resulting in an east-west precipitation gradient opposite to the one observed today. However they do not look at climate models or at proxies that indicate the seasonality of precipitation or fully consider the influence of the ITCZ in southern Africa. Chase and Meadow's (2007) conclusions disagree with other proxy data in this region. For example, in an expanded WRZ, beach ridges would be expected on the eastern shore of paleo-lakes. However, in the middle Kalahari, beach ridges are generally found on the western edge of paleo-lakes, suggesting sediments were transported there by easterly winds (Burrough et al., 2009). Chase and Meadows (2007) also consider proxies between 32 ka and 17 ka, although this is likely too long a period to attribute precipitation patterns to one climate state.

Studying paleoenvironmental proxies in concert with modeling results can produce a much clearer picture of conditions in the past than using either of these tools alone. Proxies are excellent at producing accurate results at local and regional scales but models can enhance paleoclimate understanding by providing results on the regional, continental, or global scale (Cowling et al., 2008). Studies combining models and proxies are rare for southern Africa. The studies that have been done are generally not to the scale of the work presented in this paper nor do they use as many proxies or take the seasonality of the proxies into account. Past studies include a comparison of aeolian sediment records from the Kalahari Desert with dune activity indices derived from five Ocean-Atmosphere

GCMs, including HadCM3M2 (Chase & Brewer, 2009). In this study, there was shown to be less potential for dune activity in the Kalahari Desert during the LGM. Another study using both model and proxy results looked at glacier mass balance reconstructions based on dated moraines from South Africa's Drackensburg Mountains. Mills et al. (2012) concluded that glaciers were present there during the LGM and likely resulted from an increase in winter precipitation and a decrease in annual temperature. Annual and seasonal HadCM3M2 and HadAM3h results for evaporation and precipitation were used to confirm an increase in winter precipitation as they show a slight decrease in summer precipitation but no change in average annual precipitation, implying a shift in the *timing* of precipitation in the LGM compared to modern-day.

1.2 Groundwater

Another factor that could have influenced the hydrological conditions of the LGM is patterns of groundwater discharge, something that has been generally understudied when it comes to feedbacks within the Earth's climate system. Globally, precipitation and melt-water are the primary sources for groundwater, but surface waters such as lakes and streams also contribute (MacDonald et al., 2012). The feedback occurs because higher levels of precipitation leads to greater amounts of groundwater. Greater amounts of groundwater can increase evapotranspiration (ET), thereby increasing the potential for increased precipitation. The ET-feedback is partially facilitated by plants, which act as conduits between the ground and atmosphere when roots reach the groundwater and draw water up to the canopy. A recent study on the differing isotopic effects of evaporation and transpiration showed that transpiration makes up 80-90% of the total global terrestrial evapotranspiration (Jasechko et al., 2013). Furthermore, groundwater can contribute up to 30% of evaporation in some regions (Lam et al., 2011). The effect of groundwater on climate is particularly pronounced in arid and semi-arid regions, where soil water is typically a limiting factor for evapotranspiration. In the western American states, model results show that large-scale convective processes bring moisture into an area, producing a wet period. This precipitation is then sustained by evapotranspiration and precipitation recycling, even when the large-scale processes are no longer bringing in external moisture (Anyah et al., 2008).

Groundwater recharge, discharge, and movement also depend on the permeability of the host geologic unit and the land's topography. Permeability is a measure of the ability of water to move through a porous material. In rocks with higher permeability, water is better able to enter the ground and recharge aquifers or exist as soil water. In areas with low permeability, water is more likely to leave the system as run-off and not enter the groundwater table. Groundwater also has little opportunity to reach the surface in low permeability areas. Groundwater is also more likely to contribute to surface water or soil water in areas of high geologic permeability (Gleeson et al., 2011). Topography affects groundwater mainly through the influence of gravity. Higher areas are normally recharge areas, lower areas are normally discharge areas and middle areas tend to be recharge areas in dry conditions and discharge areas in wet conditions (Brydsten, 2006).

There are a large number of input parameters for complex geohydrological models, including detailed topographic data, three-dimensional soil distribution, vegetation cover, land-use, the distribution of bedrock fracture zones, and the permeability of geologic units. Therefore, looking at groundwater conditions in the past can be quite complicated, as these parameters can be difficult to determine (or reconstruct for the past). It may be useful to model groundwater conditions in a simpler way. Models using only topography as an input have been shown to provide quite accurate estimates of discharge zones in Sweden (Brydsten, 2006). Therefore, it is very likely that a simple model incorporating topography and permeability could give a reasonably good estimate of groundwater conditions. For my thesis, I provide a simple estimate of areas of high potential groundwater discharge based on topography and permeability. In turn, this estimate will then be compared to the paleoclimatological and archaeological records of the last glacial period to investigate links between these datasets.

1.3 Southern African Archaeology

Southern Africa is a region of extreme archaeological importance because it is the location for several milestones in human development including the earliest evidence of hominin-controlled fire at Wonderwerk Cave approximately one million years ago

(Berna et al., 2012) and some of the earliest evidence of modern human behaviour (Henshilwood et al., 2009). Southern Africa is even considered a possible origin point for the dispersal of *Homo sapiens* out of Africa (Compton, 2011).

Environmental conditions are inarguably important for the biological evolution of humans in Africa, however their effects on behavioural and cultural development are slightly more difficult to predict and always controversial. For example, the reasons behind the abrupt appearance and disappearance of two major pulses of technological innovation during the Middle Stone Age, the Still Bay and Howiesons Poort industries have been attributed to both environmentally dependent and independent factors. Ziegler et al. (2013) have linked the timing of these industries not only to periods of elevated humidity but also to periods of rapid climate fluctuations, strengthening the link between climate change and these events. However, it has also been argued that these industries are the result of previous expansion of the areas of the brain associated with attentional flexibility and perspective taking (Henshilwood and Dubreuil, 2011).

Similarly, human settlement patterns have been linked to both environmental and non-environmental factors, once again with conclusions hotly debated. Environmental factors include proximity to coast lines, water availability, land cover (Vandam et al., 2013), and lithic resources (Kowalewski, 2008) and can also include barriers to migration such as forest cover (Cowling et al., 2008) lakes (Trauth et al., 2010), and sea-level rise (Compton et al., 2011). Non-environmental factors arguably include competition or interaction with other human groups, inability or unwillingness to move, and other cultural practices related to migration patterns. Recent work in Turkey has shown that during the Neolithic period (~12 ka – 6 ka), water availability and land cover class were the main determinants of the density of archaeological artefacts (Vandam et al., 2013). Very little work has been done on large scale settlement patterns in southern Africa for the LGM. Particularly, there are several archaeological sites in the extremely arid present-day Kalahari. It is not well known whether these areas were as arid when they were occupied or not. Therefore, in this thesis, I will look at the links between LGM archaeological site locations, climate, and groundwater discharge areas over the entire subcontinent to determine if there are any large-scale preferences for wet over dry regions during this time period.

1.4 Research Questions and Directions

My thesis will build upon a series of questions that are related in topic, but may contrast in spatio-temporal scale. By moving from the larger-to-smaller scale, I will discuss potential limitations and will ultimately begin to answer the question "How did climate of the LGM affect human settlement patterns?" The first series of questions is:

(1) How did the ITCZ change during the LGM?

(2) How did the westerlies change during the LGM?

Answers to these questions will help me address the following questions:

(3) What effects (if any) did groundwater have on climate during the LGM?

(4) Did the climate of the LGM affect human settlement patterns?

To answer questions 1, 2, and 3, paleoclimate records, indicators of rainfall seasonality, modeled LGM precipitation, and a simple estimate of groundwater discharge areas based on topography and permeability will all be compared. To answer question 4, I will then compare the above records with archaeological sites from the LGM and close in age to the LGM to determine if there was any large-scale preference for wet over dry areas during this time period.

2. Methods

2.1 Paleoenvironmental Proxies

The paleoenvironmental proxies presented in this thesis include terrestrial and marine pollen records, isotope studies, lacustrine and aeolian sediment analysis and others (Tables 1, 2, and 3). The proxies were chosen because they provide a good indication of hydrological conditions or the seasonality of precipitation during the LGM. Some of the seasonality proxies indicate the absolute proportion of rainfall whereas some indicate a change in rainfall seasonality compared to the present. Chosen proxies were limited in spatial extent to a maximum northern latitude of 15°S as this is currently the approximate northern extent of the Kalahari Desert. The present-day coastlines form the other boundaries of this study.

2.2 Model-Proxy Comparison

The paleoenvironmental proxies were mapped with results from HadCM3M2, a coupled atmosphere-ocean-vegetation general circulation model developed by the Hadley Centre (Gordon et al., 2000). The GCM model has an atmospheric resolution of 3.75° × 2.5° with 19 atmospheric layers and an ocean resolution of 1.25° × 1.25° with 20 oceanic layers (Braconnot, et al., 2007b). HadCM3M2 was chosen because it provides a good simulation of atmospheric circulation strength, position, and seasonal changes in the Southern Hemisphere at both near surface and upper atmosphere. Moreover, according to previous studies, the Hadley GCM shows a fairly good comparison to proxy records (Rojas et al., 2008).

Modeled difference in LGM (21 ka) and pre-industrial precipitation (0 ka) was calculated as a metric because it indicates whether areas were wetter or drier during the LGM relative to present-day. Relative differences in precipitation are much more useful than absolute rainfall values when making comparisons with paleoenvironmental proxies as most only provide qualitative estimates of hydrological conditions. The model results for January and July were mapped, as these are currently the times when the ITCZ reaches its northern and southern extents, respectively. Most studies consider averages of December, January, and February precipitation for austral summer and June, July, and August averages for austral winter. However, when considering the positions of atmospheric circulation patterns, seasonal extremes rather than averages may provide greater insight as they can better show the northern and southern extent of ITCZ and westerly migrations.

2.3 Groundwater

Areas with large amounts of groundwater storage and discharge are typically found in areas with high permeability and low topography. Figure 2a shows the saturated permeability of consolidated and unconsolidated geological units below soil horizons up to 100 m depth for southern Africa (Gleeson et al., 2011). Figure 2b shows the topography of southern Africa (USGS, 2010). These two data sets were combined and areas that had both permeabilities between $1x10^{-11}$ m^2 and $1x10^{-13}$ m^2 and elevations below 1192 m above sea level were considered to have "high" levels of groundwater discharge. However, only inland areas were considered, as the precipitation recycling effect is not relevant in low-lying coastal areas as groundwater would not be a limiting factor of atmospheric moisture. As elevations in some areas of southern Africa are up to 2000 m, and the lowest elevations in inland areas are 819 m above sea level, 1192 m provides a reasonable cut-off for lowland discharge areas.

2.4 Archaeological Sites

Archaeological sites were taken from published papers and reports. There are very few well-dated archaeological sites from the LGM, therefore sites dated directly to the LGM were supplemented by sites that are not directly dated to the LGM and sites from ~30 ka, just before the LGM. Several sites are attributed to the last glacial period by the types of artefacts present, which are attributed to either the Middle Stone Age (MSA) or the early Later Stone Age (LSA). The MSA in southern Africa is generally considered to have lasted from approximately 280 ka to 50-25 ka (McBrearty and Brooks, 2000). The LSA follows the MSA and lasted until the later Holocene. Sites with both MSA and LSA artefacts without obvious breaks in occupation were considered likely to be from the

LGM, as this likely means they were occupied before, during, and after the LGM. Sites directly dated to the LGM are listed in Table 4, sites possibly from the LGM are listed in Table 5, and pre-LGM sites are listed in Table 6. The distribution of archaeological sites was compared with the paleoclimate model simulations, paleoenvironmental proxies, and groundwater discharge to determine if there are any environmental factors that may have influenced settlement patterns during the LGM.

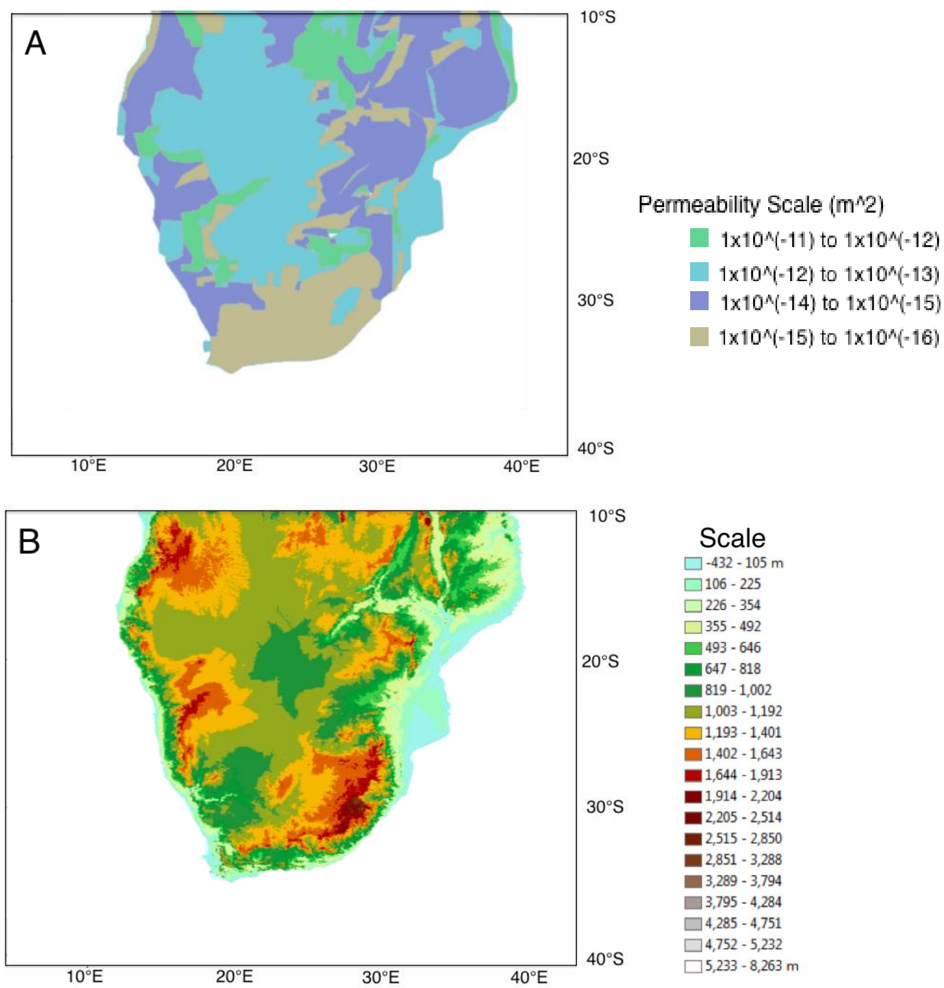

Figure 2: (a) Distribution of permeability of the geological units throughout southern Africa up to 100 m depth (modified from Gleeson et al., 2011) (b) Digital elevation model of southern Africa (USGS, 2010).

3. Results and Discussion

3.1 Hadley Centre Model

HadCM3M2 simulations for the difference in annual mean precipitation between 21 ka and 0 ka, show that there was little change in average annual precipitation in southern Africa (Figure 3). However, there were large changes in seasonal precipitation during the LGM. Figures 4a and 4b show HadCM3M2 simulation results for the LGM (21 ka) minus 0 ka precipitation for January and July respectively. In January, southern Africa is predominantly drier than present in the eastern half of the continent and wetter than present in the western half. The largest decrease in precipitation, of approximately ~2.0 x 10^{-5} kg $m^{-2}s^{-1}$, occurred in the central northeast. Today this region receives an average of 125 mm total in January, or ~5 x 10^{-5} kg $m^{-2}s^{-1}$ (World Meteorological Organization). This means there was a 40% reduction in rainfall during the LGM compared to the present-day. According to simulations, the west was wetter than present during the LGM with a maximum increase in precipitation of ~2.5 x 10^{-5} kg $m^{-2}s^{-1}$ at ~20°S, 15°E. Today, this area receives an average of approximately 3.4 x 10^{-5} kg $m^{-2}s^{-1}$ for the month (Namibia Ministry of Works and Transport), meaning there was an approximately 140% increase in precipitation between the present day and the LGM. The southern coast had a small increase in precipitation of ~2.5 x 10^{-6} kg $m^{-2}s^{-1}$, or a 44% increase compared to today (World Meteorological Organization). There was negligible change throughout the centre of the continent, near the southeastern coast at ~30°S, 30°E and within the Cape region.

In July, the northern sub-continent is predominantly wetter than present with a geographically consistent ~2.5 x 10^{-6} kg $m^{-1}s^{-1}$, a 100% increase in precipitation in some regions (World Meteorological Organization). The south and east are also wetter than present with a maximum increase of ~1.0 x 10^{-5} kg $m^{-2}s^{-1}$, or ~30% (World Meteorological Organization) in the central-south and southwest, decreasing to the northeast. The east coast is also predominantly wetter than present. For the most part, the central region shows little change in precipitation except for a small central area with an increase of ~1.0 x 10^{-6} kg $m^{-2}s^{-1}$ or ~40% (World Meteorological Organization).

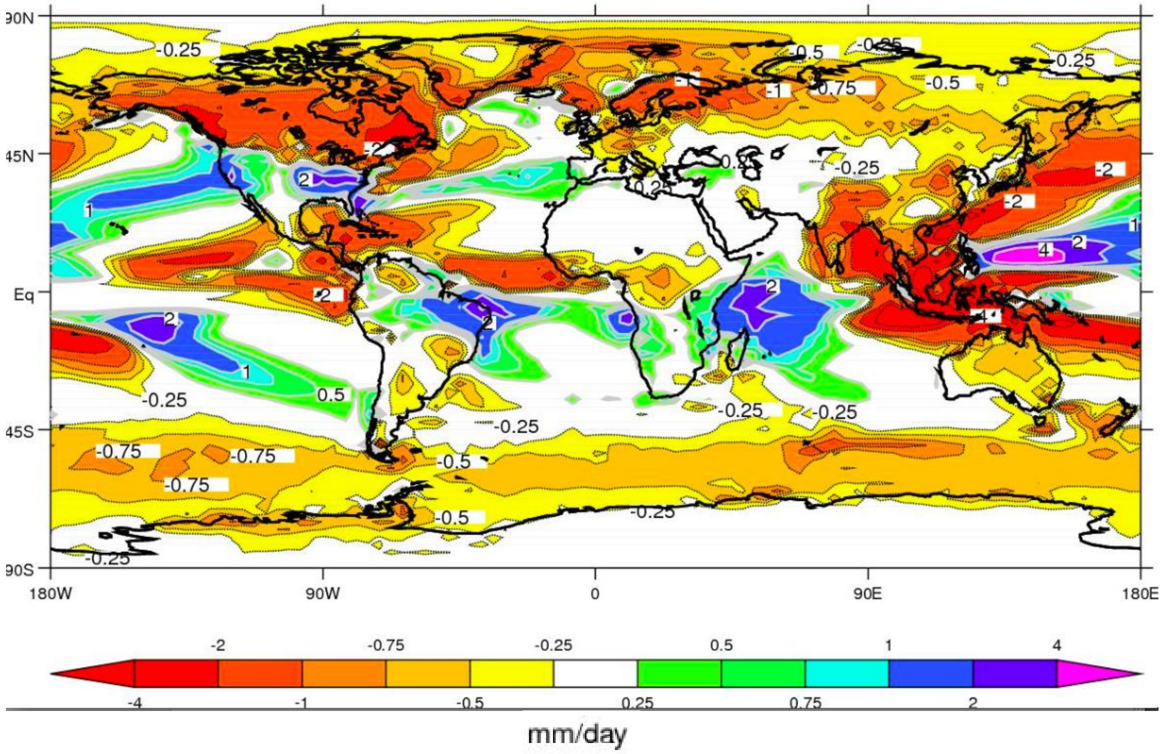

Figure 3: HadCM3M2 Results for annual mean precipitation difference 21 ka – 0 ka.

3.2 Paleoclimate Proxies

Most of the proxies fit into four major clusters of either wet or dry indicators (Figure 4). Group 1 is in the northern Kalahari and contains proxies P2, P3, and P4. Group 2 is in the southern Kalahari and contains proxies P5, P6, and P7. Group 3 (P11 – P15) is east of the Kalahari and group 4 (P16 – P19 and P22) is on or near the eastern coast.

All proxies in Group 1 show wetter than present conditions (Figure 4). At Drotsky's Cave (P2), U-Th dating of speleothems shows enhanced local rainfall at the end of the LGM (Brook et al., 1996, 1998). At Makgadikgadi Pan (P3), lacustrine sediments show that paleo-Lake Makgadikgadi was in a high-stand phase and connected to Lake Ngami and the Zambezi and Okavango Rivers between 20 ka and 15 ka, meaning it was wetter than present (Shaw and Thomas, 1996; Shaw et al., 1997). At Lake Nagami (P4), deeper lake levels are also found at the end of the LGM (19-17 ka). The authors attribute this to higher riverine input (Hunstman-Mapila et al., 2006). Increased lake levels alone aren't enough to infer greater precipitation at these locations as higher lake levels could be caused by enhanced precipitation in the large upper catchment zone or could be caused by a complete reorganization of the drainage basin. However, since there is corroborating evidence of greater rainfall at Drotsky's Cave, an increase in lake levels is likely due to increased precipitation within the Lake Makgadikgadi region.

The proxies in Group 2 also show wetter than present conditions (Figure 4). Pan sedimentation at Witpan (P5) occurred at ~20 ka, indicating wet conditions (Telfer et al., 2009). The aeolian and fluvial records at the confluence of the Auob, Nossob, Molopo and Kuruman Rivers in the SW Kalahari (P6) also indicate wet conditions 24-20 ka because of pan flooding throughout much of the year, cessation of lunette dune development, and perennial river flow (Hurkamp et al., 2011). The pollen record from a stalagmite at Wonderwerk Cave (P7) suggests wetter than present conditions from the increase of Cyperaceae, fern spores and small numbers of Restionaceae (fynbos), and *Podocarpus* pollen. Low δ^{18}O and δ^{13}C values from the same stalagmite also suggest cool, dry conditions with a greater proportion of summer rainfall than winter rainfall (Brook et al., 2010).

The proxies in Group 3 all indicate dry conditions during the LGM (Figure 4). There was minimal groundwater recharge at the Letlhakeng Aquifer (P11) between 24-16 ka, which indicates dry conditions. Low δ^{18}O values from the Letlhakeng Aquifer also indicate a decrease in precipitation occurred during the summer, but the main moisture source was still the Indian Ocean, meaning it was brought by easterly winds (Kulongoski et al., 2004). The low δ^{18}O and δ^{13}C values from stalagmites at Cold Air Cave (P12) and Lobatse Cave (P14) are have also been interpreted to represent cool and dry conditions during the LGM. The Lobatse Cave record ends at 21 ka but shows dry conditions between 27-21 ka with maximum aridity around 22-21 ka (Holmgren et al., 1995). The Cold Air Cave record shows dry conditions ~23-21 ka and 19.7-17.5 ka (Holmgren et al., 2003). However, interpreting the δ^{18}O values from stalagmites can be very complicated and depends on several factors including the air temperature inside and outside the cave, the source of moisture for drip water inside the cave, the overall amount of precipitation falling in the region, the proportion of summer to winter precipitation, the isotopic signature of the ocean water contributing to precipitation, and evaporation of water from the speleothem (McDermott, 2004; Quade, 2004). These interpretations of the Cold Air Cave and Lobatse Cave records have been questioned by some (Brook et al., 2010), as more recently low $\delta^{18}O$ and $\delta^{13}C$ values in stalagmites are taken to indicate cool and moist conditions, for example at Wonderwerk Cave (Brook et al., 2010), rather than cool and dry conditions.

A decrease in peat accumulation at Wonderkrater Spring (P13) from 35-12 ka also indicates dry conditions during this period (McCarthy et al., 2010). However, the pollen record for Wonderkrater Spring is slightly more complicated. There is no pollen data from the central LGM period (~24-20 ka). Before this period, there are wet conditions and after this period, the pollen record indicates dry conditions at ~ 19-17.5 ka followed by a steep increase in moisture. Scott et al. (2003) interpret this signal as indicating a dry LGM. At Tswaing Crater (P15), lake sediment analysis shows a rapid rainfall decline after 28 ka, reaching a minimum at ~18-17 ka (Kristen et al., 2007).

Table 1: Paleohydrological proxies that indicate wet conditions during the LGM.

Site No.	Location	Proxy Type	Latitude	Longitude	Reference
P1	MD96-2094	Sediment grain size	-19.99	9.26	Stuut et al., 2002
P2	Drotzky's Cave	Speleothems	-20.00	19.50	Brook et al., 1996, 1998
P3	Makgadikgadi Pan	Lacustrine and aeolian sediments	-20.20	26.08	Shaw and Thomas, 1996; Shaw et al., 1997; Burrough et al., 2009
P4	Lake Ngami	Lacustrine sediments	-20.47	22.80	Huntsman-Mapila et al., 2006
P5	Witpan	Pan sediments	-26.67	20.15	Telfer et al., 2009
P6	SW Kalahari	Aeolian and fluvial sediments	-26.95	20.35	Hurkamp et al., 2011
P7	Wonderwerk Cave	Pollen and $\delta^{18}O$, $\delta^{13}C$ records from stalagmite and dung deposits	-27.85	23.55	Brook et al., 2010
P8	Drakensburg Mountains	Glacier mass balance	-29.47	29.27	Mill et al., 2012

Table 2: Paleohydrological proxies that indicate dry conditions during the LGM.

Site No.	Location	Proxy Type	Latitude	Longitude	Reference
P9	GeoB 1023-5	Pollen	-17.15	11.02	Shi et al., 1998; 2000
P10	Tsolido Hills	Lacustrine and aeolian sediments	-18.50	22.00	Thomas & Shaw, 2002; Thomas et al., 2003
P11	Letlhakeng Aquifer	Noble gas and $\delta^{18}O$ in groundwater	-24.00	25.00	Kulongoski et al., 2004
P12	Cold Air Cave	Stalagmite $\delta^{18}O$, $\delta^{13}C$ isotope ratio	-24.02	29.18	Holmgren et al., 2003
P13	Wonderkrater Spring	Peat accumulation	-24.43	28.75	McCarthy et al., 2010; Scott, 1982; Scott et al., 2003
P14	Lobatse Cave	Stalagmite $\delta^{18}O$, $\delta^{13}C$	-25.33	25.92	Holmgren et al., 1995
P15	Tswaing Crater	Lacustrine sediments	-25.41	28.08	Kristen et al., 2007; Partridge et al., 1997; 2004
P16	MD96-2048	Pollen from a marine core	-26.17	34.02	Dupont et al., 2011
P17	Mfabeni Peatland	Pollen from peatland	-28.15	32.52	Finch & Hill, 2008
P18	Okhombe Valley	Hillslope analysis	-29.64	30.02	Temme et al., 2008
P19	Karoo Margin	Lacustrine and aeolian sediments	-31.33	26.67	Thomas et al., 2002
P20	Pakhuis Pass	Pollen and $\delta^{13}C$ from hyracuem	-32.10	19.07	Scott & Woodborne, 2007
P21	De Rif	Pollen and $\delta^{15}N$, $\delta^{13}C$ from hyraceum	-32.45	19.22	Chase et al., 2011; Quick et al., 2011
P22	CD154-17-17K	Ratio of Fe/K in marine sediment core	-33.27	29.12	Ziegler et al., 2013

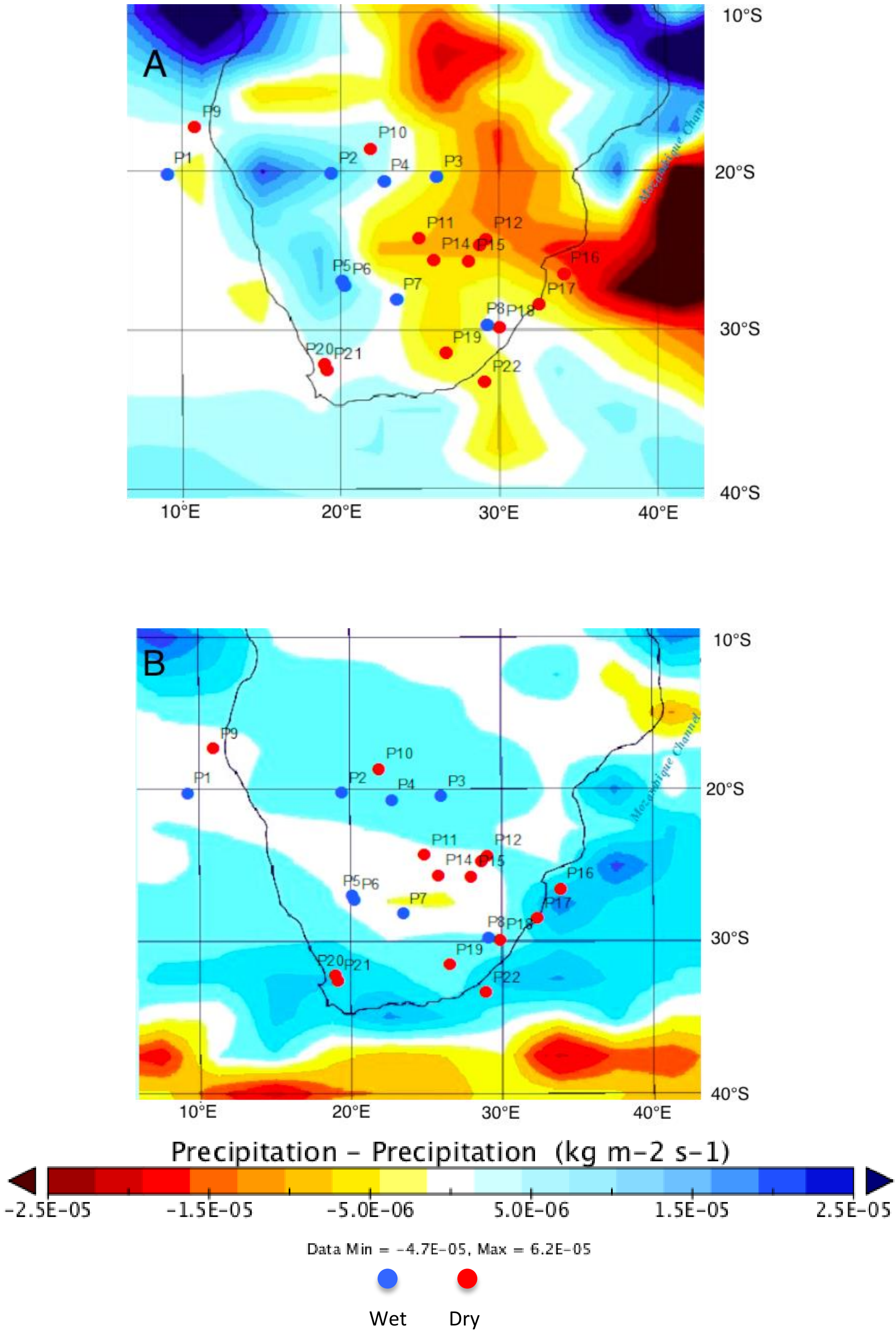

Figure 4: Paleoclimate proxies and HadCM3M2 results for precipitation difference 21 ka – 0 ka for the month of (a) January and (b) July.

Group 4 proxies also indicate dry conditions during the LGM (Figure 4). MD96-2048 (P16) is an offshore marine pollen record that shows an increase in open mountainous scrubland during MIS2 (24-11 ka). The source area for this core is mainly the adjacent coastal region inland to approximately 200 km (Dupont et al., 2011). The Mfabeni Peatland (P17) is a coastal peatland pollen record that shows a sharp increase in Poaceae at 24 ka, indicating local drying. Grasses dominate the record through to 11 ka, meaning dry conditions were sustained throughout this time (Finch & Hill, 2008). There is a break in sedimentation in the Okhombe Valley (P18) in the Drakensburg Mountains, 25-15 ka that, the authors interpret as representing a break in fluvial activity due to decreased precipitation. Clear boundaries between pre-LGM and Holocene sediments indicate this gap is not a result of erosion (Temme et al., 2008). Analysis of aeolian and fluvial deposits at the Karoo margin (P19) also indicate a dry period with periodic pan inundation and a variable water table (Thomas et al., 2002).

There are also several proxies that do not fit into these four groups, including those that show a signal that contradicts other nearby proxies and those that are isolated from other proxies. The glacier mass balance record (P8) from the Drackensburg Mountains is quite close to one of the dry proxies in Group 4 (P17), but indicates wet conditions. Large alpine glaciers here during the LGM imply colder temperatures, shading, and also likely increased cold-season precipitation (Mills et al., 2012). Both P8 and P17 are located on the eastern side of the mountains, P8 in the upper reaches and P17 in the foothills, so the difference in signal is likely not from an orographic effect.

The Pakhuis Pass site (P20) and De Rif middens (P21) are very close together, and both show variability within the LGM, rather than having a clear wet or dry signal. Both are pollen records from hyrax dung, small mammals that inhabit the caves of this region. Chase et al. (2011) also present the δ^{15}N and δ^{13}C record from the dung and Scott & Woodborne (2007) just present the δ^{13}C record. The Pakhuis Pass pollen record shows that during the LGM the vegetation here was mainly composed of low shrubs and "pure fynbos" such as Protaceae and Ericaceae. The pollen and stable isotope records indicate that cool, dry conditions occurred at 22-21 ka, followed by a slight increase in moisture and temperature 21-19 ka. Dry conditions resume between 19-17.5 ka. The $\delta^{13}C$ ratio is low between 23 ka and 10 ka, which might suggest that summer rainfall was absent from this region. However, the authors argue that under cool conditions with summer rainfall, C4 vegetation will not develop, therefore, there was likely a significant amount of summer rainfall during the LGM (Scott and Woodborne, 2007). This proxy was mapped as dry because that was the dominant condition during the LGM.

The De Rif pollen record shows less variation than the Pakhuis Pass record and shows little variation from present. However, this may be more due to the resilience of the dominant fynbos vegetation than to climatic stability as the stable carbon and nitrogen records do show a significant amount of variation. The De Rif record starts at 19.5 ka, the end of the LGM at which point $\delta^{13}C$ and $\delta^{15}N$ suggest relatively dry conditions, coinciding with dry conditions in the Pakhuis Pass record (Chase et al., 2011).

Marine pollen core GeoB 1023-5 (P9) is off the northwest coast of southern Africa and receives pollen from areas between 13°S and 21°S which includes the northern Namib Desert and semi-desert, the Angolan and northern Namibian highlands, and the northwestern Kalahari Desert. During the LGM this pollen assemblage showed an increase in temperate vegetation types such as Asteroideae, Ericaceae, and Restionaceae, compared to the present, representing cooler and more arid conditions. However, the "desert/semi-desert" pollen group varies little between the LGM and the present (Shi et al., 1998). Most of the other Kalahari proxies (Group 1) show a wet signal during the LGM, except for the record from the Tsodilo Hills (P10) on the northern edge of the Kalahari region. Lake sedimentation occurred here from 27-22 ka and 19-12 ka. The break in sedimentation during the LGM represents drier conditions (Thomas & Shaw, 2002; Thomas et al., 2003). Another marine core off the west coast, MD96-2094 (P1), received source material from farther south, between 24°S and 32°S and shows wet conditions during the LGM. During glacials there was a higher proportion of relatively fine-grained mud deposition, implying wetter conditions on land (Stuut et al., 2002).

Some of the proxies discussed above indicate the seasonality of precipitation as well as the total amount. There are also several proxies that indicate only the seasonality of precipitation (Figure 5, Table 3). A pure increase in winter precipitation occurred only at the Drakensburg Mountains glacier mass balance site (P8 and S2) (Mills et al., 2012). However, as mentioned above, a decrease in summer precipitation likely occurred at the Letlhakeng Aquifer (Kulongoski et al., 2004). A decrease in summer precipitation also occurred at Cango Cave (S3) in the Drakensburg Mountains, indicated by low $\delta^{13}C$ values from 33 to 17.9 ka, followed by a hiatus until the mid-Holocene (Talma & Vogel, 1992).

Table 3: Paleohydrological proxies that indicate the dominant season of precipitation during the LGM.

Site No.	Dominant Season of Rainfall	Location	Proxy Type	Latitude	Longitude	Reference
S1	Year-round	SW Kalahari	Fluvial and aeolian sediments	-26.95	20.35	Hurkamp et al., 2011
S2	Winter	Lesotho Highlands	Glacier mass balance	-29.47	29.27	Mills et al., 2012
S3	Winter	Cango Cave	$\delta^{13}C$ of stalagmite	-33.38	22.22	Talma & Vogel, 1992
S4	Summer	Core 8	δD_{wax}	-17.20	11.00	Collins et al., 2013
S5	Summer	Core 9	δD_{wax}	-23.30	12.40	Collins et al., 2013
S6	Summer	Strampiet Aquifer	Groundwater $\delta^{18}O$	-24.00	19.50	Stute & Talma, 1998
S7	Summer	Wonderwerk Cave	$\delta^{18}O$, $\delta^{13}C$ records from stalagmite and dung deposits	-27.85	23.55	Brook et al., 2010
S8	Summer	Pakhuis Pass	$\delta^{13}C$ of pollen	-32.10	19.07	Scott & Woodborne, 2007

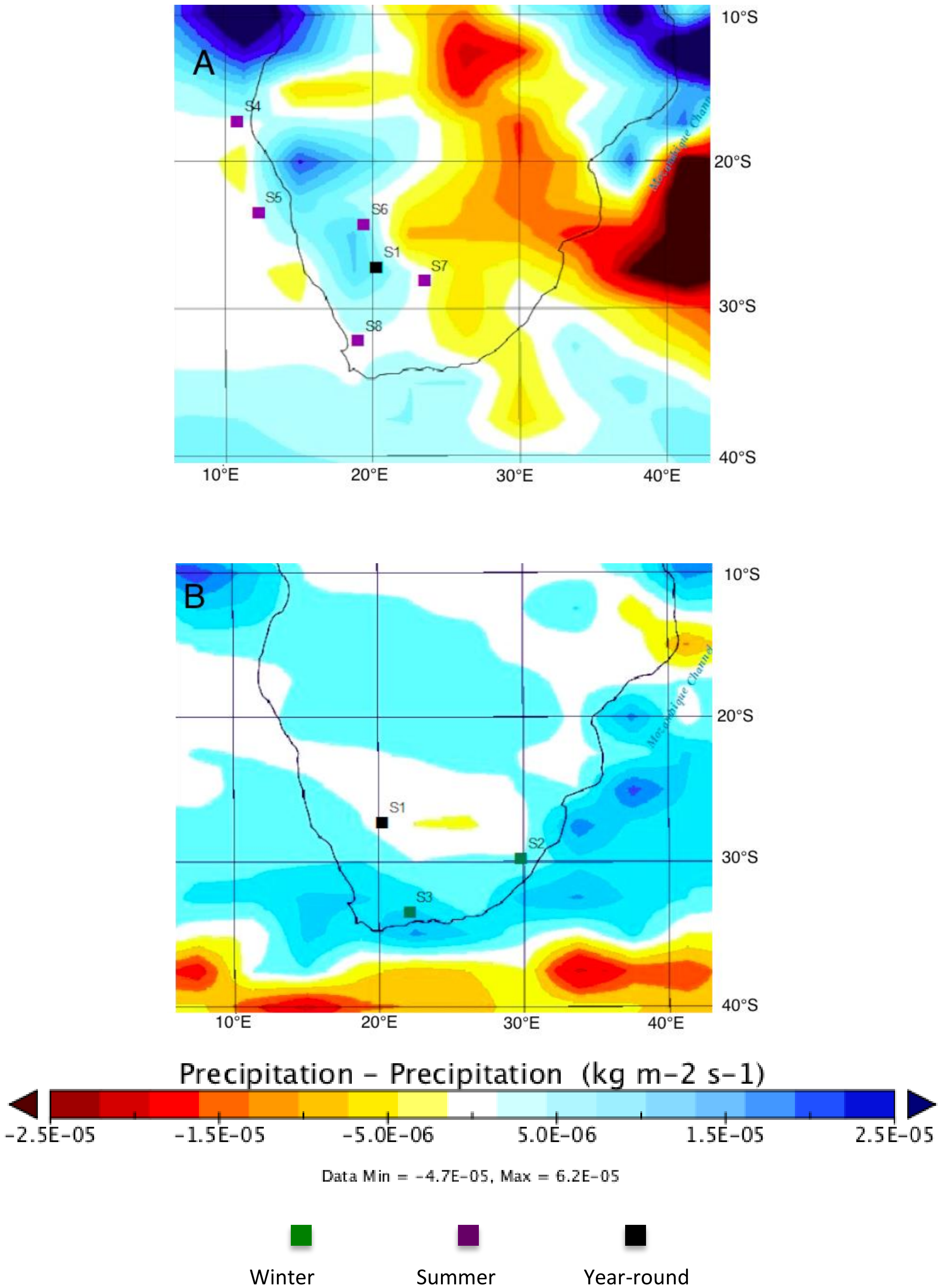

Figure 5: (a) HadCM3M2 results for precipitation difference 21 ka – 0 ka for the month of January and proxies that indicate summer and year-round rainfall and (b) HadCM3M2 results for precipitation difference 21 ka – 0 ka for the month of July and proxies that indicate winter and year-round rainfall.

An increase in summer precipitation occurred at four sites. Low $\delta^{18}O$ values from the Strampiet Aquifer in the western Kalahari are taken to indicate a switch in moisture source from the Atlantic to the Indian Ocean, meaning an increase in the proportion of summer rainfall (Stute and Talma, 1998). S4 and S5 are part of a study of nine marine cores from along the West African coast. The hydrogen isotopic composition of plant leaf-wax n-alkanes (δD_{wax}) in the cores is used to estimate the δD of past precipitation. The δD estimates of past precipitation mostly represent changes in wet season intensity and length, rather than total annual precipitation. The low δD values for this site indicate that wet season intensity increased during the LGM. Furthermore, the degree of δD change and the ratio of C3/C4 vegetation in the pollen record likely indicates that the wet season occurred during summer (Collins et al., 2013). The stable carbon isotope record from hyrax dung deposits at Pakhuis Pass (S8) show low values during the LGM. Low $\delta^{13}C$ suggests a high proportion of C_3 to C_4 vegetation, which is often interpreted as an absence of summer rainfall since currently, C_4 vegetation occurs in the SRZ. However, if temperatures are cool enough, C_4 vegetation will not grow and low $\delta^{13}C$ values can occur in a region with summer rainfall. The authors argue that the Pakhuis Pass region received significant amounts of summer rainfall during this period (Scott and Woodborne, 2007).

Year-round rainfall is indicated in the southwestern Kalahari at S1 because the area experienced contemporaneous pan flooding and cessation of lunette dune development, and the onset of perennial flow in the area's rivers. If there was seasonal aridity, and pans were not flooded year-round, dune activity likely would have continued here throughout the LGM (Hurkamp et al., 2011).

3.3 Model-Proxy Comparison, Paleoclimate Interpretations and LGM Atmospheric Circulation Patterns

In July, the proxies of Group 1 are all in a zone of increased model-simulated precipitation (Figure 4b). In January, the westernmost of these proxies is in a slightly wetter than present zone. The easternmost is in a dry zone and the middle proxy (P4) is in a zone of no change, according to the simulations (Figure 4a). There are no seasonality proxies close to these sites to help determine the seasonality of precipitation. From model simulations, an increase in winter precipitation can be inferred. The westernmost and possibly the middle proxies could be a result of a year-round precipitation increase. However, a precipitation increase associated with the westerlies and expansion of the winter rainfall zone alone here seems unlikely as proxies to the south received predominantly summer rainfall and because lake shorelines in this region are higher on the west side of the mega-lakes, which would be expected with easterly rather than westerly winds (Burrough et al., 2009).

In austral winter, all the proxies of Group 2 are in an area with little change in modeled precipitation (Figure 4b). In summer, the two western proxies are in a wetter than present zone and the eastern proxy is in a zone of no change (Figure 4a). This would seem to indicate that these proxy signals resulted from an increase in summer precipitation. The results from Wonderwerk Cave support this, with low δ^{18}O and δ^{13}C values indicating increased summer precipitation (Brook et al., 2010). However, S1 shows year-round precipitation. This could indicate that HadCM3M2 may underestimate the spread of winter precipitation and the overall wetter conditions here are a result of year-round rainfall. This would be inconsistent with the Wonderwerk isotope record. Alternatively, the S1 record could be overestimating the influence of winter precipitation or underestimating the influence of summer precipitation on the region, thus experiencing predominantly summer rainfall. If there was seasonal aridity at S1, lunette development probably would still have occurred. However, there are other reasons that could have caused dune development to stop, such as a decrease in wind strength. But this is unlikely as LGM wind conditions were generally stronger than present. There may be another climate-influencing factor here that has not previously been taken into account, such as groundwater.

The proxies of Group 3 all correspond with modeled dry summer conditions (Figure 4a) and no change in modeled winter precipitation (Figure 4b), except for the easternmost proxies, P16, which is on the edge of the increased winter precipitation zone. Therefore, it seems likely that this region experienced a decrease in ITCZ-associated precipitation. There are no seasonality proxies here to support this, unless P15 and P16 are interpreted as in Brook et al. (2010).

In summer, all of the Group 4 proxies either correspond with decreased model precipitation or no change (P8) (Figure 4a). In winter, model results for this location show increased precipitation (Figure 4b). The Drakensburg Mountains glacier mass balance reconstruction (P8 and S2) also fall within the geographic range of Group 4, near P18 and shows a wet signal in contrast to the rest of the proxies in the group and an increase in winter precipitation. The nearby Cango Cave record shows a decrease in summer precipitation. There was likely a decrease in ITCZ-associate precipitation here as well as an increase in westerly-associated winter precipitation.

Today, the northeastern section of southern Africa predominantly receives summer rainfall delivered by the ITCZ. Because there is an almost universal decrease in rainfall here during the LGM in both modeled and proxy records, it is likely that the convection of the Hadley cells decreased in strength, reducing their ability to deliver moisture to this region. There is also evidence that the ITCZ moved further south at Wonderwerk Cave and the Letlahakeng Aquifer. The Wonderwerk Cave stalagmite and dung deposits record wetter conditions with predominantly summer precipitation (Brook et al., 2010). And because the current geographic rainfall trend in southern Africa is increasing from north to south, the summer increase in precipitation at Wonderwerk Cave can be attributed to the southward movement of the ITCZ. The Letlhakeng Aquifer record shows a decrease in summer precipitation, but its moisture source is still attributed to the Indian Ocean (Kulongoski et al., 2004). This makes sense as the aquifer is further north than Wonderwerk Cave in a region that currently receives more summer rainfall. Therefore, a slight southward movement of the ITCZ would not affect the amount of moisture it receives so much as a reduction in Hadley Cell circulation strength. A southward movement of the ITCZ during the LGM is consistent with other model results and several proxy studies.

One exception to the drying trend experienced in summer in the eastern half of the subcontinent is the Drackensburg Mountain glacier reconstruction (P8). However, this can be resolved if there is an increase in winter rainfall in the southern section of the summer rainfall zone, which is shown in the modeled results (Figure 4b). Chase and Meadows (2007) propose that the WRZ expanded into the northwest section of the subcontinent but that the eastern section remained in the SRZ. This does not appear to be the case here. However, both model and proxy results show that the eastern subcontinent was receiving winter rainfall during the LGM. Therefore, it is likely that the westerlies expanded slightly north relatively uniformly across the continent. There is nothing to suggest that the strength of the westerlies changed during the LGM.

This is consistent with other proxy-based studies such as that by Kohfield et al. (2013) but not with model-based studies. The westerlies are an extremely complicated atmospheric phenomenon therefore, it is possible that global circulation models are not able to model them sufficiently.

3.4 Groundwater

Figure 6 shows the inland areas with potentially high groundwater discharge and storage. This area coincides with the current Kalahari Desert and matches the current areas of high groundwater storage from MacDonald et al. (2012) shown in Figure 7. The overlap between the current high groundwater and modeled high groundwater confirms that these areas can have large amounts of groundwater, and presumably had even more in times of higher precipitation. Figure 6 also shows the maximum extent of paleolake Makgadikgadi reconstructed from paleoshorelines (Burrough et al. (2009). Lake Makgadikgadi was an extremely large lake made of several interconnected basins that form the terminal sump of the Okavango system. Today it is almost completely dry but was filled at several different periods including between 19 and 15 ka (Burrough et al., 2009). According to Ringrose et al. (2009) much of the water in the Makgadikgadi system was derived from groundwater, therefore it makes sense that the paleolake would be within the modeled area of high groundwater discharge.

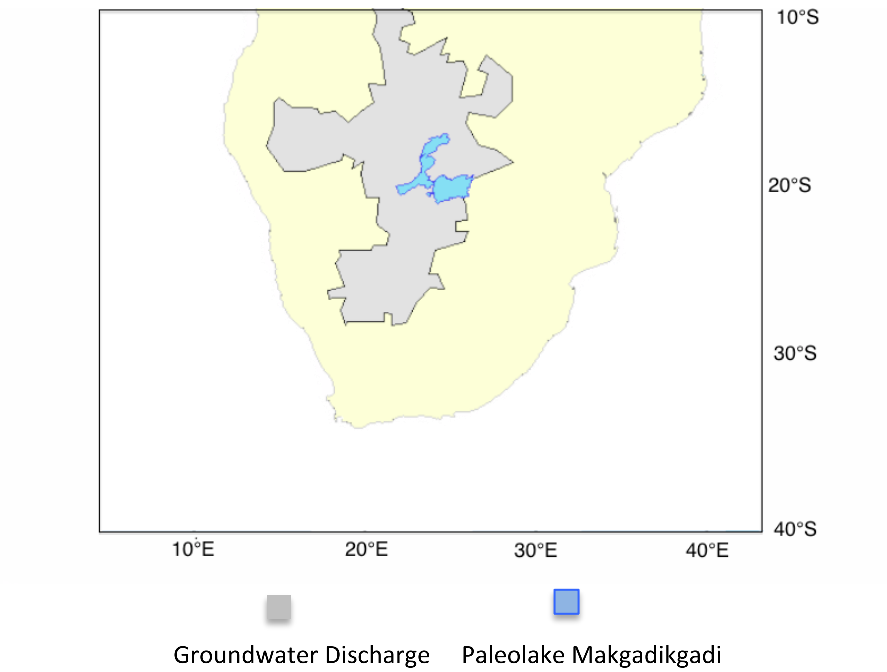

Figure 6: Simulated discharge areas and paleolake Makgadikgadi

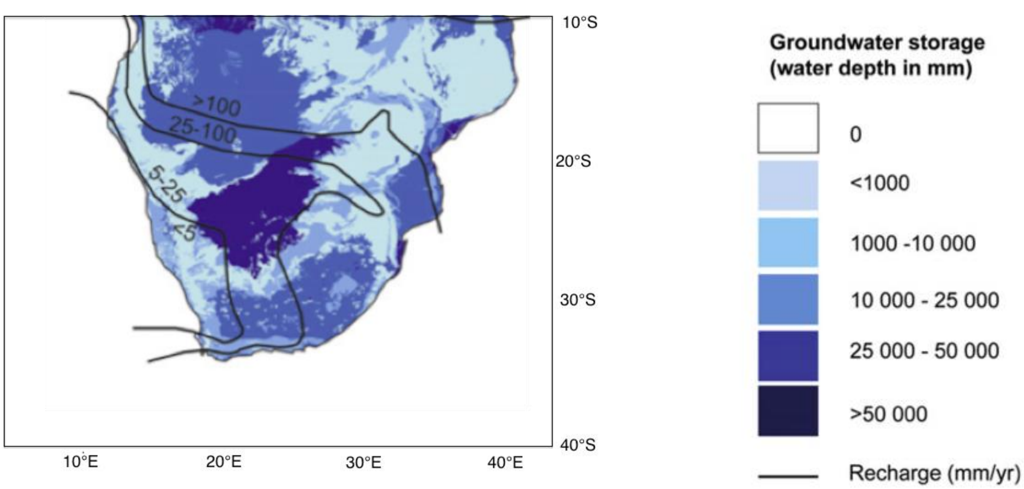

Figure 7: Modern Southern African groundwater storage and recharge rate from MacDonald et al., 2012.

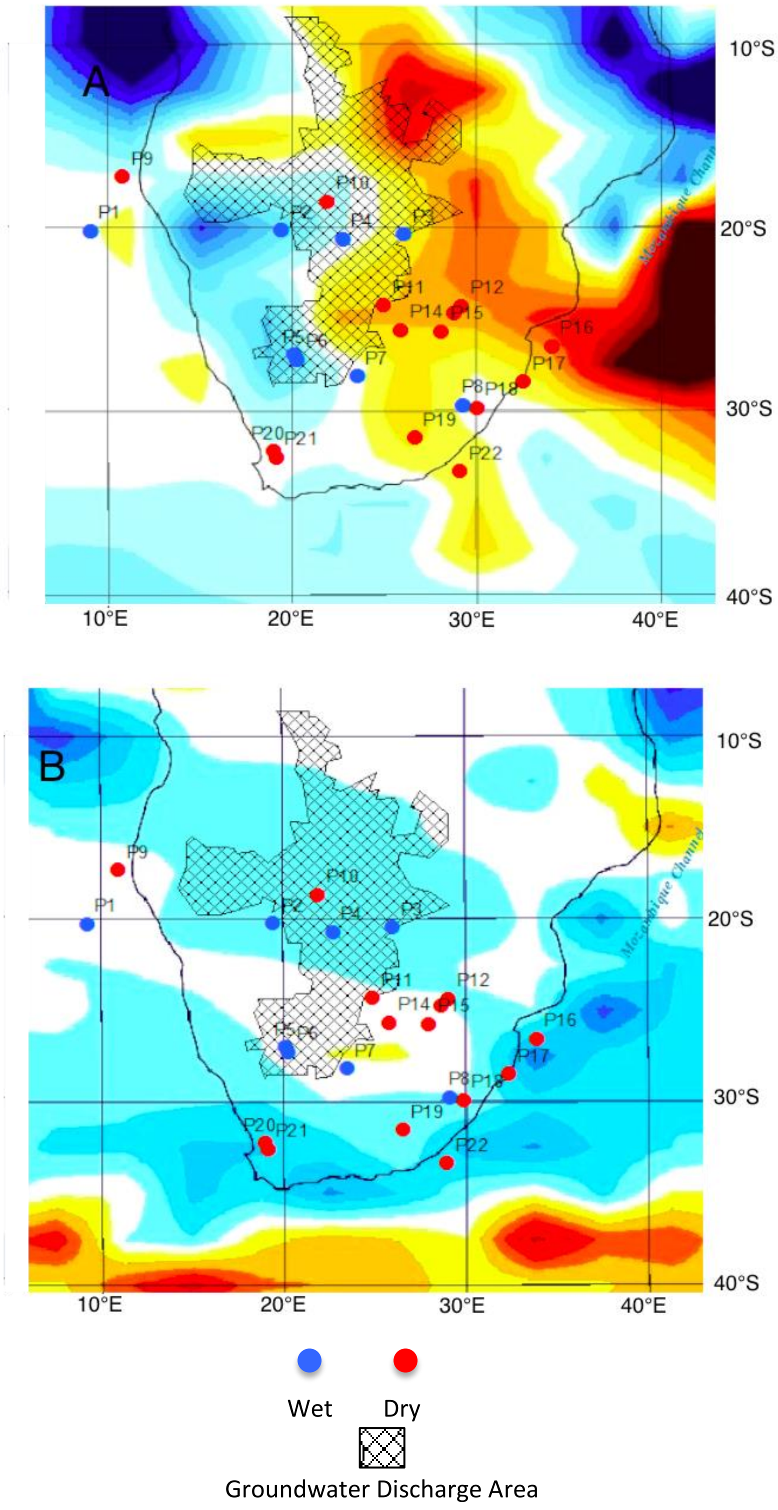

Figure 8: Groundwater discharge area, paleoenvironmental proxies, and modeled 21 ka – 0 ka precipitation difference for (a) January and (b) July.

Figure 8 shows the zone of modeled increased groundwater discharge area in relation to the paleoenvironment proxies. Group 1 falls within the boundary of this region and Group 2 is just outside this region. As discussed above, Group 1 experienced an increase in precipitation that is difficult to constrain to a purely atmospheric origin. It is possible that there was a slight increase of advected moisture associated with the ITCZ, here. A large proportion of advected precipitation would then infiltrate into the groundwater due to the high permeability of the landscape, retaining the water it in the system. During the drier winter, this groundwater could have re-entered the atmosphere through evapotranspirative processes and fallen again as recycled rainfall.

In Group 2, P5 and P6 are within the boundaries of the groundwater discharge zone but P7 is outside. Year-round precipitation is seen in the southwest Kalahari (S1 and P6) and summer precipitation is seen at Wonderwerk Cave (S7 and P7). The discrepancies between these sites could be because the sites within the groundwater discharge zone (P5 and P6) experienced the effects of precipitation recycling and thus had year-round precipitation whereas Wonderwerk Cave did not experience precipitation recycling so received predominantly summer rainfall.

3.5 Human Settlement Patterns in Southern Africa

Figure 9 shows the LGM and pre-LGM sites in relation to modeled groundwater. Most of the LGM sites are on the eastern half of the subcontinent, which was drier than present during the LGM summer (Figure 4a). The pre-LGM sites are more evenly distributed across the sub-continent. The change in the mean annual precipitation in the eastern subcontinent was quite small and skewed towards an increase in mean annual precipitation (Figure 3). Today, this area receives more annual precipitation than other regions of southern Africa, a trend that was likely upheld during the LGM. Therefore LGM archaeological sites occur more in wetter areas. The archaeological sites within the Kalahari, including A6, A11, A12, and a number of pre-LGM sites are of particular interest to archaeologists because today this region is extremely arid. The presence of these sites in this region is explained by the increase in moisture here during the LGM. As discussed above, most of the proxies found within the Kalahari (P2 – P7) indicate wetter than present conditions. The HadCM3M2 results also indicate wetter than present conditions.

Table 4: Archaeological Sites Definitively Dated to the LGM

Site No.	Site Name	Time of Occupation (ka)	Latitude	Longitude	Reference
A1	Twin Rivers	11-102	-15.52	28.18	Mitchell, 2002
A2	Duncombe Farm	~18.97	-17.40	30.92	Mitchell, 2002
A3	Pomongwe Cave	LSA to 35	-20.65	28.51	Cooke, 1980
A4	Buffelskloof	~22.5	-24.96	30.26	Mitchell 2002
A5	Heuningneskkrans	24.7-12.6	-25.55	28.18	Mitchell, 2002
A6	Kathu Pan	32.1-19.8	-27.67	23.02	Beaumont, 1990
A7	Rose Cottage Cave	20-91	-29.22	27.47	Valladas et al., 2005; Jacobs et al., 2008;
A8	Sehonghong	~26-12, 30-60	-29.77	28.78	Mitchell, 1996, Jacobs et al., 2008
A9	Shongweni South	23-11.9	-29.85	30.72	Mitchell, 2002
A10	Boomplaas	~18, 31-62	-33.38	22.18	Vogel, 2001

Table 5: Archaeological Sites Possibly Attributed to the LGM

Site No.	Site Name	Time of Occupation (ka)	Latitude	Longitude	Reference
A11	Savuti Pan	MSA, LSA	-18.76	24.50	Robbins, 1987
A12	Toteng-3A	ESA, MSA, LSA	-20.36	22.96	Brook et al., 2008
A13	Hackthorne	ESA, MSA, LSA	-22.23	29.31	Le Baron et al., 2010
A14	Kudu Koppie	ESA, MSA, LSA	-22.23	29.69	Pollarolo et al., 2010

Table 6: Archaeological sites close in age to the LGM

Site No.	Site Name	Time of Occupation (ka)	Latitude	Longitude	Reference
A15	Mumbwa	32-46, 96-194	-15.02	26.98	Barham, 2000
A16	White Paintings	31-105	-18.77	21.75	Robbins et al., 2000; Donahue et al., 2004
A17	Gi	33-65	-19.62	21.02	Brooks et al., 1990
A18	Kudiakam Pan	MSA	-20.13	20.75	Robbins, 1987
A19	Etemba-14	MSA	-21.45	15.62	Schmidt, 2011
A20	Border Cave	32-238	-27.02	31.99	Miller et al., 1999; Grun et al., 2003
A21	Pockenbank	30-50	-27.22	16.52	Vogelsang, 1998
A22	Witkrans Cave	33-106	-27.62	24.63	Butzer et al., 1978; Vogel and Partridge, 1984
A23	Equus Cave	27-103	-27.62	24.63	Klein et al., 1991; Lee-Thorp and Beaumont, 1995
A24	Apollo 11	30-83	-27.75	17.10	Miller et al., 1999
A25	Wonderwerk Cave	1.0-12.5, 70-220	-27.85	23.56	Beaumont and Vogel, 2006; Chazan et al., 2008
A26	Sibudu	37-79	-29.00	31.00	Jacobs et al., 2008a,b
A27	Umhlatuzana Cave	32-75	-29.48	30.45	Lombard et al., 2010
A28	Melikane	33-82	-29.95	28.75	Voel et al., 1986; Jacobs et al., 2008a
A29	Hofmeyr	33-39	-31.57	25.97	Grine et al., 2007
A30	Klein Kliphuis	32-69	-32.07	18.51	Jacobs et al., 2008a
A31	Pinnacle Point	30-40, 90-130, 160-170	-34.21	22.09	Marean et al., 2010

The association between wetter areas and archaeological sites is not unexpected considering that access to freshwater resources for drinking water is extremely important to the survival of any human population. There are also several other proximate reasons why LSA peoples might prefer wetter areas such as resource abundance. Ethnographic research shows that foragers rely predominantly on plant foods such as the mushrooms, seeds, tubers, and roots (Kusimba, 1999), which would be much more abundant in wetter areas. These wet areas also likely had more surface water and thus more access to fish. Evidence of fishing dates back to approximately 70 ka (Henshilwood et al., 2001) and likely increased significantly as a food source during the LSA (Kusimba, 1999).

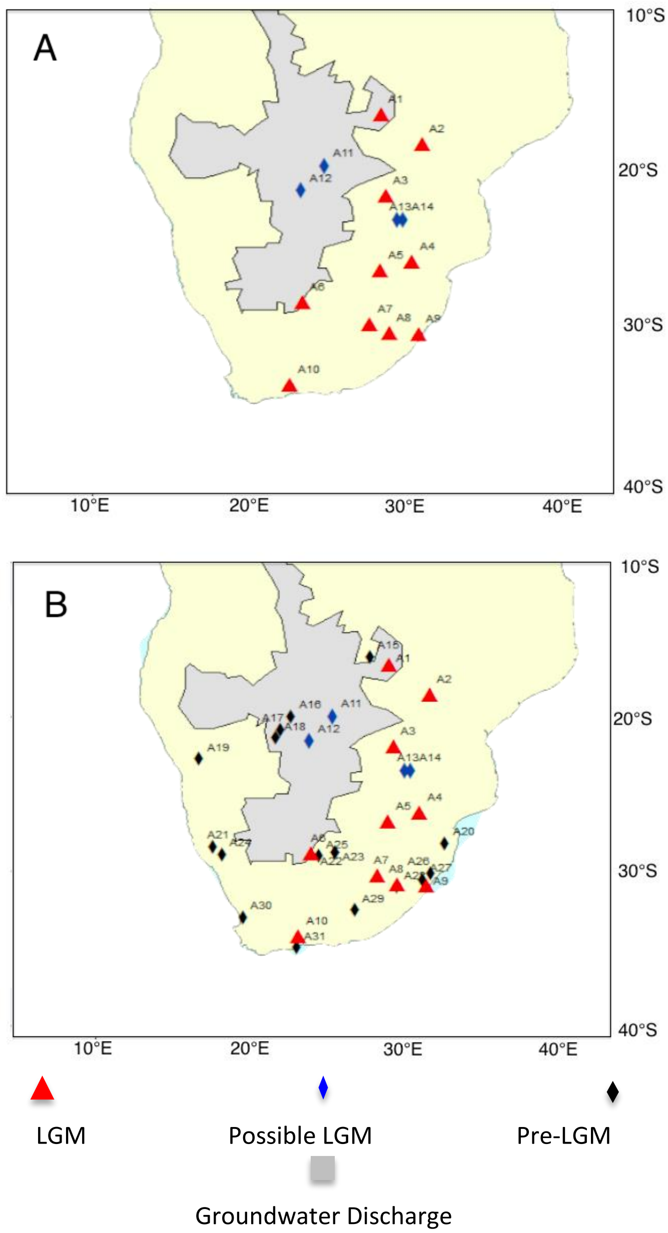

Figure 9: Groundwater discharge area and (a) LGM archaeological sites, (b) LGM and pre-LGM archaeological sites.

Based on predicted patterns in groundwater, there are very few LGM sites within the groundwater discharge area. However, many of the LGM sites appear on the eastern side of the groundwater discharge zone. Increased groundwater discharge could have caused this area to be marshy, making it difficult for people to live in or move across, essentially forming a natural barrier. The pre-LGM sites form a much more even distribution across the sub-continent than the LGM sites. And notably, there are some pre-LGM sites both within and west of the groundwater discharge zone. It is possible then that this area was less swampy at this time allowing people to live in and migrate through this area to the coastal region.

It is also useful to look at individual clusters of sites in relation to groundwater hydrology, as archaeological sites would likely aslo depend on small-scale variations in hydrology, such as springs and streams that are not shown in this large, coarse feature. For example, Kathu Pan is just within the groundwater discharge zone and has LGM occupation as well as an extremely dense concentration of artefacts extending back to the Early Stone Age (Porat et al., 2010). Wonderwerk Cave does not have any occupation during the LGM and has a much lower concentration of artefacts (Beaumont, 1990; Chazan et al., 2008). This could be because the higher potential for groundwater at Kathu Pan provides much more surface water than at Wonderwerk.

4. Conclusions and Directions for Future Research

When used together, climate models, paleoproxy records, and climate forcing mechanisms can provide a much clearer picture of paleoclimate dynamics than any alone. Results show that during the LGM, Hadley Cell convection likely weakened, and thus delivered less moisture to southern Africa during the austral summer relative to the present. The austral summer position of the ITCZ was likely further south than it is today. On the other hand, the westerlies may have shifted towards the equator, resulting in an expanded winter rainfall zone.

The climate of southern Africa likely had a large effect on human settlement patterns during the LGM. My results show that more sites dated to this period are found in the eastern, wetter area of the sub-continent. The presence of modeled groundwater discharge areas was also proposed to explain the difference in occupation densities at with and east of this zone during the LGM. An increase in the number of well-dated, reliable proxy and archaeological records would greatly strengthen the results presented here. Hydrological models of the Kalahari LGM could also help confirm the influence of groundwater on climate in this region, as they can be used to determine the contribution of groundwater to evapotranspiration on a regional scale.

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