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Influence of Agulhas forcing of Holocene climate change in South Africa's southern Cape

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Abstract

This paper analyses a series of high-quality continuous records from southeastern Africa to study the spatiotemporal patterning of Holocene hydroclimatic anomalies in the region. Results indicate dominant frequencies of variability at millennial time scales, and a series of anomalies broadly common to all records. Of particular interest, data from the southern Cape coast exhibit periods of wetter/drier conditions that are out of phase with the sites less than 150 km away in the adjacent interior, but in phase with sites in tropical regions over 1000 km to the northeast. To explain such spatial patterns and gradients, we propose that the Agulhas Current may be a critical vector by which tropical climatic signals are propagated along the littoral zone, exerting a dominant, highly localized influence on near-coastal environmental conditions. Limitations in the data available do not allow for a detailed examination of the climatic dynamics related to these phenomena, but this paper highlights a series of avenues for future research to clarify the spatial extent and stability of the patterns observed.

Keywords: Southern Africa; Palaeoclimate; Holocene; Agulhas Current

INTRODUCTION

Southern African climatic variability is determined by the influence of two primary circulation systems: (1) the tropical easterlies, which advect moisture to the continent from the Indian Ocean, and (2) the southern westerlies and associated storm track (Tyson and Preston-Whyte, 2000). Precipitation across most of the subcontinent is related to the tropical easterlies and falls primarily in the summer months (the "summer rainfall zone" [SRZ]; sensu Chase and Meadows, 2007), when evaporation and convective potential are highest. In contrast, the southwestern Cape receives the bulk of its rainfall in the winter months (the "winter rainfall zone" [WRZ]), when the westerly storm track shifts equatorward. This seasonal dynamic has been widely applied as a model to understand and explore Quaternary climatic dynamics, with a coeval inverse relationship being proposed wherein summer (winter) rainfall systems are relatively more invigorated during interglacial (glacial) periods (van Zinderen Bakker, 1976; Cockcroft et al., 1987; Chase and Meadows, 2007).

In recent years, focused efforts to test and refine this model have shown that, while it may be applicable in broad terms (Chase et al., 2017), there exists a much greater degree of spatiotemporal complexity than was previously predicted. Evidence indicates, for example, that the eastern SRZ cannot be treated as a homogeneous region, as there exist at least two (southern-central and northern) subregions (Chevalier and Chase, 2015), and that climatic variability across much of the interior is driven by the interaction between temperate and tropical systems, rather than by either system in isolation (Chase et al., 2017). It has also been suggested that the influence of the tropical easterlies has at times been a key determinant of climatic variability not only in the SRZ, but in parts of the modern WRZ as well (Chase et al., 2015b), and a comparison of records from sites along the interface between the SRZ and WRZ seem to suggest that strong dipoles may exist over very short distances (<100 km) (Chase et al., 2015a, 2015b).

In this paper, we apply a selection of recent data sets to explore the spatiotemporal distribution of millennial-scale hydroclimatic anomalies during the Holocene in the southern

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Cape of South Africa. This region receives precipitation from both tropical and temperate systems (in what is referred to here as the "aseasonal rainfall zone" [ARZ]; cf. "YRZ" definition of Chase and Meadows, 2007) and is further influenced by the warm Agulhas Current, which may induce either localised precipitation (Jury et al., 1993) or may contribute to the development of larger regional convective systems (Tyson and Preston-Whyte, 2000). As such, the southern Cape is recognised as being a climatically complex region, and while it is currently one of the most mesic regions in South Africa, it may also be one of the most sensitive to change as a result of perturbations in any one of the elements that comprise its climatic system.

SITE SELECTION

For this study, we consider sites from the central and eastern SRZ and both the interior and coastal zones of the southern Cape (Fig. 1). As we focus on identifying millennial-scale hydroclimatic anomalies, we have selected only those records that (1) are continuous, (2) have sampling intervals that are a consistently less than 500 yr, and (3) can be related with reasonable certainty to changes in precipitation and/or aridity. Underpinning our analyses at the regional scale are the northern and southern-central SRZ (N-SRZ and SC-SRZ, respectively) summer precipitation reconstructions of Chevalier and Chase (2015) (Fig. 2a and e). These reconstructions (1) include data from the best-resolved fossil pollen records from eastern southern Africa, (2) analyse the data using the CREST software (Chevalier et al., 2014) to obtain quantified estimates of past precipitation, and (3) allow for the identification the N-SRZ and SC-SRZ as two largely distinct regions based on differences observed between the records considered (see Chevalier and Chase [2015] for more details). To explore the extent of the climatic anomalies observed in these regional reconstructions and the influence of the dominant climatic systems, we consider four additional records (Fig. 1). The first, a δD record recovered from a marine core off the coast from the Zambezi River mouth (Schefuß et al., 2011), is of relatively low resolution, but as an indicator of rainfall amount/intensity it provides information regarding the northern extent of the patterns observed. Along the southeastern African coastal margin, Holocene pollen records have been recovered from Lake Eteza (Neumann et al., 2010) and the Mfabeni Peatland (Finch and Hill, 2008), but the resolution of these records is too low (sampling intervals exceed 500 yr in some portions of the records) for the level of analysis undertaken in this study. We instead use the $\delta^{13}C$ record from the Mfabeni Peatland, which provides a higher-resolution measure of C_3 (primarily trees and shrubs) versus C_4 (primarily tropical drought-adapted grasses) vegetation and has been interpreted as relating to general changes in humidity during the Holocene (Baker et al., 2014). While general, this index of vegetation change is similar to the interpretive basis of the Mfabeni and Lake Eteza pollen records, and the patterns of change observed in the records are similar. From the southern Cape coast, the high-resolution pollen record from Eilandvlei provides valuable insight into regional hydroclimatic conditions, with changes in afrotemperate taxa being strongly linked to changes in humidity (Quick et al., 2018). Inland of Eilandvlei, 130 km to the northwest in the Groot Swartberg mountains, rock hyrax middens from Seweweekspoort have provided a detailed $\delta^{15}N$ record, reflecting changes in hydroclimate over the last 22,000 yr (Chase et al., 2013, 2017). While other records do exist from this region of southern Africa—such as those recovered from Groenvlei (Martin, 1968) and Rietvlei-Stillbaai (Quick et al., 2015)—and results do share similarities with the Eilandvlei record (see Quick et al., 2018), their continuity, resolution, chronologic control, and/or significance in terms of hydroclimatic variability limit their suitability for this study (see Deacon and Lancaster [1988], Chase and Meadows [2007], and Scott et al. [2012] for further information).

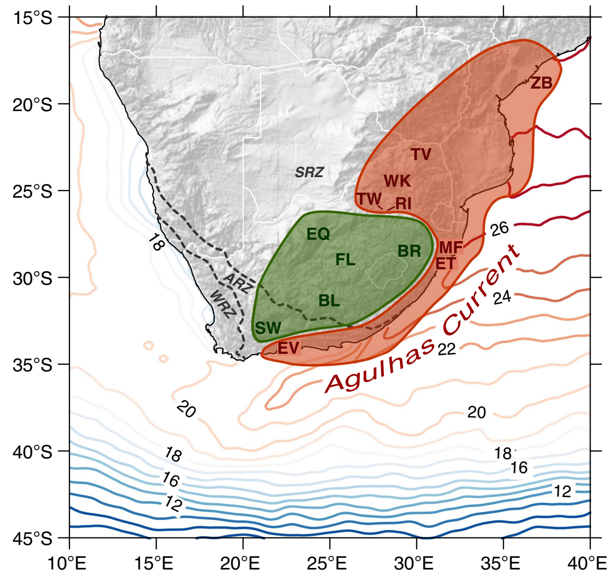

Figure 1. Map of southern Africa showing sea-surface temperature isolines (°C), the extent of the southern African winter rainfall zone (WRZ), aseasonal rainfall zone (ARZ), and summer rainfall zone (SRZ) (sensu Chase and Meadows, 2007), and the location of the sites considered in this study. They are: the palaeoenvironmental sites used for the reconstruction (Chevalier and Chase, 2015) of northern summer rainfall zone climates (Tate Vondo [TV; Scott, 1987a], Wonderkrater [WK; Scott, 1982], Tswaing Crater [TW; Scott, 1999; Metwally et al., 2014], and Rietvlei [RI; Scott and Vogel, 1983]); southern-central summer rainfall zone climates (Braamhoek [BR; Norström et al., 2009], Florisbad [FL; Scott and Nyakale, 2002], Equus Cave [EQ; Scott, 1987b], and Blydefontein [BL; Scott et al., 2005] according to Chevalier and Chase [2015]); the GeoB9307-3 marine core (ZB; Schefuß et al., 2011); Mfabeni Peatland (MF; Baker et al., 2014); Lake Eteza (ET; Neumann et al., 2010); Eilandvlei (EV; Quick et al., 2018); and Seweweekspoort (SW; Chase et al., 2017). Sites are colour coded to reflect similarities in climatic variability phasing, and regions (as defined by these findings) are described by shaded areas. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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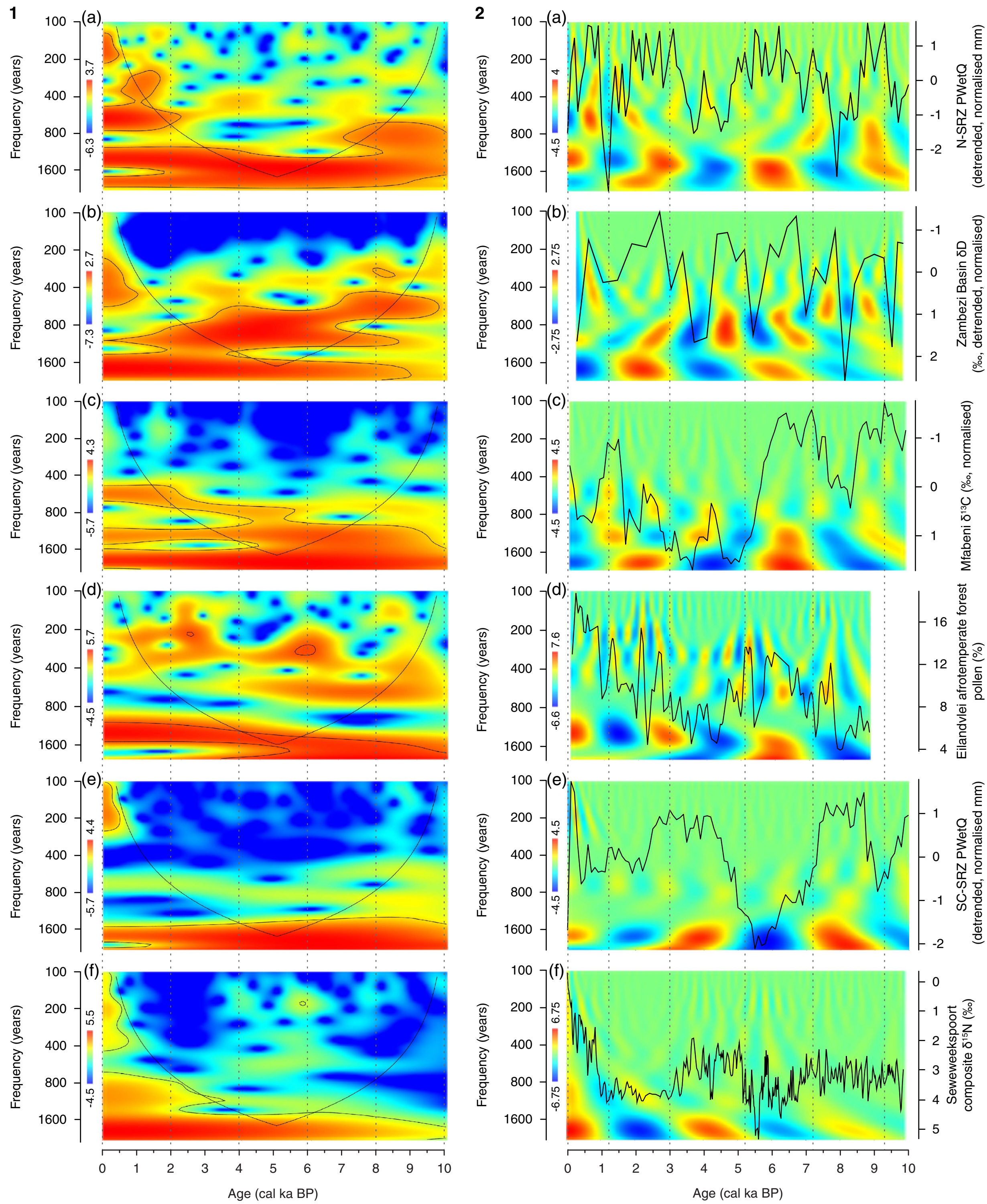

Figure 2. (color online) Comparison of the records considered for this study: (a) the northern summer rainfall zone (N-SRZ) and (e) southern-central summer rainfall zone (SC-SRZ) summer precipitation stacks (Chevalier and Chase, 2015), (b) the δD record from the GeoB9307-3 marine core (Schefuß et al., 2011), (c) the $\delta^{13}C$ record from the Mfabeni Peatland (Baker et al., 2014), (d) the Eilandvlei afrotemperate forest pollen record (Quick et al., 2018), and (f) the Seweweeksspoort $\delta^{15}N$ composite record (Chase et al., 2017). Each record has been analysed using continuous Morlet wavelet transforms. Panel 1 shows the local wavelet power spectrum for each record, with black lines indicating the cone of influence to show where boundary effects are present and the regions of greater than 95% confidence using a white-noise model. Panel 2 highlights the real-value signal power at different time scales. In this paper, we are considering the common millennial-scale variability identified at >1600 yr frequencies, which highlights an antiphase relationship between tropical and coastal sites (panels a–d) and those from the interior (panels e and f). Each record has been oriented according to interpretations of aridity, with "wetter" conditions towards the top of the graph and with higher real-value signal power.

DEFINING MILLENNIAL-SCALE CLIMATIC VARIABILITY IN THE STUDY REGION

As we are concerned here with the mechanistic relationships between sites/regions, we focus primarily on the direction and timing of change rather than amplitude. To highlight this clearly, we have removed low-frequency multimillennial/orbital-scale trends (cubic polynomial) from the SRZ stacks and the Zambezi Basin record, as they are dominated by a signal linked to direct insolation forcing during the Holocene (Schefuß et al., 2011; Chevalier and Chase, 2015). For this study, we have also removed the pollen records from the coastal sites of Lake Eteza and the Mfabeni Peatland from the SC-SRZ stack, as defined by Chevalier and Chase (2015), to more clearly differentiate between coastal and interior signals. Chronologies for all records presented were established by the original authors using Bacon (Blaauw and Christen, 2011) and the SHCal13 (Hogg et al., 2013) or Marine13 (Reimer et al., 2013) calibration data. We have updated the Mfabeni Peatland and Zambezi Basin records using these same calibration data to ensure comparability.

To identify patterns of millennial-scale climatic variability within the Holocene, we have used continuous Morlet wavelet transforms (Torrence and Compo, 1998) (Fig. 2). Before analysis, each record was linearly interpolated to a common 100 yr resolution for analytical purposes, but the differing sampling resolutions limit the scope of robust comparisons to lower, millennial-scale frequencies. While the variable sampling resolutions result in the appearance of significant bands at different frequencies, we focus here on the common bands of high significance in the 1600 to 2400 yr frequencies to distil millennial-scale variability (Fig. 2, panel 1). Real-value wavelets show positive or negative oscillations in the data, and strength of the anomalies at these frequencies (Fig. 2, panel 2). These results indicate that common cycles of variability are identifiable in records from across the study region, and anomalies can be seen to manifest between approximately 0–1.2 cal ka BP, 1.2–3 cal ka BP, 3–5.2 cal ka BP, 5.2–7.2 cal ka BP, and 7.2–9.3 cal ka BP. These signals have been isolated in Figure 3, which plots the average signal strength and sign for the 1600 to 2400 yr frequencies for each record across the Holocene.

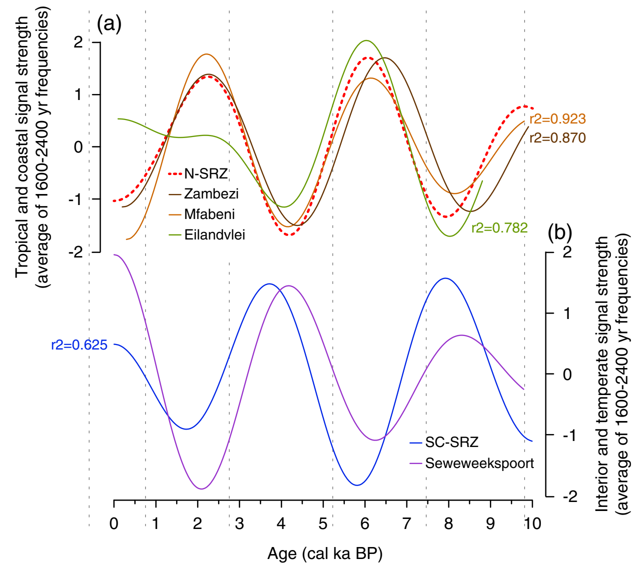

Figure 3. (color online) Comparison of millennial-scale signals (1600–2400 yr frequencies) from (a) the northern summer rainfall zone (N-SRZ; Chevalier and Chase, 2015), Zambezi Basin (Schefuß et al., 2011), Mfabeni Peatland (Baker et al., 2014), and Eilandvlei (Quick et al., 2018); and (b) the southern-central summer rainfall zone (SC-SRZ; Chevalier and Chase, 2015) and Seweweekspoort (Chase et al., 2017). In panel a, correlations are calculated relative to the N-SRZ signal, which is considered to be most representative of tropical variability in the region.

DISCUSSION

When considered together, records from the study region indicate a strong antiphase relationship between the N-SRZ and the SC-SRZ over millennial time scales (Figs. 2a and e, and 3), and the pattern exhibited in the SC-SRZ extends well into the ARZ. It has been proposed that this latter phenomenon may be determined by the interaction between temperate and tropical systems to create composite synoptic systems such as tropical–temperate troughs (Chase et al., 2017).

Of particular interest is the strong dipole that has been revealed to exist within the ARZ between Eilandvlei (Quick et al., 2018) on the southern Cape coast and Seweweekspoort (Chase et al., 2013, 2017) (Fig. 2). Considering their position and proximity, it would be expected that they share similar climatic histories. Instead, for most of the Holocene, the progression of hydroclimatic anomalies are strongly opposed between the sites. The differences between these sites are unlikely to be related to Seweweekspoort's position closer to the WRZ, as a similarly antiphase relationship can be observed between the Eilandvlei record and the SC-SRZ stack (Figs. 2 and 3).

We propose that the similarities in phasing between Eilandvlei and the N-SRZ are the result of the transport of warm waters along the east coast via the Agulhas Current, which, by modifying the surface heat flux and the onshore flow of moist air (Jury et al., 1993, 1997), effectively propagates a tropical climate signal along its zone of influence. As suggested earlier, the influence of this vector is apparently both strong and highly localized. While its resolution precludes it from the methods of analysis employed here, analyses of the Lake Eteza pollen record indicate distinct similarities with the Eilandvlei data, supporting this finding (Fig. 4).

The consideration of the interior-coastal dipole may thus be critical when either (1) extrapolating results from coastal sites to understand broader palaeoenvironmental conditions across the subcontinent or (2) drawing on data from non-coastal sites to establish a context for the rich archaeological sites of the southern Cape coastal region (Klein, 1975; Henshilwood et al., 2002; Marean, 2010). However, at this stage, the observation of this phenomenon is restricted to those few records of sufficient resolution and palaeoclimatic

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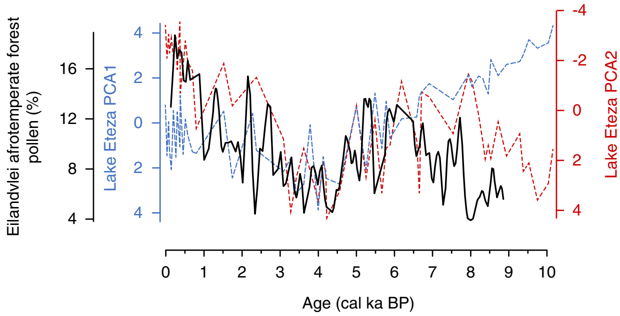

Figure 4. (color online) Comparison of Eilandvlei afrotemperate pollen percentages (Quick et al., 2018) with PCA1 and PCA2 from the Lake Eteza pollen record (Neumann et al., 2010). Each record has been oriented according to interpretations of aridity, with "wetter" conditions towards the top of the graph.

significance that have been recovered from the southern Cape coastal region. Thus, several key questions await the recovery of suitable records:

1. What is the spatial extent of the dominant Agulhas influence? Similarities between records from Mfabeni (Baker et al., 2014) and Eilandvlei (Quick et al., 2018) (Figs. 2, 3, and 4) may indicate that the Agulhas has a strong influence along the whole of the southeastern South African coast, but confirmation will require the recovery of further records from the region between these sites. Further, it may be predicted that the signal observed at Eilandvlei will diminish to the west of Eilandvlei, towards the zone of Agulhas Current retroflection and the cooler waters of the Benguela Current (Lutjeharms and Van Ballegooyen, 1988; Jury et al., 1993), but better-resolved records from the southwestern Cape coast will be required to test this hypothesis.
2. Is the dominance of the Agulhas Current restricted to specific climate states? Even within the Holocene there are some indications that the localized influence of the Agulhas Current and the establishment of the coastal-interior dipole may be restricted to specific global boundary conditions. As an example, the strong relationship between the Eilandvlei and N-SRZ records at millennial time scales appears to break down over the last 2000 yr (Fig. 3). Recent work has shown that the dominant drivers of millennial-scale climate change across the interior may have changed significantly as global climates evolved from glacial to interglacial states (Chase et al., 2017). Considering changing spatial relationships in the earliest Holocene and the last millennium (Fig. 2), it may be that the coastal-interior dipole did not exist during the last glacial period, and it may not exist in the future. Here again, more records from the region are required to study these possibilities.
3. How might changes in sea-surface temperatures versus changes in the position, strength, and/or extent of Agulhas Current flow combine or counteract each other to modulate the degree of Agulhas influence on terrestrial environments? To some degree, a positive relationship exists between the temperature of the Agulhas Current and the strength and extent of its flow along the southern Cape coast. During glacial periods, the source regions for the Agulhas Current were cooler (Bard et al., 1997; Sonzogni et al., 1998; Caley et al., 2011) and the westward flow of the Agulhas may have been restricted as the subtropical front shifted equatorward (Rau et al., 2002; Peeters et al., 2004; Bard and Rickaby, 2009). At finer spatiotemporal scales, however, the relationship between temperature and flow, and the influence on the climates of the subcontinent may be significantly more complex (Cohen and Tyson, 1995), and it remains to be seen to what extent changes in the Agulhas Current's sea-surface temperatures may be applied as a proxy for coastal-zone humidity during periods not covered by the available records. To date, no sea-surface temperature records of sufficient resolution have been recovered from the region to adequately explore these dynamics.

CONCLUSIONS

Recent data from South Africa highlight the existence of a strong dipole in hydroclimatic conditions between interior and coastal regions of the southern Cape during the Holocene. The coastal signal appears to be highly localized, and observations of its spatial extent suggest that the Agulhas Current is a strong determinant of Holocene coastal climatic variability, operating to propagate climate change signals from the tropics to the southern Cape coast. Consideration of this mechanism is critical for understanding the extent to which data from interior or coastal sites may be extrapolated to understand or predict change in other regions of the subcontinent. Research targeting coastal and marine sites with the goal of obtaining high-resolution hydroclimatic and sea-surface temperature records extending into the last glacial period will allow for a clearer understanding of the stability and dynamics of the relationship observed during the Holocene. This is ISEM contribution no. 2018-112.

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