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Southern Hemisphere high-resolution palaeoclimate records of the last 2000 years

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Abstract

This study presents a comprehensive assessment of high-resolution Southern Hemisphere (SH) paleoarchives covering the last 2000 years. We identified 174 monthly to annually resolved climate proxy (tree ring, coral, ice core, documentary, speleothem and sedimentary) records from the Hemisphere. We assess the interannual and decadal sensitivity of each proxy record to large-scale circulation indices from the Pacific, Indian and Southern Ocean regions over the twentieth century. We then analyse the potential of this newly expanded palaeoclimate network to collectively represent predictands (sea surface temperature, sea level pressure, surface air temperature and precipitation) commonly used in climate reconstructions. The key dynamical centres-of-action of the equatorial Indo-Pacific are well captured by the palaeoclimate network, indicating that there is considerable reconstruction potential in this region, particularly in the post AD 1600 period when a number of long coral records are available. Current spatiotemporal gaps in data coverage and regions where significant potential for future proxy collection exists are discussed. We then highlight the need for new and extended records from key dynamical regions of the Southern Hemisphere. Although large-scale climate field reconstructions for the SH are in their infancy, we report that excellent progress in the development of regional proxies now makes plausible estimates of continental- to hemispheric-scale climate variations possible.

Keywords

last 2000 years, multiproxy, palaeoclimatology, proxy calibration, Southern Hemisphere

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Introduction

Quantifying climate fluctuations over the last 2000 years is essential for isolating natural climate variability from human-caused climate change. This period contains marked regional to global-scale variations in temperature, such as the 'Medieval Climate Anomaly', 'Little Ice Age' and late twentieth-century warming (Büntgen et al., 2011; Mann et al., 2009). As the last 2000 years contains the majority of the Earth's annually resolved palaeoclimate records, the period is an important 'test bed' for assessing changes high frequency changes in radiative forcing associated with natural solar and volcanic variations, and increases in anthropogenic greenhouse gas concentrations (Alley et al., 2007; Hegerl et al., 2011; Mann et al., 2005). Despite advances in estimating hemispheric and global mean temperature trends over the last 2000 years (Wahl et al., 2010), there are still considerable uncertainties in understanding regional responses to large-scale temperature changes from global radiative forcing (D'Arrigo et al., 2009b; Mann et al., 2009).

In the Intergovernmental Panel on Climate Change (IPCC)'s Fourth Assessment Report (AR4), Jansen et al. (2007) concluded that 'Average Northern Hemisphere temperatures during the second half of the 20th century were … likely (> 66% certainty) the highest in at least the past 1300 years'. Contrastingly, for the Southern Hemisphere (SH) and the tropics, they find that knowledge of climate variability over the past 1000–2000 years in these regions is still 'severely limited by the lack of palaeoclimate records' (Jansen et al., 2007). While a number of review papers dealing with high-resolution records of the past millennium have provided summaries of data, methodology and uncertainties (Jones and Mann, 2004; Jones et al., 1998, 2009), they offer limited insight into the availability and potential of records available from the Southern Hemisphere, instead emphasising the need to develop more climate proxies from the region.

The challenge of using a relatively sparse data network compared with the Northern Hemisphere's rich palaeoclimate archive may help explain the limited large-scale data synthesis efforts that have been developed for the region to date. This is compounded by the oceanic dominance of the Southern Hemisphere, which makes the collection of high-resolution palaeoclimate records in the remote, uninhabited regions around 45–65°S very difficult or indeed impossible. In contrast, the corresponding latitudinal band in the land-dominated Northern Hemisphere contains the majority of the region's terrestrial proxy records. Interestingly, at the lower latitudes from the equator to 30°S and 30°N, both hemispheres are likely to contain a comparable number of records.

In the IPCC's AR4, assessment for the Southern Hemisphere focused on four regional temperature reconstructions from South America, New Zealand and Australia using tree ring records or coarse resolution borehole estimates (Cook et al., 2000, 2002; Huang et al., 2000; Jansen et al., 2007; Villalba et al., 2003). Since then, further progress has been made using proxies from single and multiple archives (Duncan et al., 2010; Neukom et al., 2011). Aside from temperature reconstructions, there have been

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some attempts to reconstruct Southern Hemisphere-based circulation associated with the El Niño–Southern Oscillation (ENSO; Braganza et al., 2009; Evans et al., 2002; D'Arrigo et al., 2006b; McGregor et al., 2010; Wilson et al., 2010), Indian Ocean Dipole (IOD; Abram et al., 2008; Zinke et al., 2009) and Southern Annular Mode (SAM; Gong and Wang, 1999; Jones and Widmann, 2003; Moreno et al., 2009; Villalba et al., 1997b; Zhang et al., 2010). Fewer studies have focused on understanding decadal variability associated with the Interdecadal Pacific Oscillation (IPO; Linsley et al., 2008; McGregor et al., 2010). Most recently, a handful of multiproxy precipitation or river flow reconstructions from the Southern Hemisphere have emerged in response to regional water scarcity issues (Cullen and Grierson, 2009; D'Arrigo et al., 2009a; Gallant and Gergis, 2011; Gergis et al., 2011; Neukom et al., 2010).

It is still unclear how anthropogenic warming will influence interannual–decadal variability (Meehl et al., 2009) in ENSO, IOD, SAM and the IPO. Abram et al. (2008) report an increase in the frequency and strength of IOD events during the twentieth century, suggesting that this may reflect a redistribution of rainfall across the Indian Ocean consistent with anthropogenically forced model projections. Similarly, a link between warm global temperatures and enhanced La Niña conditions has been reported (Mann et al., 2009), with an overall trend toward increased large-scale ENSO variance in the late twentieth century (Braganza et al., 2009; McGregor et al., 2010). Regional changes in rainfall and temperature extremes associated with ENSO, the dominant circulation feature in the Southern Hemisphere, however, remain complex and poorly understood (Gergis et al., 2011; Nicholls, 2008; Nicholls et al., 2005). Thus, improved palaeoclimate reconstructions of the key circulation features influencing the Southern Hemisphere have the potential to improve our understanding of the long-term stability and low frequency variations of regional temperature and precipitation beyond the instrumental period.

In 2009, the International Geosphere–Biosphere Programme (IGBP)'s Past Global Changes (PAGES) developed the Regional 2k Network; a set of working groups to collect and process the best available proxy data to develop climate reconstructions in eight regions of the world (Newman et al., 2009). Of these groups, four incorporate the Southern Hemisphere regions of South America (LOTRED-SA), Australasia (Aus2k), Africa (Africa2k) and Antarctica (Antarctica2k). Given the importance of global circulation features like ENSO, IOD, SAM and the IPO, a concerted effort is now underway to consolidate existing high-resolution palaeoclimate records from these regions in time for the IPCC fifth assessment report (AR5) (Gergis et al., 2011; Neukom et al., 2010, 2011).

Ideally, we would reconstruct past climate variability in the Southern Hemisphere using local proxies registering regional climate variables with high fidelity. In reality, proxy availability in the region is sparse, historically leaving regional climate reconstructions often dependent on single proxy studies, or more recently, multiproxy analyses that exploit the strength and stability of teleconnection relationships with large-scale circulation features associated with the Pacific, Indian and Southern Oceans (Gergis et al., 2011; Villalba et al., 1997b).

Therefore, before developing large-scale multiproxy climate field reconstructions (CFR), it is helpful to reassess the climate sensitivity of individual proxy records against a common suite of instrumental data. This reassessment allows records to be considered for climate reconstructions other than the variable of interest published by the original investigators. This is particularly important in areas where a high covariabilty between variables may exist (e.g. high temperatures associated with low rainfall and high atmospheric pressure), or when using remote proxies responding to global circulation features like ENSO to derive regional climate variations (Allan et al., 1996). Exploiting these heterogeneous teleconnection signatures allows, for instance, a precipitation record from Antarctica to be used to deduce past changes in rainfall variability in southern Australia (Van Ommen and Morgan, 2010). Note, however, that the inclusion of proxies in more than one reconstruction may introduce circular reasoning in interpreting any apparent climate variations so should be approached cautiously.

When using remote proxies to infer regional climate variations it is essential to bear a number of interpretational caveats in mind. Any reconstruction of regional climate variations based on remote proxies can only capture the spatially coherent portion of the total variability related to large-scale circulation features such as ENSO, the IOD and SAM that influence the region. This assumes that the underlying dynamical properties influencing observed twentieth-century teleconnection patterns have remained stable over time, and are adequately captured by linear statistical techniques. Although not ideal, the combination of local and remote predictors in assessing regional variability is an approach that has been successfully applied in the palaeoclimate literature where insufficient local proxies are available (Neukom et al., 2011; Villalba et al., 1997b).

Aside from the early effort of Jones and Allan (1998), no comprehensive inventory of high-resolution proxy records from the Southern Hemisphere has been compiled. Information about individual proxy records, chronological issues and climate sensitivity is found in a series of disparate publications spanning a number of disciplines using various techniques. While a few publications have sought to consolidate information for a particular archive such as coral (Grottoli and Eakin, 2007; Lough, 2004) or ice core records (Russell and McGregor, 2010; Vimeux et al., 2009), they are often regional compilations that use a range of (non-comparable) statistical techniques. Such factors, along with the practical challenges of researchers collaborating over such a vast geographical area, have slowed the progress of large-scale consolidation of palaeoclimate records in the Southern Hemisphere.

The aim of this paper is to provide an overview of the existing high-resolution palaeoclimate records of the SH and to systematically assess their climate sensitivity and their potential for developing SH climate reconstructions over the past 2000 years. The objectives of this paper are to: (1) review the availability of monthly to annually resolved Southern Hemisphere proxy records; (2) assess proxy climate sensitivity to surface air temperature, precipitation, sea level pressure (SLP) and Sea Surface Temperature (SST) on annual and decadal timescales over the instrumental period, and (3) identify target 'proxy collection' regions needed to fill gaps in Southern Hemisphere climate field reconstructions.

Similar to Luterbacher et al.'s (2011) review for the Mediterranean region, the purpose of the current paper is to provide a consolidated review for researchers working in the region. While forthcoming work will present explicit climate reconstructions, here we focus on reassessing the existing palaeo records for multivariate climate sensitivity. Section 'A review of Southern Hemisphere palaeoarchives' provides an overview of high-resolution paleoclimate archives from the SH and their possibilities and limitations. In section 'Southern Hemisphere proxy data availability', we present the availability of records from each archive, and in section 'Climate sensitivity of the Southern Hemisphere proxy network' we assess the large-scale climate sensitivity of these records. In section 'Conclusions and recommendations', finally we draw our conclusions and present recommendations for future research.

A review of Southern Hemisphere palaeoarchives

Tree ring records

Tree ring records form the basis of most annually resolved multiproxy climate reconstructions (Jones and Mann, 2004). The mass replication inherent to dendrochronology improves chronological control by having a number of samples for any given year, negating dating uncertainties associated with single proxy measurements (Cook and Kairiukstis, 1990; Fritts, 1976). A number of tree species in the Southern Hemisphere achieve ages greater than 250 years, with a few in New Zealand, Australia and South America living up to 3500 years (Cook et al., 2000, 2002, 2006; Fowler, 2008; Fowler et al., 2008; Lara and Villalba, 1993). Typically, however, there are few long series available from living trees in the Southern Hemisphere that extend back in time, which results in most tree ring chronologies being developed from relatively young trees covering approximately the last 500 years. To bolster the availability of material covering the pre-AD 1500 period, 'subfossil' or archaeological wood entombed in swamps, fallen logs in forests and building timbers have all been used successfully in New Zealand, Australia and Argentina (Boswijk et al., 2006; Cook et al., 2006; Roig et al., 2001).

Most tree ring chronologies from the Southern Hemisphere are derived from the temperate mid-latitude forests. In New Zealand, after early exploratory work (LaMarche et al., 1979d), five main species have been used to develop multicentennial tree ring records: silver pine (*Lagarostrobus colensoi*), cedar (*Libocedrus bidwillii*), pink pine (*Halocarpus biformis*), silver beech (*Nothofagus menziesii*) and kauri (*Agathis australis*). These species have predominately been used to reconstruct temperature (Cook et al., 2002; D'Arrigo et al., 1995, 1998; Duncan et al., 2010; Norton and Palmer, 1992; Norton et al., 1989; Salinger et al., 1994; Xiong and Palmer, 2000), with fewer studies investigating atmospheric pressure (D'Arrigo et al., 2000; Fowler, 2005; Fowler et al., 2008; Salinger et al., 1994; Villalba et al., 1997b) and streamflow variations (Norton, 1987) using total ring width chronologies.

In Australia, the longest tree ring records come from the island of Tasmania, located approximately 42°S 147°E. The most remarkable is the Huon pine (*Lagarostrobos franklinii*), which has been used to reconstruct warm season temperature over the past 4136 years (Buckley et al., 1997; Cook et al., 1991, 1992, 2000). In recent years another long-lived native conifer, *Phyllocladus aspleniifolius* (celery top pine), has been shown to be temperature sensitive (Allen, 2002; Allen et al., 2001), representing potential to reconstruct temperatures for at least 500 years. Currently tree ring chronologies are also being developed using *Athrotaxis cupressoides* (Pencil Pine) *Athrotaxis selaginoides* (King Billy Pine) from a number of sites across Tasmania and may yield similarly valuable material in coming years (Allen et al., 2011).

On the Australian mainland, there has been recent success using *Callitris columellaris* from Western Australia to reconstruct precipitation change in the region since AD 1655 (Cullen and Grierson, 2009). The dominant genus on the continent, however, is *Eucalyptus,* which is notoriously difficult to cross-date (Brookhouse, 2006). Recently, some promising progress has been made in the Mount Baw Baw alpine region of Victoria where *Eucalyptus pauciflora* (snow gum) has been used to reconstruct streamflow back to the late eighteenth century (Brookhouse et al., 2008).

In equatorial regions, the major success of tropical dendrochonology has been the development of multicentennial chronologies from the Indonesian archipelago using *Tectona grandis* (D'Arrigo et al., 1994, 2008a, 2009a). These chronologies have been used to study Pacific and Indian Ocean interactions, monsoonal drought and reconstruct streamflow in this densely populated region (D'Arrigo et al., 2008a, 2009a). In Australia, recent research effort has yielded chronologies spanning the last 150 years from *Callitris intratropica* in the Northern Territory (Baker et al., 2008a; D'Arrigo et al., 2008b) and *Toona ciliata* in North Queensland (Heinrich et al., 2008). In Africa, *Pterocarpus angolensis* has been used to reconstruct tropical rainfall from Zimbabwe (Therrell et al., 2006), a first for the south of the continent. In South America, first chronologies from tropical regions extending prior to 1900 are now available (López and Villalba, 2010). Other promising work from Amazonia exists (e.g. Schöngart et al., 2005) but insufficient sample depth currently precludes these records from extended climate analysis. See Jones et al. (2009) for an overview of the potential of tropical dendroclimatology.

A recent review by Boninsegna et al. (2009) shows the immense progress that has been made in South American dendroclimatology over recent decades. Tree ring width chronologies from subtropical and temperate forests have been used to reconstruct temperature, precipitation, streamflow, and regional atmospheric circulation spanning 16–56°S along the Andes (Boninsegna et al., 2009) using a variety of different species. The longest is the landmark study by Lara and Villalba (1993) which presented a 3622 year summer temperature reconstruction from Chile using *Fitzroya cupressoides*. Perhaps some of the most important advances of recent years have been the development of *Polylepis tarapacana* from the ENSO-influenced Bolivian Altiplano region (Christie et al., 2009b; Solíz et al., 2009) and *Austrocedrus chiensis* from the Chilean–Argentinean boarder spanning the past 700 years (Christie et al., 2009a; Le Quesne et al., 2009). Records from subtropical South America (Ferrero and Villalba, 2009; Morales et al., 2004; Villalba et al., 1998b) and Patagonia (e.g. Aravena et al., 2002; Villalba et al., 1997b, 2003) show strong relations to not only local climate variations but also teleconnections patterns associated with large-scale circulation features such as the SAM and ENSO (Villalba, 2007).

There are various methods dendrochronologists use to remove biological growth signals from tree ring data in preparation for climate analysis. Commonly used techniques involve fitting an empirical growth curve using negative exponential, smoothing spline or pith–bark age estimation to detrend multiple tree ring series (Briffa and Jones, 1990; Cook and Peters, 1981; Esper et al., 2002; Fritts, 1976; Jones and Mann, 2004; Jones et al., 2009; Melvin and Briffa, 2008). Removing the expected biological growth signal from the observed tree ring measurements produces detrended or standardised tree ring indices suitable for statistical analysis. It is well recognised that the assembling of individual tree ring sequences of different lengths can limit the degree of low frequency climate information captured by the resultant master chronology (Cook et al., 1995). This 'segment length curse' means that care must be taken when standardising tree ring data explicitly for investigating climate variability on multicentennial timescales (Cook et al., 1995; Esper et al., 2002).

In this study we are only dealing with the calibration of tree ring data against 100 years of climate observations (i.e. relatively high frequency variations). As such, detailing the influence of tree ring standardisation techniques was considered beyond the scope of the current study. Instead the reader is directed to the extensive literature base where these issues of retaining medium–low frequency variations in tree ring data are discussed (Briffa and Jones, 1990; Cook and Peters, 1981; Esper et al., 2002; Fritts, 1976; Jones and Mann, 2004; Jones et al., 2009; Melvin and Briffa, 2008; Melvin et al., 2007).

Coral records

Corals are particularly useful in the Southern Hemisphere and at lower latitudes where they can provide proxy climate records from tropical and subtropical marine regions poorly represented by tree rings (Dunbar and Cole, 1999; Felis and Patzold, 2004; Gagan et al., 2000; Grottoli and Eakin, 2007; Lough, 2004, 2010). Although the vast majority of modern corals do not extend back beyond the early-mid seventeenth century, their primary advantage is that many have subannual resolution as far back as the early eighteenth century making seasonal analyses possible (Asami et al., 2005; Charles et al., 2003; Linsley et al., 2000b). High temporal resolution is essential for reconstructing specific circulation features associated with ENSO, the monsoon and wind-driven oceanic upwelling (Dunbar and Cole, 1999; Felis and Patzold, 2004; Gagan et al., 2000; Grottoli and Eakin, 2007;

Lough, 2004, 2010; Wilson et al., 2006). While the bulk of the multicentury records come from southwest and central Pacific islands (Grottoli and Eakin, 2007; Lough, 2004), there have been significant advances in the Indian Ocean coral science in the past decade (Abram et al., 2008; Cole et al., 2000; Pfeiffer and Dullo, 2006; Pfeiffer et al., 2004; Zinke et al., 2005, 2009).

Climate reconstructions from coral records typically rely on fluctuations in geochemical tracers recorded in coral skeletons. These are mostly based on measurements of stable oxygen isotope ratios that vary as a function of water temperature, hydrological processes, evaporation and the advection of water masses (Felis and Patzold, 2004; Gagan et al., 2000; Lough, 2010). In open ocean conditions where $\delta^{18}O$ is considered to be constant, changes in coral $\delta^{18}O$ levels reflect changes in sea surface temperature masses (Felis and Patzold, 2004; Gagan et al., 2000; Lough, 2010). In near-shore environments where land surface hydrological processes influence coral communities, coral $\delta^{18}O$ records changes in sea surface salinity, rainfall and runoff from coastal catchments (Gagan et al., 2000; Hendy et al., 2003; Isdale et al., 1998; Lough, 2004, 2007).

The carbon isotopic signal in corals is more complex to interpret climatically because of physiological processes that result in large isotopic fractionations (Dunbar and Cole, 1999). Often $\delta^{13}C$ correlates poorly with environmental variables and the signal can vary greatly between adjacent corals or even different sampling transects within a single core (Dunbar and Cole, 1999). At present it is doubtful whether carbon isotopes in corals can provide useful climate information, so here we exclude carbon isotope records from our analysis.

Aside from oxygen isotopes, Sr/Ca ratios or luminescent bands are the most common geochemical tracers in coral palaeoclimatology. The behaviour of strontium in aragonite is known to be predominately temperature-dependent so is commonly used as a more direct proxy for sea surface temperature (Dunbar and Cole, 1999; Gagan et al., 2000; Lough, 2010). Often coral $\delta^{18}O$ reflects a mixture of both salinity and temperature so looking at Sr/Ca ratios together with the oxygen isotope record allows the separation of these variables through the removal of the temperature component of the coral $\delta^{18}O$ variations calculated from the Sr/Ca signal (Felis and Patzold, 2004; Nurhati et al., 2011; Ren et al., 2002). There are fewer published long-term Sr/Ca records in part because of the analytical expense and time required to process samples (Lough, 2010). Another less common measure is the density of luminescent bands responding to freshwater flood pulses that provides very useful histories of rainfall and runoff variations from coastal catchments (Hendy et al., 2003; Isdale et al., 1998; Lough, 2007, 2010, 2011).

The majority of the 30 or so published long coral records of the SH available from the World Data Center for Palaeoclimatology are sampled from the coral genera *Porites* found in Pacific and Indian Ocean regions, and *Pavona* and *Platygyra* to a lesser extent (Felis and Patzold, 2004; Grottoli and Eakin, 2007; Lough, 2010). The ability of $\delta^{18}O$ and Sr/Ca ratios in the coral genera *Porites* and *Pavona* to monitor interannual climate fluctuations in the tropical Pacific region has been demonstrated with live coral specimens (Cole et al., 1993; Dunbar et al., 1994; Guilderson and Schrag, 1999; Urban et al., 2000) and fossil corals for time slices since the last interglacial (Correge et al., 2000; Gagan et al., 2004; McGregor and Gagan, 2004; Tudhope et al., 2001).

To date, most of the studies of past climate have used the coral genus *Porites* because it is abundant throughout the Indo–Pacific region and can be sampled at high temporal resolution because of its rapid growth rate of 8–24 mm/yr (Bagnato et al., 2004; Watanabe et al., 2003). However, at present, continuous geochemical records from *Porites* do not extend past approximately 300–400 years (Watanabe et al., 2003), with similar age barriers noted by studies using *Pavona* from the equatorial Pacific and the Caribbean (Watanabe et al., 2003).

Recently, studies based on the massive, annually banded coral *Diploastrea heliopera* that is known to live for up to 1000 years throughout the tropical Indian and Pacific Oceans have been reported (Bagnato et al., 2004; Damassa et al., 2006; Watanabe et al., 2003). *Diploastrea* is well preserved in late-Quaternary raised coral reefs within the Pacific warm pool regions of Indonesia, Papua New Guinea and Vanuatu representing significant opportunities for the development of long tropical palaeoclimate records (Watanabe et al., 2003). Individual colonies are known to grow 3–4 m high and could potentially double the typical time span of existing coral palaeoclimatic records (Watanabe et al., 2003). Linsley et al. (2008), however, caution that since the non-climatic components of the slow-growing species are still not as well understood as they are in *Porites, Diploastrea* records should be used cautiously in climatic analyses.

While many coral records have absolute annual chronologies, others typically have errors of around 1–2 years per century (Dunbar and Cole, 1999), with greater errors also reported (Dunbar et al., 1994). Dating typically involves successively counting the density bands back from the date of collection at the top of the coral, or is determined from the annual cycle of the measured isotope (Felis and Patzold, 2004; Hendy et al., 2003). Difficulties can arise due to changing growth orientation down the coral core and the three-dimensional structure of the coral skeleton which can produce artifacts in the x-radiograph such as multiple peaks and ambiguous banding patterns (Felis and Patzold, 2004; Hendy et al., 2003). Stable isotopic analysis is also commonly used to cross verify age estimates (Dunbar et al., 1994; Quinn et al., 1998).

Strict dating control is required to maintain the reliability of coral records and the multiproxy climate reconstructions to which they contribute (Ault et al., 2009; Evans et al., 2002; Mann et al., 2009; Wilson et al., 2006). Ideally, a more rigorous approach to coral dating accuracy, comparable with cross-dating techniques routinely used in dendroclimatology, would be desirable. Realistically, however, conservation issues associated with the sampling of multiple coral colonies from tropical areas are likely to be problematic. Nonetheless, multiple coral cores can be cross-dated like tree ring sequences and developed into replicated chronologies, reducing dating uncertainties associated with single core measurements (DeLong et al., 2007; Hendy et al., 2003; Lough, 2007, 2010, 2011).

While the practice of building composite coral chronologies is not as well developed as for tree rings, a number of very useful multicore reconstructions have been developed in recent years from Australia's Great Barrier Reef and other regions of the southwest Pacific (Hendy et al., 2003; Linsley et al., 2008; Lough, 2007, 2011). To extend records of tropical climate variability beyond the length of living corals, fossil coral sequences have been collected to provide 'floating chronologies' spanning the late Holocene and as far back as the last interglacial around 130 000 years ago (Abram et al., 2003; Cobb et al., 2003; Correge et al., 2000; Felis and Patzold, 2004; McGregor and Gagan, 2004; Tudhope et al., 2001).

Ice core records

Ice cores provide climate information over millennia from snow accumulating in the polar regions of the Southern Hemisphere and tropical–subtropical alpine environments (Jones and Mann, 2004; Jones et al., 2009). Ice core information is spatially complementary to that provided by either tree rings or corals, but it is available only over a very small fraction of the global surface (Fisher, 2002). Ice cores can provide several climate proxies, including the fraction of melting ice, the precipitation accumulation rate, and concentrations of various geochemical records such as oxygen isotopes that provide information about the atmospheric environment at the time of snow formation (Russell and McGregor, 2010; Thompson, 2000; Vimeux et al., 2009). Ice cores also contain cosmogenic isotopes of beryllium and volcanic dust, both providing sources of vital information regarding the past radiative forcing of climate (Fiedel et al., 1995; Shindell et al., 2003; Zielinski, 2000).

Annual dating in ice sequences is sometimes possible, but in practice it is often quite difficult (Jones and Mann, 2004; Jones et al., 2009). Use of stratigraphic markers, such as known volcanic dust events are also used in conjunction with isotopic indicators to help anchor any age model (Zielinski, 2000). Stacking of multiple annual ice core records can reduce the age model uncertainty in chronologies and reduce site specific variability (Fisher, 2002). One year's accumulation is usually made up by a number of discrete precipitation events. Particularly in regions with low snowfall, annual dating may not be possible and there is the potential for a substantial temporal (and seasonal) sampling bias. In regions where accumulation is high (e.g. Law Dome, Antarctica) or where a number of cores can be cross-dated like trees (e.g. Greenland), seasonal resolution may be possible (Goodwin et al., 2004; Thompson et al., 2006; Vinther et al., 2010). Given the increasing number of ice core records from western Antarctica, seasonal analyses and cross-dating approaches may substantially improve understanding of this region's climate variability.

One of the key features of the Southern Hemisphere is Antarctica, containing the largest ice mass on Earth. Given that a sparse network of meteorological station data is primarily available since the International Geophysical Year of 1957–1958 (Jones, 1990), the collection of ice core data from the continent is our only way of understanding its long-term climate variability. Palaeoclimate records from high latitudes are important for providing insight into the behaviour of hemispheric circulation features such as the SAM (Jones and Widmann, 2003; Marshall, 2003; Mayewski et al., 2004; Villalba et al., 1997b), linkages with tropical climate features such as ENSO (Fogt et al., 2010; Turner, 2004), and their association with mid-latitude regional rainfall variations (Arblaster and Meehl, 2006; Goodwin et al., 2004; Van Ommen and Morgan, 2010; White, 2000).

Since the mid 1980s, there has been considerable effort directed toward collecting ice core samples from Antarctica and the tropical glaciers of South America (Russell and McGregor, 2010; Thompson, 2000; Thompson et al., 2006; Vimeux et al., 2009). These records are important for understanding polar and high altitude climate variations in southern latitudes. Historically there has been a focus on sampling that targets long interglacial–glacial climate fluctuations (EPICA, 2004), however, in recent years there has been acknowledgement of the need to target shorter, high-resolution ice cores covering the past 200–2000 years through programs such as the International Trans-Antarctic Scientific Expedition (ITASE) and International Partnerships in Ice Core Science (IPICS; Goodwin et al., 2004; Mayewski et al., 2004; Schneider et al., 2006; Steig et al., 2005; Van Ommen and Morgan, 2010; Vimeux et al., 2009; Xiao et al., 2004).

Russell and McGregor (2010) provide a comprehensive review of the current availability and climate reconstructions of Southern Hemisphere atmospheric circulation from Antarctic ice cores. In summary, there are a limited number of annually resolved records currently available from the continent. There are ice cores drilled from Law Dome, Princess Elizabeth Island, Dronning Maud Land and Talos Dome in eastern Antarctica (Graf et al., 2002; Goodwin et al., 2004; Stenni et al., 2002; Taufetter et al., 2004; Van Ommen and Morgan, 2010; Van Ommen et al., 2004; Xiao et al., 2004), Siple Dome, Siple Station, Berkner Island and several cores from the ITASE project in West Antarctica (Mayewski et al., 2004; Mosley-Thompson et al., 1990; Mulvaney et al., 2002; Steig et al., 2005) and Dolleman Island, Dyer Plateau, Gomez and James Ross Island from the Antarctic Peninsula (Aristarain et al., 1990, 2004; Peel et al., 1988; Russell et al., 2006; Schneider et al., 2006; Steig et al., 2005; Thomas et al., 2008, 2009; Thompson et al., 1994).

Another recent review paper by Vimeux et al. (2009) summarises 30 years of tropical and mid-latitude ice core research from South America spanning the last millennium. Some of the ice core records from the tropical Andes cover several millennia (Huascaràn, Coropuna, Sajama; Vimeux et al., 2009), however provide annual resolution only at the top of the core in the most recent decades (Vimeux et al., 2009). The only exceptions are the records from Quelccaya and Illimani. The Quelccaya accumulation and $\delta^{18}O$ record from Peru covers the AD 488–2003 period (Thompson et al., 1984, 1985, 2006). New records from the Illimani ice cap in Bolivia cover the period 362–1998 (ammonium-record; Kellerhals et al., 2010) and 898–1998 (deuterium-record; Ramirez et al., 2003), both with reliable annual resolution back to about 1800. First records from the subtropical Andes (Mercedario and Tapado) and the Patagonian Icefields (San Valentin and Pio XI) indicate sensitivity of the sites to large-scale climate, but those records do not (yet) extend prior to the twentieth century (Bolius et al., 2006; Ginot et al., 2006; Vimeux et al., 2008, 2009)

Speleothem records

Cave systems respond to surface climate and environmental changes, because of local variations in soil and vegetation, different flow through the karst aquifer and differing responses to surface rainfall events (Ford and Willams, 2007; Genty et al., 2001). Cave deposits (speleothems) such as stalagmites, stalactites and flowstones are formed when calcium carbonate precipitates from groundwater seeping into limestone caves (Ford and Willams, 2007; Jones et al., 2009). Stable oxygen and carbon isotopes, and Sr/Ca and Ba/Ca trace element ratios sampled from speleothem calcite from Australia (Desmarchelier et al., 2006; Fischer and Treble, 2008; McDonald et al., 2004; Nott et al., 2007; Treble et al., 2005a, b), New Zealand (Ford and Willams, 2007; Lorrey et al., 2008; Williams et al., 2004, 2005), Africa (Brook et al., 1999; Holmgren et al., 1999), Indonesia (Griffiths et al., 2009), South America (Reuter et al., 2009) and Nuie (Rasbury and Aharon, 2006) have been used to investigate past precipitation, hydrological, cyclone and temperature variability.

Palaeoclimate studies focus on stalagmites whose growth patterns are more regular than other spelothems (Baker et al., 2008b). Growth rates vary between ~ 0.05 and 0.4 mm/yr and, in some instances, provide annual bands (Baker et al., 2008b). The combination of annual lamination counts and Uranium/Thorium-series (U/Th) dating may produce near-absolute chronologies suitable for high-resolution studies. Annual dating, however, presents a major challenge because even within the same cave, some speleothems can have different growth rates, temporal resolution, and idiosyncratic histories because of changes in drip pathways and drip position (Betancourt, 2002). Without replication, uncertainties associated with dating the speleothem by lamina counting and uranium series dating can be high, despite apparent annual resolution reported at many sites (Betancourt, 2002; Jones and Mann, 2004). As has been shown for coral records (DeLong et al., 2007; Lough, 2007, 2011), cross-dating against other samples from a given site may help resolve apparent dating uncertainties.

Typically the resolution of many speleothems is more likely to be subdecadal or multidecadal, particularly if growth hiatuses are present. Uncertainties in dating led Jones et al. (2009) to conclude that reliable comparison with higher resolution proxies such as tree rings, corals, ice cores and documentary records is not yet possible. Unfortunately, only two composite speleothem records from the SH were publically available at suitably high resolution for calibration with instrumental records. This is likely to reflect a combination of resolution issues and the lack of published records lodged with international data repositories (e.g. Brook et al., 1999; Nott et al., 2007). As such, only two cave records are included in this study.

Sedimentary records

In regions with high sedimentation rates, annually laminated (varved) freshwater and marine sediments can provide high-resolution proxy climate information (Jones and Mann, 2004). Varves are formed in environments with seasonally varying sedimentation, for example forced by seasonal peaks of meltwater discharge into closed-basin glacial lakes (Jones and Mann, 2004). New analytical techniques such as *in situ* reflectance spectroscopy allow development of subdecadally resolved records also from non-varved sediments (von Gunten et al., 2009). Owing to the limited number of these proxies, sedimentary records are rarely combined with tree ring, coral, ice core and documentary records in multiproxy high-resolution palaeoclimatology of the past millennium (Jones et al., 2009). Even in laminated lake sediments dating uncertainties over the last 2000 years are usually still in the range of several years to even decades (Boës and Fagel, 2008; Elbert et al., 2011). Once again, cross-dating using multiple cores may help improve reduce dating uncertainties and improve the climate signal.

Unfortunately, there are not many areas of the Southern Hemisphere where annual or near-annual sedimentary records currently meet these requirements and the data are publically available (Black et al., 2007; Boës and Fagel, 2008; Rein, 2007; von Gunten et al., 2009). While a small number of 'high resolution' (decadal to centennial) sedimentary records covering the last 1000 years are available from South America (Conroy et al., 2008; Haberzettl et al., 2007; Lamy et al., 2001; Mohtadi et al., 2007; Moreno et al., 2009; Moy et al., 2002, 2009; Piovano et al., 2009), Africa (Garcin et al., 2007; Johnson et al., 2001; Russell and Johnson, 2007; Stager et al., 1997; Verschuren et al., 2000), Indonesia (Langton et al., 2008; Oppo et al., 2009; Van Der Kaars et al., 2010), New Zealand (Eden and Page, 1998; Orpin et al., 2010; Page et al., 2010), Australia (Mooney, 1997; Moros et al., 2009; Skilbeck et al., 2005) and Antarctica (Verleyen et al., 2011), in practice they are better for independent decadal verification to preserve the chronological accuracy of the (still relatively small) absolutely dated network of high annual palaeoclimate records currently available from the Southern Hemisphere. There is great potential to use these lower resolution records to examine decadal–multidecadal low frequency climate variability alongside high resolution records as has been done for a handful of multiproxy studies (Mann et al., 2008, 2009; Moberg et al., 2005).

Documentary records

Documentary records are major sources of pre-instrumental climate variability in areas such as Europe and Asia with long written histories (Brazdil et al., 2005, 2010; Jones, 2008; Jones and Mann, 2004; Jones et al., 2009; Lamb, 1982; Pfister et al., 2008). These historical records include details of frost dates, droughts, floods, famines, crop yields, river height and phenological signals (Jones and Mann, 2004). Colonial records are particularly important in areas such as Africa, South America and Australia where long instrumental or evidence from natural climate archives is unavailable or underdeveloped (Gergis et al., 2009, 2010; Nash and Endfield, 2002, 2008; Nash and Grab, 2010; Nicholls, 1988; Prieto and García Herrera, 2009; Vogel, 1989). Increasingly, human accounts of past weather conditions are of interest for comparing past societies' response to climate extremes and variability to recent conditions (Gergis et al., 2010; Zhang et al., 2007).

Jones (2008) discusses how historical documentary information tends to emphasise extreme conditions (e.g. 'the coldest winter in living memory') as these events were the most noteworthy that deserved recording. Owing to their event-based nature, these records tend to represent mostly high frequency variations and usually cannot capture variability on frequencies lower than decadal timescales (Dobrovolny et al., 2010). There are also observer-dependent issues associated with qualitative data, so should be cross-checked with quantitative data such as weather observations, crop harvest dates or frost day counts wherever possible (Gergis et al., 2009, 2010; Jones, 2008; Lamb, 1982). To overcome these issues it is best to consult a number accounts from multiple independent records, ideally from primary source material rather than modern compilations, to ensure the reliability of the transcription and interpretation (Jones, 2008).

Calibration of documentary records is often achieved by using subjective scaling or classification schemes ranging from very cold to very warm or very wet to very dry (Brazdil et al., 2005, 2010; Glaser and Stangl, 2004; Pfister, 1999). Quantitative documentary series are then developed by assigning numerical values to the magnitude categories; for example, 'Very wet' could have a value of +3, 'wet' +2, 'above average' +1, and, 'normal' or 'average' a zero value (Brazdil et al., 2010; Glaser and Stangl, 2004; Pfister, 1999). In many instances, documentary series do not overlap extensively with instrumental weather records so cannot be calibrated and also cannot be used for quantitative reconstructions. A possible solution is to extend these records using 'pseudo-documentary' data derived from instrumental time series that mimic the properties of documentary records (Mann and Rutherford, 2002; Neukom et al., 2009; Pauling et al., 2003; Xoplaki et al., 2005).

Documentary-based reconstructions of large-scale phenomena such as the El Niño–Southern Oscillation have much wider importance, however care must be taken extrapolating regional teleconnection signatures for Pacific-basin wide ENSO signals (Gergis and Fowler, 2009; Gergis et al., 2006). Decades of research on documentary information from South America has produced various El Niño event chronologies (García-Herrera et al., 2008; Ortlieb, 2000; Quinn and Neal 1992; Quinn et al., 1987) and local rainfall histories from Argentina, Peru and Bolivia spanning the past few centuries (Neukom et al., 2009; Prieto and García Herrera, 2009). Although the majority of documentary records from the Southern Hemisphere come from South America and Africa, a rainfall chronology back to 1788 is currently being compiled for southeastern Australia (Gergis et al., 2009, 2010).

Early instrumental records

It is commonly believed that instrumental weather records only extend as far back as the founding of national meteorological services (Jones et al., 2009). However, in many parts of the Southern Hemisphere early colonial records contain a wealth of terrestrial climate data (Gergis et al., 2009; Jones et al., 2009; Nash and Endfield, 2008; Nash and Grab, 2010; Page et al., 2004). Although much of this information is still found in historical archives in paper format, there is considerable potential to rescue early instrumental observations for incorporation to global gridded data sets (Allan and Ansell, 2006; Compo et al., 2011; Page et al., 2004; Rayner et al., 2003). This is particularly important in the Southern Hemisphere where meteorological records from remote regions such as Antarctica or some Pacific island nations where instrumental observations begin or have only been digitised from the mid-twentieth century onward (Page et al., 2004).

Instrumental series are an essential part of palaeoclimatology as they provide the basis for calibrating proxy records (Jones et al., 2009). It is very uncommon, however, for the temperature, pressure and rainfall records to be homogeneous over their full length of record because of changes in site location, instruments, exposure and recording times (Böhm et al., 2010; Brunet et al., 2010; Jones et al., 2009; Nicholls et al., 1996; Trewin, 2010). To address these issues, a number of statistical techniques have been applied to homogenise early instrumental measurements, providing an extension of the global climate record (Jones et al., 2009;

Peterson and Vose, 1997; Trewin, 2010). Further work addressing these inhomogeneities may substantially improve the early part of the instrumental record throughout the hemisphere.

Early instrumental measurements recovered from ship logbooks have also been studied extensively to extend the global network of marine observations (Brohan et al., 2009; Garcia et al., 2001; García-Herrera et al., 2005; Woodruff et al., 2010; Worley et al., 2005). The two main data banks of global marine data are the International Comprehensive Ocean-Atmosphere Data Set (ICOADS; Woodruff et al., 2010), and the Climatological Database for the World's Oceans (CLIWOC; García-Herrera et al., 2005) that focused on the 1750–1850 period. Küttel et al. (2010) have shown that the combined CLIWOC–ICOADS record has large potential to improve climate field reconstructions from terrestrial records. Currently the coverage of early instrumental data from Southern Hemisphere locations of the Indian, Southern and Pacific Oceans is very sparse (García-Herrera et al., 2005), highlighting the urgency of recovering century-long marine observations from exploration, naval and merchant ships sailing through the southern latitudes of the hemisphere during the eighteenth and nineteenth centuries. In an attempt to address this global issue an international 'data rescue' initiative, Atmospheric Circulation Reconstructions over the Earth (ACRE), is now underway to recover terrestrial and marine observations from all regions including the Southern Hemisphere (Allan et al., 2011).

Southern Hemisphere proxy data availability

In this study we assess SH climate proxy records of potential use in high-resolution climate reconstructions covering the last 2000 years. Each record must:

- extend prior to 1900
- be calendar dated or have at least 70 age estimates in the 20th century
- extend beyond 1970 to allow sufficient overlap with instrumental records
- be accessible through public data bases or upon request from the original authors

Eight marine records from tropical sites up to 13° north of the equator were included in our proxy network as they display strong associations with tropical SH dynamics. Their inclusion allows us to work with the complete set of tropical marine records that currently fulfill the above criteria. Tree ring chronologies located relatively close together and displaying similar climate sensitivities were merged into composite chronologies to enhance the common climatic signal. The method used to develop regional composites and subsequent tree ring standardization is detailed in the supplementary material (SM, available online).

The above selection criteria identified the 174 proxy records presented in Figure 1 and Tables 1–4. Some of the records contain multiple climate proxies e.g. $\delta^{18}O$ and Sr/Ca in corals or stable isotopes, and chemical species or accumulation measurements in ice cores. Andean tree rings are by far the largest proxy group (63 records), most of them being regional composites. Note that all tree ring records matching our selection criteria are tree ring width measurements, reflecting the lack of tree ring density and isotopic chronologies currently available in the Southern Hemisphere. The most densely covered areas are the mid-latitudes between 35°S and 55°S, i.e. Tasmania, New Zealand and Patagonia, where the longest tree ring records are available. Other areas with relatively good data coverage are the western tropical Indian and Pacific Oceans, the Altiplano of the tropical Andes, subtropical northwestern Argentina and Western Antarctica (Figure 1).

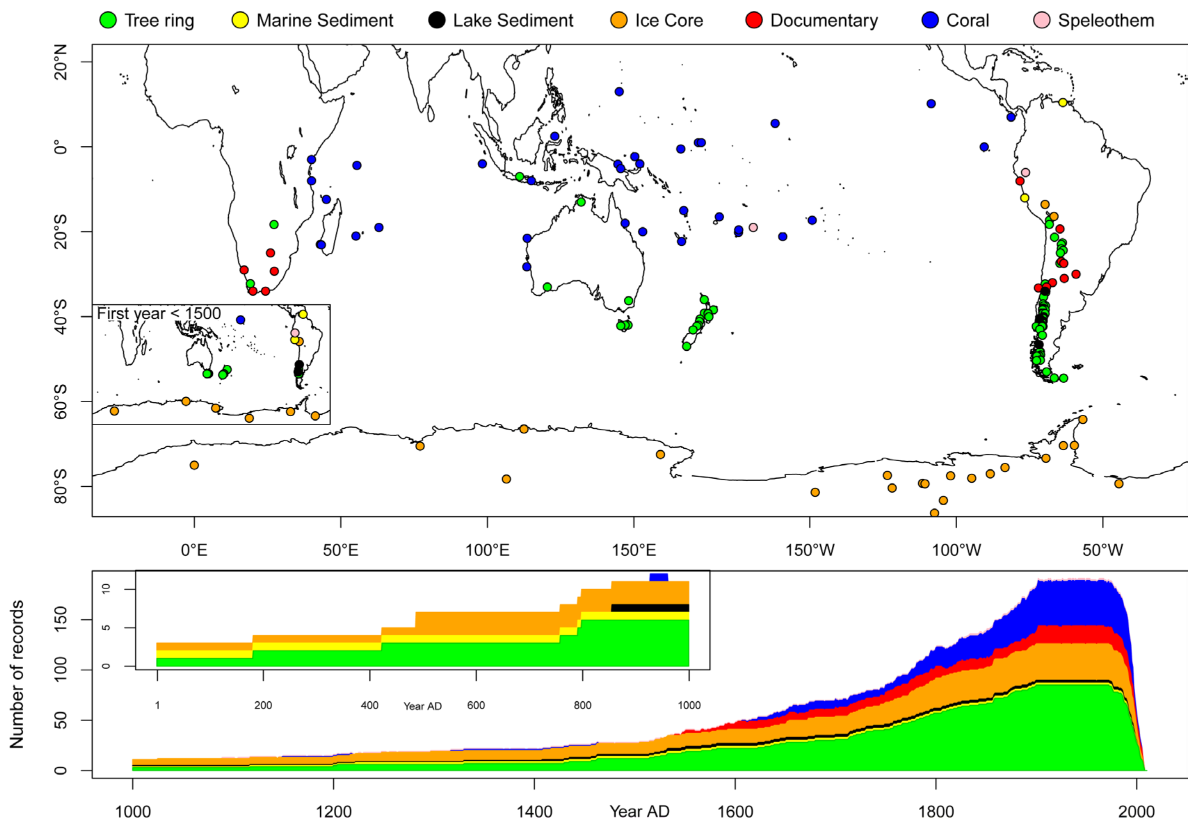

Figure 1. Top panel: Spatial distribution of the Southern Hemisphere high-resolution proxy network. Each circle represents a proxy site for each of the following archives: tree ring (green), marine sediment (yellow), lake sediment (black), ice core (orange), documentary (red), coral (blue) and speleothem (pink). Inset shows proxy records that extend prior to AD 1500. Lower panel: Temporal evolution of the number of available proxy time series from AD 1000–2010. Inset shows proxy record availability for the AD 1–999 period.

Table 1. Metadata of Southern Hemisphere tree ring records: longitude (°E), latitude (°N), altitude (m a.s.l.), start year (AD), end year (AD), species code, sample depth, number of subsites for composite records and reference(s). More details are provided in the supplementary material (available online).

Site name	Long.	Lat.	Alt.	Start	End	Species	*n*	Subs	Reference(s)
Africa									
Zimbabwe	27.33	−18.5	1000	1851	1996	PTAN	36		Therrell et al. (2006)
Die Bos, South Africa	19.2	−32.4		1763	1976	WICE	55		Dunwiddie and LaMarche (1980)
Australasia									
Teak Indonesia	111	−7		1771	2005	TEGR	239		D'Arrigo et al. (2006b)
Northern Territory Callitris	132	−13		1897	2006	CAIN	54		Baker et al. (2008a)
Western Australia Callitris	120.77	−33.03	300	1759	2005	CACO	62		Cullen and Grierson (2009)
Kauri NZ	174	−36	200	1589	2002	AGAU	527		Cook et al. (2006), Fowler et al. (2008)
Baw Baw Victoria	148.33	−36.42	2000	1792	2002	EUPA	223		Brookhouse et al. (2008)
Urewera NZ	177.2	−38.68	930	1442	1992	LIBI	68		Xiong and Palmer (2000)
North Island LIBI Composite 2	174.1	−39.27	1000	1671	1990	LIBI	129	2	Xiong and Palmer (2000)
Mangawhero NZ	175.48	−39.35	1000	1551	1994	LGCO	56		D'Arrigo et al. (2000)
North Island LIBI Composite 1	175.5	−39.5	1100	1522	1992	LIBI	235	5	Xiong and Palmer (2000)
Takapari NZ	175.98	−40.07	960	1530	1992	LIBI	63		Xiong and Palmer (2000)
Moa Park NZ	172.93	−40.93	1036	1634	1991	LIBI	49		Xiong and Palmer (2000)
Flanagans Hut NZ	172.6	−41.27	950	1780	1991	LIBI	33		Xiong and Palmer (2000)
CTP East Tasmania	148	−42	600	1431	1994	PHAS	165	2	Allen et al. (2001)
CTP West Tasmania	146	−42	600	1514	1998	PHAS	301	8	Allen et al. (2001), Allen (2002), LaMarche et al. (1979c)
Mount Read Tasmania	147	−42	600	−1444	1990	LGFR	317		Cook et al. (2000), Cook et al. (2006)
Pink Pine NZ	172	−42		1433	1999	HABI	356	7	Duncan et al. (2010)
Buckley's Chance Tasmania	145.85	−42.26	900	1458	1991	LGFR	84		Buckley et al. (1997)
Ahaura NZ	171.8	−42.38	244	1331	2009	LGCO	74		Cook et al. (2006), D'Arrigo et al. (2000)
Oroko Swamp NZ	170.28	−43.23	110	792	2009	LGCO	330		Cook et al. (2002)
Stewart Island NZ	168	−47	450	1724	1994	HABI	106	3	D'Arrigo et al. (1995), D'Arrigo et al. (2000)
South America									
ALT Composite 1	−69	−17.5	4300	1860	1993	POTA	77	3	Soliz et al. (2009)
ALT Composite 2	−69.08	−18.45	4730	1542	2002	POTA	78	2	Soliz et al. (2009), Christie et al.(2009b)
ALT Composite 3	−67.5	−21.5	4500	1630	2003	POTA	214	6	Argollo et al. (2004), Soliz et al. (2009), Morales et al. (2004)
La Meseda	−65.02	−23	1600	1826	1999	CELI	23		unpublished (R. Villalba, personal communication, 2007)
NWA Composite 1	−65	−23	1200	1858	2002	JGAU	35	2	Villalba et al. (1992)
NWA Composite 4	−65	−24	1750	1858	1999	CEAN	73	2	Villalba et al. (1992)
NWA Composite 2	−65	−24	2200	1818	1995	ALAC, CELI, JGAU	126	4	Villalba et al. (1992), Morales et al. (2004)
Rio Sala and Popayan	−64.6	−24.6	700	1881	2002	JGAU	39		Villalba et al. (1992)
NWA Composite 5	−65.5	−25	2000	1853	2002	JGAU	92	3	Villalba et al. (1992)
Dique Escaba	−65.78	−27.7	900	1887	1985	JGAU	24		Villalba et al. (1992)
El Asiento	−70.82	−32.48	1800	1280	1972	AUCH	65		LaMarche et al. (1979b)
Le Quesne precip recon	−70.5	−34	1700	1200	2000	AUCH	525	7	Le Quesne et al. (2006)
CAN Composite 1	−70.5	−34.5	1200	1520	1975	AUCH	165	3	LaMarche et al. (1979b)
Vilches	−71.03	−35.6	1530	1880	1996	NOPU	49		Lara et al. (2001)
Christie AUCH Composite	−71.3	−37	1135	1346	2004	AUCH	511	5	Christie et al. (2009a)
Huinganco	−70.6	−37.75	1400	1070	2000	AUCH	101		LaMarche et al. (1979a), Christie et al. (2009a)
CAN Composite 2	−71	−37.83	1530	1673	2006	ARAR	83	3	LaMarche et al. (1979a), Mundo et al. (2011)
CAN Composite 3	−71.25	−38	1570	1716	1975	ARAR	41	2	LaMarche et al. (1979a)
Volcan Lonquimay	−71.57	−38.38	1510	1718	1975	ARAR	47		LaMarche et al. (1979b)
CAN Composite 6	−71.5	−38.5	1400	1419	2006	ARAR	357	8	LaMarche et al. (1979a), Villalba (1990a), Mundo et al. (2011)
CAN Composite 5	−71.58	−38.62	1640	1822	1996	NOPU	76	2	Lara et al. (2001)
Pino Hachado	−70.75	−38.63	1400	1541	1974	ARAR	31		LaMarche et al. (1979a)
Conguillio (Lenga abajo)	−71.6	−38.63	1490	1774	1996	NOPU	55		Lara et al. (2001)
CAN Composite 4	−71.5	−39	1500	1812	1994	NOPU	120	4	Lara et al. (2001), Schmelter (2000)
CAN Composite 8	−71.17	−39.17	1125	1732	1989	AUCH	69	2	Villalba and Veblen (1997)
CAN Composite 31	−71.3	−39.2	1168	1700	2006	ARAR	83	2	Mundo et al. (2011)
Lago Rucachoroi	−71.17	−39.22	1330	1691	1976	AUCH	26		LaMarche et al. (1979a)
CAN Composite 9	−71.25	−39.33	1100	1596	2006	ARAR	283	6	LaMarche et al. (1979a), Mundo et al. (2011)
CAN Composite 10	−70.83	−39.5	1320	1596	1989	ARAR, AUCH	44	2	LaMarche et al. (1979a), Villalba and Veblen (1997)

Table 1. (Continued)

Site name	Long.	Lat.	Alt.	Start	End	Species	*n*	Subs	Reference(s)
CAN Composite 12	−71	−40	800	1658	1992	AUCH	175	5	LaMarche et al. (1979b), Villalba and Veblen (1997)
Chapelco	−71.23	−40.33	1700	1822	1985	NOPU	29		ITRDB series arge029
CAN Composite 11	−72.32	−40.62	805	1493	2002	PLUV	146	3	Lara et al. (2008)
Paso Cordova	−71.25	−40.67	1890	1760	1986	NOPU	37		ITRDB series arge050
CAN Composite 13	−71.25	−41	1000	1497	2003	AUCH	254	11	Villalba and Veblen (1997), Lara et al. (2008)
CAN Composite 16	−71.8	−41.13	1500	1845	1994	NOPU	152	2	Villalba et al. (1997a)
CAN Composite 14	−71.8	−41.13	1500	1869	1994	NOPU	152	3	Villalba et al. (1997a), Schmelter (2000)
CAN Composite 17	−71.83	−41.17	1700	1892	1994	NOPU	55	3	Villalba et al. (1997a), Schmelter (2000)
CAN Composite 15	−71.92	−41.17	1300	1566	1991	NOPU	123	4	Villalba et al. (1997a)
CAN Composite 19	−72.27	−41.17	1225	1865	1998	NOPU	130	2	Lara et al. (2005)
CAN Composite 18	−71.5	−41.25	1550	1634	1994	NOPU	113	3	Schmelter (2000)
CAN Composite 20	−71.83	−41.33	900	182	1995	FICU	184	4	Villalba (1990b), Lara et al. (2000)
CAN Composite 21	−71.5	−41.5	670	1796	1989	AUCH	38	2	Villalba and Veblen (1997)
CAN Composite 22	−71.75	−41.75	1300	1720	1997	NOPU	123	4	Villalba et al. (1998a), Schmelter (2000)
CAN Composite 23	−71.83	−42	1220	799	1993	FICU	60	2	Lara et al. (2000)
CAN Composite 24	−71.33	−42.5	765	1750	2002	AUCH	33	2	LaMarche et al. (1979a), Lara et al. (2008)
CAN Composite 26	−73.83	−42.5	750	1585	1987	FICU, PLUV	60	2	Villalba (1990a), Roig (1991)
CAN Composite 25	−71.83	−42.5	550	424	1990	FICU	137	3	Lara et al. (2000)
Santa Lucia	−72.5	−43	540	1646	1986	PLUV	60		Szeicz et al. (2000)
Cisnes	−71.7	−44.65	1100	1811	1997	NOPU	54		Lara et al. (2005)
Puesto Miraflores	−72.15	−48.45	1039	1759	1998	NOPU	23		Unpublished (R. Villalba, personal communication, 2010)
CAN Composite 32	−72.25	−48.45	945	1669	2007	NOPU	88	2	Villalba et al. (2003)
O Higgins	−72.5	−48.5	1200	1892	1999	NOPU	24		Lara et al. (2005)
CAN Composite 27	−72	−49	800	1699	1996	NOPU	418	5	Boninsegna et al. (1989), Aravena et al. (2002), Lara et al. (2005), Srur et al. (2008)
El Chalten bajo	−72.9	−49.37	760	1837	2003	NOPU	100		Srur et al. (2008)
CAN Composite 33	−73.33	−49.45	775	1694	2007	NOPU	125	3	Villalba et al. (2003), unpublished (R. Villalba, personal communication, 2010)
Torre Morena 4	−73.5	−49.5	658	1802	2007	NOPU	42		Unpublished (R. Villalba, personal communication, 2010)
Valle Ameghino	−72.17	−50.42	700	1743	1997	NOPU	41		Masiokas and Villalba (2004)
CAN Composite 34	−73.7	−50.6	461	1797	2007	NOPU	67	2	Unpublished (R. Villalba, personal communication, 2010)
Heim Morena Este	−73.7	−50.6	650	1807	2007	NOPU	33		Unpublished (R. Villalba, personal communication, 2010)
CAN Composite 30	−70	−53	220	1852	1984	NOPU	128	2	Aravena et al. (2002)
SAN Composite 5	−67.67	−54.75	600	1725	1984	NOPE, NOPU	131	4	Boninsegna et al. (1989)
Puerto Parryn	−64.37	−54.83	20	1859	1986	NOBE	25		Boninsegna et al. (1989)
SAN Composite 6	−64.33	−54.83	40	1785	1986	NOBE	49	2	Boninsegna et al. (1989)

Table 2. Metadata of Southern Hemisphere coral records: longitude (°E), latitude (°N), start year (AD), end year (AD), species, temporal resolution, proxy variable(s) and reference(s).

Site name	Longitude	Latitude	Start	End	Species	Resolution	Proxy	Reference(s)
Indian Ocean								
Malindi	40.00	−3.00	1801	1994	*Porites lutea*	Annual	$\delta^{18}O$	Cole et al. (2000)
Mafia, Tanzania	40.00	−8.00	1622	1998	*Diploastrea heliopora*	Monthly	$\delta^{18}O$	Damassa et al. (2006)
Ifaty, Madagascar 1	43.00	−23.00	1882	1994	*Porites lutea*	Annual	$\delta^{18}O$, Sr/Ca	Unpublished (J. Zinke, personal communication, 2010)
Ifaty, Madagascar 4	43.58	−23.15	1660	1995	*Porites lutea*	Bim., ann.	$\delta^{18}O$, Sr/Ca	Zinke et al. (2004), unpublished data, 2010
Mayotte	45.10	−12.65	1865	1993	*Porites solida*	Bimonthly	$\delta^{18}O$	Zinke et al. (2009)
La Reunion	55.25	−21.03	1832	1995	*Porites*	Bimonthly	$\delta^{18}O$	Pfeiffer et al. (2004)
Seychelles	55.80	−4.62	1846	1995	*Porites lutea*	Monthly	$\delta^{18}O$	Charles et al. (1997), Abram et al. (2008)
Rodrigues	63.00	−19.00	1789	2005	*Porites*	Ann., mon.	$\delta^{18}O$, Sr/Ca	Unpublished (J. Zinke, personal communication, 2010)
Mentawai West Sumatra	98.50	−4.00	1858	1997	*Porites*	Monthly	$\delta^{18}O$	Abram et al. (2008)
Abrolhos	113.77	−28.45	1794	1993	*Porites lutea*	Bimonthly	$\delta^{18}O$	Kuhnert et al. (1999)
Ningaloo	113.97	−21.90	1878	1995	*Porites lutea*	Seasonal	$\delta^{18}O$	Kuhnert et al. (2000)

(Continued)

Table 2. (Continued)

Site name	Longitude	Latitude	Start	End	Species	Resolution	Proxy	Reference(s)
Bali	115.00	−8.00	1783	1990	*Porites*	Monthly	$\delta^{18}O$	Charles et al. (2003)
Bunaken	123.00	2.80	1863	1990	*Porites*	Monthly	$\delta^{18}O$	Charles et al. (2003)
Pacific Ocean								
Laing	144.88	−4.15	1884	1993	*Porites*	Seasonal	$\delta^{18}O$	Tudhope et al. (2001)
Guam	145.00	13.00	1790	2000	*Porites lobata*	Monthly	$\delta^{18}O$	Asami et al. (2005)
Madang Lagoon	145.82	−5.22	1880	1993	*Porites*	Seasonal	$\delta^{18}O$	Tudhope et al. (2001)
Great Barrier Reef precip recon	147.00	−18.00	1639	1981	*Porites*	Annual	Luminescence	Lough (2011)
Kavieng, Papua New Guinea	150.50	−2.50	1823	1997	*Porites*	Monthly	Sr/Ca, Ba/Ca	Alibert and Kinsley (2008a,b)
Rabaul	152.00	−4.00	1867	1997	*Porites*	Monthly	$\delta^{18}O$, Sr/Ca	Quinn et al. (2006)
Abraham	153.00	−20.00	1638	1983	*Porites*	Annual	$\delta^{18}O$	Druffel and Griffin (1999)
Nauru	166.00	−0.83	1897	1995	*Porites lutea*	Seasonal	$\delta^{18}O$	Guilderson and Schrag (1999)
Amedee New Caledonia	166.45	−22.48	1657	1992	*Porites lutea*	Seasonal	$\delta^{18}O$	Quinn et al. (1998)
Vanuatu	167.00	−15.00	1806	1979	*Platygya*	Annual	$\delta^{18}O$	Quinn et al (1993)
Tarawa	172.00	1.00	1893	1989	*Hydnophora microconos*	Monthly	$\delta^{18}O$	Cole et al. (1993)
Maiana	173.00	1.00	1840	1994	*Porites* spp.	Bimonthly	$\delta^{18}O$	Urban et al. (2000)
Fiji 1F	179.23	−16.82	1780	1997	*Porites lutea*	Monthly	$\delta^{18}O$, Sr/Ca	Linsley et al. (2004)
Fiji AB	179.23	−16.82	1617	2001	*Porites lutea*	8/year	$\delta^{18}O$	Linsley et al. (2006)
Savusavu, Fiji	179.23	−16.82	1776	2001	*Diploastrea heliopora*	Annual	$\delta^{18}O$	Bagnato et al. (2005)
Tonga TNI2	−174.82	−20.27	1849	2004	*Porites lutea*	8/year	$\delta^{18}O$	Unpublished (B Linsley, personal communication, 2011)
Tonga TH1	−174.72	−19.93	1794	2004	*Porites lutea*	Annual	$\delta^{18}O$	Unpublished (B Linsley, personal communication, 2011)
Palmyra Island	−162.13	5.87	1886[a]	1998	*Porites*	Monthly	$\delta^{18}O$, Sr/Ca	Cobb et al. (2003), Nurhati et al. (2011)
Rarotonga 3R	−159.83	−21.23	1874	2000	*Porites*	Seasonal	$\delta^{18}O$	Linsley et al. (2006),Linsley et al. (2008)
Rarotonga	−159.83	−21.23	1761	1996	*Porites*	Seas., mon.	$\delta^{18}O$, Sr/Ca	Linsley et al. (2006),Linsley et al. (2008)
Moorea	−149.83	−17.50	1852	1990	*Porites lutea*	Annual	$\delta^{18}O$	Boiseau et al. (1999)
Clipperton Atoll	−109.22	10.30	1893	1994	*Porites lobata*	Monthly	$\delta^{18}O$	Linsley et al. (2000a)
Urvina, Galapagos Islands	−91.23	−0.03	1607	1981	*Pavona clavus*	Annual	$\delta^{18}O$	Dunbar et al. (1994)
Secas	−82.05	7.00	1707	1983	*Porites*	Seasonal	$\delta^{18}O$	Linsley et al. (1994)

[a]Non-continuous fossil $\delta^{18}O$ sequences extend back to AD 928

Table 3. Metadata of the Southern Hemisphere ice core records: longitude (°E), latitude (°N), altitude (m a.s.l.), start year (AD), end year (AD), proxy variable(s) and reference(s).

Site name	Longitude	Latitude	Altitude	Start	End	Proxy	Reference(s)
South America							
Quelccaya	−70.83	−13.93	5670	488	2003	$\delta^{18}O$, accumulation	Thompson et al. (1984, 2006)
Illimani	−67.78	−16.65	6300	362[a]	1998	δD, NH_3	Hoffmann et al.(2003), Ramirez et al. (2003), Kellerhals et al. (2010)
Antarctica							
James Ross Island	−58.13	−64.37	1640	1791	2000	δD	Aristarain et al. (2004)
Law Dome	112.80	−66.77	1370	179[b]	2005	$\delta^{18}O$, accumulation, chem. species.	Van Ommen and Morgan (2010), Unpublished (M. Curran, personal communication, 2010)
Dyer Plateau	−54.50	−70.66	2002	1505	1988	$\delta^{18}O$	Thompson et al. (1994)
Princess Elizabeth Land	77.1	−70.85	1850	1745	1996	$\delta^{18}O$, accumulation, chem. species.	Xiao et al. (2004)
Dolleman	−61.55	−70.97	398	1652	1992	$\delta^{18}O$, Cl, NO_3, SO_4, MSA	Russell et al. (2006)
Talos	159.10	−72.80	2316	1217	1996	δD	Stenni et al. (2002)
Gomez	−70.35	−73.60	1400	1854	2006	$\delta^{18}O$, accumulation	Thomas et al. (2008, 2009)
Dronning Maud Land	0.00	−75.00	2900	1025	1997	$\delta^{18}O$, accumulation, SO_4, Na	Graf et al. (2002), Taufetter et al. (2004)
Siple Station	−84.15	−75.92	1054	1417	1983	$\delta^{18}O$	Mosley–Thompson et al. (1990)
ITASE 2001 5	−89.14	−77.06	1239	1779	2000	$\delta^{18}O$	Schneider et al. (2005)
ITASE 2000 5	−124.00	−77.67	1828	1800	1999	$\delta^{18}O$	Schneider et al. (2005)
ITASE 2001 2	−102.91	−77.84	1336	1891	2001	$\delta^{18}O$	Steig et al. (2005)
ITASE 2000 4	−120.08	−78.08	2595	1794	1999	$\delta^{18}O$	Steig et al. (2005)

Table 3. (Continued)

Site name	Longitude	Latitude	Altitude	Start	End	Proxy	Reference(s)
ITASE 2001 3	−95.65	−78.12	1620	1858	2000	$\delta^{18}O$	Steig et al. (2005)
Vostok Pits	106.83	−78.45	3500	1774	1999	$\delta^{18}O$, accumulation	Ekaykin et al. (2004)
WDC05A	−112.13	−79.46	1759	1775	2004	Accumulation	Banta et al. (2008)
WDC05Q	−112.09	−79.47	1759	1521	2004	Accumulation	Banta et al. (2008)
Berkner Island	−45.72	−79.61	886	1000	1994	$\delta^{18}O$, accumulation	Mulvaney et al. (2002)
ITASE 2000 1	−111.38	−79.63	1791	1800	1999	$\delta^{18}O$, accumulation	Schneider et al. (2005), Banta et al. (2008)
ITASE 1999 1	−122.63	−80.62	1350	1723	1999	$\delta^{18}O$	Steig et al. (2005)
Siple Dome A	−148.81	−81.65	615	1000	1993	δD	unpublished (White and Steig, personal communication, 2010)
Siple Dome B	−148.81	−81.65	615	1654	1994	$\delta^{18}O$	unpublished (White and Steig, personal communication, 2010)
Siple Dome Na	−148.81	−81.65	615	0	1980	Na	Mayewski et al. (2004)
ITASE 2002 2	−104.99	−83.50	1957	1894	2001	$\delta^{18}O$	Jacobel et al. (2005)
ITASE 2002 4	−107.99	−86.50	2586	1593	1997	$\delta^{18}O$	Jacobel et al. (2005)

[a] Annual resolution only extends back to around AD 1800
[b] Only $\delta^{18}O$ goes back to AD 179, the other proxies are available back to the 13th century

Table 4. Metadata of the documentary, sediment and speleothem records: longitude (°E), latitude (°N), start year (AD), end year (AD), proxy variable and reference(s).

Site name	Longitude	Latitude	Start	End	Proxy	Reference(s)
Documentary – Africa						
Southern Kalahari precipitaition[a]	26.00	−25.00	1815	2002	Historical documents	Nash and Endfield (2008)
Namaqualand precipitaition[a]	17.00	−29.00	1817	1997	Historical documents	Kelso and Vogel (2007)
Lesotho precipitaition[a]	27.50	−29.50	1824	1994	Historical documents	Nash and Grab (2010)
Eastern Cape South Africa precipitaition[a]	24.50	−34.00	1821	2007	Historical documents	Vogel (1989)
Southern Cape South Africa precipitaition[a]	20.00	−34.00	1821	1996	Historical documents	Vogel (1989)
Documentary – South America						
Peru ENSO index	−79.02	−8.10	1550	1990	Historical documents	Garcia–Herrera et al. (2008), Quinn and Neal (1992)
Potosi precipitation[a]	−65.75	−19.58	1585	2005	Historical documents	Gioda and Prieto (1999)
Rio Sali / Rio Dulce streamflow[a]	−65.00	−27.00	1750	1977	Historical documents	Herrera et al. (2003)
Tucuman precipitaition[a]	−65.00	−27.03	1548	2005	Historical documents	Prieto et al. (2000)
Santiago del Estero precipitaition[a]	−64.27	−27.77	1750	2005	Historical documents	Herrera et al. (2003)
Santa Fe and Corrientes precipitation[a]	−60.00	−30.00	1590	2006	Historical documents	Prieto (2007)
Rio Parana streamflow[a]	−60.00	−30.00	1590	1994	Historical documents	Prieto (2007)
Cordoba precipitaition[a]	−64.00	−31.00	1700	2005	Historical documents	Prieto and Herrera (2001)
Mendoza precipitaition	−68.00	−32.00	1600	1985	Historical documents	Prieto et al. (2000)
Rio Mendoza streamflow[a]	−68.00	−32.00	1601	2000	Historical documents	Prieto et al. (1999)
Central Andes snow depth	−70.00	−33.00	1760	1996	Historical documents	Neukom et al. (2009)
Central Andes snow occurrence	−70.00	−33.00	1885	1996	Historical documents	Prieto et al. (2001)
Santiago de Chile precipitaition[a]	−70.78	−33.38	1540	2006	Historical documents	Taulis (1934)
Lake Sediment						
Laguna Aculeo	−70.90	−33.83	856	1997	Pigment reflection	von Gunten et al. (2009)
Lago Puyehue	−72.45	−40.65	1408	1997	Varve thickness	Boes and Fagel (2008)
Lago Plomo	−72.87	−46.98	1530	2000	Mass accumulation rate	Elbert et al. (2011)
Marine Sediment						
106KL off Peruvian Coast	−77.67	−12.05	−13550	2000	Lithics concentration	Rein (2007)
Cariaco Basin	−64.77	10.75	1222	1990	Mg/Ca	Black et al. (2007)
Speleothem						
Avaiki Cave, Niue	−169.83	−19.00	1829	2001	Lamina thickness	Rasbury and Aharon (2006)
Cascayunga Cave, Peru	−77.20	−6.05	1089	2005	$\delta^{18}O$	Reuter et al. (2009)

[a] The documentary record ends in the nineteenth or early twentieth century and was extended to present using 'pseudo documentaries' (see supplementary material available online and Neukom et al. (2009).

The most striking lack of proxy records is found in most of Africa, central Australia, South America east of the Andes, the south Atlantic and Southern Oceans. These areas are mostly covered by desert, rainforest or oceanic ecosystems that limit the development of long and highly resolved proxy records. In some of these areas there may be considerable potential for the development of new proxies (e.g. Africa and eastern South America), whereas in other areas such as Central Australia, the South Atlantic and the Southern Ocean may never yield high-resolution palaeoclimate records. South America is the only region where various high resolution records from several different archives exist (Neukom et al., 2010, 2011), allowing multiple records to be assessed for seasonal sensitivity on high and low frequency timescales.

Only 14 records that match the above criteria extend back to the year 1000 or further (Figure 1, lower panel). These are the ice cores from Quelccaya, Siple Dome, Law Dome and Berkner Island, a marine sedimentary record from Peru, a lake sediment from Laguna Aculeo, the discontinuous coral record from Palmyra Island and some tree ring records from Tasmania, New Zealand and South America. Forty nine records are available in AD 1601 and, after this time, the number of records increases significantly. Most records end in the 1980s or early 1990s; 57 records extend to the year 2000 or beyond. There are only three (Antarctic ice core) records that cover the full 2000 year period.

Climate sensitivity of the Southern Hemisphere proxy network

Data and methods

To evaluate the large-scale climate sensitivity of the proxy records, we use SH circulation indices and gridded climate variables (SLP, SST, land surface air temperature and precipitation). The proxy–climate index comparisons were performed using a May–April year because ENSO phase changes often take place in the austral autumn (Karoly, 1989; Karoly and Vincent, 1998; Karoly et al., 1996; Trenberth and Hurrell, 1994) and the growing season of most SH trees extends over two calendar years during the austral summer. All coral records in monthly or bimonthly resolution were averaged based on May–April years. If $\delta^{18}O$ and Sr/Ca chronologies were available for the same site, both were used separately. For ice cores with different proxies available, we use the stable isotope value (δD or $\delta^{18}O$) along with other proxies that were found to have large-scale climate sensitivity reported by the original authors. This resulted in a total of 191 proxy time series for subsequent analysis.

In this study, we use the following circulation indices: the Southern Oscillation index (SOI; CRU data set, Allan et al., 1991) the NINO 3.4 tropical Pacific SST index (HadISST data set; Rayner et al., 2003), the Southern Annular Mode (SAM; Nan and Li, 2003) and the Indian Ocean Dipole (IOD; Dipole Mode Index calculated from the HadISST data set (Rayner et al., 2003) using the Saji et al. (1999) definition). Finally we use the Inter-decadal Pacific Oscillation (IPO; Folland et al., 2002; Power et al., 1999), which is a Pacific basin-wide index of the Mantua (1997) Pacific Decadal Oscillation (PDO) that takes in SST conditions in the southwest Pacific. All indices cover the full twentieth century except for the SAM index, which is only available after 1948.

To assess the potential of seasonal climate reconstructions, correlations with instrumental grids were calculated using Southern Hemisphere winter–spring (JJASON) and summer–autumn (DJFMAM) half years. For the gridded analyses we used the following data sets: HadISST (Rayner et al., 2003) SST on 1°×1° spatial resolution, HadSLP2r (Allan and Ansell, 2006) SLP on 5°×5° resolution and CRU TS 3.0 (updated from Mitchell and Jones, 2005) land surface air temperature (LSAT) and precipitation (PP) on 0.5°×0.5° resolution. The latter two data sets do not cover Antarctica. Since instrumental data from Antarctica are more sparse than elsewhere in the SH, we focus on the low- and mid-latitudes, but still analyse Antarctic ice cores to assess their teleconnectivity to lower latitudes. We use all grid cells with available data between 90°S and 20°N, enclosing the SH and core ENSO and IOD regions.

Spearman correlation coefficients between proxy records and all instrumental data were calculated over the 1901–2000 period (or where both series have overlapping data) after linearly detrending both the proxy and instrumental records over the twentieth century. The detrending was applied to remove long-term trends in the data that can inflate apparent statistical significance. Correlations were then recalculated after applying a decadal 'loess' filter that removed all frequencies higher than ten years. All 5% significance levels used herein were estimated based on Monte Carlo estimates from 3000 correlation coefficients of AR(1) noise time series with the same length and lag-1 autocorrelations as the original (filtered and unfiltered) proxy and instrumental time series.

To assess the stability of proxy–climate relationships, we calculated the correlations between each proxy record and the five climate indices over the three subperiods 1901–1933, 1934–1966, and 1967–2000. As the strongest sensitivity of some records may be shifted by one year, and some records were derived based on other annual definitions (e.g. calendar years), +1 and −1 year lag correlations were also calculated. The highest of the three values was then selected as the 'optimal' correlation. To assess the spatial sensitivity of the proxy records to each climate variables, the (detrended) records were correlated to all (detrended) cells of the instrumental grids for the austral summer-autumn (DJFMAM) and winter-spring (JJASON) half years over the 1901–2000 period at lags −1, 0 and +1.

Next we examine the potential importance of each location (y_{ij}) to the full SH domain (y). In this way we can identify 'centres-of-action' that may be dynamically important for modulating SH climate variations. To do this, we correlated each grid cell (y_{ij}) against all remaining cells in the domain (y) and determined its statistical significance. We then defined the latitude-weighted fraction of the statistically significant cells (as a percentage) as a metric to identify the relative importance of each grid cell in the full SH domain. Latitude weighting was calculated by multiplying the correlation of each grid cell with the cosine of the latitude of the grid cell. The sum of these products was then divided by the sum of the cosines for all grid cells. A cross-variable analysis was also performed to determine important regions of covariation of SH climate variables. The same method was used, except that each grid location (y_{ij}) was correlated against all other grid cells in the variable x domain. The four grids (SST, SLP, LSAT or PP) were treated as x after linear interpolation onto the same 5°×5° resolution grid using linear interpolation. Once again, all values were detrended prior to performing the calculations.

Similarly, we calculated the number of proxy records that are significantly correlated with each grid cell and the associated explained variance by the proxy records at each grid cell (as a percentage). For the latter calculation, we only selected the records with a significant correlation on both interannual and decadal timescales. We use an adjusted r^2 penalizing for lower degrees of freedom. Significance levels for the explained variance were again estimated using Monte Carlo simulations based on 191 AR(1) time series (equal to the number of proxy times series available).

Results and discussion

Proxy–Southern Hemisphere circulation correlations

Tables 5–8 (available online) show that the majority of records are significantly correlated to one or more SH circulation indices, indicating a response to large-scale circulation influencing the hemisphere. The association of tree ring records to the SH climate modes seems to be strongly dependent on the individual sites, i.e. there is not always spatial coherency among series from nearby sites, which is likely to reflect factors such as local topography and elevation. The exceptions are records from western Australasia and the northern North Island and southern South Island of New Zealand, which are strongly correlated to the SOI. In South America, most records from the Altiplano region are strongly influenced by ENSO indices (SOI and NINO3.4).

The coral records generally have the highest correlations of all archives, particularly on interannual timescales. For the decadal non-ENSO correlations, these records perform at similar levels to the other archives. The relatively direct influence of ocean temperatures on coral proxies is nicely illustrated by the strong and stable correlations of the Pacific coral records to the Pacific SST indices NINO3.4 and IPO on both interannual and decadal timescales. Tropical Andean ice cores show mostly good and remarkably stable correlations with ENSO and IPO indices. Interestingly, the Antarctic ice cores show generally better relationships to Pacific indices rather than to the high-latitude SAM, perhaps a reflection of the short length of this instrumental index. Many of the South American documentary records show significant correlations with ENSO. The generally low correlation of the documentary records on decadal timescales reflects the very white (stochastic) nature of documentary records, as they are event-based time series.

On interannual timescales, 74 proxies correlate significantly with the SOI, 71 with NINO3.4, 15 with SAM, and 43 with IOD. Coral records make up the majority of the ENSO-sensitive proxies; with a somewhat surprisingly large fraction of significant correlations seen in the Antarctic ice core records, compared with the terrestrial proxies from lower latitudes. The majority of SAM correlations are seen in the South American tree rings and Pacific coral records, contrasting to only three significantly correlated ice core records. A broad range of records from outside of the Indian Ocean basin show significant correlations with the IOD.

The number of significant correlations is notably lower using decadally filtered data and only four records show statistical significance with decadal SAM variations. However, these low numbers are also a consequence of the loss of degrees of freedom when using filtered data and the resulting increase of significance thresholds. This is particularly striking for the SAM with its short observational period (post 1948 only) leading to an average significance threshold of 0.55. Thirty six records show significant correlations with the low-frequency IPO index. The Pacific corals display the strongest and most stable correlations with low frequency SST fluctuations of all the archive groups.

Tables 5–8 show that a number of records show stronger correlations on decadal rather than interannual timescales (e.g. some ice core and tree ring records), suggesting that some records may be more useful for low frequency analyses because of dating resolution or lagged biological growth characteristics. Conversely, most coral and documentary records display stronger interannual correlations. The superscript numbers next to each correlation coefficient in Tables 5–7 indicate the subperiods for which the correlations are above the significance threshold. In some instances, the correlations are significant but not stable over time, which could indicate site-specific fluctuations or real variations in regional teleconnection patterns. These findings indicate that proxy selection for regional climate analyses must be done carefully, especially when proxies from remote teleconnection regions are included.

Proxy–climate field correlations

The left panels of Figures 2–5 illustrate teleconnectivity of climate variables in the SH. They show that SLP, SST and LSAT have strong spatial autocorrelations in large parts of the hemisphere. This indicates that a proxy record from a red-shaded area that has a strong local signal may be representative of variations in the broader SH domain. However, it must be noted that these strong correlations are partly due to the low number of observations available for the SH in all gridded data sets, especially at high latitudes and in the early part of the twentieth century where many grid cells are interpolated using a very small number of observations (Allan and Ansell, 2006; Mitchell and Jones, 2005; Rayner et al., 2003). Furthermore as the SLP and SST grids are based on EOF analysis this may artificially enhance the apparent spatial coherence (Allan and Ansell, 2006; Rayner et al., 2003). Owing to the very localised nature of precipitation, there are very few areas where spatially coherent signals over large parts of the SH can be observed (Figure 5). Equivalent maps for the decadally filtered results are provided in the supplementary material (available online).

Figure 6 is an integration of the inter-grid correlation analyses for all SLP, SST, land surface air temperature and precipitation

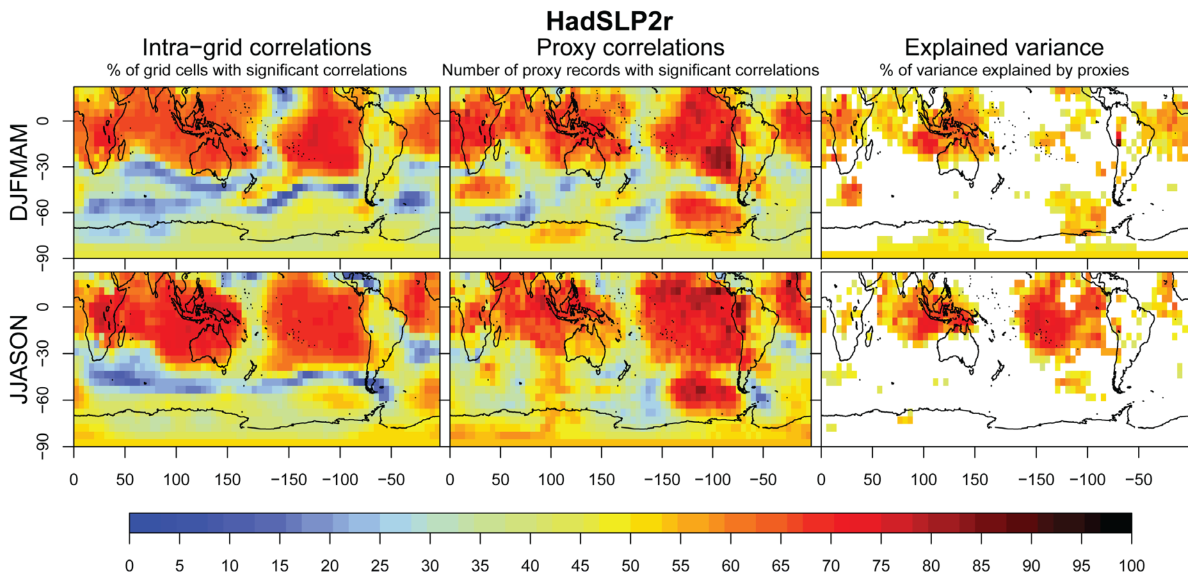

Figure 2. Summary maps for the HadSLP2r grid 1901–2006. Left panel: Latitude-weighted fraction (in %) of grid cells of the entire Southern Hemisphere domain that each individual grid cell is significantly (p<0.05) correlated with. Middle panel: Number of proxy records (out of a total of 191) that each grid cell correlates significantly with. Right panel: The fraction of variance at each grid cell that can be explained by the proxies (%). Only proxies with significant correlations on interannual and decadal timescales are included. Only significant results (p<0.05) are shaded. Top: Summer/autumn season (December–May); bottom: Winter/Spring season (June–November). All time series were detrended over the twentieth century prior to performing the calculations.

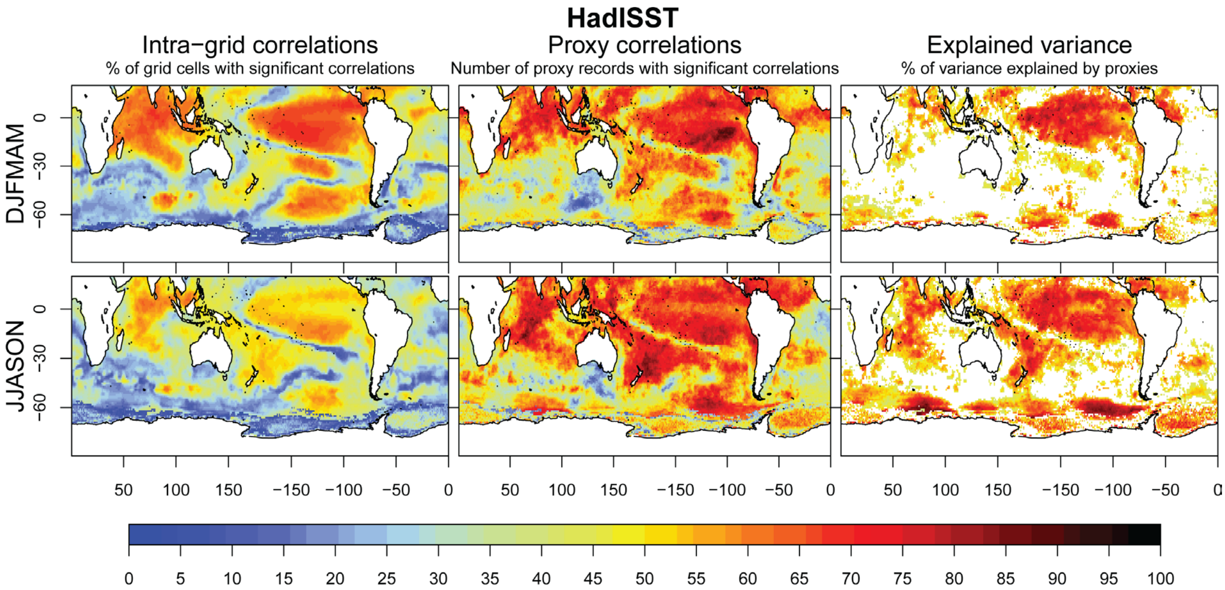

Figure 3. Same as Figure 2 but for the HadISST grid.

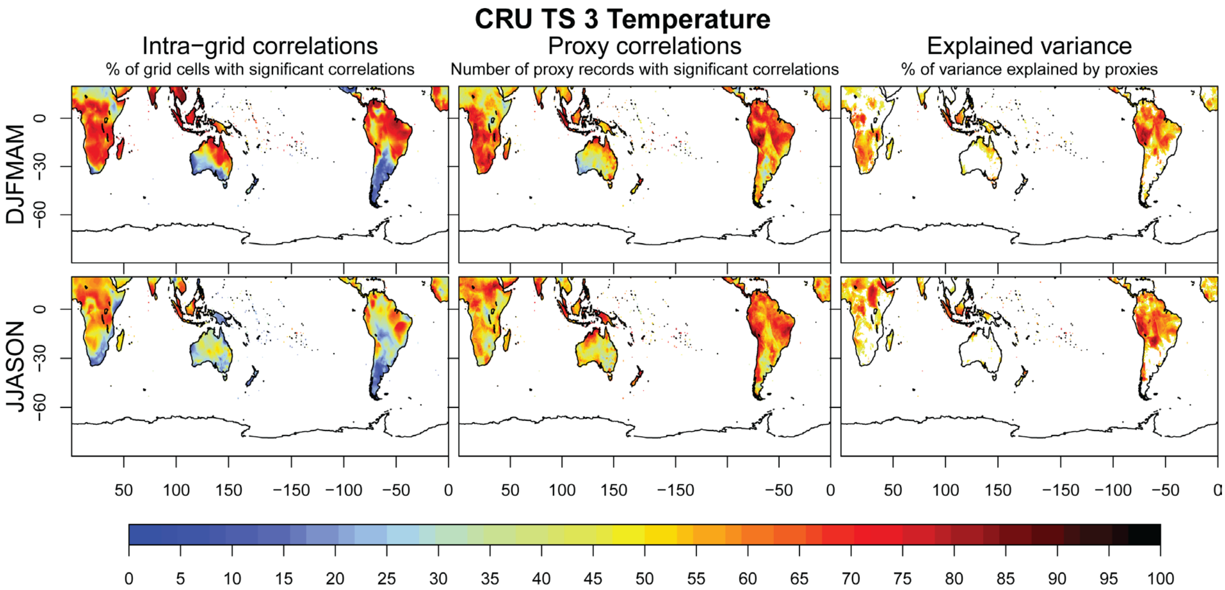

Figure 4. Same as Figure 2 but for the CRU TS 3.0 temperature grid.

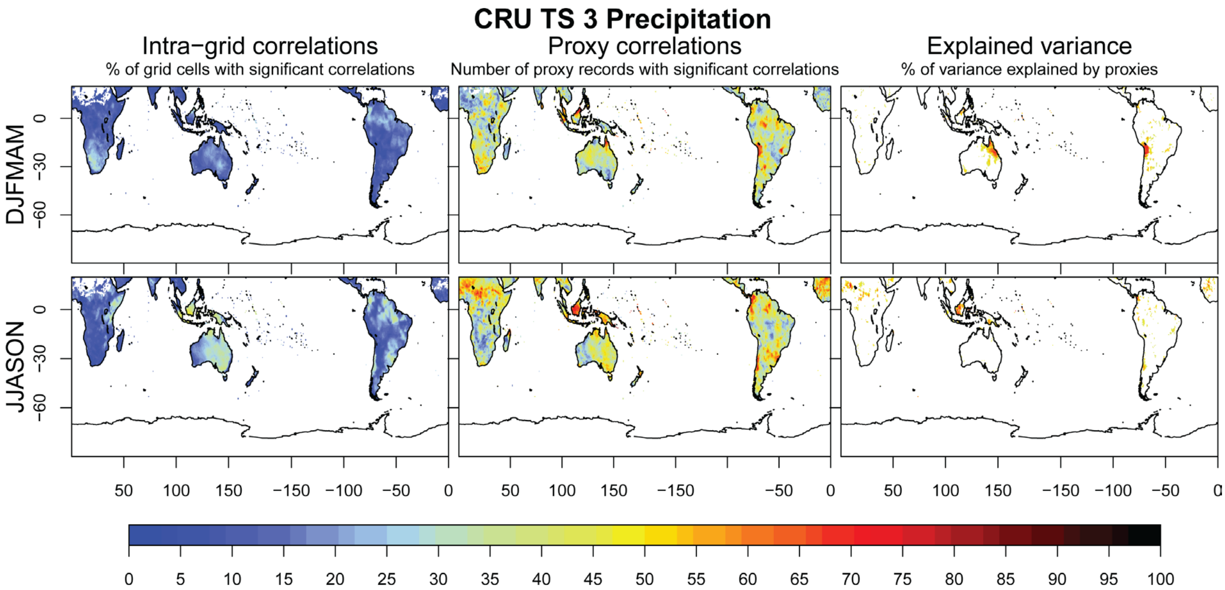

Figure 5. Same as Figure 2 but for the CRU TS 3.0 precipitation grid.

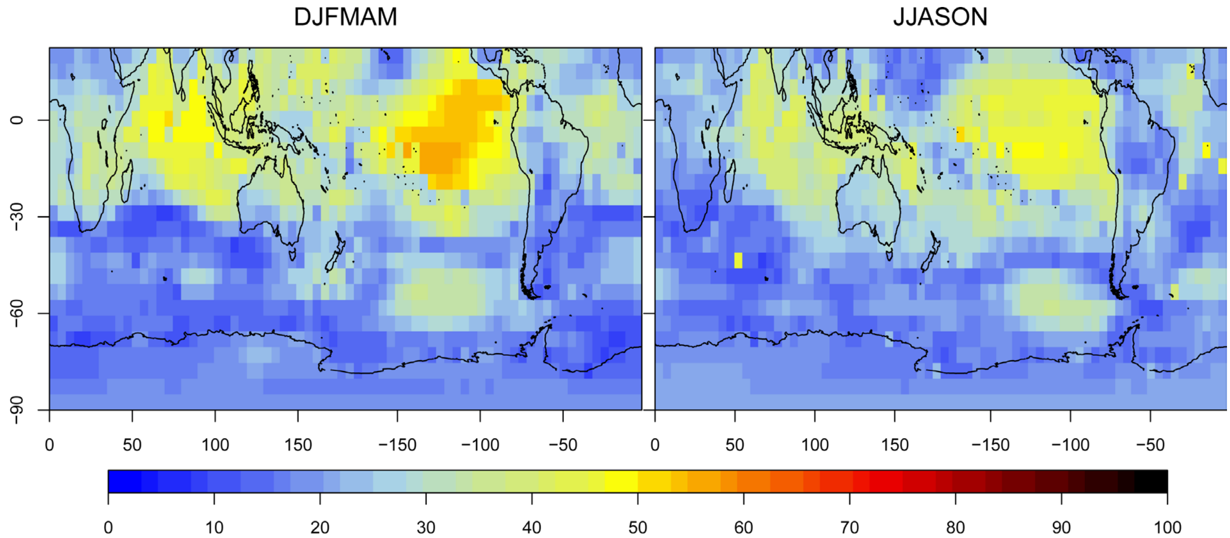

Figure 6. An integration of the inter-grid correlation analyses for all SLP, SST, land surface air temperature and precipitation grids. All grids were interpolated to 5°×5° spatial resolution for this analysis. The latitude-weighted fraction of the grid cells for each variable on the *x* domain that displays a statistically significant correlation (p<0.05) at point y_{ij} in all four grids as presented in Figures S6 and S7 (available online). This figure was generated by averaging the values of all inter-grid correlation maps. Correlations were calculated over the period 1901–2000 for DJFMAM and JJASON half years.

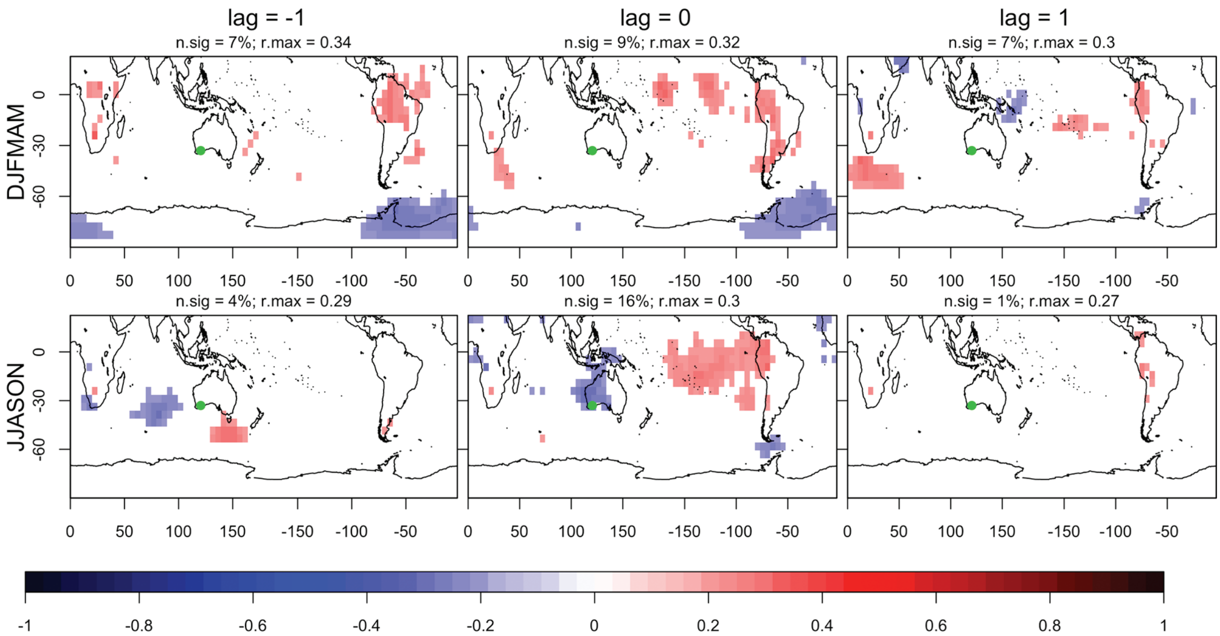

Figure 7. Correlation maps for the Western Australian *Callitris* tree ring record and the HadSLP2r grid over the 1901–2000 period. Areas with significant (p<0.05) spearman correlations are shaded. The proxy location is indicated by a green circle. Maps are shown for the DJFMAM (top) and JJASON (bottom) seasons and the proxy records shifted by −1 (left), 0 (middle) and +1 (right) years. The latitude-weighted fraction of grid cells with significant correlations (n.sig) as well as the highest absolute correlations (r.max) are also given. Corresponding maps for all proxies and grids can be downloaded from the NOAA Paleoclimatology database (http://www.ncdc.noaa.gov/paleo/).

grids for DJFMAM and JJASON. This assesses the relative importance of each grid cell in representing the entire domain, highlighting 'centres-of-action' that may be dynamically important for modulating SH climate variations. This 'teleconnectivity index' clearly identifies the tropical Indo–Pacific Oceans as the area that most strongly influences climate variability in the Southern Hemisphere. This confirms previous results that ENSO is the primary driver of SH climate variations on interannual to decadal timescales (Karoly, 1989; Karoly and Vincent, 1998; Karoly et al., 1996; Trenberth and Hurrell, 1994). Note that the apparent importance of SAM variations may be masked in Figure 6 because of the lack of instrumental data currently available at high latitudes.

Spatial field correlation maps for every proxy record with each climate field can be downloaded from the NOAA Paleoclimatology database (http://www.ncdc.noaa.gov/paleo/). An example is shown in Figure 7 for the correlation of Western Australian *Callitris columellaris* tree ring record with SLP fields. Tables 9–12 (available online) list the (latitude-weighted) fraction of grid cells (as a percentage) that each proxy correlates significantly with, for all grids in the DJFMAM and JJASON half years. A subjective threshold of 20% was chosen to highlight proxies with 'good' large-scale sensitivity, indicated as bold numbers.

Many tree ring records from Australasia, the Altiplano and the central-southern Andes around 30°S can represent a high proportion of the SH domain for one or more climate variables. Results are poorer in the southern Andes. This area, which lies in the core latitudes influenced by the westerly wind belt, is less representative of large-scale variability (as seen for SLP in the left panels of Figure 2). The Pacific coral records show much better spatial coherence than records from the Indian Ocean for all variables, underlining the dominance of the tropical Pacific (ENSO) on SH climate variability.

The high percentage of grid cells with significant correlations with ice cores and tree rings from the tropical Andes indicate that this region is a key teleconnection area (see also Tables 5 and 7; available online). A number of Antarctic ice cores show a good association with SLP, SST and (non-Antarctic) LSAT, indicating that in some areas and for some proxies, teleconnectivity to mid-latitude SH variability exists (Goodwin et al., 2004; Van Ommen and Morgan, 2010). The documentary records are less representative for large-scale variations, except from the Peruvian ENSO-chronology and the precipitation sensitive records from the Andes around 30°S, an area which is very strongly influenced by ENSO.

Figures 2–5 show the relationship of the multiproxy network with each climate variable (SLP, SST, LSAT and PP). They show the number of proxy records with significant correlations (middle panels) and the fraction of variance collectively explained by these proxies (right panel), respectively, for each grid cell. In most cases the two panels show qualitatively similar patterns, with a few exceptions. For example, DJFMAM-PP in NE Australia, where relatively few proxies with significant correlations explain a large fraction of variance. This indicates that a carefully screened network of proxies may in fact produce better results than a larger data network that incorporates proxies that have less skill.

For SLP (Figure 2), the SH proxy network captures conditions over large parts of the tropical oceans, particularly the SOI centers-of-action. Coverage is best in JJASON when the subtropical ridge of the SH mid-latitudes (~30°S) migrates equatorward as the north–south (meridional) temperature gradient intensifies between the tropics and poles as Antarctic sea ice extent reaches a maximum. The results are poor over parts of the central western tropical Pacific, indicating that the proxy network cannot capture large-scale atmospheric circulation in this region, but is displaying remarkable skill in both the eastern and western Pacific poles of the SOI.

For SST (Figure 3), results are best over the eastern tropical Pacific, again suggesting the importance of ENSO in modulating SH climate variations. During JJASON, Indian Ocean SST variability is also well represented by the proxies and the explained variance is also high in the southwest Pacific. The apparently good results over the Southern Ocean must be interpreted cautiously as they are most probably interpolation artifacts caused by the very limited number of direct twentieth-century SST observations in this area.

For LSAT (Figure 4) the results are surprisingly good over tropical areas, reflecting the importance of ENSO on climate variability. Problematic regions are Western Australia, SE-South America and southern Africa in JJASON, where the teleconnectivity is low (left panels) and very few proxy records exist. The proxy network cannot explain high fractions of variance in precipitation (Figure 5), except in a few regions with very strong SST-PP connections (e.g. NE Australia). Skillful reconstructions of this variable on a hemispheric scale are probably still not possible with the currently available proxy network, but are viable on more regional scales using local meteorological grids (Gergis et al., 2011). Since Figures 2–7 focus on hemispheric-scale coherency, the reconstruction potential that may be possible on regional/continental scales may be masked. For example the significance thresholds for the explained variance would be lower for smaller areas, using only regional proxies as predictors. The correlation maps generated for each proxy record can be used to assess the feasibility of regional climate reconstructions. For regional-scale reconstructions, it is essential to experiment with proxy subsets to assess the reconstruction skill that may be possible using for instance, a small predictor network of more local/regional proxies, or those with strong correlations with large-scale circulation indices of ENSO, IPO, IOD or SAM (Gergis et al., 2011).

Conclusions and recommendations

This review paper provides the first comprehensive overview and climate assessment of existing high-resolution SH palaeoarchives. Our purpose is to provide a starting point for researchers interested in reconstructing climate over the past 2000 years from the region. We identify a network of 174 proxy records, many of which are significantly correlated to one or more of the dominant SH climate modes (ENSO, IPO, IOD and SAM). Collectively these circulation features can explain significant fractions of variance for SLP, SST and LSAT over large parts of the SH (Karoly and Vincent, 1998; Karoly et al., 1996). This said, large-scale field reconstructions of the SH are still challenging because of the following factors:

- The proxy records are unevenly distributed in space and time. There are only three (Antarctic ice core) records extending more than 500 years between 50°W and 140°E (i.e. around half of the SH).
- The sparse coverage of instrumental data in most parts of the SH during the early twentieth century requires careful selection of calibration/verification periods depending on the target region and variable. This, however, is compounded by the issue of many proxy records ending in the late 1970s–mid 1990s, highlighting the need to update key tree ring records for improved calibration.
- Teleconnections stability is an issue for regional–large-scale climate reconstructions. The results presented represent twentieth-century relationships therefore may change over the reconstruction period. The low number of records with very stable correlations with the SH climate indices (Tables 5–8, available online) indicate that even within the twentieth century teleconnectivity may have changed in some areas. This issue could be addressed in future studies by comparing the temporal stability between different proxy subsets, e.g. the corals from the core ENSO region versus ENSO-sensitive teleconnection locations (as represented in twentieth-century instrumental records).

To improve SH climate reconstructions, future data development should address a number of key issues. The first relates to developing new and longer proxy records from core dynamical regions of the tropical Pacific and Indian Oceans; areas where few records currently exist (e.g. the Atlantic Ocean, mainland Australia and Africa); and regions that are strongly teleconnected to dynamical centres-of-action, e.g. the eastern Indian Ocean which has a strong influence on Australian climate variability (Nicholls, 1989). To date, the potential of many archives has not been exploited in many areas e.g. documentary, lacustrine and speleothem records from Australasia, Africa and eastern South America, but appears very promising for improving our understanding of regional climate variability.

The recovery of early instrumental data can dramatically improve the quality and length of calibration data and reduce subsequent uncertainties associated with palaeoclimate estimates in the pre-calibration era. In the absence of a spatially comprehensive network of instrumental observations needed to extend gridded data sets, individual long series could be treated as additional proxies. Ongoing recovery of early instrumental data in Australasia, Africa and the oceanic regions of the SH will deliver new data sets in the future (Allan et al., 2011; Compo et al., 2011). There is also a pressing need for correcting and homogenizing existing instrumental station data in many parts of the SH to significantly improve the understanding of regional climate and the quality of calibration/verification in reconstructions (Aravena and Luckman, 2009; Peterson and Vose, 1997).

Importantly, given the relatively sparse proxy network currently available from the SH, we strongly encourage researchers to submit published records to international data banks such as the NOAA World Data Centre for Paleoclimatology. This will improve data access to all scientists interested in performing multiproxy climate reconstructions on regional–hemispheric scales. Even though large-scale circulation features such as ENSO and the monsoon are anchored in the tropical oceans of the SH, the influence of Pacific Ocean variability is also felt in geographically remote regions of the Northern Hemisphere. As such, even modest improvements in our understanding of the long-term behaviour of major modes of SH climate circulation are crucial to breakthroughs in understanding global climate variability.

While our results show that the availability of palaeoclimate data from the SH is limited compared with the NH, we do not wish to discourage the development of climate reconstructions in areas where our results indicate limited proxy coverage. Considerable skill may still be possible on regional/continental scales with a smaller, more-refined data network. Future climate reconstruction work should carefully assess proxy selection and reconstruction techniques depending on the target variable, season and region. This study should not be used as a stand-alone tool for the pre-selection of proxy records for climate reconstruction, as experience has shown that correlation analysis alone is not an optimal predictor of reconstruction skill. Instead, we seek to highlight recent developments in high-resolution SH palaeoscience and provide a consistent climate sensitivity assessment of all currently available proxy records from the region. We show how commonly targeted climate predictands (SST, SLP, air temperature and precipitation) display considerable covariations and, in key dynamical regions, a good association with the currently available proxy network in the twentieth century.

We have shown that although large-scale climate reconstructions for the SH are in their infancy, excellent progress in the development of regional proxies now makes plausible estimates of continental–hemispheric climate variations more feasible than ever before. Although it is challenging working with a sparse data network, new climate reconstruction approaches now offer improved uncertainty estimates (Gergis et al., 2011; Li et al., 2010; Neukom et al., 2010; Tingley and Huybers, 2010). These enhanced data and methods along with GCM simulations and detection and attribution studies will allow a better quantification of the factors driving Southern Hemisphere climate variability (Hegerl et al., 2006, 2007, 2011; Mann et al., 2005). This paper is intended to encourage the development of much-needed climate reconstructions and additional proxy records from the Southern Hemisphere for the forthcoming IPCC assessment report and beyond.

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Table 5. Spearman correlations of the Southern Hemisphere tree ring records with climate indices on inter-annual and decadal (10-year loess filtered) timescales 1901–2000. All data were detrended over the 20th century prior to the calculations. Bold number indicate significant (p<0.05) results. The superscript numbers next to each correlation coefficient represent three sub-periods: 1=1901–1933, 2=1934–1966, and 3=1967–2000. If a superscript appears, the correlation for the corresponding sub-period is above the significance threshold used for the centennial correlations. The second column indicates the number of years available in the 20th century

		SOI (1901-2000)		NINO3.4 (1901-2000)		SAM (1951-2000)		IOD (1902-2000)		IPO (1901-2000)	
Name	n	interannual	decadal	interannual	decadal	interannual	decadal	interannual	decadal	interannual	decadal
Africa											
Zimbabwe	96	0.18[1]	0.32[13]	-0.14[3]	-0.13	0.15	-0.16	0.12[2]	-0.06	-0.14[13]	-0.28[3]
Die Bos, South Africa	76	0.14	0.21	-0.16[2]	-0.35[23]	-0.27	-0.2	0.21[1]	0.28[13]	-0.22[23]	-0.29[23]
Australasia											
Teak Indonesia	100	**0.24[13]**	0.16	**-0.33[123]**	-0.35[12]	0.15	0.3	**-0.26[13]**	-0.07[1]	-0.23[12]	-0.15[13]
Northern Territory Callitris	100	**0.29[123]**	0.16[3]	**-0.25[13]**	0.04[3]	0.16	0.27	-0.18[23]	-0.1[2]	-0.16[3]	0.07[3]
Western Australia Callitris	100	**0.24[13]**	0.23[1]	-0.12[13]	-0.05	-0.09[2]	-0.39	**-0.2[13]**	0.07	-0.15[1]	-0.14[1]
Kauri NZ	100	**-0.35[13]**	**-0.54[123]**	**0.3[13]**	**0.43[23]**	-0.18	-0.22	0.12	-0.24[23]	**0.32[13]**	**0.41[3]**
Baw Baw Victoria	100	0.1[3]	-0.15[2]	-0.19[23]	-0.11	-0.28[3]	0.07	0.09[3]	0.16	-0.17[2]	-0.07
Urewera NZ	92	-0.16[1]	-0.24	**-0.22[3]**	0.24[1]	0.26	0.16[3]	-0.1[3]	-0.03[13]	-0.16[3]	0.18[1]
North Island LIBI Composite 2	90	0.17[13]	-0.22	**-0.23[13]**	-0.26	-0.27[2]	0.08	-0.1	-0.14	-0.21[2]	-0.21[23]
Mangawhero NZ	94	0.12[2]	-0.15[3]	-0.15[13]	-0.1[3]	-0.21[3]	-0.08	**-0.3[12]**	**-0.44[1]**	-0.14[1]	0.04[3]
North Island LIBI Composite 1	92	0.18[3]	0.09	-0.17[3]	0.07	0.03	0.22	0.08	0.12[23]	-0.13[3]	-0.05
Takapari NZ	92	-0.13[3]	-0.24[3]	0.14[3]	0.34	-0.05	-0.14	0.07[1]	-0.04[3]	0.26[1]	**0.45[3]**
Moa Park NZ	91	-0.11[3]	-0.18[3]	0.08	0.23[3]	-0.24[2]	-0.45[2]	**0.29[12]**	**0.4[12]**	0.15[3]	0.29[3]
Flanagans Hut NZ	91	**-0.22[12]**	-0.21	**-0.25[2]**	-0.33[2]	-0.17	-0.07	-0.1[23]	-0.16	-0.27[2]	-0.19
CTP East Tasmania	94	-0.14[3]	-0.24[23]	0.17[3]	0.32[3]	-0.18[2]	-0.51[3]	0.11[13]	0.21[1]	0.16[3]	0.25[23]
CTP West Tasmania	98	0.18[1]	**0.4[13]**	-0.17[2]	-0.2[3]	-0.15	-0.05	-0.09	0.17[2]	-0.17[3]	-0.14[13]
Mount Read Tasmania	99	0.17[13]	0.19[3]	0.08	0.15	-0.19	0.12	0.06	0.06[13]	-0.08[3]	0.13[23]
Pink Pine NZ	99	**0.38[123]**	**0.5[13]**	**-0.28[13]**	-0.25[13]	**0.37[2]**	0.5[2]	**-0.24[2]**	-0.05[2]	**-0.33[13]**	-0.34[13]
Buckley's Chance Tasmania	91	0.13[23]	0.11[3]	-0.07[3]	0.11[3]	0.3[2]	0.41	-0.09[23]	-0.11[2]	-0.17[3]	-0.26[13]
Ahaura NZ	90	-0.18[1]	-0.21[123]	-0.17	-0.13[3]	0.24[2]	0.19	-0.18[13]	-0.24	-0.17[3]	-0.12[3]
Oroko Swamp NZ	100	**0.21[13]**	0.2[3]	-0.17[13]	0.14	**0.34[23]**	0.43[2]	**-0.21[1]**	0.09[12]	-0.15[13]	0.11
Stewart Island NZ	94	**0.21[1]**	0.22[1]	-0.2[1]	-0.07[1]	0.19[2]	0.3[2]	-0.21[2]	-0.12[2]	-0.24[1]	-0.27[1]
South America											
ALT Composite 1	93	-0.16[123]	0.08	0.19[123]	-0.14[12]	-0.12[2]	-0.17	0.16[123]	0.13[2]	0.08[1]	-0.11[1]
ALT Composite 2	100	**-0.31[13]**	-0.22[3]	**0.39[13]**	0.32[3]	-0.26[2]	-0.52[2]	**0.27[13]**	0.3[1]	**0.25[13]**	0.12[23]
ALT Composite 3	100	**-0.26[1]**	0.29[3]	**-0.23[23]**	**-0.51[23]**	-0.15	0.34[3]	**0.21[1]**	-0.12[3]	**-0.27[23]**	**-0.47[23]**
La Meseda	99	0.09[3]	0.26[13]	0.08[2]	0.12[23]	0.26[2]	0.14[2]	-0.12[13]	-0.14[3]	0.14[23]	0.21[23]
NWA Composite 1	99	-0.1[1]	-0.21[1]	0.07[3]	-0.07[1]	-0.16	-0.43[3]	-0.15[3]	-0.27[3]	-0.16[12]	-0.3[2]
NWA Composite 4	81	0.07[3]	0.25[3]	0.15[123]	0.23[13]	0.29	0.24	-0.14[23]	-0.39[2]	0.12[13]	-0.08[3]
NWA Composite 2	95	-0.15[2]	-0.15	0.16[13]	0.05	-0.13[2]	-0.37	**0.25[23]**	0.12[2]	0.2[1]	0.25[1]
Rio Sala and Popayan	100	-0.14[3]	-0.29[3]	0.17[23]	**0.4[123]**	-0.18	0.25	**-0.21[2]**	**-0.42[23]**	**0.28[13]**	**0.4[13]**
NWA Composite 5	100	0.09	0.13	-0.12	-0.28[1]	-0.13	-0.22	0.11[2]	0.2	-0.12	-0.13
Dique Escaba	85	-0.18[1]	-0.35[12]	0.21[1]	**0.43[12]**	0.05	-0.12[3]	0.11	-0.12[3]	0.22[2]	0.26[2]
El Asiento	72	-0.18[1]	-0.23	**0.25[1]**	**0.44[13]**	0.28	-0.26	-0.19[2]	-0.31	0.25[1]	0.33[13]
Le Quesne precip recon	100	**-0.32[13]**	-0.27[2]	**0.35[13]**	**0.41[1]**	-0.22	-0.44[2]	0.16[1]	-0.13	**0.29[13]**	0.24[1]
CAN Composite 1	75	0.08[3]	-0.25	-0.15[23]	0.02[13]	**-0.56[2]**	-0.57[2]	**-0.27[2]**	-0.32	-0.2[23]	-0.18[3]
Vilches	96	-0.12[2]	-0.22[2]	**0.23[12]**	**0.39[2]**	-0.23	-0.44[3]	-0.12[3]	-0.25	0.24[12]	0.32[12]
Christie AUCH Composite	100	-0.19[23]	-0.32[23]	**0.24[23]**	**0.42[23]**	**-0.47[23]**	**-0.63[23]**	0.11[3]	0.1[3]	**0.26[23]**	0.3[2]
Huinganco	100	0.08[2]	0.24	-0.08[2]	-0.21[3]	-0.15[2]	-0.29	-0.09	-0.12[3]	-0.13	-0.19[3]
CAN Composite 2	100	-0.17[3]	**-0.36[3]**	0.1	0.25[12]	-0.23	-0.41	-0.09	-0.15	0.21[13]	0.33[13]
CAN Composite 3	75	-0.19	-0.22	-0.13[3]	0.05[3]	-0.37	-0.35	0.1[3]	0.11[3]	0.15[1]	0.13[13]
Volcan Lonquimay	75	-0.2[13]	-0.28[3]	0.22[13]	0.37[13]	-0.25	-0.52[3]	0.19[3]	0.24[3]	0.23[13]	0.21[13]
CAN Composite 6	100	**-0.32[13]**	**-0.37[3]**	**0.29[13]**	0.29[12]	-0.33[2]	-0.3	0.12	0.16[1]	**0.43[13]**	**0.53[13]**
CAN Composite 5	96	-0.09[1]	-0.08[1]	-0.05	0.08	0.21	0.42	-0.19[3]	-0.33[1]	0.05	-0.07
Pino Hachado	74	0.18[13]	-0.2	0.2	0.28[1]	-0.37	-0.5	-0.14[23]	-0.2	**0.29[1]**	0.32[1]
Conguillio (Lenga abajo)	96	0.04[3]	0.07	0.08[2]	0.07[23]	0.26[2]	0.23	0.08[3]	0.08	0.07[23]	-0.08[23]
CAN Composite 4	94	0.16[1]	0.09	0.14	0.2	**-0.35[2]**	-0.49[2]	0.16[1]	**0.4[12]**	0.21[12]	0.28[2]
CAN Composite 8	89	-0.08[2]	-0.12[2]	-0.11[3]	-0.12	**-0.57[23]**	**-0.73[23]**	0.1	0.14[2]	-0.08[3]	0.04[3]
CAN Composite 31	100	-0.13[3]	-0.18[3]	0.12[3]	0.22	-0.24	-0.28	-0.11[2]	-0.07[13]	0.19[3]	0.15[3]
Lago Rucachoroi	76	-0.05	0.08[23]	0.09[1]	-0.12[3]	-0.28	-0.36[2]	0.1[2]	0.13[23]	0.1	-0.05
CAN Composite 9	100	0.16[3]	0.14	0.08	-0.08[1]	-0.18	-0.14[2]	-0.06	0.13[1]	-0.11[13]	-0.06[13]
CAN Composite 10	89	-0.07	-0.15	0.11	0.09	-0.13	-0.18	**0.25[1]**	0.36[12]	0.22[13]	0.31[13]
CAN Composite 12	92	0.15[1]	0.28[13]	-0.06[3]	-0.08[3]	-0.24[2]	-0.19[2]	0.17[1]	**0.47[12]**	-0.1[3]	-0.14[13]
Chapelco	85	-0.12[1]	-0.18[3]	0.08[3]	0.09[3]	0.24	0.29[2]	-0.12[3]	0.08	0.16[3]	0.15[3]
CAN Composite 11	100	**-0.24[23]**	0.2[3]	**0.26[123]**	-0.09[3]	-0.29[2]	-0.39[2]	0.2[2]	0.27[12]	0.22[1]	-0.07[3]

Table 5. (Continued)

Name	n	SOI (1901-2000) interannual	SOI (1901-2000) decadal	NINO3.4 (1901-2000) interannual	NINO3.4 (1901-2000) decadal	SAM (1951-2000) interannual	SAM (1951-2000) decadal	IOD (1902-2000) interannual	IOD (1902-2000) decadal	IPO (1901-2000) interannual	IPO (1901-2000) decadal
Paso Cordova	86	**0.23**[12]	0.19[3]	-0.19[23]	-0.14[3]	-0.12	-0.04	0.11[2]	0.31[13]	-0.12[3]	0.03[3]
CAN Composite 13	100	-0.1[2]	-0.03[2]	0.11[1]	-0.08	-0.27[2]	-0.32[2]	0.09[2]	0.05[23]	0.11[12]	0.05[1]
CAN Composite 16	94	**-0.3**[12]	**-0.43**[3]	**0.21**[2]	0.33[23]	0.05	-0.13	-0.07[12]	-0.22[1]	**0.33**[23]	**0.43**[23]
CAN Composite 14	91	**-0.25**[1]	**-0.37**[13]	0.17	0.31[3]	0.13	-0.18	-0.1[1]	-0.21[1]	0.17	0.24[3]
CAN Composite 17	94	-0.2[12]	**-0.38**[13]	0.07	0.17[3]	0.11	-0.23[2]	0.03[12]	-0.1[12]	0.15[3]	0.33[3]
CAN Composite 15	91	-0.13[3]	**-0.44**[13]	0.15[3]	0.31[3]	0.15[2]	-0.03	-0.15[13]	-0.35[12]	0.13[3]	0.23[3]
CAN Composite 19	98	-0.14[3]	-0.26[13]	0.13[2]	0.15[1]	0.1	0.12	-0.13[2]	-0.28[2]	0.07[23]	0.09[23]
CAN Composite 18	94	-0.08	-0.1[3]	0.06	0.14[23]	-0.1	-0.21	0.03	0.15	0.1[3]	0.21[13]
CANComposite 20	95	-0.14[12]	0.01	-0.1[3]	-0.11	-0.2[2]	-0.15[2]	-0.07[1]	-0.12[1]	0.13	0.26[1]
CAN Composite 21	89	0.1[1]	-0.1[2]	0.14[2]	0.28[13]	-0.33[23]	-0.29[2]	0.21[3]	0.35[12]	0.18[123]	0.26[13]
CAN Composite 22	97	-0.08[1]	-0.16[1]	0.05	0.25	-0.2[3]	0.15	-0.15[2]	-0.24[2]	0.08[3]	0.05
CAN Composite 23	93	-0.14[1]	-0.12	0.1[1]	-0.03	-0.2[2]	-0.25[2]	-0.09[1]	-0.19[1]	0.15[1]	0.2
CAN Composite 24	100	0.19[2]	0.19	0.11[1]	0.12[1]	-0.24	-0.26[2]	0.17[1]	0.3[1]	-0.11[123]	-0.24[13]
CAN Composite 26	87	0.16[3]	0.24[3]	-0.16[2]	-0.25[23]	-0.23[2]	-0.35[2]	0.14[2]	0.3[23]	-0.18[23]	-0.22[123]
CAN Composite 25	90	0.07[1]	0.11	-0.08	-0.15[2]	-0.1[2]	-0.1	-0.1[1]	-0.21[1]	0.07[3]	0.27[13]
Santa Lucia	86	**0.32**[12]	0.26[1]	-0.21[23]	-0.12	-0.17[2]	-0.17[2]	**0.31**[2]	**0.41**[12]	-0.07	0.17[3]
Cisnes	97	-0.12[1]	-0.16	-0.13	-0.15[2]	-0.26[2]	-0.35[2]	-0.12[2]	0.11[3]	-0.18[3]	-0.24[1]
Puesto Miraflores	98	**-0.22**[12]	-0.31[1]	0.11[2]	0.07	-0.34[2]	-0.35[2]	-0.04[2]	-0.19[12]	0.15[2]	0.1
CAN Composite 32	98	0.11[12]	0.12	-0.11[2]	-0.2[2]	0.12	0.24[3]	0.17[23]	0.23[3]	0.03[2]	0.16[3]
O Higgins	99	-0.16[2]	-0.26[12]	0.1[2]	-0.08[1]	-0.1[2]	-0.31[2]	0.12[1]	0.14[1]	0.06[3]	-0.07[1]
CAN Composite 27	96	0.14	-0.11	-0.07[2]	0.12	-0.15	-0.09[2]	0.18[23]	0.17	0.17[2]	0.31[2]
El Chalten bajo	100	0.09	0.09[2]	0.01[2]	0.05	-0.16	-0.22	**-0.21**[13]	-0.1	0.06	-0.09[123]
CAN Composite 33	100	0.09	0.05	-0.1[123]	-0.11	-0.19	0.05[2]	-0.16[3]	-0.11[1]	-0.07[12]	-0.14
Torre Morena 4	100	0.08[2]	-0.06[23]	0.05	0.09	-0.09	0.11	-0.17[23]	-0.15[1]	0.09	0.1[23]
Valle Ameghino	97	0.08[2]	0.07[2]	-0.1[3]	0.08[1]	0.1	0.06	-0.09[123]	-0.32[123]	0.05	0.21[1]
CAN Composite 34	100	0.14[2]	-0.05[23]	0.13[1]	0.26	0.19	0.32[2]	0.05	-0.05[3]	**0.23**[3]	**0.39**
Heim Morena Este	100	**0.21**[23]	0.1	-0.18[23]	-0.09[2]	0.09	0.13	-0.13[2]	-0.2[13]	-0.2[2]	-0.18[2]
CAN Composite 30	84	-0.17[13]	-0.1	**0.21**[13]	0.07	-0.13	0.18	0.14[13]	0.15[1]	0.13	-0.01[3]
SAN Composite 5	84	**0.26**[13]	0.16[1]	-0.15[3]	0.31[1]	-0.33	-0.31	-0.19[2]	-0.14[3]	-0.13[3]	0.12[1]
Puerto Parryn	86	**0.24**[13]	0.19[3]	**-0.22**[3]	-0.2[3]	0.25[3]	0.25	-0.14[23]	-0.06[2]	-0.22[23]	-0.23[3]
SAN Composite 6	86	-0.06[2]	-0.18[2]	0.1[2]	0.29[3]	-0.27[3]	-0.49[2]	**0.27**[23]	**0.41**[13]	0.17[2]	0.28

Table 6. Same as Table 5 but for coral records

Name	n	SOI (1901-2000) interannual	SOI (1901-2000) decadal	NINO3.4 (1901-2000) interannual	NINO3.4 (1901-2000) decadal	SAM (1951-2000) interannual	SAM (1951-2000) decadal	IOD (1902-2000) interannual	IOD (1902-2000) decadal	IPO (1901-2000) interannual	IPO (1901-2000) decadal
Indian Ocean											
Malindi	94	**0.36**[123]	**0.48**[13]	**-0.36**[13]	**-0.48**[13]	0.07	0.27	-0.16[2]	0.08	**-0.49**[123]	**-0.67**[13]
Mafia	96	0.18[1]	0.11[12]	**-0.26**[1]	-0.15[1]	0.18	0.18	0.2[2]	0.32[2]	-0.2[1]	0.14[13]
Ifaty 1 d18O	94	**0.3**[13]	0.33[13]	-0.19[13]	-0.29[3]	-0.09[2]	0.09	-0.08	-0.04	**-0.23**[13]	**-0.39**[23]
Ifaty 1 Sr/Ca	94	0.15[13]	-0.14	-0.16[1]	-0.1[2]	0.15	-0.28[2]	-0.21[13]	-0.27[1]	-0.18[12]	-0.09[2]
Ifaty 4 Sr/Ca	94	0.09[1]	-0.11[3]	-0.11[2]	0.07[3]	-0.07	-0.3	**0.22**[13]	0.23	0.11[3]	0.24[3]
Ifaty, 4 d18O	94	0.2[13]	0.18[3]	-0.19[123]	-0.11[2]	-0.11	-0.13[2]	**0.24**[12]	0.32[2]	-0.13[3]	-0.1[3]
Mayotte	92	0.08	-0.03	-0.2[13]	-0.24[1]	0.34	0.26	-0.18[3]	0.34[12]	-0.18[1]	-0.15[1]
La Reunion	94	-0.2[3]	-0.32[3]	-0.18[2]	-0.21[2]	-0.1	-0.07	0.15[3]	-0.14[3]	0.1[3]	0.18[3]
Seychelles	93	**0.45**[123]	0.29[1]	**-0.49**[123]	-0.25[1]	0.31[2]	0.4	**-0.25**[13]	0.21	**-0.36**[13]	-0.11[1]
Rodrigues Sr/Ca	100	0.04[3]	-0.04	-0.09	0.08	0.12	0.21	-0.1[1]	-0.09[1]	0.07	0.11
Rodrigues d18O	100	0.07	0.13	-0.1	-0.28	0.15	-0.14[2]	0.17[23]	0.2	-0.14	**-0.36**[23]
Mentawai West Sumatra	96	**0.24**[13]	0.28[2]	**-0.36**[123]	**-0.53**[12]	0.24[3]	0.3	-0.16[13]	-0.13[12]	**-0.36**[13]	-0.27[1]
Abrolhos	92	-0.17[1]	-0.28[1]	0.13[13]	0.26[1]	-0.16	-0.31	0.09[1]	0.12	0.18[1]	0.25[1]
Ningaloo	94	**-0.29**[123]	-0.24[3]	**0.34**[123]	**0.39**[3]	0.15	-0.31[3]	0.18[13]	0.04	0.24[2]	0.15
Bali	88	**-0.27**[23]	-0.2[2]	**0.37**[23]	**0.45**[23]	-0.23	-0.18[3]	**0.32**[13]	0.34[13]	**0.32**[23]	0.26[2]
Bunaken	89	**-0.67**[123]	**-0.49**[13]	**0.62**[123]	0.2[3]	**-0.33**[23]	-0.4[2]	**0.27**[13]	-0.17[2]	**0.41**[123]	-0.2[23]
Pacific Ocean											
Laing	91	**-0.32**[13]	**-0.42**[13]	**0.33**[13]	0.25[23]	**-0.38**[23]	-0.38	-0.17[1]	-0.27[2]	-0.24[12]	-0.26[23]
Guam	98	**-0.23**[13]	0.16	-0.2[12]	**-0.38**[12]	-0.19	-0.25	-0.02[13]	-0.04	**-0.34**[12]	**-0.53**[12]
Madang Lagoon	91	**-0.37**[123]	**-0.39**[23]	**0.41**[23]	0.22[23]	-0.33[3]	-0.18	0.16[3]	-0.19	**0.41**[23]	0.36[23]
Great Barrier Reef precip recon	81	**0.29**[13]	0.36[3]	**-0.33**[13]	-0.32[23]	0.3[3]	0.31	-0.13	-0.3	**-0.28**[3]	-0.29[3]
Kavieng Sr/Ca	96	-0.18[2]	-0.07	0.17[23]	-0.06[1]	-0.14	-0.42[2]	0.18	0.12	-0.24[1]	-0.33[1]
Kavieng Ba/Ca	96	**-0.24**[12]	-0.17[1]	**0.25**[13]	-0.08	-0.11	0.23	**0.3**[12]	**0.38**[12]	0.25[13]	0.25[3]
Rabaul Sr/Ca	96	**-0.22**[13]	-0.1[2]	**-0.24**[13]	-0.17[1]	**-0.38**[2]	-0.33[2]	**-0.25**[13]	-0.1	**-0.28**[13]	-0.33[1]
Rabaul d18O	96	**0.23**[123]	0.14[3]	-0.17[1]	0.09[12]	-0.24[2]	-0.23[2]	-0.09[1]	-0.15[3]	0.14[2]	-0.07[3]
Abraham	83	0.21[23]	0.25[3]	0.22[13]	0.22[1]	0.28[3]	0.16[3]	0.05	0.07[3]	-0.21[3]	0.23[2]
Nauru	93	**0.68**[123]	**0.61**[123]	**-0.59**[123]	**-0.46**[13]	0.38	**0.57**[3]	0.13[3]	0.11	**-0.5**[123]	-0.32[13]
Amedee New Caledonia	91	**-0.32**[123]	**-0.51**[123]	**0.37**[123]	**0.65**[12]	-0.09	-0.09	0.03	-0.12	**0.54**[123]	**0.74**[123]
Vanuatu	81	**-0.27**[12]	-0.36[12]	**0.32**[13]	**0.46**[1]	0.29[3]	0.38	-0.15[12]	-0.25[2]	**0.38**[123]	0.31[1]
Tarawa	88	**0.69**[123]	**0.6**[123]	**-0.72**[123]	**-0.66**[123]	-0.37[2]	-0.25	**-0.25**[1]	0.14	**-0.71**[123]	**-0.57**[23]
Maiana	93	**0.7**[123]	**0.64**[123]	**-0.74**[123]	**-0.63**[123]	0.31[2]	0.41[23]	**-0.32**[13]	-0.12[1]	**-0.67**[123]	**-0.56**[3]
Fiji 1F d18O	96	**-0.6**[123]	**-0.61**[123]	**0.58**[123]	**0.62**[12]	**-0.48**[23]	-0.43	0.19[13]	-0.19[2]	**0.63**[123]	**0.55**[12]
Fiji 1F Sr/Ca	96	**-0.33**[123]	-0.34[23]	**0.33**[123]	**0.52**[123]	-0.31	-0.36	0.07	-0.06[3]	**0.37**[123]	**0.42**[12]
Fiji AB	100	**-0.6**[123]	**-0.66**[123]	**0.61**[123]	**0.67**[123]	**-0.36**[2]	-0.41[2]	**0.44**[13]	0.24[1]	**0.65**[123]	**0.64**[123]
Savusavu	100	**-0.46**[123]	-0.35[3]	**0.55**[123]	**0.56**[123]	-0.33[2]	-0.23	**0.22**[1]	0.33[13]	**0.61**[123]	**0.68**[123]
Tonga_TNI2	100	**-0.5**[123]	**-0.45**[123]	**0.42**[123]	0.33[2]	0.25	-0.2	-0.18[1]	-0.31[1]	**0.41**[123]	0.22[2]
Tonga_TH1	100	**-0.5**[123]	**-0.73**[123]	**0.5**[123]	**0.67**[123]	**-0.43**[23]	-0.42[2]	0.15[3]	-0.09	**0.53**[123]	**0.52**[23]
Palmyra d18O	97	**0.68**[123]	**0.63**[123]	**-0.76**[123]	**-0.77**[123]	0.27	0.44[2]	**-0.28**[13]	0.03[3]	**-0.76**[123]	**-0.76**[123]
Palmyra Sr/Ca	97	**0.51**[123]	**0.47**[123]	**-0.51**[123]	**-0.48**[123]	0.21	**0.57**[23]	**-0.29**[23]	-0.14[2]	**-0.36**[123]	-0.27[3]
Rarotonga 3R d18O	99	**-0.38**[123]	**-0.36**[3]	**0.46**[123]	**0.47**[123]	-0.33[2]	-0.5[2]	**0.33**[123]	0.19[123]	**0.51**[123]	**0.52**[12]
Rarotonga d18O	95	**-0.38**[123]	-0.33[1]	**0.43**[123]	0.34[1]	-0.23[2]	-0.23[2]	**0.29**[123]	0.17[23]	**0.46**[123]	**0.4**[12]
Rarotonga Sr/Ca	95	**-0.47**[123]	**-0.5**[123]	**0.35**[23]	0.3[23]	0.18	0.14	-0.2[1]	-0.33[1]	**0.48**[23]	**0.44**[23]
Moorea	90	**0.21**[23]	0.13	-0.2[23]	0.27[2]	-0.25	-0.21	0.13	0.11[3]	0.24[12]	0.24[2]
Clipperton	92	**0.45**[123]	**0.39**[13]	**-0.55**[123]	**-0.59**[123]	0.3	0.23	0.16[2]	0.26[2]	**-0.54**[123]	**-0.57**[123]
Urvina, Galapagos Islands	79	**0.4**[123]	0.21[23]	**-0.44**[123]	-0.39[2]	-0.46[23]	-0.18[3]	0.23[2]	0.3[2]	**-0.38**[123]	-0.19
Secas	83	-0.2[2]	-0.3[2]	-0.14	-0.11[23]	0.17[2]	-0.08	0.14[1]	0.26[1]	-0.09	-0.08

Table 7. Same as Table 5 but for ice core records

Name	n	SOI (1901-2000) interannual	SOI (1901-2000) decadal	NINO3.4 (1901-2000) interannual	NINO3.4 (1901-2000) decadal	SAM (1951-2000) interannual	SAM (1951-2000) decadal	IOD (1902-2000) interannual	IOD (1902-2000) decadal	IPO (19010-2000) interannual	IPO (19010-2000) decadal
South America											
Quelccaya accumulation	84	**0.28**^{13}	0.2^{13}	**-0.22**^{13}	-0.08^{23}	-0.14	-0.21	**0.25**^{23}	0.28	**-0.24**^{12}	-0.13^{23}
Quelccaya d18O	100	**-0.32**^{13}	**-0.48**^{13}	**0.33**^{123}	**0.53**^{123}	-0.32	-0.33	0.04^{1}	0.13	**0.49**^{123}	**0.57**^{123}
Illimani dD	98	-0.13^{2}	-0.07	0.1^{2}	-0.05^{2}	0.07	0.17	-0.1	-0.2	0.11^{2}	0.19^{23}
Illimani ammonium	89	**-0.43**^{123}	**-0.51**^{23}	**0.49**^{123}	**0.59**^{123}	**-0.39**^{23}	-0.42^{2}	**0.29**^{13}	0.29^{1}	**0.54**^{123}	**0.64**^{23}
Antarctica											
James Ross Island dD	100	0.05	-0.21	0.1^{1}	**0.43**^{1}	0.12	0.28^{3}	**0.23**^{12}	**0.39**^{23}	**0.31**^{13}	**0.53**^{123}
Law Dome d18O	85	0.08	0.09^{1}	-0.09^{12}	-0.06	-0.16	-0.17	-0.18^{3}	-0.29^{2}	-0.09^{12}	-0.08^{2}
Law Dome accumulation	100	0.11	-0.14^{123}	0.09^{3}	0.12	-0.21	0.18^{2}	-0.08^{3}	-0.28^{3}	0.08	0.27^{1}
Law Dome Na	95	0.1^{2}	0.13	-0.15^{1}	-0.31^{1}	-0.2	0.31	**-0.21**^{1}	**-0.36**^{1}	**-0.29**^{1}	-0.36^{1}
Dyer Plateau	88	-0.05	-0.11	0.03	0.04	0.04	0.35	-0.1	-0.11	0.09^{2}	0.1^{2}
Princess Elizabeth d18O	96	-0.13	-0.2^{3}	0.15^{3}	0.22^{3}	-0.11	-0.19	0.03^{23}	0.14^{12}	0.24^{3}	0.29
Princess Elizabeth Chem PC1	96	**-0.21**^{13}	-0.24^{3}	**0.21**^{1}	0.31^{3}	-0.06	0.13^{2}	0.14^{2}	0.2^{2}	**0.3**^{23}	**0.47**^{23}
Dolleman d18O	92	0.16	0.06	0.12^{1}	0.06^{23}	0.12	0.39^{3}	0.15^{2}	0.25^{12}	0.24^{12}	0.26^{2}
Dolleman NO3	92	0.13^{3}	0.14^{3}	-0.15^{3}	-0.18^{3}	0.28^{3}	0.36^{2}	-0.18^{12}	-0.17	**-0.23**^{3}	-0.34^{3}
Talos dD	96	**-0.2**^{3}	-0.17	**0.28**^{13}	0.33^{1}	0.24	0.14^{2}	0.14^{12}	0.15^{1}	**0.33**^{123}	**0.44**^{12}
Gomez accumulation	100	0.17^{2}	0.15^{12}	**-0.21**^{1}	-0.18^{1}	0.14	0.32	**0.25**^{3}	-0.13^{12}	0.13^{3}	0.15^{3}
Gomez d18O	100	**0.25**^{12}	0.31^{13}	**-0.26**^{123}	-0.19^{3}	0.23^{2}	0.23	0.15^{12}	0.27^{2}	-0.14^{13}	0.23^{2}
Dronning Maud Land d18O	97	0.12^{2}	0.17	0.18^{2}	0.24^{2}	-0.17	-0.15	-0.03	-0.05	0.24^{2}	0.16^{2}
Dronning Maud Land Na	94	**-0.22**^{13}	-0.32^{3}	0.17^{13}	0.22^{3}	**-0.35**^{23}	-0.36^{3}	-0.08	-0.15	-0.12^{1}	-0.12
Siple Station	83	-0.07^{2}	-0.09	-0.08^{3}	0.06	0.29	0.3	0.09	0.18	0.09^{23}	0.17^{2}
ITASE 2001 5	100	-0.19^{1}	-0.22^{12}	0.16^{13}	-0.26^{13}	-0.15	-0.29	0.13^{12}	0.21^{1}	0.15^{1}	0.15^{2}
ITASE 2000 5	98	-0.07^{2}	-0.28^{1}	0.12^{12}	**0.36**^{12}	0.26^{2}	-0.03	-0.17^{3}	-0.06^{3}	0.19^{2}	**0.41**^{12}
ITASE 2001 2	100	0.11^{13}	-0.14	0.12^{1}	0.24^{13}	0.11	-0.16	0.15^{2}	0.2	0.11	0.31^{2}
ITASE 2000 4	99	-0.07	-0.11	0.12^{1}	0.28^{1}	0.11	-0.22	0.15^{1}	0.24^{13}	0.19^{2}	**0.36**^{2}
ITASE 2001 3	100	-0.11^{3}	-0.14	0.08^{3}	0.17	0.14	0.24	0.16^{3}	0.26^{1}	0.14^{3}	0.31^{3}
Vostok d18O	99	-0.19^{23}	-0.13	0.18^{3}	0.13	0.24^{2}	0.13	-0.05	-0.14	0.16	0.13^{2}
Vostok accumulations	99	0.12^{3}	0.22^{1}	-0.07	-0.1	-0.25^{2}	-0.13	**-0.25**^{12}	0.19^{12}	-0.08	-0.1^{3}
WDC05A accumulation	100	**-0.24**^{123}	-0.29^{23}	**0.22**^{12}	**0.41**^{123}	-0.11^{2}	-0.41^{2}	-0.11^{3}	0.12	**0.2**^{12}	**0.43**^{123}
WDC05Q accumulation	100	**-0.25**^{23}	**-0.47**^{23}	**0.27**^{123}	**0.58**^{123}	**-0.41**^{23}	-0.49^{2}	0.17^{13}	0.1	**0.26**^{123}	**0.52**^{123}
Berkner Island	92	0.18^{12}	-0.24	**-0.26**^{12}	0.1	0.25	0.17	**-0.27**^{13}	-0.19	-0.22^{12}	0.13^{3}
ITASE 2000 1	100	**-0.23**^{2}	-0.32^{2}	**0.21**^{12}	0.29^{2}	-0.19^{2}	-0.21	0.11^{1}	0.22^{1}	**0.24**^{2}	0.32
ITASE 1999 1	99	-0.07	-0.07	0.08^{13}	0.06	-0.24	-0.22	-0.1^{1}	-0.07^{1}	0.08^{1}	-0.06
Siple Dome A dD	93	0.1^{3}	0.09^{3}	-0.1^{3}	0.04	0.2	0.22	**-0.29**^{12}	-0.26^{2}	-0.09^{3}	-0.1^{123}
Siple Dome B d18O	94	**0.24**^{2}	0.24	-0.14^{2}	0.07^{2}	0.25^{2}	-0.12	-0.13^{3}	-0.11	-0.23^{3}	-0.19^{13}
Siple Dome Na	80	0.22^{1}	**0.46**^{123}	-0.19^{1}	-0.29^{3}	0.31	0.54^{3}	-0.07^{3}	0.07^{3}	-0.19	-0.19^{3}
ITASE 2002 2	100	0.17^{3}	0.17	**-0.21**^{23}	-0.16^{2}	-0.19	-0.41^{2}	0.2^{2}	0.31^{2}	-0.14^{3}	0.14^{2}
ITASE 2002 4	97	-0.13^{1}	-0.08	0.13^{1}	0.23^{1}	-0.17	-0.15	0.15^{3}	0.27^{13}	**0.25**^{123}	0.33^{1}

Table 8. Same as Table 5 but for documentary, sediment and speleothem records

		SOI (1901-2000)		NINO3.4 (1901-2000)		SAM (1948-2000)		IOD (1902-2000)		IPO (1901-2000)	
Name	n	interannual	decadal	interannual	decadal	interannual	decadal	interannual	decadal	interannual	decadal
Documentary - Africa											
Southern Kalahari precip.	100	-0.16[1]	0.25[3]	0.13[1]	0.12	0.2	0.34	**0.2[1]**	0.11[123]	0.15[1]	0.13
Namaqualand precip.	96	0.18[13]	0.13[3]	**-0.23[13]**	-0.21[13]	0.19	-0.12	-0.13[2]	0.21[1]	-0.22[1]	-0.11[1]
Lesotho precip.	95	0.09[3]	0.1	-0.14[1]	-0.16	0.2	0.23[2]	-0.17	-0.28[2]	0.12	0.07
Eastern Cape precip.	100	0.11	0.08	**-0.25[3]**	**-0.37[12]**	0.21[3]	-0.16	-0.2[13]	-0.32[1]	**-0.22[12]**	-0.31[1]
Southern Cape precip.	96	-0.11	-0.12[3]	-0.12[2]	-0.11[2]	0.15	0.1	-0.15[2]	0.07[1]	-0.13[2]	-0.11
Documentary - South America											
Peru ENSO index	90	**-0.48[123]**	-0.26[2]	**0.49[123]**	0.22[2]	-0.31[2]	0.42[3]	**-0.23[2]**	-0.24[2]	**0.43[123]**	0.22
Potosi precip.	99	0.13[2]	0.04[2]	0.11[2]	0.06[1]	-0.05	0.28	-0.1[3]	-0.05[3]	0.09	0.11
Rio Sali / Dulce streamflow	77	**0.39[123]**	0.23[3]	**-0.37[123]**	0.13	-0.26[3]	0.41	-0.24[2]	-0.31[3]	**-0.34[13]**	0.17
Tucuman precip.	99	**-0.34[123]**	**-0.42[12]**	**0.31[123]**	0.24[2]	0.18	0.29[2]	0.13[23]	-0.31[3]	**0.33[23]**	0.3[2]
Santiago del Estero precip.	100	-0.11[2]	-0.18	0.11[12]	-0.04[3]	0.13	0.12	-0.15[1]	**-0.38[23]**	-0.1[13]	-0.14[3]
Santa Fe / Corrientes precip.	100	-0.17[1]	-0.21	0.16[12]	0.07[12]	0.23	0.22[2]	**-0.28[23]**	-0.15	0.14[3]	-0.02[12]
Rio Parana streamflow	92	-0.08	-0.15[2]	0.09[1]	0.13	-0.14	0.16	-0.09[2]	-0.21	0.12[1]	0.11
Cordoba precip.	99	-0.19[1]	**-0.37[13]**	0.11[1]	0.32[1]	0.21[2]	-0.2	0.07[1]	-0.02	0.18[1]	**0.36[1]**
Mendoza precip.	85	-0.12[1]	0.18	-0.1[2]	-0.21	0.43[3]	0.55	-0.2[23]	-0.17[3]	-0.18[2]	-0.35[2]
Rio Mendoza streamflow	100	**-0.32[23]**	**-0.4[13]**	**0.31[23]**	0.25[3]	-0.25[2]	-0.25	-0.14[2]	-0.32[23]	**0.28[3]**	0.3[3]
Central Andes snow depth	96	**0.27[23]**	-0.21	**-0.3[23]**	0.26[12]	0.13	0.21	-0.14[23]	-0.2[3]	0.2[2]	0.19
C - Andes snow occurrence	96	**-0.31[123]**	-0.25[2]	**0.34[123]**	**0.38[3]**	-0.06	-0.28	**0.29[123]**	0.23[3]	**0.32[13]**	0.23[1]
Santiago de Chile precip.	100	**-0.3[13]**	-0.23[2]	**0.25[13]**	0.31[1]	0.25[2]	0.18	0.09	-0.12[3]	**0.24[13]**	0.27
Lake Sediment											
Laguna Aculeo	97	-0.13[3]	-0.21[3]	-0.02	0.04[3]	0.14	-0.21	-0.15	-0.24[3]	-0.1[23]	-0.1[2]
Lago Puyehue	97	-0.12[3]	-0.25[3]	0.12[3]	0.19[3]	-0.15	-0.34[2]	0.13[1]	0.14	**0.27[3]**	**0.47[123]**
Lago Plomo	100	0.1	0.17	0.14[12]	0.34[12]	0.19[2]	0.32[2]	-0.07[2]	0.04	0.22[2]	0.29[2]
Marine Sediment											
106KL off Peruvian Coast	100	0.09[3]	0.12	0.11	0.27[3]	0.11	0.23	**0.23[2]**	**0.49[123]**	0.22[3]	0.34
Cariaco Basin	90	**-0.23[3]**	0.15[1]	**0.27[13]**	0.14[3]	0.25	0.35[2]	0.17[2]	-0.16[1]	**0.35[13]**	0.31[3]
Speleothem											
Avaiki Cave, Niue	100	0.08[2]	-0.12[3]	0.15[1]	0.31[13]	-0.11[2]	-0.19	0.14[1]	0.14[3]	**0.28[1]**	**0.44[13]**
Cascayunga Cave, Peru	92	**-0.25[13]**	-0.26	**0.22[13]**	0.29[13]	-0.22	-0.47	-0.04[1]	0.04	0.05	-0.08

Table 9. Latitude-weighted fraction of grid cells, each tree ring record correlates significantly (p<0.05) with in the 1901–2000 period for the HadSLP2r, HadISST, CRU TS 3.0 LSAT and CRU TS 3.0 PP grids for the DJFMAM and JJASON seasons. Numbers exceeding 20% are bolded

	HadSLP2r		HadISST		CRU TS 3 Temperature		CRU TS 3 Precipitation	
Name	DJFMAM	JJASON	DJFMAM	JJASON	DJFMAM	JJASON	DJFMAM	JJASON
Africa								
Zimbabwe	16	**23**	7	4	17	18	11	8
Die Bos, South Africa	17	**24**	13	17	**27**	**26**	13	13
Australasia								
Teak Indonesia	**36**	**44**	**27**	**39**	**42**	**46**	14	**20**
Northern Territory Callitris	**31**	**21**	11	7	**26**	14	11	14
Western Australia Callitris	9	16	7	5	11	12	6	12
Kauri NZ	**55**	**53**	**44**	**37**	**37**	17	12	18
Baw Baw Victoria	14	7	13	6	11	12	9	6
Urewera NZ	**30**	**23**	**29**	**21**	**21**	17	11	13
North Island LIBI Composite 2	**25**	8	**20**	16	10	10	8	9
Mangawhero NZ	13	14	20	11	15	11	8	9
North Island LIBI Composite 1	12	18	3	2	5	5	7	5
Takapari NZ	**37**	**40**	**34**	**47**	**37**	**41**	14	**21**
Moa Park NZ	9	13	12	17	16	17	9	8
Flanagans Hut NZ	**24**	16	11	13	**28**	**22**	8	7
CTP East Tasmania	19	15	13	8	14	12	9	8
CTP West Tasmania	**25**	**24**	10	13	20	**22**	9	9
Mount Read Tasmania	7	7	8	9	11	14	7	14
Pink Pine NZ	**51**	**32**	**32**	**41**	**33**	**22**	13	15
Buckley's Chance Tasmania	**32**	17	**22**	**24**	**39**	**37**	13	12
Ahaura NZ	**21**	16	13	17	14	15	11	11
Oroko Swamp NZ	**31**	17	**25**	14	17	14	9	9
Stewart Island NZ	**20**	8	**22**	**30**	**21**	13	8	7
South America								
ALT Composite 1	**37**	**29**	**23**	**27**	**35**	**43**	15	20
ALT Composite 2	**47**	**44**	**33**	**30**	**44**	**22**	11	13
ALT Composite 3	**24**	**33**	**22**	**24**	19	**22**	8	14
La Meseda	7	9	6	8	14	17	7	8
NWA Composite 1	6	8	15	**23**	13	**24**	6	8
NWA Composite 4	8	8	15	11	19	17	12	11
NWA Composite 2	17	8	9	14	16	16	8	6
Rio Sala and Popayan	19	**28**	13	19	**20**	15	10	6
NWA Composite 5	13	13	8	16	14	14	8	4
Dique Escaba	**31**	**34**	17	**21**	19	13	12	11
El Asiento	**33**	**31**	**26**	**31**	12	13	14	13
Le Quesne precip recon	**36**	**30**	**26**	**23**	6	6	7	16
CAN Composite 1	4	15	16	15	**33**	**22**	12	13
Vilches	**27**	**21**	18	17	13	9	9	9
Christie AUCH Composite	20	**31**	**25**	**30**	15	17	10	13
Huinganco	19	11	12	17	**29**	**41**	8	11
CAN Composite 2	11	10	12	18	7	8	10	6
CAN Composite 3	11	12	**22**	16	**25**	20	10	10
Volcan Lonquimay	13	**22**	**22**	**30**	10	**20**	16	15
CAN Composite 6	**21**	**38**	13	**29**	12	**21**	13	7
CAN Composite 5	8	14	5	7	12	17	7	7
Pino Hachado	19	**22**	11	**24**	17	**20**	13	12
Conguillio (Lenga abajo)	6	5	4	5	12	10	7	9
CAN Composite 4	13	10	8	8	12	19	7	8
CAN Composite 8	**24**	19	13	8	**21**	19	10	7
CAN Composite 31	6	20	18	19	9	14	10	10
Lago Rucachoroi	13	12	16	**21**	15	**22**	16	**20**
CAN Composite 9	**34**	14	12	14	**25**	**39**	13	9
CAN Composite 10	**28**	**24**	9	14	**31**	**27**	9	8
CAN Composite 12	**26**	4	15	17	**20**	**27**	6	8

Table 9. (Continued)

Name	HadSLP2r		HadISST		CRU TS 3 Temperature		CRU TS 3 Precipitation	
	DJFMAM	JJASON	DJFMAM	JJASON	DJFMAM	JJASON	DJFMAM	JJASON
Chapelco	3	8	8	12	19	15	7	8
CAN Composite 11	**36**	16	14	8	19	**31**	6	7
Paso Cordova	**33**	**26**	17	**21**	**23**	**24**	10	12
CAN Composite 13	**29**	14	4	9	**23**	**35**	8	7
CAN Composite 16	**32**	**47**	**25**	**35**	**33**	**37**	13	16
CAN Composite 14	**20**	**42**	12	11	17	19	11	9
CAN Composite 17	12	13	**21**	19	**26**	18	13	8
CAN Composite 15	19	17	12	15	13	9	6	6
CAN Composite 19	13	10	18	11	16	9	12	9
CAN Composite 18	13	13	17	18	20	15	10	15
CAN Composite 20	12	7	9	7	14	19	8	6
CAN Composite 21	**22**	12	4	7	6	17	6	11
CAN Composite 22	3	9	7	8	6	4	6	4
CAN Composite 23	13	9	3	7	8	11	7	6
CAN Composite 24	11	13	13	16	12	**36**	5	8
CAN Composite 26	**25**	12	15	15	19	**24**	8	6
CAN Composite 25	11	9	19	**23**	**21**	**24**	9	14
Santa Lucia	17	19	**30**	**26**	**22**	**27**	9	8
Cisnes	2	10	6	8	4	11	4	6
Puesto Miraflores	8	10	10	14	10	12	9	6
CAN Composite 32	5	2	4	2	4	2	5	4
O Higgins	4	3	9	8	12	5	9	5
CAN Composite 27	15	6	9	8	17	12	6	7
El Chalten bajo	9	8	7	10	8	11	9	5
CAN Composite 33	14	12	5	6	10	9	6	9
Torre Morena 4	16	5	5	3	11	7	9	7
Valle Ameghino	11	12	16	17	14	18	14	12
CAN Composite 34	**25**	17	14	**22**	19	**30**	8	9
Heim Morena Este	7	14	18	14	**27**	19	7	4
CAN Composite 30	15	11	8	12	20	**20**	6	7
SAN Composite 5	9	13	8	13	**21**	19	9	7
Puerto Parryn	15	**21**	9	17	18	14	10	11
SAN Composite 6	14	7	8	10	16	18	8	9

Table 10. Same as Table 9 but for coral records

	HadSLP2r		HadISST		CRU TS 3 Temperature		CRU TS 3 Precipitation	
Name	DJFMAM	JJASON	DJFMAM	JJASON	DJFMAM	JJASON	DJFMAM	JJASON
Indian Ocean								
Malindi	**51**	**50**	**50**	**58**	**52**	**45**	14	19
Mafia	15	**25**	19	18	11	**28**	9	9
Ifaty 1 d18O	**20**	**25**	**26**	**29**	**32**	**29**	9	11
Ifaty 1 Sr/Ca	**21**	16	18	15	11	16	8	12
Ifaty 4 Sr/Ca	6	5	7	11	7	15	6	6
Ifaty, 4 d18O	18	9	10	12	18	15	8	9
Mayotte	13	**24**	18	17	**21**	7	11	10
La Reunion	12	11	14	11	13	19	5	7
Seychelles	**53**	**35**	**50**	**42**	**47**	18	14	13
Rodrigues Sr/Ca	5	19	3	10	6	**23**	6	10
Rodrigues d18O	12	10	17	13	16	**26**	6	7
Mentawai West Sumatra	**35**	**47**	**38**	**33**	**28**	7	12	17
Abrolhos	11	9	11	11	11	7	8	11
Ningaloo	16	**36**	13	**22**	6	11	6	10
Bali	**37**	**45**	17	**34**	18	**22**	8	**26**
Bunaken	**56**	**60**	**57**	**47**	**51**	**33**	20	**35**
Pacific Ocean								
Laing	19	**43**	**29**	**38**	**28**	**30**	9	16
Guam	**28**	**23**	**28**	**37**	**28**	**22**	12	13
Madang Lagoon	16	**57**	**21**	**47**	**29**	**47**	11	**25**
Great Barrier Reef precip recon	**43**	**44**	**47**	**27**	**46**	17	**21**	**22**
Kavieng Sr/Ca	**21**	19	17	**33**	19	**23**	7	13
Kavieng Ba/Ca	18	**24**	20	14	**29**	**28**	8	12
Rabaul Sr/Ca	**30**	**32**	**23**	**30**	**28**	16	7	**21**
Rabaul d18O	**23**	**35**	**27**	**33**	**29**	17	10	**20**
Abraham	**30**	**22**	**26**	14	19	**20**	11	8
Nauru	**65**	**55**	**46**	**53**	**37**	**35**	16	**24**
Amedee New Caledonia	**49**	**48**	**46**	**46**	**49**	**30**	**22**	16
Vanuatu	**37**	**26**	**38**	**30**	**29**	11	13	17
Tarawa	**61**	**64**	**56**	**60**	**74**	**56**	**26**	**39**
Maiana	**65**	**68**	**57**	**61**	**69**	**51**	**29**	**40**
Fiji 1F d18O	**67**	**63**	**57**	**51**	**64**	**37**	18	**27**
Fiji 1F Sr/Ca	16	**47**	19	**43**	16	**32**	7	16
Fiji AB	**70**	**62**	**55**	**54**	**59**	**58**	19	**27**
Savusavu	**60**	**60**	**55**	**54**	**58**	**38**	18	**21**
Tonga_TNI2	**51**	**64**	**47**	**50**	**41**	**44**	14	**23**
Tonga_TH1	**63**	**53**	**49**	**47**	**51**	**36**	16	**28**
Palmyra d18O	**61**	**70**	**60**	**58**	**79**	**60**	**27**	**34**
Palmyra Sr/Ca	**37**	**57**	**40**	**44**	**45**	**45**	14	**30**
Rarotonga 3R d18O	**62**	**45**	**55**	**44**	**46**	**23**	17	20
Rarotonga d18O	**54**	**57**	**46**	**46**	**42**	**24**	12	**26**
Rarotonga Sr/Ca	**36**	**59**	**31**	**44**	**30**	**55**	9	**25**
Moorea	**34**	8	15	14	**23**	17	9	12
Clipperton	**44**	**53**	**43**	**45**	**47**	19	10	**27**
Urvina, Galapagos Islands	**31**	**53**	**41**	**42**	**46**	**29**	12	**26**
Secas	8	19	5	16	6	9	9	9

Table 11. Same as Table 9 but for ice core records

Name	HadSLP2r DJFMAM	HadSLP2r JJASON	HadISST DJFMAM	HadISST JJASON	CRU TS 3 Temperature DJFMAM	CRU TS 3 Temperature JJASON	CRU TS 3 Precipitation DJFMAM	CRU TS 3 Precipitation JJASON
South America								
Quelccaya accumulation	**22**	9	13	12	7	9	8	7
Quelccaya d18O	**48**	**34**	**47**	**43**	**40**	**47**	18	13
Illimani dD	8	6	5	4	5	12	6	7
Illimani ammonium	**62**	**59**	**59**	**61**	**72**	**79**	18	**20**
Antarctica								
James Ross Island dD	**28**	**25**	**35**	**40**	**34**	**45**	15	14
Law Dome d18O	5	12	7	6	14	8	6	4
Law Dome accumulation	4	11	5	3	5	10	9	5
Law Dome Na	6	12	6	5	8	7	6	4
Dyer Plateau	3	5	10	6	4	6	7	14
Princess Elizabeth d18O	8	14	6	13	17	**28**	8	10
Princess Elizabeth Chem PC1	**22**	13	**21**	**31**	**20**	**37**	7	6
Dolleman d18O	8	13	16	15	12	14	10	11
Dolleman NO3	14	11	4	10	10	10	9	12
Talos dD	**26**	**29**	**31**	**23**	**26**	14	7	11
Gomez accumulation	9	3	9	10	11	**20**	6	10
Gomez d18O	**31**	**29**	**22**	**21**	**49**	**22**	11	10
Dronning Maud Land d18O	4	7	9	14	20	14	6	10
Dronning Maud Land Na	5	4	5	1	8	3	6	5
Siple Station	3	5	10	13	9	7	9	9
ITASE 2001 5	5	7	7	7	8	8	6	10
ITASE 2000 5	4	4	13	13	4	9	6	4
ITASE 2001 2	8	9	7	9	10	14	10	3
ITASE 2000 4	6	5	5	11	14	11	7	5
ITASE 2001 3	5	9	9	9	12	15	8	5
Vostok d18O	**34**	12	10	12	**21**	**22**	8	19
Vostok accumulations	11	4	3	3	5	9	6	5
WDC05A accumulation	16	**31**	15	11	9	5	4	8
WDC05Q accumulation	**27**	**29**	**28**	**20**	15	3	7	7
Berkner Island	10	9	17	**22**	8	10	7	11
ITASE 2000 1	4	4	9	18	11	**33**	7	7
ITASE 1999 1	4	5	5	4	9	9	6	5
Siple Dome A dD	3	2	9	4	11	11	4	6
Siple Dome B d18O	13	11	13	14	**20**	18	8	6
Siple Dome Na	**31**	10	18	**24**	15	14	11	15
ITASE 2002 2	3	3	8	4	11	4	5	4
ITASE 2002 4	5	5	16	15	12	16	5	4

Table 12. Same as Table 9 but for documentary, sediment and speleothem records

	HadSLP2r		HadISST		CRU TS 3 Temperature		CRU TS 3 Precipitation	
Name	DJFMAM	JJASON	DJFMAM	JJASON	DJFMAM	JJASON	DJFMAM	JJASON
Documentary - Africa								
Southern Kalahari precip.	4	19	4	3	5	3	11	4
Namaqualand precip.	7	**21**	**23**	18	10	4	8	6
Lesotho precip.	1	8	3	3	8	9	8	7
Eastern Cape precip.	**27**	18	**30**	15	**25**	**21**	8	7
Southern Cape precip.	8	4	8	4	4	11	5	7
Documentary - South America								
Peru ENSO index	**48**	**45**	**39**	**37**	**36**	**27**	14	**25**
Potosi precip.	10	2	6	5	7	6	8	6
Rio Sali / Dulce streamflow	**32**	**34**	**29**	**21**	**36**	18	13	15
Tucuman precip.	11	**40**	8	**28**	5	12	6	15
Santiago del Estero precip.	3	8	6	5	1	4	6	5
Santa Fe / Corrientes precip.	3	8	2	3	2	4	5	6
Rio Parana streamflow	18	7	3	5	4	4	8	8
Cordoba precip.	11	6	9	13	5	9	7	8
Mendoza precip.	12	6	**32**	19	**22**	**23**	10	8
Rio Mendoza streamflow	**39**	**41**	**31**	18	**30**	16	7	12
Central Andes snow depth	**25**	**33**	15	**23**	20	15	8	11
C - Andes snow occurrence	**30**	**46**	**35**	**38**	**31**	17	13	**24**
Santiago de Chile precip.	**37**	**37**	**25**	**33**	**37**	**24**	5	14
Lake Sediment								
Laguna Aculeo	19	14	**23**	**27**	**30**	**39**	12	**21**
Lago Puyehue	**27**	18	**28**	**20**	**34**	**25**	8	6
Lago Plomo	8	14	8	9	5	10	7	10
Marine Sediment								
106KL off Peruvian Coast	14	6	**21**	**24**	**23**	**35**	9	6
Cariaco Basin	**21**	17	**33**	**39**	**36**	**33**	12	13
Speleothem								
Avaiki Cave, Niue	8	5	11	18	19	**28**	6	13
Cascayunga Cave, Peru	18	7	9	11	10	16	8	15