A 2000-YEAR CONTEXT FOR MODERN CLIMATE CHANGE

BY
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ABSTRACT. Although considerable attention has been paid to the record of temperature change over the last few centuries, the range and rate of change of atmospheric circulation and hydrology remain elusive. Here, eight latitudinally well-distributed (pole–equator–pole), highly resolved (annual to decadal) climate proxy records are presented that demonstrate major changes in these variables over the last 2000 years. A comparison between atmospheric ^{14}C and these changes in climate demonstrates a first-order relationship between a variable Sun and climate. The relationship is seen on a global scale.

Introduction

A key aspect of the debate about future climate change is centred on the magnitude, frequency and causes of natural climate variability. Recent work highlights the importance of major changes in near-surface temperature such as those of the **Little Ice Age** (**LIA**) and the **Medieval Warm Period** (**MWP**) relative to the warming of the past century (Mann *et al.* 1999; Esper *et al.* 2002). In general, the LIA is characterized by a widespread cooling on the order of 0.5–1.0°C and a lowering of the **equilibrium line altitude** (**ELA**) of mountain glaciers around the world of about 100 m (e.g. Broecker 2001). The MWP preceded the LIA and was characterized by temperatures that were slightly higher than present-day conditions in many parts of the world. There are no universally accepted, precise definitions for the duration of the LIA or the MWP. In this paper, we consider the MWP to cover the period from roughly AD 800 to AD 1200. The MWP–LIA transition culminated at around AD 1400 ± 40, superimposed upon a pattern that began as early as AD 1220 ± 40. In terms of temperature and glacier fluctuations, the LIA has at least two phases and may or may not be over.

The best measure of climate is not necessarily temperature. The magnitude and cause of changes in other climate parameters are explored in this paper. In particular, we concentrate on hydrologic and atmospheric circulation changes occurring over the last 2000 years. Changes in these parameters are important because they are involved in more than half of Earth's poleward heat transport (Peixoto and Oort 1992). Previous work in Greenland has demonstrated that the onset of the LIA was the most dramatic polar circulation reorganization of the last 7000 years (O'Brien *et al.* 1995). Tropical droughts during the LIA were among the most severe of the Holocene (Haug *et al.* 2001). Perhaps most important, changes in climate over the last 2000 years have been associated with major disruptions in civilization (Buckland *et al.* 1996; Fagan 2000; Gill 2000).

We use records that span the last two millennia, a time period represented by well-dated high-resolution records with the best possibility of determining and understanding climate variability on timescales and magnitudes of relevance to modern society. The range and rate of change of climate variability exceed those observed in the instrumental record, giving a better perspective on potential future climate extremes.

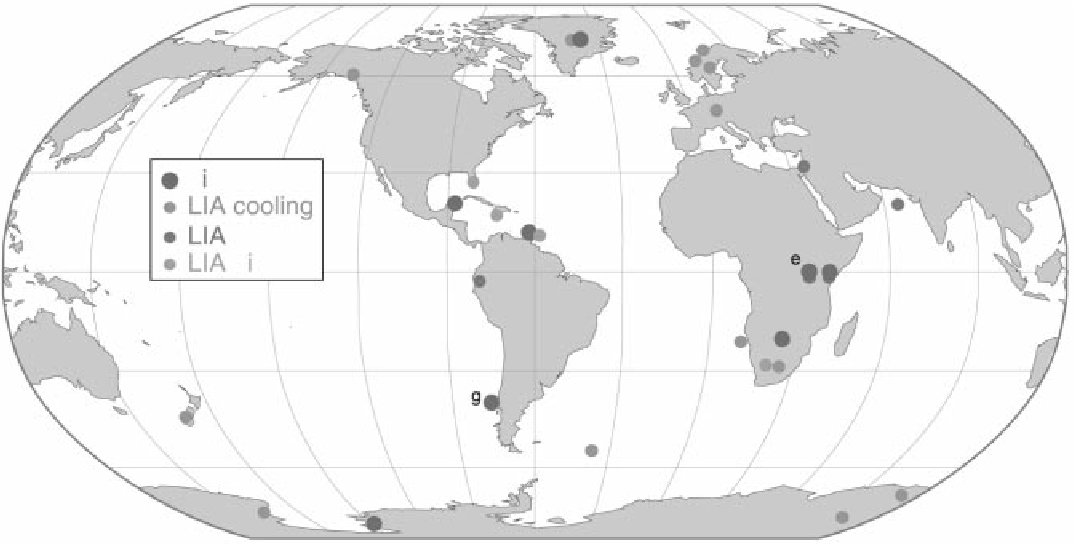

Fig. 1. Map showing locations of palaeoclimate records used in this study are shown with red dots. Blue, green, and orange dots denote locations where a shift toward cooler, wetter, and drier conditions occurred at the Little Ice Age–Medieval Warm Period transition as described in Mayewski *et al.* (2004)

Global distribution of climate variability

To illustrate the global nature of major climate events during the last 2000 years, we present eight well-dated high-resolution records that share similar centennial-scale signatures (Figs 1 and 2). We recognize that not all published records contain this signature (e.g. Cook *et al.* 1991), but the broad geographic distribution (pole–equator–pole) of records presented here indicates that they are indeed global, corroborating previous work (e.g. Denton and Karlén 1973; Grove 1988; O'Brien *et al.* 1995). The clearest of these signatures is the LIA, which follows the MWP, as described above.

The LIA–MWP transition is one of several global-scale **rapid climate change** (**RCC**) events to have occurred in the Holocene (Mayewski *et al.* 2004). As shown in Mayewski *et al.* (2004) this RCC was not merely a temperature change, but was also a time of rapid atmospheric circulation and hydrologic change across the planet. In Fig. 1 blue, green, and orange dots mark locations where shifts toward cooler, wetter, and drier conditions occurred at the LIA–MWP transition (see Mayewski *et al.* (2004) and references therein).

Atmospheric circulation and hydrology

Ice core chemistry has a quantitatively strong relationship to atmospheric circulation. Changes in the position and strength of semi-permanent high and low pressure centres impact the delivery of chemical species from their source region to the ice that ends up in a glacier. Calibrating the relationship between present-day meteorological measurements of pressure and wind fields with the chemical signals measured in ice cores allows past ice chemistry to be used as a proxy for atmospheric circulation at earlier times. Previous work on the GISP2 ice core shows that high K^+ concentrations (Fig. 2a) are coincident with intensification of the Siberian High, and that high Na^+ concentrations (not shown) represent a deeper Icelandic Low (Mayewski *et al.* 1997, Meeker and Mayewski 2002). In the high latitude southern hemisphere, Kreutz *et al.* (1997) demonstrated that higher Na^+ concentrations in the Siple Dome ice core (Fig. 2h) coincide with higher levels of cyclone intensity in one of the major quasi-stationary lows in the circumpolar trough, the Amundsen Sea Low.

The levels of certain trace elements measured in some marine cores can be used to infer past changes in river discharge, and are related to the variability of precipitation. In a core from ODP Site 1002, in the Cariaco basin, the %Ti (Fig. 2c) and %Fe (not shown) have been interpreted as a proxy for the amount of **Inter Tropical Convergence Zone** (**ITCZ**) precipitation over northern South America (Haug *et al.* 2001). Using a marine core from near the coast of mid-latitude Chile, Lamy *et al.* (2001)

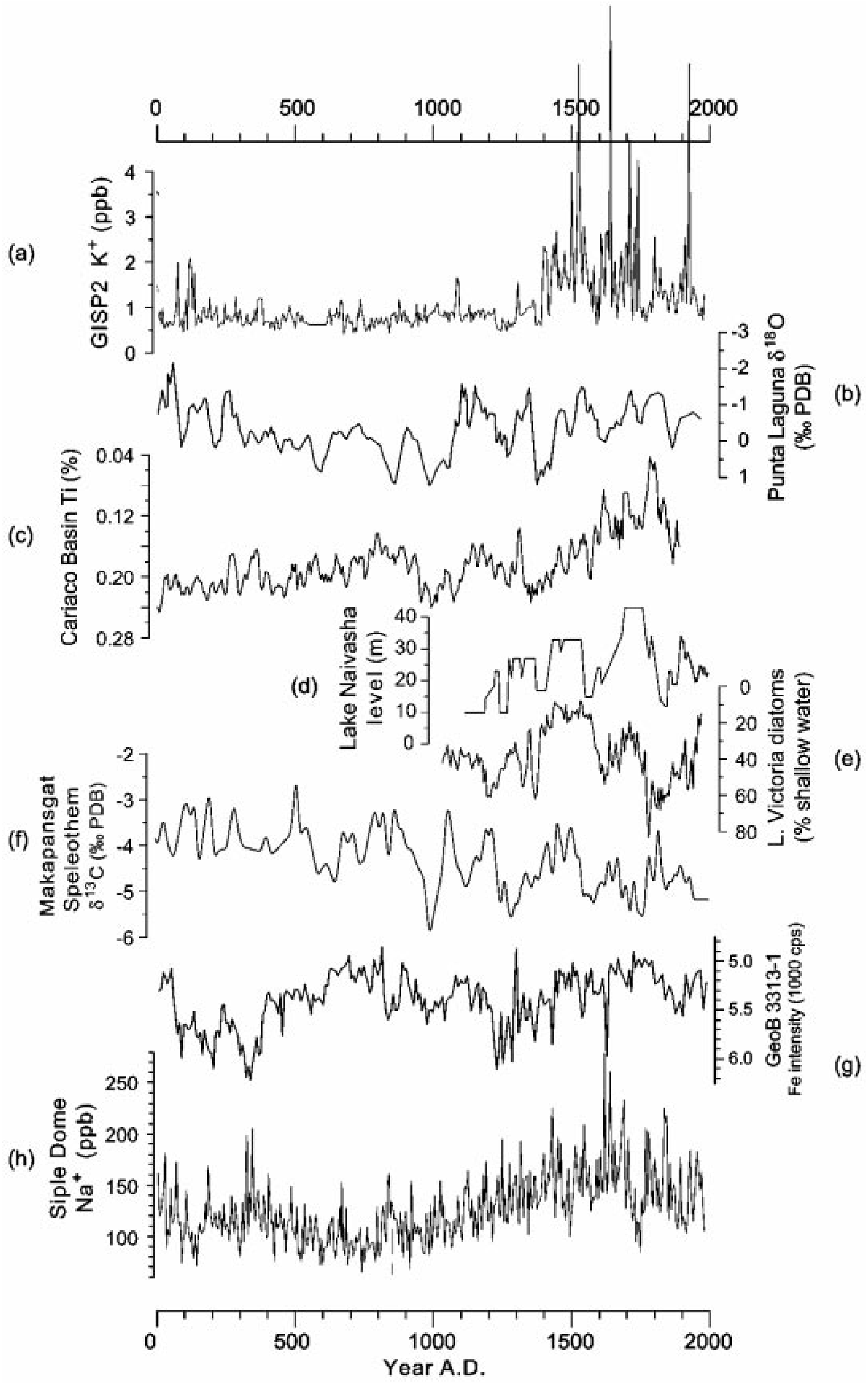

Fig. 2. Eight palaeoclimate records from locations corresponding to red dots in Fig. 1 arranged by latitude from north to south. (a) GISP2 K$^+$, (b) Punta Laguna δ^{18}O, (c) Cariaco Basin percentage titanium, (d) Lake Naivasha level, (e) Lake Victoria percentage shallow water diatoms, (f) Makapansgat speleothem δ^{13}C, (g) Core GeoB 3313–1 iron intensity, (h) Siple Dome Na$^+$

have shown a link between the iron content of sediment (Fig. 2g) and precipitation, which in turn is related to changes in the position of the southern hemisphere westerlies. Increased input of iron-poor material (low Fe intensity) coincides with a higher amount of rainfall.

Oxygen and carbon isotope fractionations are related to precipitation. The oxygen isotope ($\delta^{18}O$) record from Punta Laguna (Fig. 2b) has been interpreted as a proxy for changes in precipitation in the Yucatan (Hodell *et al.* 2001). Carbon isotopes ($\delta^{13}C$) measured in a speleothem from Cold Air Cave, Makapansgat, South Africa (Fig. 2f) were used to infer the extent of grasslands in southern Africa (Holmgren *et al.* 1999) that is in turn related to rainfall.

In equatorial Africa lake levels have been used as an indicator of changes in precipitation minus evaporation. Past levels in Lake Naivasha determined by Verschuren *et al.* (2000) are shown in Fig. 2d. Changes in the level of Lake Victoria based on the percentage of shallow water diatoms (Stager, this study) are shown in Fig. 2e.

External forcing

The time series of potentially important climatic forcing factors are shown in Fig. 3. Incoming shortwave radiation from the Sun is the dominant source of energy on Earth and a primary candidate for introducing variability in the climate system. Globally averaged outgoing long-wave radiation must ultimately balance the incoming radiation. However, on its return to space a portion of this radiation is temporarily trapped by greenhouse gases, thus warming the lower troposphere. The amount of aerosols in the atmosphere also alters the energy balance, in some cases leading to near-surface cooling. Proxies for solar variability, astronomical calculations for changes in the seasonal and geographical distribution of incoming radiation, measurements of past levels of greenhouse gases, and a proxy for volcanic aerosols are presented in Fig. 3.

Cosmogenic nuclides such as ^{10}Be and ^{14}C, produced by the interaction of cosmic ray particles with the atmosphere, can be used to provide long-term records of the intensity of the cosmic ray flux and its modulation by solar activity. Atmospheric ^{14}C is incorporated along with the other stable isotopes of carbon into biological organisms, including trees. Some of the ^{10}Be is removed from the atmosphere by snow and incorporated into ice sheets and glaciers. These proxies for solar variability, $\Delta^{14}C$ measured in tree rings (Stuiver *et al.* 1998), and ^{10}Be measured in ice from Greenland (Yiou *et al.* 1997) and the South Pole (Bard *et al.* 2000) are shown in Fig. 3a. Low production rates of cosmogenic nuclides correspond with increased solar output. Calibration of the measured ^{10}Be to total irradiance (Bard *et al.* 2000) shows that variations on the order of about 5 W/m^2 occur on multi-decadal to centennial time scales.

Variations in the geometry of Earth's orbit (eccentricity, obliquity, and precession of the equinoxes) lead to changes in the distribution of insolation (Berger 1978a, b) as a function of latitude and season (Fig. 3b). Eccentricity is the only factor that causes a net change in the globally averaged amount of energy received by Earth over an entire annual cycle. These variations are on the order of 0.1% on a time scale of *c.* 100 000 years. Variations in obliquity and precession lead to changes of the spatial and seasonal patterns of incoming solar radiation on the order of 10% on time scales of *c.* 19 000–41 000 years. Obliquity variations redistribute incoming radiation symmetrically about the equator, while the precession changes result in an asymmetric redistribution out of phase between hemispheres. Changes in summer and winter insolation over the past 2000 years are smooth, unidirectional, and small (Fig. 3b).

The concentration of greenhouse gases in Earth's atmosphere have varied on time scales ranging from millions of years to seasons. The record of CO_2 and CH_4 for the last 2000 years is shown in Fig. 3c. Carbon dioxide from 1958 to 2000 comes from continuous measurements made at Mauna Loa, Hawaii (Keeling and Whorf 2004). Methane measurements from 1979 to 1992 are from Cape Meares, Oregon (Khalil *et al.* 1993). Estimates of the levels of atmospheric greenhouse gases prior to this come from measurements made on air bubbles trapped in glacial ice from Antarctica (Neftel *et al.* 1985; Friedli *et al.* 1986; Etheridge *et al.* 1998a, b; Indermühle *et al.* 1999; Flückiger *et al.* 2002). The increase in greenhouse gas concentration over the last one to two centuries is clearly due to human activities including the burning of fossil fuels, deforestation, and cement production (Intergovernmental Panel on Climate Change 2001). These increases mirror the exponential rise of human population (United Nations 1999; US Bureau of the Census 2004) also shown in Fig. 3c.

Large volcanic eruptions inject significant amounts of sulphate into the atmosphere. When

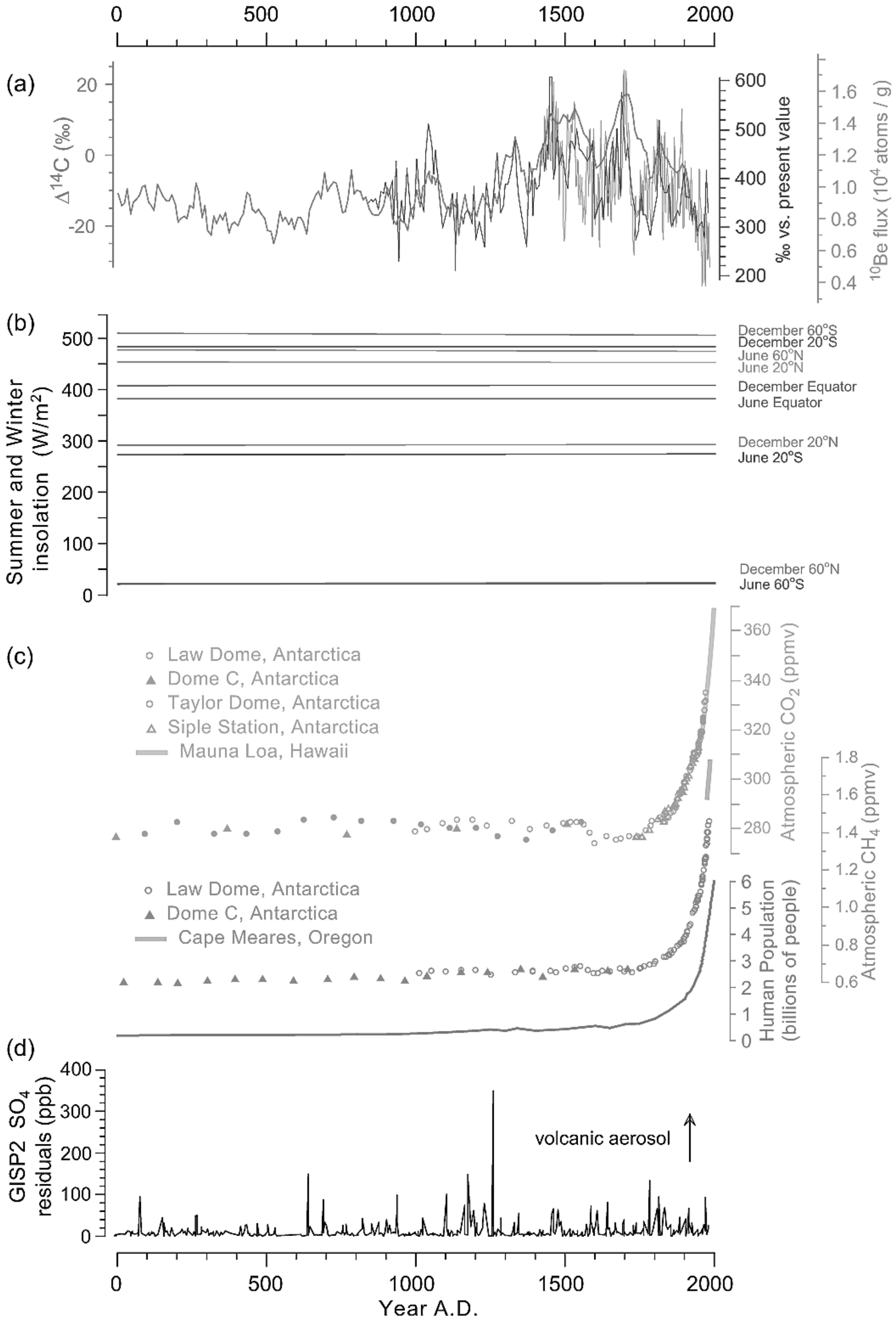

Fig. 3. Climate forcing functions. (a) Proxies for solar variability including Δ^{14}C measured in tree rings (red), ^{10}Be measured in ice from Greenland (green) and South Pole (blue). (b) Summer and winter insolation at latitudes 60°N, 20°N, equator, 20°S, and 60°S. (c) Greenhouse gas concentration, atmospheric CO$_2$ (light blue) and CH$_4$ (green) along with human population (pink). (d) SO$_4$ residuals (volcanic aerosols) measured in ice from Greenland

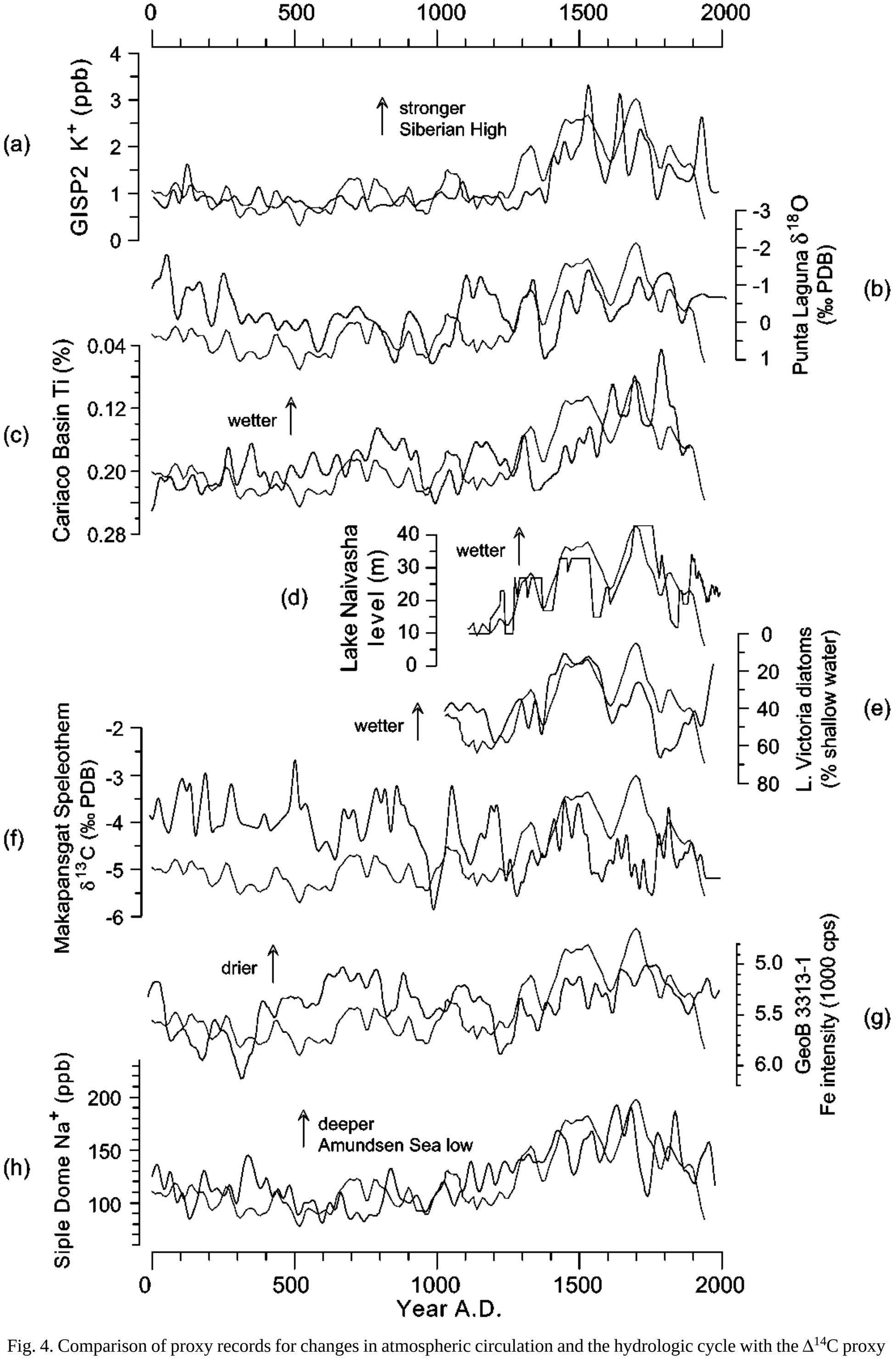

Fig. 4. Comparison of proxy records for changes in atmospheric circulation and the hydrologic cycle with the Δ^{14}C proxy for solar variability.

this sulphate gets into the stratosphere it is transported long distances, and has the potential to impact climate for several years. Large spikes of SO_4 that stand well above tropospheric background levels (SO_4 residuals) serve as a proxy for volcanic aerosols. The SO_4 residuals measured in ice from GISP2 in Greenland (Zielinski *et al*. 1996) are shown in Fig. 3d.

Insolation changes due to Earth's orbital geometry, and variations of greenhouse gases (CO_2, CH_4), and human population growth show little resemblance to the response records shown in Fig. 2. Forcing due to Earth's orbital changes is too slow and not even of the same sign in the northern and southern hemispheres. Greenhouse gases have increased exponentially with sharp increases from 1850 onwards with the exception of a 10 ppmv drop in CO_2 within the LIA (Etheridge *et al.* 1998b). Episodic volcanic aerosol forcing likewise shows little resemblance to the multi-decadal scale variability shown in Fig. 2.

Previous work has suggested a connection between solar variability and individual climate records (e.g. Suess 1970; Denton and Karlén 1973; Eddy 1976; Stuiver and Braziunas 1993; Jirikowic and Damon 1994; Lean *et al.* 1995; O'Brien *et al.* 1995; Mayewski *et al.* 1997; Beer 2000; van Geel *et al.* 2000; Bond *et al.* 2001). Below we show that global climate change correlates with solar variability by comparing the eight pole–equator–pole distributed records shown in Fig. 2 with atmospheric ^{14}C residuals ($\Delta^{14}C$), a proxy for variability of solar output (Stuiver *et al.* 1998; Beer 2000), to evaluate the likelihood of a solar–climate association.

Solar–climate connection

A connection between solar variability and climate change has previously been noted in many individual records, including two used in this study (Verschuren *et al.* 2000; Hodell *et al.* 2001). Here we illustrate that such a connection is of global proportions by comparing eight records arrayed in latitudes extending from the Arctic to the Antarctic. Fig. 4 shows the comparison between each of the eight records shown in Fig. 2 and the $\Delta^{14}C$ record from Fig. 3. In order to clearly see the multi-decadal to centennial variability, each record has been smoothed by removing periodicities less than 30 years. This comparison reveals a transition in atmospheric circulation and hydrology at around AD 1400 ± 40 along with an increase in the $\Delta^{14}C$ (representing a decrease in solar output). During the LIA there is a remarkable coherence between fluctuations in the $\Delta^{14}C$ series and both atmospheric circulation and hydrology. Reduced solar output thus coincides with changes in climate on a global scale

The most prominent RCC of the late Holocene (LIA–MWP transition; Mayewski *et al.* 2004) can be traced at various latitudes. Changes at this transition include intensified polar atmospheric circulation in both hemispheres (Mayewski *et al.* 1993, 1997; O'Brien *et al.* 1995; Kreutz *et al.* 1997), increased tropical humidity in Yucatan (Hodell *et al.* 2001) as well as in tropical Africa at Lake Victoria (this study), and Lake Naivasha (Verschuren *et al.* 2000), an expansion of grasslands in southern Africa (Holmgren *et al.* 1999), reduced ITCZ precipitation over northern South America (Haug *et al.* 2001), and increased precipitation in mid-latitude Chile (Lamy *et al.* 2001). These Sun–climate relationships are most clearly seen during the LIA. In the earlier part of the record the solar–climate association also reveals some similarities, but the relationship is not straightforward.

Conclusions

The proxy climate and $\Delta^{14}C$ records presented in this study show a good match with minor exceptions. In summary, six out of these eight records to a large extent match the signal structure and timing of $\Delta^{14}C$ variability. The Cariaco basin and South African speleothem records match the structure, but have some small age-offsets. The global distribution of the LIA and MWP and the agreement between climate proxy records and the $\Delta^{14}C$ series over the last 2000 years indicate a strong association between solar variability and globally distributed climate change. This shows that change in the output of the Sun has significant impacts on climate. Additional study is needed to investigate the higher frequency changes seen in palaeoclimate records because of the societal relevance of climate change on these time scales.

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