Abrupt Climate Change: *The Next Major Challenge*

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Introduction

Prior to the early 1990's the concept of dramatic changes in climate characterized by onset and decay of less than a decade was suspected, but definitely not demonstrated. Today we know that even "milder" versions of abrupt climate change are significant enough to radically alter the course of civilizations and ecosystems (eg., Buckland et al. 1995, Mayewski and White, 2002; Gill et al., 2008) and that these events are taken seriously enough to be the subject of numerous governmental scientific and security reports (eg., NRC, 1999; 2003).

To understand the mechanisms, the timing, and probable regions of impact of future abrupt climate change requires detailed examination of the pre-instrumental era record since analogs for abrupt climate change pre-date the short ~100 years of northern hemisphere and shorter southern hemisphere instrumental era.

What is known about abrupt climate change does not preclude the occurrence of these events in the near future. In fact, as warming progresses climate will likely become less stable, increasing the probability for abrupt climate change events. Projections for future climate change suggest that many developing areas may experience the most adverse impacts of warming, drought, and sea level rise.

As demonstrated in the following understanding of abrupt climate change is primarily dependant on paleo-analogs. While future abrupt climate change may or may not operate in a similar fashion to naturally occurring abrupt change events the paleo-record has and still does offer the most significant potential for understanding these events.

Ice Core Contributions to the Understanding of Abrupt Climate Change

Pre-Holocene Abrupt Climate Change Events

The now classic central Greenland ice core isotopic temperature records show 23 interstadial or Dansgaard./Oeschger events, now commonly referred to as abrupt climate change events, first recognized in the GRIP record (Dansgaard et al., 1993) and verified in the GISP2 record between 110 and 15 kyr B.P. (Grootes et al., 1993). Examination of the GISP2 glaciochemical record demonstrates that abrupt climate change events are also characterized by massive shifts in atmospheric circulation (Mayewski et al., 1993a, 1994, 1997). Modeling common temporal behavior of the GISP2 chemical series reveals a record of change in the relative size and intensity of the atmospheric circulation system that transports well-mixed air masses to Greenland (defined as the polar circulation index (PCI)). Increased levels of seasalt and dust in the GISP2 record are associated with periods of more intense and expanded PCI circulation (stadial (cold) intervals) (Mayewski et al., 1994). Massive iceberg discharge events (Heinrich events) defined from the marine record and correlated with several stadials in the ice core record (Bond et al., 1993) can also be interpreted from the glaciochemical PCI record as can notable expansions of ocean ice cover (Mayewski et al., 1994). The most recent, notably large abrupt climate change event observed in marine and ice core records is the Younger Dryas (YD), a return to near-glacial conditions that punctuated the last deglaciation. GISP2 high-resolution, continuous glaciochemical records show that both onset and termination of the YD occurred within 10-20 years and that massive, frequent and short-term (decadal or less) changes in atmospheric composition occurred throughout this event (Mayewski et al., 1993a). These dramatic climate changes were not restricted to Greenland and nearby boreal areas as evidenced by the GRIP CH_4 record (Chappellaz et al., 1993).

Knowledge of event phasing on regional to hemispheric scales is essential to understanding the physical mechanisms and controls on the climate system. Correlations based on the similarities seen in Greenland and Antarctic ice core CH_4 signals suggest that climatic events of millennial to multi-centennial duration are correlated between the north and south polar regions (EPICA, 2006). Glacial age Antarctic warm events correlate with but precede Greenland warm events (Huybers, 2003; Roe and Steig, 2004; EPICA, 2006). The start of each warming signal in the Antarctic takes place when Greenland is at its coldest, the period when armadas of icebergs crossed the North Atlantic (Heinrich events). Moreover warming in the Antarctic is gradual whereas warming in the associated Greenland signal is abrupt. These relationships may be interpreted as reflecting connection between the two hemispheres via the ocean's meridional overturning circulation (MOC) (EPICA, 2006). The lag may reflect the slow speed of the MOC, with complete ocean overturning taking several centuries plus. The data also show a strong relationship between the magnitude of each warming event in the Antarctic and the duration of the warm period that follows each abrupt warming event in Greenland (EPICA, 2006). This relationship is interpreted to reflect the extent to which the MOC is reduced, with reduced overturning assumed to lead to the retention of more heat in the Southern Ocean. These associations are indirectly supported by marine sediment records off Portugal that reveal changes in deep water masses related to Antarctic Bottom Water formation and in Atlantic surface water, at the same time as the events seen in the central Greenland deep ice cores (Shackleton et al., 2000).

The cause(s) of pre-Holocene era millennial scale climate abrupt climate change events are not fully understood but slowing of the MOC has been attributed to North Atlantic meltwater flood events, and/or to massive iceberg discharges (Heinrich Events) that slow the formation of North Atlantic Deep Water. Changes in the intensity and extent of atmospheric circulation plus sea ice extent and overall ice sheet extent also played a major role in the radiation balance and thermohaline circulation of the ocean and climate change (Stocker and Wright, 1991; Mayewski et al., 1994, 1997; Knorr and Lohman, 2003; Li et al., 2005).

Holocene Abrupt Climate Change Events

Over the past 12,000 years (Holocene) there have been several abrupt changes in climate in the polar regions; albeit significantly more subdued than those during the preceding glacial period. These abrupt changes in polar climate, as well as the abrupt changes in climate recorded in a global array of paleoclimate records covering the same period, are associated with short term fluctuations in solar variability, aerosols, and greenhouse gases superimposed on longer term changes in insolation, greenhouse gases, and ice sheet dynamics (Mayewski et al., 2004). It is highly notable that changes in temperature, precipitation, and storminess during these events have been of sufficient magnitude to cause major disruptions to ecosystems and civilizations (eg., Buckland et al. 1995, Mayewski and White, 2002; Mayewski et al., 2004; Gill et al., 2008), demonstrating that this natural variability must be taken into account in understanding modern climate and the potential for future climate change.

Comparison of similarly resolved and analyzed ice core records from our work in Greenland (GISP2) and West Antarctica (Siple Dome) reveals evidence related to phasing, magnitude, and possible forcing of changes in atmospheric circulation and temperature over the Holocene (Fig. 1) as follows. Intensification of atmospheric circulation in the northern hemisphere (stronger Siberian High and northern circumpolar westerlies, deeper Icelandic Low) and to a lesser degree in the southern hemisphere (stronger circumpolar westerlies and deeper Amundsen Sea Low) occurs ~8200 years ago. This event is associated with cooling in Greenland (Grootes et al., 1993) and in East Antarctica (Masson et al., 2000), and with a small drop in CH_4, a long-term decline in CO_2, and an increase in solar energy output (based on the ^{14}C proxy for solar variability). The latter may have led to increased melting of portions of the North American ice sheet, consequent decrease in salinity and a reduction in thermohaline circulation in the North Atlantic. Between ~8200-7800 years ago there is a decrease in precipitation in equatorial Africa suggested to have been the consequence of an expanding Antarctic polar cell and consequent displacement of moisture bearing winds (Stager and Mayewski, 1997).

Intensification of the southern circumpolar westerlies ~6000-5000 years ago is associated with cooling in West Antarctica ~6400-6200 years ago. At the same time there is also intensification of the Icelandic Low, Siberian High and northern circumpolar westerlies. This period of change coincides with a reverse in the trend of orbitally forced insolation, a drop in CH_4, a small rise in CO_2, a decrease in solar energy output, and collapse of the Ross Sea ice sheet (Conway et al., 1999).

From ~3200-2800 years ago the Siberian High and Icelandic Low experience a period of intensification that coincides with a decrease in solar energy output.

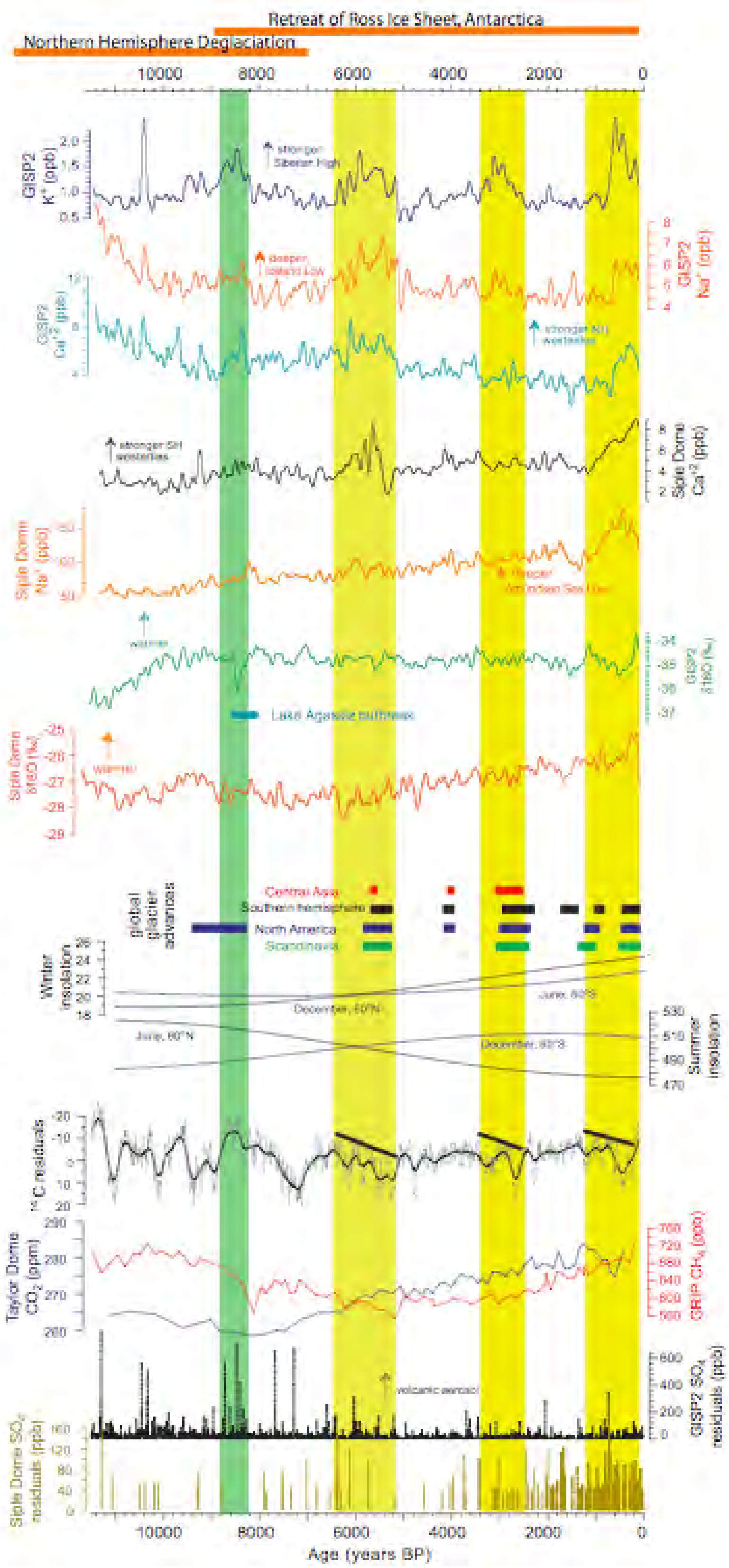

Figure 1. Examination of potential controls on and sequence of Antarctic Holocene climate change compared to Greenland climate change using 200 year Gaussian smoothing of data from the following ice cores (top to bottom): GISP2 (Greenland) ice core, K^+ proxy for the Siberian High (Meeker and Mayewski, 2002); GISP2 Na^+ proxy for the Icelandic Low (Meeker and Mayewski, 2002); GISP2 Ca^{++} proxy for the Northern Hemisphere westerlies (Mayewski and Maasch, 2006); Siple Dome (West Antarctic) Ca^{++} ice core proxy for the Southern Hemisphere westerlies (Yan et al., 2005); Siple Dome Na^+ proxy for the Amundsen Sea Low (Kreutz et al., 2000); GISP2 $\delta^{18}O$ proxy for temperature (Grootes and Stuiver, 1997); Siple Dome $\delta^{18}O$ proxy for temperature (Mayewski et al., 2004, White unpub.); timing of the Lake Agassiz outbreak that may have initiated Northern Hemisphere cooling at ~8200 years ago, (Barber et al., 1999); global glacier advances (Denton and Karlen, 1973; Haug et al., 2001; Hormes et al., 2001); prominent Northern Hemisphere climate change events (shaded zones, Mayewski et al., 2004); winter insolation values (W m^{-2}) at 60°N (black curve) and 60°S latitude (blue curve) (Berger and Loutre, 1991); summer insolation values (W m^{-2}) at 60°N (black curve) and 60°S latitude (blue curve) (Berger and Loutre, 1991); proxies for solar output: $\Delta^{14}C$ residuals (Stuiver et al., 1998): raw data (light line) with 200 year gaussian smoothing (bold line);

atmospheric CH_4 (ppbv) concentrations in the GRIP ice core, Greenland (Chappellaz et al., 1993), atmospheric CO_2 (ppmv) concentrations in the Taylor Dome, Antarctica ice core (Indermühle et al., 1999); and volcanic events marked by SO_4^{2-} residuals (ppb) in the Siple Dome ice core, Antarctica (Kurbatov et al., 2006)., and by SO_4^{2-} residuals (ppb) in the GISP2 ice core (Zielinski et al., 1994). Timing of Northern Hemisphere deglaciation is from Mayewski et al., (1981), and retreat of Ross Sea Ice Sheet is from Conway et al., (1999). Green bar denotes the 8800-8200 year ago event seen in many globally distributed records associated with a negative $\Delta^{14}C$ residual (Mayewski et al., 2004). Yellow denotes 6400-5200, 3400-2400, and since 1200 year ago events seen in many globally distributed records associated with positive $\Delta^{14}C$ residuals (Mayewski et al., 2004). Figure modified from Mayewski et al. (2004, 2005).

Abrupt Climate Change Over the Last ~2000 Years

Increase in atmospheric circulation intensity commencing ~1200-1000 years ago is the most significant Antarctic climate circulation event of the last ~5000 years (Mayewski and Maasch, 2006) (Fig. 1). It is characterized by strengthening of the Amundsen Sea Low (Siple Dome Na^+) and the southern circumpolar westerlies (Siple Dome Ca^{++}), with slight cooling both at Siple Dome ($\delta^{18}O$), until recent decades, and in the East Antarctic composite proxy temperature record (Masson et al., 2000). In the North Atlantic the most dramatic change in atmospheric circulation of arguably the Holocene (minimally the last 7000 years) occurs ~600 years ago with abrupt intensification of the Icelandic Low (GISP2 Na^+), Siberian High (GISP2 K^+), and the circumpolar westerlies (GISP2 Ca^{++}) accompanied by general cooling revealed by the composite temperature record for the northern hemisphere (Mann and Jones, 2003). Change over the last ~1000 years is generally associated with a decrease in solar energy output, a drop in CO_2, and increased frequency of volcanic source sulfate aerosols over Antarctica.

Detailed investigation of a high-resolution (annual and near annual scale) global scale array of ice cores reveals phasing associations for the last major global scale climate change event of the Holocene similar to that noted for glacial age millennial scale events (Fig. 2). Onset is gradual (~AD1100-1200) in Antarctica (Siple Dome - Kreutz et al., 2000), the North Pacific (Mt. Logan - Osterberg et al., in prep.), and Asia (Mt. Everest – Kaspari et al., 2007) followed in AD1400-1420 by abrupt change in the North Atlantic (O'Brien et al., 1995; Mayewski et al., 1993b). Similar phasing and transition style is noted for earlier Holocene age abrupt climate change events such as the ~6000-5000 year ago event, but comparison between records is less definitive in pre-2000 year old records due to potential dating errors (Mayewski et al., 2004).

Comparison of ice core proxies for atmospheric circulation and temperature between West Antarctica (Siple Dome) and East Antarctica (Law Dome) covering the last 700 years reveals that East and West Antarctica have operated inversely with respect to temperature and to strength of atmospheric circulation on multi-decadal to centennial scales for many centuries and presumably much longer (Fig. 3) (Mayewski et al. 2005). The exception is a climate change event commencing ~AD 1700 and ending by ~AD1850, during which circulation and temperature acted synchronously in both regions. This cooling period is coincident with an increase in the frequency of El Niño events impacting Antarctica as determined from the distribution of methane sulphonic acid (MSA) in a South Pole ice core (Meyerson et al., 2002) and with an increase in solar energy output. The close of this cooling event coincides with the onset of the modern rise

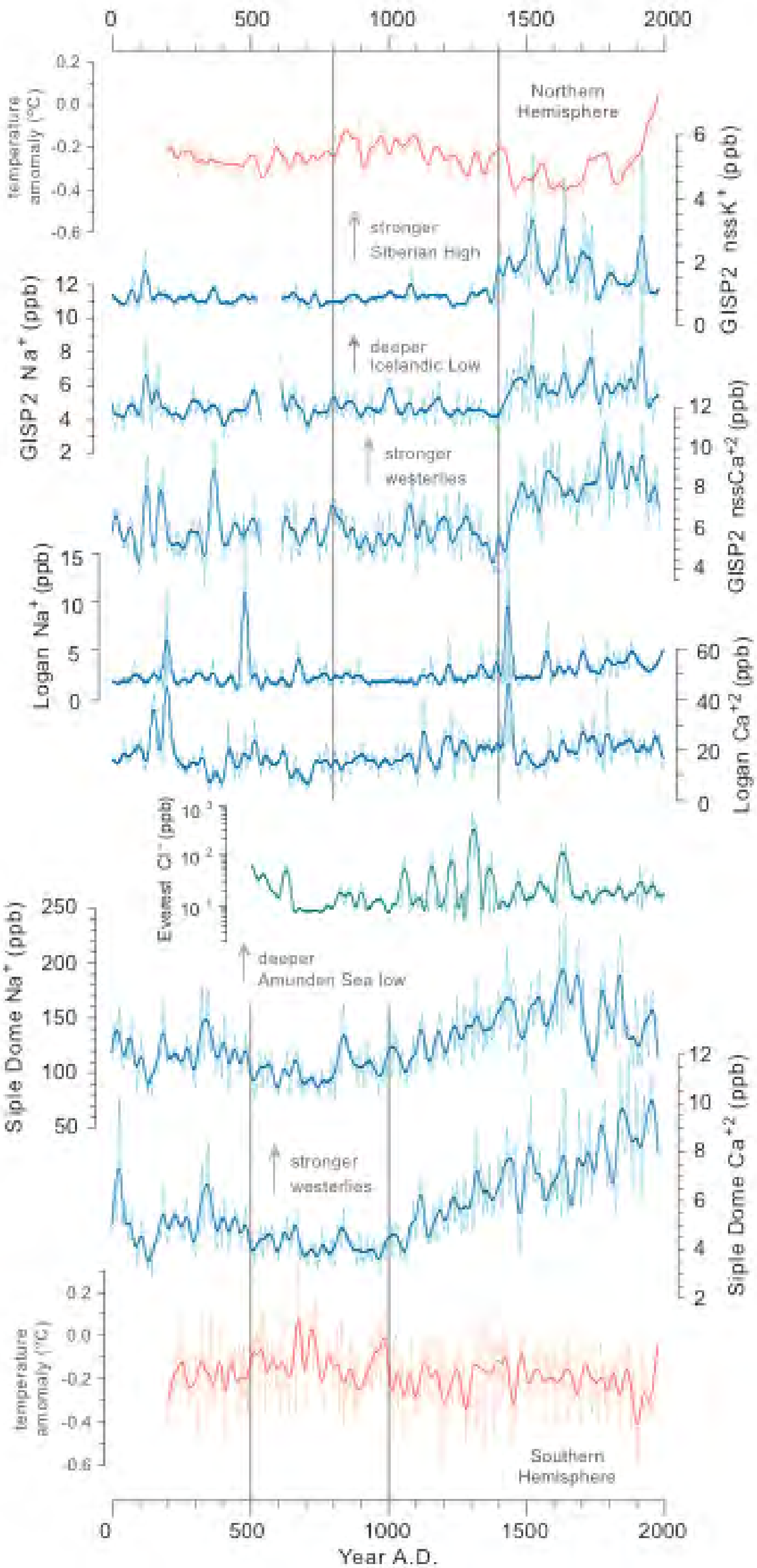

Figure 2. Northern and southern hemisphere reconstructed temperatures (in red from Mann and Jones (2003)) and ice core reconstructed atmospheric circulation systems (in blue) referred to in text - Icelandic Low (GISP2 Na$^+$), Siberian High (GISP2 K$^+$), northern hemisphere westerlies (GISP2, Mt. Logan Ca^{++}), southern hemisphere westerlies (Siple Dome Ca^{++}), Amundsen Sea Low (Siple Dome Na$^+$), summer Indian monsoon (Mt. Everest Cl$^-$), and Aleutian Low (Mt. Logan Na$^+$). Data is presented with less than 10-yr signal (light line) extracted to approximate the original annual to multi-annual series and with the less than 30-yr signal (dark line) extracted series to facilitate examination at decadal scales. Vertical lines refer to onset for temperature change referred to in the text. Modified from Mayewski and Maasch (2006). For references see Fig. 1.

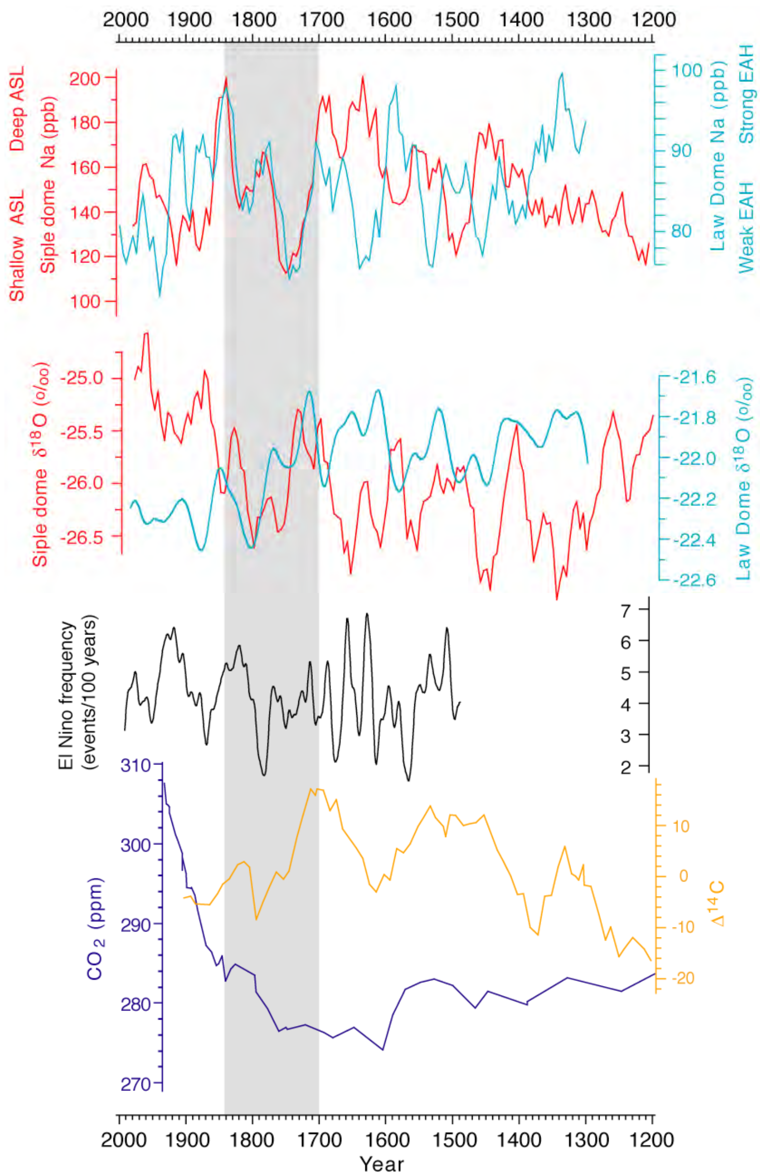

Figure 3. 25 year running mean of SD (Siple Dome) (red) and DSS (Law Dome) (blue) Na (ppb) used as a proxy for the ASL (Amundsen Sea Low) and EAH (East Antarctic High), respectively, with estimated sea level pressure developed from calibration with the instrumental and NCEP reanalysis (based on Kreutz et al., 2000; Souney et al., 2002). 25 year running mean SD (red) and DSS (blue) $\delta^{18}O$ (°/oo) used as a proxy for temperature, with estimated temperature developed from calibration with instrumental mean annual and seasonal temperature values (van Ommen and Morgan, 1997; Steig et al., 2000). Frequency of El Niño polar penetration ((51-yr Gaussian filter), black) based on calibration between the historical El Niño frequency record (Quinn et al., 1987; Quinn and Neal, 1992) and South Pole methane sulphonate (MS) (Meyerson et al., 2002). Figure from Mayewski et al. (2005). $\Delta^{14}C$ series used as an approximation for solar variability (Stuiver and Braziunas, 1993); values younger than 1950 are bomb contaminated. CO_2 from DSS ice core (Etheridge et al., 1996). Darkened area shows 1700-1850 year era climate anomaly discussed in text. From Mayewski et al. (2005).

in CO_2, followed by the warmest temperatures of the last 700 years in West Antarctica based on the $\delta^{18}O$ Siple Dome ice core record (Mayewski et al., 2005). Examination of the full ~100,000 year long $\delta^{18}O$ Siple Dome ice core record (provided by J. White, unpublished) suggests that recent warming is unique over this entire period. The close of this event is coincident with a major transition from zonal to mixed flow in the North Pacific Mt. Logan ice core record (Fisher et al., 2006), suggesting a global scale association between Antarctic and North Pacific climate. Further investigation into this most recent abrupt climate change event to impact Antarctica could have relevance to events that might occur as polar climates adjust to future warming.

A satisfactory explanation for the forcing of Holocene abrupt climate change remains elusive, though the link to variations in solar energy output is highly suggestive. More detailed examination of forcing over the last 2000 years using the ice cores in Fig. 1 and other palaeoclimate records supports the close association in timing between changes in atmospheric circulation (notably along the edge of the polar vortex) and solar energy output (Maasch et al., 2005). Highly resolved, annually dated, calibrated proxies for atmospheric circulation from the ITASE (International Trans Antarctic Scientific Expedition) ice core array and deep ice cores (Siple and Law Dome) reveal decadal-scale associations with a South Pole ice-core ^{10}Be proxy for solar variability over the last ~600 years and annual-scale associations with solar variability since AD1720 (the oldest continuous sunspot records) demonstrating that increased (decreased) solar irradiance is associated with increased (decreased) zonal wind strength near the edge of the Antarctic polar vortex (Mayewski et al., 2006). The association is particularly strong in the Indian and Pacific Oceans and as such may contribute to understanding climate forcing that controls drought in Australia and other Southern Hemisphere climate events (Mayewski et al., 2006). The solar-irradiance–atmospheric-circulation association invoking solar induced changes in UV production, consequent changes in stratospheric O_3, and thence in thermal gradients generating atmospheric circulation changes suggested by Shindell et al. (1999) coupled with the atmospheric circulation-solar variability association presented in Mayewski et al. (2006) may play a key role in understanding Holocene climate variability, and perhaps abrupt climate-change events. Recent changes in Southern Hemisphere tropospheric circulation, such as anthropogenically driven photochemical ozone depletion in the lower stratosphere over Antarctica (Thompson and Solomon, 2002), and other anthropogenically-induced changes in climate provide challenges to the natural order imposed by the sun–climate association. Decoding the natural climate system, however, is essential to the prediction of global climate change.

Summary

From the foregoing several key abrupt climate change characteristics can be identified: these events are more abrupt in the North Atlantic; change in the Antarctic is more gradual and precedes change in the North Atlantic; there may be some quasi-periodic structure for Holocene events, but some are singular in occurrence; forcing is a consequence of underpinning by longer term forcing, but may be triggered by relatively small threshold achieving forcing such as changes in thermohaline circulation in localized regions such as the North Atlantic and changes in solar variability; the polar cells and associated circumpolar westerlies and lows change in extent, magnitude, and shape during these events; perhaps as a consequence of changes in thermal gradients driven potentially by changes in solar energy output that drive photochemical change and energy balance; and humanly induced changes in greenhouse gases (CO_2, CH_4, N_2O, O_3, water vapor) and aerosols (sulfates, dusts) impact thermal gradients at the edge of the polar cells and thermohaline circulation through ocean freshening related to glacier melting, so humans are definitely, potential agents of abrupt change.

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