

**Volcanic forcing and
climate variations
during the last glacial
period**

A. F. Flinders

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Abstract

Measurements of $\delta^{18}\text{O}$ in the Greenland Ice Sheet Project 2 (GISP2) ice-core from Summit, Greenland, show repeated temporal variations associated with rapid warming events throughout the last glacial period of the Pleistocene-10–110 kya. The majority of these warming events are preceded in the ice-core record by an increased concentration of insoluble micro-particulate sulfate, indicative of increases in global volcanism. Wavelet analysis of ice-core and marine-sediment records show a repeated 5000–6000 yr periodicity in both volcanic SO_4 and $\delta^{18}\text{O}$ ice records, as well as a 5000–8000 yr cycle in the lithic concentration of ice-rafted debris, atmospheric CO_2 concentration, and a database of late Quaternary volcanic eruptions. Increasing concentrations in atmospheric CO_2 and CH_4 initiated during periods of increased volcanism, peaking during a warm transition, reflect a volcanic-atmospheric-deglaciation feedback, regulated by meridional overturning current-shutdown related cooling.

1 Introduction

Oxygen isotope ($\delta^{18}\text{O}$) measurements from the Greenland Ice Sheet Project 2 (GISP2) ice-core (Summit, Greenland) provide an approximate 400 year resolution record of repeated temporal variations associated with rapid global warming cycles – *Dansgaard-Oeschger* (DO) events (Dansgaard et al., 1993) – throughout the last glacial period of the Pleistocene, 10–100 kya (Grootes and Stuiver, 1997). Transitions between cold stadials and warm interstadials occurred rapidly, with warming of up to 16°C over decades (Lang et al., 1999; Severinghaus et al., 1999) immediately followed by millennial-scale decays in global temperature to their mean cold-stadial values. Twenty-five of these events are observed in the past 120 kyr, the last of which transitioned the global climate from the cold Younger Dryas to the warm Preboreal 11 650 yr ago (Stocker et al., 2001). Warm interstadials spurred increased average global precipitation (high $\delta^{18}\text{O}$ ice – Fig. 1), subsequent ice-sheet accumulation (Fig. 3), and the deposition of large

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volumes of ice-rafted debris (IRD) in North Atlantic marine sediments (Fig. 1) – originating from glacial break up and/or retreat of circum-North Atlantic ice-sheets (Bond et al., 1992, 1999; Bond and Lotti 1995; Hodell et al., 2010). Ice-sheet rafting strengthened, as shown by increasing thickness of IRD sequences, during the millennial-scale decline of inland ice-sheet growth and the decay of elevated temperatures to their mean cold-stadial values. The thickest of these IRD sequences – *Heinrich* events – occurred during the coldest intervals between DO events (Bond et al., 1992, 1993; Bond and Lotti 1995). The approximate onset of increasing IRD deposition with (1) the sudden increase in temperature, (2) the thickening of IRD deposits during the following period of temperature decay, and (3) the sudden loss of IRD sequences once temperatures had returned to their mean cold-stadial values, suggests a causal link between ice-sheet behavior and ocean-atmosphere temperature changes. Temperature induced ice-sheet rafting generated an increase in rafted icebergs that likely moved into open oceanic waters and melted. This freshwater influx may have inhibited the formation of North Atlantic Deep Water (NADW), prompting a shutdown of Meridional Overturning Circulation (MOC) and associated heat transport into the North Atlantic. A self regulating negative feedback by which increasing global temperatures generate more rafted icebergs, the melting of which shuts down MOC thereby causing global cooling, explains the millennial scale decay time of warming events. The increased rates of rafting over this decay time – thickening of IRD deposits – that culminate in a sudden halt (Fig. 1), can therefore be attributed to either the end of the warming event and/or the limit of temperature driven ice calving – a function of the nature of the warming event, ice-sheet location, and ice-sheet/ice-shelf grounding line dynamics. Once ice-rafting halted a 500–2500 yr repose is observed, during which MOC likely equilibrates and ice-core $\delta^{18}\text{O}$ approaches their mean cold-stadial values, before the next rapid warming event (Fig. 1).

While the connection between glacial $\delta^{18}\text{O}$ variations and IRD deposition is well understood, the initiating mechanism from cold stadial to warm interstadial is poorly constrained and is mistakenly attributed to effects on ocean-circulation from both internal

ice-sheet dynamics (Bond et al., 1999) and/or non-Milankovitch solar variability (Finkel and Nishiizumi, 1997; Grootes and Stuiver, 1997). However, here we show – through investigation of the time-series data and new wavelet analysis – that increases in volcanic activity (Zielinski et al., 1997) regularly precede the cold-warm transitions and reflect a previously proposed, periodic feedback between deglaciation, volcanism and atmospheric greenhouse gas concentrations (Huybers and Langmuir, 2009) coupled with tropospheric heat transport (Robock and Mao, 1992).

2 Initiation of warming events and controlling mechanisms

The majority of warming events (increasing $\delta^{18}\text{O}$) are preceded in the GISP2 ice-core record by an increased concentration of insoluble micro-particulate sulfate (Fig. 1), indicative of increases in global volcanic activity (Zielinski et al., 1997; Zielinski and Mer-
shon., 1997). These increases are also observed in the other paleo-volcanic proxies, notably the magnetic susceptibility record of North-Atlantic marine sediments (Stoner et al., 2000), and for between 20–40 kya in a calibrated radiocarbon database of late Quaternary volcanic eruptions (Bryson et al., 2006) (Fig. 1). Cross-correlation of the $\delta^{18}\text{O}$ ice-core and a 400 yr-smoothed volcanic sulfate record yields a mean lag time of 1060 yr – the time by which, on average, increases in global volcanic activity precede the transition from cold stadial to warm interstadial. Over these time periods the atmospheric concentrations of CO_2 (Byrd-Antarctica, ice-core; Ahn and Brook, 2008) and CH_4 (GISP2; Brook et al., 1996) increased by up to 32 ppm and 290 ppbV, respectively (Fig. 1). These increasing concentrations of CO_2 and CH_4 are repeatedly associated with peak increases in global volcanic activity (Fig. 1), and represent the initiating mechanism instigating the transition from cold stadial to warm interstadial.

While volcanic eruptions are typically associated with global atmospheric cooling, increased volcanic activity can lead to elevated global temperatures through (1) direct addition of greenhouse gases into the atmosphere, (2) changing tropospheric circulation patterns and/or (3) affecting the atmospheric generation of hydroxyl radicals

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(OH). While the magnitude of direct addition is difficult to quantify, Huybers and Langmuir (2009), using a modern value 0.15 Gt of volcanically produced CO₂ per year scaled by past eruption frequency, estimated the volcanic contribution to atmospheric CO₂ to be as high as 60 ppm during the past 40 kyr. Using their estimate as a maximum for the volcanic contribution to global atmospheric CO₂ the observed 10–30 ppm rise in CO₂ in the Antarctica ice-core record, preceding a warm interstadial transition (Fig. 1), could easily be accommodated by a volcanic source – directly contributing to increased atmospheric warming.

Volcanic eruptions inject large quantities of sulfur dioxide (SO₂) into the troposphere and – through large vulcanian and plinian eruptions – directly into the stratosphere. Sulfur dioxide oxidizes rapidly (2–14 days), condensing in the atmosphere to form fine sulfate aerosols (SO₄). These aerosols increase the solar-reflectivity of the upper atmosphere – reducing downward ultraviolet radiation – leading to typically short-lived mean global cooling effects (< 10 yr; Hansen et al., 1992). In the stratosphere however, sulfate aerosols lead to increased absorption of solar near-IR and outgoing long-wavelength radiation, causing stratospheric heating (Robock and Mao, 1992). In the tropical lower stratosphere this heating perturbs atmospheric temperature gradients, modifying tropospheric circulation patterns, producing winter warming up to 3 °C for the proceeding 1–2 yr after a major eruptive event (Robock and Mao, 1992). Sustained increased global volcanism could have led to successive and compounding winter warming, thereby initiating ice-sheet rafting and decreases in global albedo.

The increased solar-reflectivity of the lower stratosphere, and subsequent reduced flux of ultraviolet radiation into the troposphere, decreases OH production (Manning et al., 2005) and therefore its availability to oxidize other reduced trace gases such as CH₄. This mechanism helps to explain observed correlations between increased CH₄ concentrations and warming events (Fig. 1), previously attributed to climate variations on terrestrial biosphere methane production (Brook et al., 1996). As a historical example, the 1991 eruption of Mt Pinatubo injected approximately 15–19 Mt of SO₂ into the lower atmosphere, raising the concentration by 2–3 ppbV, and causing a 15 %

to 20% decrease in OH concentrations (Manning et al., 2005). This decrease in OH concentration has been used to explain anomalously high CH₄ growth rates over the following year. The observed mean 400 year increases of 25–50 ppbV in the volcanic sulfate record (Fig. 1), with discrete events greater than 350 ppbV, could thereby catastrophically reduce tropospheric OH production and lead to global-scale retention of atmospheric CH₄.

2.1 Wavelet analysis

Until recently, calculating the periodicity of *Dansgaard-Oeschger* events had been hindered by classical Fourier analysis, which assumes signal continuity and breakdowns under discontinuous changes in frequency content. To circumvent this limitation a wavelet analysis based method was adopted (Debret et al., 2007) to investigate the periodicity of the warming events and their proposed initiating mechanisms. The $\delta^{18}\text{O}$ ice record has previously been reported as being dominated by a 1500 year cycle, reflecting the fundamental pacing of transitions (Grootes and Stuiver, 1997). While a strong spectral peak occurs at this value, it is only dominant between 20–40 kya, and is synchronous with a peak in the volcanic sulfate record (Fig. 2). For the majority of the past 100 kyr, the variation is controlled by a 5000–6000 yr cyclicity – seen in both the volcanic sulfate and $\delta^{18}\text{O}$ ice records (Fig. 2). This periodicity was not observed in past studies of warming events in the Holocene due to the limited time-series investigated (Debret et al., 2007). A second prominent spectral band is seen in the volcanic sulfate record between 50–90 kya, with a periodicity of 2900 years. This period is sporadically seen in the $\delta^{18}\text{O}$ ice record becoming more dominant between 30–45 kya (Fig. 2), and has been previously interpreted as a possible harmonic of the 1500 year cycle (Shultz, 2002). The 5000–8000 yr pacing of massive ice-berg discharges associated with Heinrich events is seen in both the IRD and CO₂ records, but more notably, for the past 40 kyr in the radiocarbon database of late Quaternary volcanic eruptions (Fig. 3) – suggesting not only a volcanic-atmospheric mechanism but a volcanic-atmospheric-deglaciation interaction.

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Deglaciation has been correlated with historical millennial-scale increases in volcanism in Iceland (Sigvaldason et al., 1992; Pagli et al., 2007), France and Germany (Nowell et al., 2006), and the Western United States (Jellinik et al., 2004). Global increases in subaerial volcanism in the deglacial to mid Holocene (12–7 kya) have previously been attributed to feedbacks between deglaciation, volcanism and atmospheric CO₂ (Huybers and Langmuir, 2009). Deglaciation and post-glacial rebound could induce depressurization of mantle melt leading to increased magma production. Subsequent increases in volcanic activity would lead to increased concentrations of CO₂, and through reduced atmospheric oxidation, increased CH₄ – warming global temperature and promoting further deglaciation. Without an oceanic negative feedback (shutdown of MOC) this mechanism would be self-reinforcing leading to massive ice-sheet retreat. Decreases in the formation of NADW – from increased ice-sheet rafting – and associated heat transport into the North Atlantic, act to attenuate the volcanically induced atmospheric warming. The 5000–6000 yr observed periodicity of the DO events (Fig. 2) may therefore be due to direct volcanic forcing, or from modulation of the 5000–8000 yr *Heinrich* cycle with the 2900 yr cycle of increased volcanic activity (Fig. 3).

2.2 Solar forcing revisited

Increases in non-Milankovitch solar forcing have been proposed as the driving mechanism responsible for the the rapid transition between cold stadials and warm interstadials (van Gee et al., 1999). Decreases in ice-core recorded cosmogenic Beryllium 10 (¹⁰Be) (GISP2; Finkel and Nishizumi, 1997), created from interaction with high-energy cosmic rays in the upper atmosphere, is used to justify the increased solar activity (van Gee et al., 1999). Decreases in ¹⁰Be concentration suggest increases in solar-wind – acting to shield the earth – and an associated increase in solar activity. Both the δ¹⁸O and ¹⁰Be ice records show strong contributions from a 1500 year period cycle between 20–40 kya, yet this relationship is misleading (Fig. 4). Deposition of atmospheric ¹⁰Be is a complicated process with inherent uncertainties that have not been adequately addressed. Beryllium 10 in polar snow has two important sources: directly deposited

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Contributions from volcanically produced CO₂ and induced CH₄ increases, combined with changes in tropospheric circulation, are estimated to be 1–5°C for the largest of warm transitions. Other mechanisms, such as changes in global albedo and restart of MOC, likely play an important role. Analysis of these mechanisms and past warming transitions is important in predicting the potential effects of both volcanic and anthropogenic sulfate aerosols. Proposed geoengineering projects to combat global warming through injection of sulfate aerosols into the lower stratospheric may in fact lead to long scale greenhouse gas retention. Our current path of anthropogenic warming and deglaciation could initiate previously unforeseen global volcanic feedbacks, resulting in dramatic and rapid warming not predicted by current climate models.

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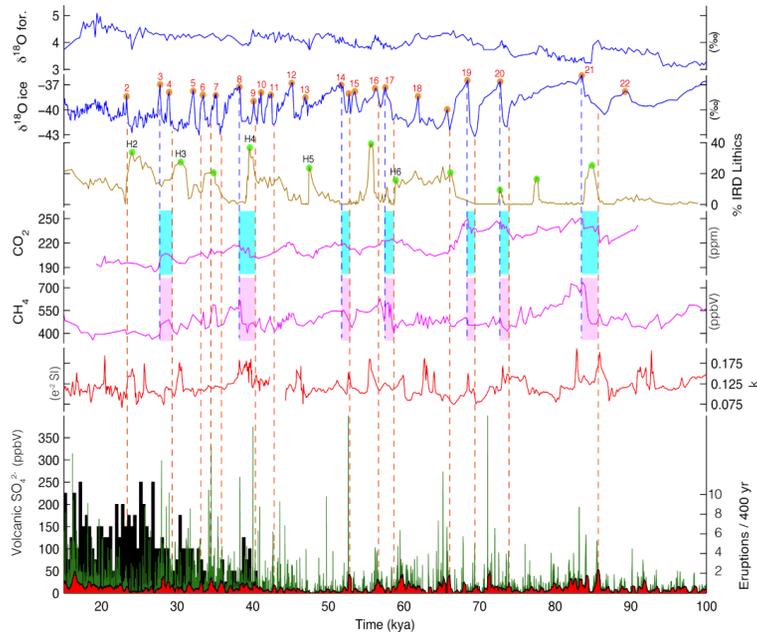


Fig. 1. Variations in the Greenland ice-sheet (GISP2) $\delta^{18}\text{O}$ record (Grootes and Stuiver, 1997), showing correlations in global DO warming-events and increases in atmospheric concentrations of Antarctic CO_2 (Ahn and Brook, 2008), Greenland CH_4 (Brook et al., 1996) and volcanic SO_4^{2-} (green bars) (Zielinski et al., 1997; Zielinski and Mershon, 1997). Peaks in the 400-yr smoothed volcanic SO_4^{2-} record (bottom red-filled area) initiate extended periods of CO_2 and CH_4 increases and directly precede peaks in the $\delta^{18}\text{O}$ ice-record. Numbered peaks refer to previously documented Dansgaard-Oeschger (red text/orange points) and Heinrich (black text/green points) events. Also shown are North-Atlantic marine sediment values for: benthic foraminifera $\delta^{18}\text{O}$ (Hodell et al., 2010) – a measurement of global ice-coverage – magnetic susceptibility (Stoner et al., 2000) and ice rafted debris lithic content – % IRD lithics (Hodell et al., 2010). Black histogram bars show documented volcanic events over the past 40 kyr.

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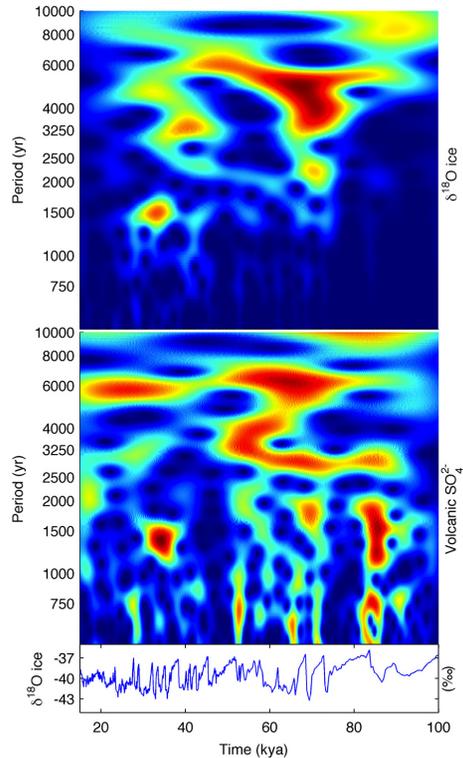


Fig. 2. Wavelet-analysis spectral intensities over time for $\delta^{18}\text{O}$ ice (Grootes and Stuiver, 1997) and volcanic SO_4^{2-} records (Zielinski et al., 1997; Zielinski and Merchon, 1997). The bottom blue line shows the $\delta^{18}\text{O}$ ice time series for reference. Synchronous periodicities of 1500, 2900 and 5000–6000 yr are clearly visible.

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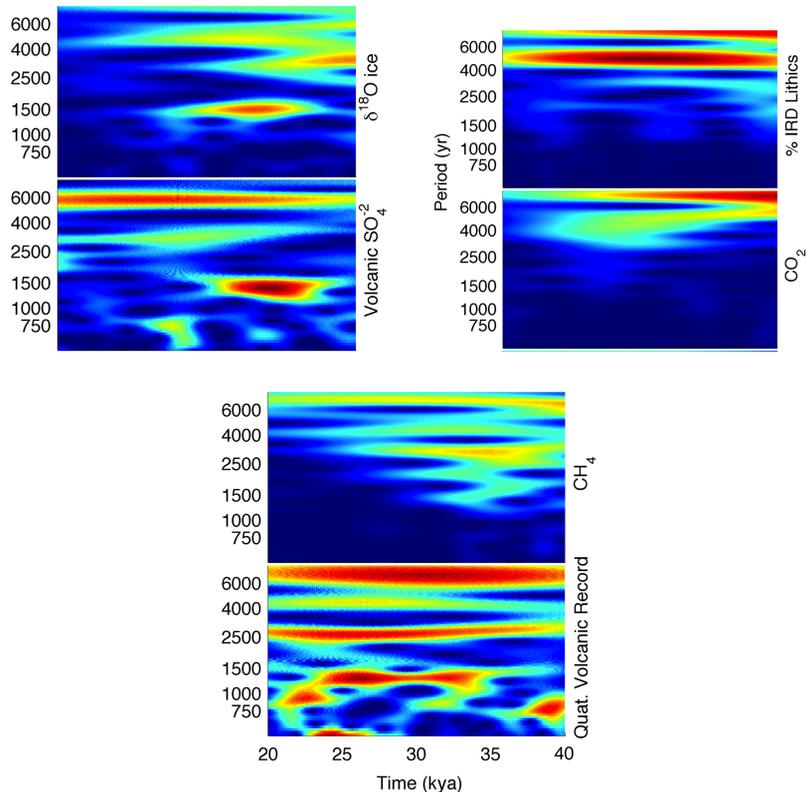


Fig. 3. Wavelet-analysis spectral intensities over time for $\delta^{18}\text{O}$ ice (Grootes and Stuiver, 1997), volcanic SO_4^{2-} concentration (Zielinski et al., 1997; Zielinski and Mershon, 1997), ice rafted debris lithic content (Hodell et al., 2010), CO_2 (Ahn and Brook, 2008) and CH_4 (Brook et al., 1996) atmospheric concentration, and the documented Quaternary volcanic record (Bryson et al., 2006).

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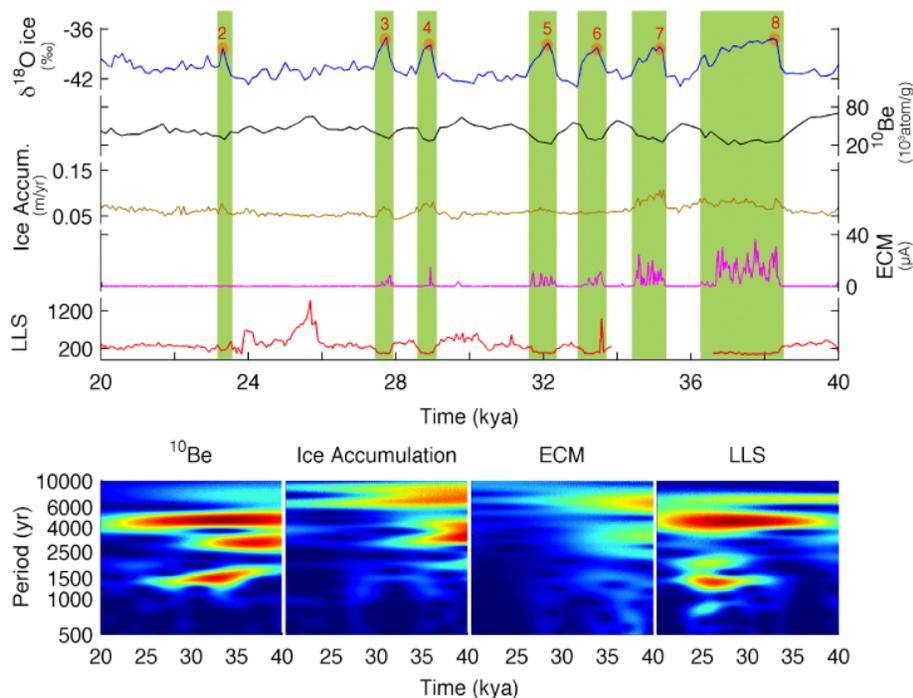


Fig. 4. (top) Variations in $\delta^{18}\text{O}_{\text{ice}}$ (Grootes and Stuiver, 1997) and cosmogenic ^{10}Be (Finkel and Nishiizumi, 1997), showing correlations with ice-accumulation (Cuffey and Clow, 1997), and dust content – a function of the intensity of laser light scattering (LLS) and electrical conductivity measurements (ECM) (Donarummo et al., 2002; Taylor et al., 2002). (bottom) Wavelet-analysis spectral intensities over time for the same time-series.

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