GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L24703, doi:10.1029/2005GL024486, 2005

The 'flickering switch' of late Pleistocene climate change revisited

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Received 25 August 2005; revised 25 October 2005; accepted 28 October 2005; published 16 December 2005.

[1] Extremely rapid fluctuations observed in records of electrical conductivity measurements (ECM) from Greenland ice-cores provoked the idea that the climate system may be capable of flickering between two states during rapid climate transitions. Here it is shown that in general, the flickers seen in ECM records probably reflect the highly non-linear response of electrical conductivity as ice approaches acid/base neutrality, rather than significant changes in the climate system. High frequency, relatively low amplitude changes in chemistry, superimposed upon the broader changes typical of climate transitions would be capable of producing the observed characteristics of ECM records. It must be stated that this result does not detract from the observation of extremely rapid changes in, for example, ice core chemistry and isotopes, which clearly demonstrate that Earth's climate is capable of very rapid and major reorganisations. **Citation:** Barker, S. (2005), The 'flickering switch' of late Pleistocene climate change revisited, *Geophys. Res. Lett.*, *32*, L24703, doi:10.1029/2005GL024486.

1. Introduction

[2] Ice-cores provide some of the highest temporally resolved records of climatic variability. Of these, electrical conductivity measurements (ECM) are perhaps the most highly resolved [*Taylor et al.*, 1993]. In ice, electrical current is carried by protons rather than electrons so that its conductivity is a function mainly of its acidity, which depends on the relative supply of acids (mainly HNO_3 and H_2SO_4) and neutralising agents such as carbonate dust. In Greenland, ice of Holocene age is characterised by high acidities and high ECM values [*Taylor et al.*, 1993; *Wolff et al.*, 1995], whereas colder periods are dominated by alkaline conditions and low ECM values due to enhanced dust input (Figure 1a). The observation of repeated, extremely rapid transitions or 'flickers' between low and high ECM values during particular climate transitions such as the onset of the Bølling warming and the end of the Younger-Dryas interval (Figures 1b and 1c) led to the idea that the climate system may be capable of flickering between glacial and near-interglacial conditions in periods of just a few years. Here, published chemical measurements from the GISP2 ice-core [*Mayewski et al.*, 1997] are used to investigate ECM flickers in terms of changes in the acid/base balance.

2. Rapid Climate Oscillations During the Last Glacial Period

[3] Oxygen isotope records from Greenland ice-cores record rapid transitions between cold (stadial) and warmer (interstadial) conditions in the northern hemisphere during the last glacial and deglacial periods [*Johnsen et al.*, 1997; *Stuiver and Grootes*, 2000] (Figure 1a). Dansgaard–Oeschger events (including the Bølling-Allerød warm interval) represent episodes of extremely rapid warming (several °C in a few tens of years or less), followed by more gradual (hundreds of years) cooling back to stadial conditions. D-O events are commonly thought to be linked to variations in the mode of North Atlantic deep water formation and circulation, perhaps driven by changes in the supply of freshwater to the region of deep water formation [*Broecker et al.*, 1985]. Their cause, or trigger is the subject of ongoing debate but is of obvious importance to our understanding of rapid climatic change.

[4] Records from ice-cores collected from around the globe suggest that the atmosphere was more dusty during the last glacial period than during the Holocene (Figure 1a) [*Petit et al.*, 1981; *Fuhrer et al.*, 1999]. Furthermore, the dust content of Greenland ice-cores has varied over much shorter timescales, with dustier conditions during stadial relative to interstadial (D-O) events [*Fuhrer et al.*, 1999]. These transitions are generally matched by changes in electrical conductivity (Figure 1a). Since electrical techniques can give higher resolution than most other measurements, they are useful for highlighting periods where changes may be particularly rapid. Examples include the onset of the Bølling warming, the beginning and end of the Younger-Dryas interval and during certain interstadials such as D-O 5 (Figures 1b–1d). During these periods, the GISP2 ECM record shows fluctuations of greater than 2 orders of magnitude within a few years [*Taylor et al.*, 1993]. Furthermore, since the ECM record fluctuates between 2 'states' during climate transitions rather than making a single step, it appears that dust input and therefore atmospheric circulation is also fluctuating between 2 states before settling into a new regime. This gave rise to the notion of a 'flickering switch' within the climate system that allows repeated and very rapid transitions between glacial and near-interglacial conditions rather than a single, smooth transition.

3. Sensitivity of Electrical Conductivity to the Acid/Base Balance

[5] The electrical conductivity of ice depends on the flow of protons and is therefore sensitive to acidity. The response of ECM at the transition between basic and acidic conditions is predicted to be non-linear and this has been cited as a caveat to interpreting rapid ECM fluctuations in terms of actual climatic variations, particularly during interstadial events [*Taylor et al.*, 1993; *Wolff et al.*, 1995]. However, although detailed chemical analyses have been performed on both the GRIP and GISP2 ice cores [*Mayewski et al.*,

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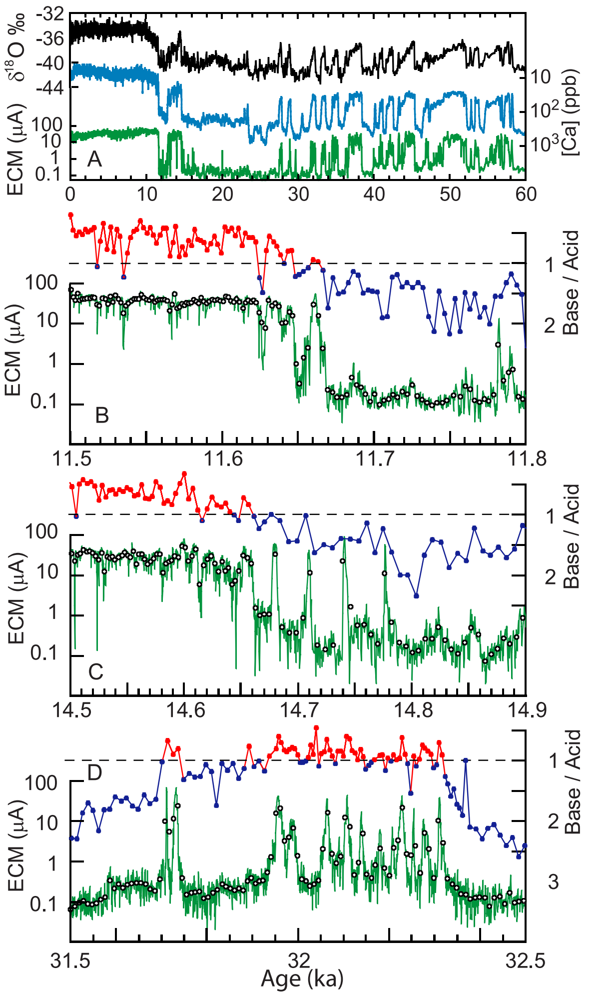

Figure 1. (a) $\delta^{18}O$ (an indicator of temperature) [*Stuiver and Grootes*, 2000], [Ca] [*Mayewski et al.*, 1997] and ECM [*Taylor et al.*, 1993] from the GISP2 ice-core. ECM values are generally low during glacial periods, indicating more dusty (basic) conditions, and high during interstadial events. Base/Acid and ECM records for the end of the Younger Dryas (b), onset of the Bølling-Allerød (c) and D-O event 5 (d). Hollow circles in the ECM records are averages giving comparable resolution to the chemical data.

1997; *Fuhrer et al.*, 1999], a detailed comparison of the ECM to acid/base relationship has not been made. To this end, measurements of dissolved Na, NH_4, K, Mg, Ca, Cl, NO_3 and SO_4 concentrations from GISP2 [*Mayewski et al.*, 1997] were combined as follows to give an estimate of the acid/base balance:

$$\mathrm{Base/Acid} = \left(2[\mathrm{Ca}^{++}]^* + 2[\mathrm{Mg}^{++}]^* + [\mathrm{NH}_4^+]^*\right)/\left(2[\mathrm{SO}_4^-]^* + [\mathrm{NO}_3^-]^* + [\mathrm{Cl}^-]^*\right)$$

where $[X]^*$ represents the ‘non-sea salt’ contribution of X, attained by subtracting the measured Na content multiplied by the seawater ratio of X/Na [*Legrand and Mayewski*, 1997]. In this expression, non-sea salt Ca and Mg are assumed to represent carbonate phases, NH_4^+ is the presumed product of ammonia hydration and all sulphate is assigned to sulphuric acid. This is necessarily over simplified and ignores phases such as $CaSO_4$ but appears to give a reasonable approximation to the acid/base balance (Figure 2a). The strongly non-linear relationship between conductivity and the acid/base balance is clear; ECM increases by more than 2 orders of magnitude as the ice becomes acidic (Base/Acid → 1). The chemical data shown here were measured on 20 cm intervals of ice and so it could be argued that their resolution is too low to be compared with the ECM data which were measured with a resolution of 1 mm. To allow a more direct comparison, the ECM data shown in Figure 2 have been re-sampled to represent the same 20 cm intervals as the chemical data (i.e. each ECM point represents the mean of ~200 measurements). Direct acidity measurements are not available for GISP2. However, by combining the measured ionic concentrations to calculate a charge budget and assuming that the resulting excess negative and positive charges are balanced by H^+ and HCO_3^- respectively, a reasonably good approximation of the acidity can be made. Again, ECM is seen to increase by more than 2 orders of magnitude as neutrality is approached and $[H^+]$ increases above zero (Figure 2b).

4. ECM Flickers: A Consequence of Non-Linearity

[6] Plots of the Base/Acid balance with time reflect changing conditions between stadials and interstadials as well as the general increase in acidity between glacial and interglacial time (Figure 1). The detailed intervals shown in Figure 1 reveal that during periods where the ECM record shows flickering between 2 contrasting states, ice chemistry displays a somewhat smoother transition. ECM flickers appear to occur just as the ice switches from acidic to basic or vice versa, as a consequence of the highly non-linear response of ECM at the titration point. This is highlighted by the occurrence of ECM flickers during interstadial events where the ice barely becomes acidic, such as D-O 5 (Figure 1d). Here, flickers in the ECM record occur throughout a period where the chemistry does not vary significantly but is fluctuating about the neutral point. Again it could be argued that the relatively low resolution of chemical measurements in GISP2 is simply smoothing

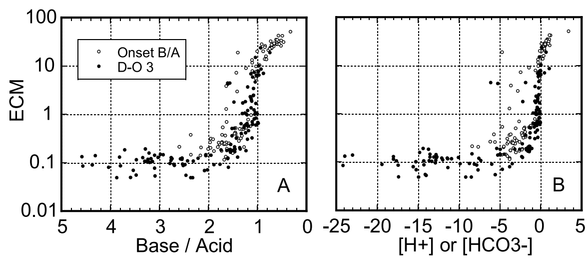

Figure 2. Relationship between measured ECM [*Taylor et al.*, 1993] and dissolved ionic species [*Mayewski et al.*, 1997] in the GISP2 ice core for the onset of the Bølling warming and D-O event 3. Each interval is represented by 20 m of core. The ECM data (published at 1 mm resolution) have been re-sampled to represent the same 20 cm intervals as the chemical data, (a) Base/Acid balance, (b) charge balance.

out the large fluctuations observed in the ECM record. However, re-sampling the ECM data to allow a more meaningful comparison does not eliminate the 2 orders of magnitude changes seen in the higher resolution dataset.

[7] It is most likely that the flickers observed in ECM records are an artefact of non-linearity and probably reflect high frequency (possibly low amplitude) changes in chemistry superimposed upon the broader changes typical of climate transitions. Having said this, it should be re-emphasised that ice-core chemistry does show extremely rapid changes during climate transitions. The reduction in [Ca] between stadial to interstadial conditions during D-O 3 in the GRIP ice-core occurred in two discrete steps totalling just 5 years [*Fuhrer et al.*, 1999].

5. The 'Pre-Bølling' ECM Flickers

[8] The very high resolution attainable with electrical measurements such as ECM is of great value for stratigraphic correlation between ice-cores. A good example is given by comparison of the GRIP and GISP2 ECM records for the onset of the Bølling warming at ~14.7 Ka (Figure 3). The ECM records allow confident alignment of the 2 cores to within a few cm (~ 1 yr). This comparison also demonstrates, in this case at least, that the rapid fluctuations seen in ECM records reflect actual environmental conditions rather than anomalous disturbances particular to individual ice-cores. These particular peaks have also been identified in the North GRIP (NGRIP) ice-core (D. Dahl-Jensen, personal communication, 2005). NGRIP is approximately 220 miles from GRIP and GISP2, suggesting that these electrical 'events' are not a local phenomenon.

[9] The 'pre-Bølling' ECM flickers are interesting because they are so regular and because they appear to precede the shift in oxygen isotopes marking the start of the Bølling-Allerød warm interval. Four isolated peaks, each lasting 5–10 years, are spaced approximately 30–35 years apart. They are preceded in the GRIP record by 2 or 3 earlier peaks with similar spacing. If the peaks in ECM represented dramatic shifts in the climate system (i.e. from glacial to near interglacial conditions), they would potentially represent precursor events to the Bølling transition. However, other evidence suggests that the peaks in ECM do not reflect transitions to interstadial conditions. [Ca] measurements from both cores reveal increased levels (more indicative of dusty, stadial conditions) during three of the four main ECM peaks (Figures 3a and 3b). This is supported by Laser-Light Scattering (LLS) data from GISP2 [*Ram and Koenig*, 1997] (Figure 3c). LLS measurements are performed either on solid ice or melt-water (as in this case) and reflect the concentration of dust within the ice. In general, LLS values are highest during cold, stadial events, reflecting increased atmospheric dust content [*Ram and Koenig*, 1997]. Three of the four main peaks in ECM during the Bølling warming show an increase in LLS intensity and therefore dust content. It should be noted that while the chemical analyses represent dissolved species, LLS is sensitive to particulate phases.

[10] An increase in dust seems at odds with the increase in acidity as indicated by the peaks in ECM. On the other hand, the SO_4 content in GISP2 also increases during a number of the ECM peaks (Figure 3a). In fact, the ratio of

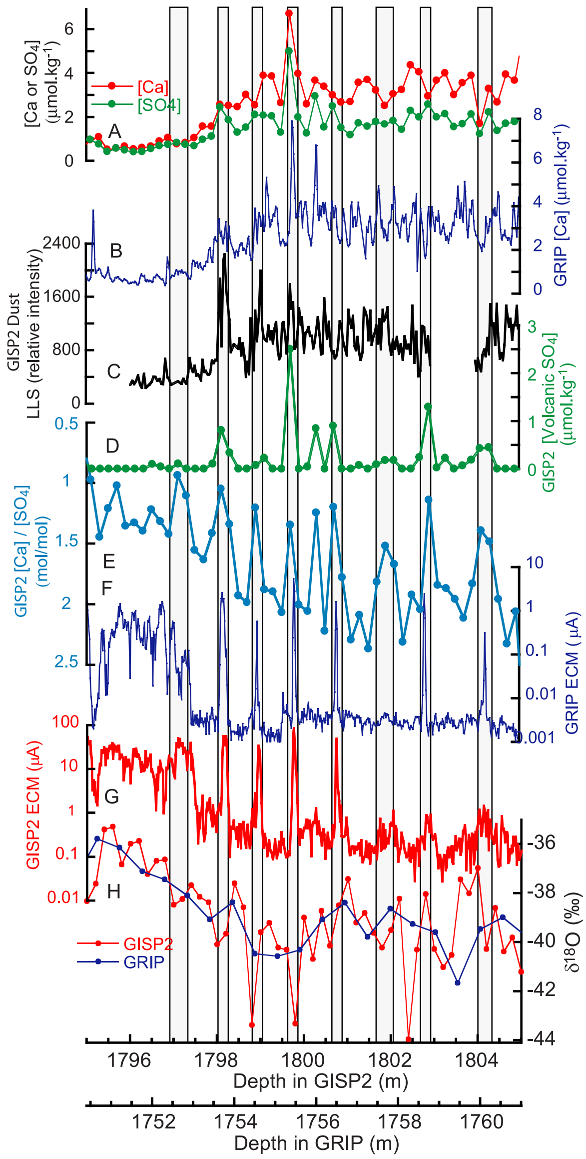

Figure 3. Records from the GRIP and GISP2 ice-cores aligned by correlating the peaks in ECM occurring during the onset of the Bølling warming (a) [Ca] and [SO_4] from GISP2 [*Mayewski et al.*, 1997], (b) [Ca] from GRIP [*Fuhrer et al.*, 1999], (c) Laser-Light Scattering (LLS) from GISP2 (an indicator of dust content) [*Ram and Koenig*, 1997], (d) 'volcanic SO_4' from GISP2 [*Zielinski et al.*, 1996], (e) [Ca]/[SO_4] from GISP2, (f) ECM from GRIP [*Wolff et al.*, 1995], (g) ECM from GISP2 [*Taylor et al.*, 1993], (h) $\delta^{18}O$ from GRIP [*Johnsen et al.*, 1997] and GISP2 [*Stuiver and Grootes*, 2000].

[Ca]/[SO_4] shows a strong decrease during every one of the peaks in ECM (Figure 3e). Increased SO_4 may reflect volcanic release of SO_2 (which would convert to H_2SO_4). *Zielinski et al.* [1996] developed a record of 'volcanic SO_4' for the GISP2 ice-core by applying an empirical orthogonal function (EOF) to the bulk [SO_4] measurements of *Mayewski et al.* [1997] (Figure 3d). These authors noted that the largest and most abundant volcanic signals over the past 110 Kyr occurred during and following the last deglacia-

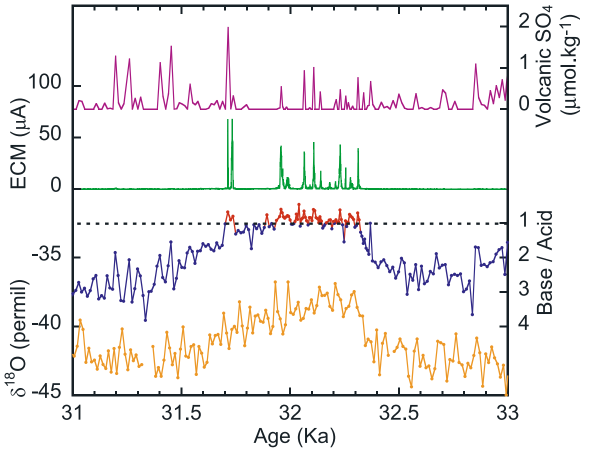

Figure 4. ‘Volcanic SO_4’ [*Zielinski et al.*, 1996], ECM [*Taylor et al.*, 1993], Base/Acid and $\delta^{18}O$ [*Stuiver and Grootes*, 2000] records from the GISP2 ice-core for D-O event 5. Although volcanic pulses occur throughout the entire period, ECM flickering occurs only around the titration point.

tion, perhaps reflecting changes in crustal loading. Their reconstruction suggests that most of the ECM peaks during the Bølling onset may be associated with volcanic events. The observed peaks in LLS may then reflect pulses of volcanic ash. The question as to why volcanic events during the Bølling transition should occur with such apparent regularity remains open.

[11] It is worth noting that volcanic episodes, as reconstructed by *Zielinski et al.* [1996], are observed throughout the entire 110 Kyr period but generally result in ECM flickering only when the ice is close to the acid/base titration point. This is highlighted by the interval around D-O 5 (Figure 4) (the single ECM flicker seen at the close of the Younger Dryas (Figure 1) has also been ascribed to volcanic activity [*Taylor et al.*, 1997]) and emphasises the point that the appearance of ECM flickering reflects high frequency chemical variations superimposed upon the broader changes associated with climate transitions. It is particularly interesting that ECM flickers are observed prior to particular climate transitions, such as the Bølling onset and the end of the Younger Dryas, as defined by the oxygen isotopic record (Figure 3). This suggests that changes in the input of dust to Greenland (which define the broad changes in ice-core chemistry) may actually proceed the associated isotopic change. This observation should provide impetus for future research.

6. Conclusions

[12] Records of electrical conductivity in Greenland ice-cores have provoked interest because of the appearance of repeated, rapid fluctuations between glacial and near-interglacial conditions during climate transitions. The extremely high resolution attainable by ECM measurements allows very precise correlation between records from different ice-cores that may be hundreds of miles apart. This is in of itself an extremely valuable property. The electrical conductivity of ice (in this case determined by ECM) has been shown to display a highly non-linear response as the ice approaches acid/base neutrality. It is most likely that this feature, rather than significant changes in the climate system, is the cause of most flickers observed in the Greenland records. It must be re-emphasised however, that climate is capable of extremely rapid changes during climatic transitions.

[13] **Acknowledgments.** I thank the Vetlesen Foundation Climate Centre at L-DEO for supporting a mini-conference on the ECM flickers. I also thank the participants, R. Alley, P. Biscaye, W. Broecker, E. Brook, D. Dahl-Jensen, M. Kelly, K. Maasch, P. A. Mayewski, J. Severinghaus, K. Taylor, J. White and E. Wolff, for valuable discussions and comments and W. Broecker for initiating the present discussion. I thank the Comer Science Foundation for financial support. This is Lamont-Doherty contribution #6838.

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