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Research paper

Modulation of ice ages via precession and dust-albedo feedbacks

Ralph Ellis [a,*], Michael Palmer [b]

[a] 105 – 6817 Route Pommier, St Martin Bellevue 74370, France
[b] University of Waterloo, Department of Chemistry, Waterloo, Ontario, Canada

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ABSTRACT

We present here a simple and novel proposal for the modulation and rhythm of ice-ages and interglacials during the late Pleistocene. While the standard Milankovitch-precession theory fails to explain the long intervals between interglacials, these can be accounted for by a novel forcing and feedback system involving CO_2, dust and albedo. During the glacial period, the high albedo of the northern ice sheets drives down global temperatures and CO_2 concentrations, despite subsequent precessional forcing maxima. Over the following millennia more CO_2 is sequestered in the oceans and atmospheric concentrations eventually reach a critical minima of about 200 ppm, which combined with arid conditions, causes a die-back of temperate and boreal forests and grasslands, especially at high altitude. The ensuing soil erosion generates dust storms, resulting in increased dust deposition and lower albedo on the northern ice sheets. As northern hemisphere insolation increases during the next Milankovitch cycle, the dust-laden ice-sheets absorb considerably more insolation and undergo rapid melting, which forces the climate into an interglacial period. The proposed mechanism is simple, robust, and comprehensive in its scope, and its key elements are well supported by empirical evidence.

1. Introduction

Since the discovery of ice-age cycles almost two centuries ago, a large amount of geological evidence has been assembled from a variety of sources, and many different hypotheses have been advanced to account for their approximate 100 kyr periodicity and asymmetric, saw-tooth temperature response. Improved calculations of Milankovitch insolation cycles and greater precision of Antarctic ice-core records demonstrate that each major deglaciation coincides with maximum summer insolation in the northern hemisphere. And yet many of the other insolation maxima only trigger minor warming events, and so interglacials only occur after four or five insolation cycles. No generally accepted explanation exists for this peculiar intermittent climate response, and any comprehensive explanation for ice-age modulation and periodicity has to be able to explain this anomaly.

The answer to this conundrum can be found in a novel reanalysis of the effects of decreasing atmospheric CO_2 concentrations during an ice-age. Ice age CO_2 reductions coincide with an increase in ice sheet extent and therefore an increase in global albedo, and this should result in further cooling of the climate. But what actually happens is that when CO_2 reaches a minimum and albedo reaches a maximum, the world rapidly warms into an interglacial. A similar effect can be seen at the peak of an interglacial, where high CO_2 and low albedo results in cooling. This counterintuitive response of the climate system also remains unexplained, and so a hitherto unaccounted for agent must exist that is strong enough to counter and reverse the classical feedback mechanisms.

The answer to both of these conundrums lies in glacial dust, which was deposited upon the ice sheets towards the end of each glacial maximum. Previous research has considered two effects of this aeolian dust on the glacial climate: the increased albedo of atmospheric dust cooling the climate, and the mineral fertilization of marine life reducing atmospheric CO_2. But both of these effects would result in a cooling feedback, and therefore provide no

Abbreviations: NH, Northern hemisphere; SH, Southern hemisphere; CGY, Celestial Great Year averaging 25,700 years (caused by precession); SGY, Seasonal Great Year averaging 22,200 years (including apsidal precession); ESS, Earth System Sensitivity; ECS, Equilibrium Climate Sensitivity; YD, Younger Dryas; ITCZ, Inter-Tropical Convergence Zone; ISA, International Standard Atmosphere; ICAO, International Civil Aviation Organisation; MPT, Mid-Pleistocene Transition; PMIP, Paleoclimate Modeling Intercomparison Project; amsl, above mean sea level; TSI, Total Solar Irradiance; D-O, Dansgaard-Oeschger warming event.

* Corresponding author.
E-mail address: ralph.ellis@me.com (R. Ellis).

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explanation for the interglacial warming that appears to result from dust deposition. In great contrast to these explanations it is proposed here that during the glacial maximum, CO_2 depletion starves terrestrial plant life of a vital nutrient and causes a die-back of upland forests and savannahs, resulting in widespread desertification and soil erosion. The resulting dust storms deposit large amounts of dust upon the ice sheets and thereby reduce their albedo, allowing a much greater absorption of insolation. Up to 180 W/m^2 of increased absorption can be provided to the northern ice sheets, when calculated seasonally and regionally instead of annually and globally.

This dramatic increase in insolation and absorption results in melting and dissipation of the northern ice sheets, and the establishment of a short interglacial period. Ice ages are therefore forced by orbital cycles and Milankovitch insolation, but regulated by ice-albedo and dust-albedo feedbacks. And the warming effects of dust-ice albedo are counterintuitively caused by a reduction in global temperatures and a corresponding reduction in CO_2 concentrations. And while this proposal represents a reversal of conventional thinking it does explain each and every facet of the glacial cycle, and all of the many underlying mechanisms that control its periodicity and temperature excursions and limitations.

2. Orbital forcing of ice-ages and interglacials

2.1. Late Pleistocene climatic cycles

The graph of ice-age temperature vs. CO_2 in Fig. 1 demonstrates that glacial cycles over the last 800 kyr display a quasi-100 kyr cycle that superficially mimics the Earth's approximately 100 kyr orbital eccentricity. To be more precise, recent ice-age cycles are either ~90 kyr or ~115 kyr in length, and this is a fundamentally important distinction as will be explained later. The precise agent, periodicity, and mechanism through which these late Pleistocene ice-ages have been modulated remains a contentious issue, and so the IPCC's 2014 AR5 report says of this scientific lacuna:

> *Orbital forcing is considered the pacemaker of transitions between glacials and interglacials (high confidence), although there is still no consensus on exactly how the different physical processes influenced by insolation changes interact to influence ice sheet volume. (*IPCC AR5 5.2.1.1. See also AR4 B6.1, FAQ 6.1)

It will be demonstrated shortly that the primary orbital cycle controlling paleoclimate over the last 800 kyr is precession, because the variations in regional insolation generated by this orbital cycle are demonstrably linked to interglacial warming. Yet this common assumption, which has been endorsed yet not fully explained by the IPCC, is by no means universally accepted. Huybers invoked axial obliquity as the controlling cycle (Huybers, 2006); Kirkby suggested cosmic ray flux (Kirkby et al., 2004); Muller championed orbital inclination (Muller and MacDonald, 1997); Lisiecki pointed towards an 'internally driven climate oscillation phase locked to eccentricity' (Lisiecki, 2010); while Liu introduced a 'pulse modulation' to the precessional cycle (Liu, 1998).

Because of these many competing theories, a short explanation of the precessional cycle and its effects on climate is required. And there is an obvious and frequently highlighted problem with invoking the precessionary cycle for glacial modulation, and that is the curious issue of the missing cycles in the climatic record. This has been a major stumbling block in all paleoclimatic research, because the reason for the climate displaying a selective response to orbital forcings has never been adequately explained. However, the missing precessionary cycle problem forms the very foundation of this thesis and so it will be comprehensively and conclusively accounted for.

2.2. Orbital cycles and forcing

There are three main orbital cycles that influence and regulate the intensity of terrestrial insolation in the high latitudes, and these are obliquity, eccentricity and precession. Although each of these cycles has a unique effect, it is the complex interplay between these orbital cycles that provides the insolation forcing for each ice age cycle:

Precession:

Precession describes the rotational motion of the Earth's axial orientation. Axial precession has a roughly 25.7 kyr cycle, and it was known to the ancient Egyptians, Greeks and Chinese as the Great Year (Yoke, 1985; Campion and Dally, 1997). And its comparison to an annual year is quite valid, because the Celestial Great Year combines with orbital eccentricity to produce warm and cool seasons in each hemisphere. However, apsidal precession reduces the approximate 25.7 kyr Celestial Great Year down to an approximate 23 kyr cycle, which will be called herein the 'Seasonal Great Year' (SGY). So each Great Season of this Seasonal Great Year is approximately 5700 years long, and this is a significant periodicity because most of the interglacial warming events last about 5000 years.

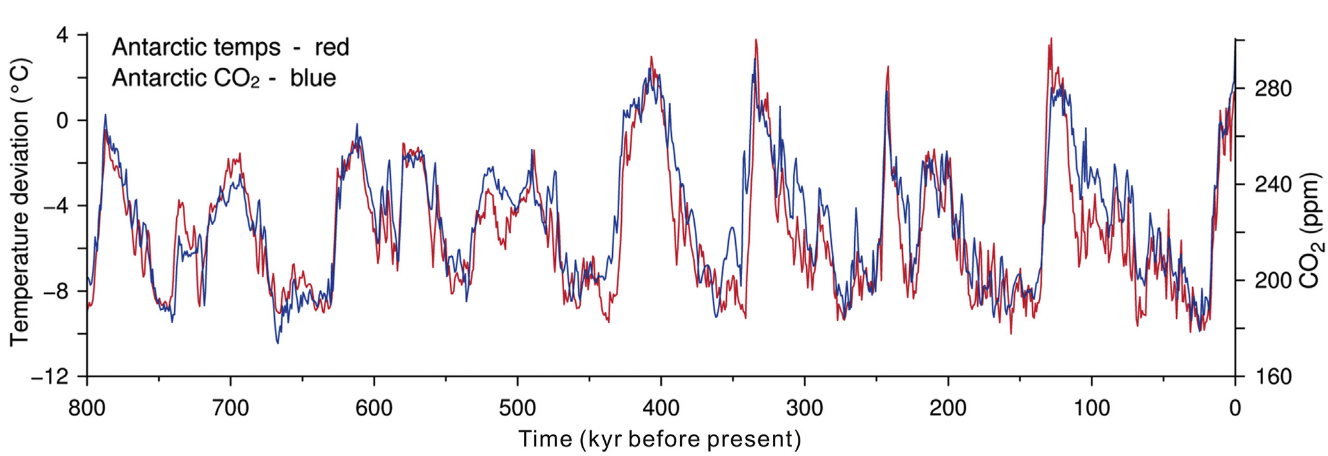

Figure 1. Antarctic temperature vs. CO_2 over 800 kyr from the Epica3 ice core. Note that CO_2 concentrations follow global temperatures very closely, giving the illusion of CO_2 being the primary causal feedback factor. Source: Epica3, 2007.