1

Introduction

There is abundant geological evidence on the Earth's surface, particularly in characteristic landforms and drift sediments, that in the relatively recent geologic past global climate was very much colder than at present, with extensive ice sheets covering much of higher northern hemisphere latitudes [*Imbrie and Imbrie*, 1979]. In fact, such evidence points to there having been more than one cold episode, each punctuated by periods of relatively warm climatic conditions. Once this interpretation had become generally accepted during the 19th century, the search started for an explanation as to why these events should have occurred at all. On the basis that periods of low solar insolation would result in a cooling of the planet (thus allowing ice sheets to grow) variations in the amount of sunlight received was the obvious starting point. Initial explanatory theories included sun spot cycles, the existence of dust clouds in space through which the Earth might pass (therefore attenuating solar radiation) and in a similar vein, major sub-aerial volcanic eruptions. However, none of these could be reasonably tested at that time and had little supporting evidence. It was not until the French mathematician Joseph Adhémar, noting that the Earth's orbit is elliptical rather than spherical that the first true astronomical theory was born. Adhémar proposed that the precession of the equinoxes would produce antagonistic variations in insolation received by the two hemispheres during winter with ice ages occurring alternately in each, a full cycle taking 22 thousand years (ka) to complete.

Later that same century, a Scotsman, James Croll, realized that Adhémar had overlooked the fact that the shape of the Earth's orbit (eccentricity) varied over time, a detail which could potentially hold the key. Croll calculated orbital eccentricity for the past 3 Ma and determined a cyclicity of approximately 100 ka. The occurrence of ice ages was still linked to the precession of the equinoxes as postulated by Adhémar, but now the envelope of eccentricity modified the precessional cycle, such that when eccentricity was close to zero no ice age would occur in either hemisphere. However, since variations in eccentricity produced only very minor changes in the annual radiation budget of the Earth Croll considered that this was not sufficient to drive the ice ages, and therefore invoked positive feedbacks in the climate system through changes in surface albedo. Although widely welcomed at the time, this theory gradually fell out of acceptance as circumstantial geological evidence started to accumulate, with indications that the last ice age might have ended as recently as ~10 ka BP (Before Present), rather than the ~70 ka BP predicted by Croll.

No further progress was made with astronomical descriptions of the ice ages until during the first half of the 20th century when Milutin Milankovitch, a Serbian mathematician, constructed a theoretical framework for describing the distribution of insolation over the Earth's surface as a function of three orbital properties (precession, obliquity, and eccentricity). Not only did Milankovitch apply this to the present-day but was also able to make calculations for any point in time during the past 650 ka. Noting that summertime melting appeared to be the key season in controlling the growth of modern glaciers, he suggested that it was insolation levels during this half of the year that was critical to the control of ice ages rather than the winter months as had previously been assumed. This received strong support through the remarkable match made between summer insolation calculated at 65°N and variability in the reconstructed terminal limits of Alpine glaciers.

It was not until the late '60s and early '70s with the advent of sufficiently-sensitive analytical techniques for determining isotopic composition that Milankovitch's astronomical theory of the ice ages would be confirmed. Sediment cores recovered from the deep sea had already confirmed earlier geological evidence based upon glacial till sequences. Measurements of the abundance ratio of the stable isotopes ^{18}O and ^{16}O ($\delta^{18}O$) contained within foraminiferal calcite now revealed the occurrence of as many as 7 major ice age cycles (Figure 1). Location of the Brunhes-Matuyama magnetic reversal (then dated to around 730 ka BP) in particularly long sediment sequences allowed the period of the cycles to be estimated at around 100 ka, matching that of orbital eccentricity. Further support for the theory came with the realization that variations in $\delta^{18}O$, (particularly in benthic foraminifera) must reflect changes in global ice volume. Finally, spectral analysis of this ice volume proxy verified the presence of primary periods of variability occurring at 100 ka and 41 ka, corresponding to the orbital components of eccentricity and obliquity. Furthermore, the presence of not one but two precessional peaks (23 ka and 19 ka) was revealed by the sediment core data, an orbital feature not previously predicted by calculations.

From the very outset, the most problematic aspect of Milankovitch's astronomical theory of ice ages has been that eccentricity, which appears to match the frequency of the glacial-interglacial cycles, is far weaker than either precessional or obliquity orbital components in terms of the spectral power of insolation variability. Indeed, variations in eccentricity alter annual radiation received by the Earth by less than 0.1% [*Imbrie et al.*, 1993]. With the use of computers as a standard scientific tool in the mid 1970s, possible climatic mechanisms that could produce such a non-linear response began to be investigated with complex numerical models. The first such model calculated increases in global ice volume simply in proportion to an insolation (50°N summer) deficit [*Calder*, 1974]. Non-linearities in ice

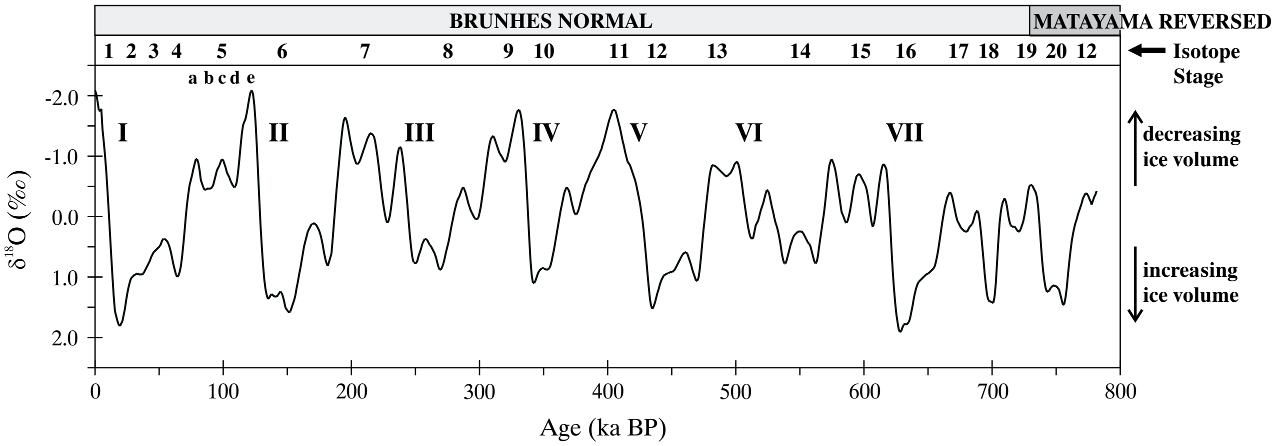

Figure 1-1 The SPECMAP stacked marine δ^{18}O record [*Imbrie et al.*, 1984], where increasing δ^{18}O values approximately scale with increasing global ice volume. Labelled are the Marine Isotope Stages after *Shackleton and Opdyke* [1973] (with Stage 5 sub-divided 'a' through 'e') together with the location of the Brunhes-Matuyama magnetic reversal, taken at 730 ka BP [*Imbrie et al.*, 1984]. Also marked are the last 7 major glacial terminations, labelled "I" through "VII".

sheet response were represented by taking a different proportionality for melt-back than for growth. Remarkably, this model produces a distinct 100 ka cycle in spite of the relatively low power at the corresponding period inherent in the forcing. A similar formulation, but with non-linearities in ice sheet response now represented explicitly was presented by *Imbrie and Imbrie* [1980], proving a fruitful basis for further development [*Pisias and Shackleton*, 1984; *Snieder*, 1985]. This model improved upon the overall sawtooth shape of the glacial-interglacial cycles of that produced by *Calder* [1974]. Other simple methods were also found of accounting for much of the variance contained within the marine δ^{18}O record directly from insolation, including multivarient regression [*Berger et al.*, 1981] and astronomical climate index [*Kukla et al.*, 1981] models, and through consideration of albedo-radiation feedbacks [*Wigley*, 1976].

One direction of development taken from these initial studies was in what were often highly abstracted models of the Earth system. In these, 100 ka cycles were various obtained through stochastic resonance [*Matteucci*, 1989], the selective frequency amplification of an internal oscillation [*Le Trent and Ghil*, 1983; *Van der Sluijs et al.*, 1996], as a free-running oscillation driven by an inherent climatic instability [*Saltzman*, 1987, 1990; *Saltzman and Maasch*, 1988, 1990, 1991; *Saltzman and Sutera*, 1984, 1987; *Saltzman and Verbitsky*, 1992, 1993, 1994a,b; *Saltzman et al.*, 1993], or through the existence of multiple thresholds prescribed within the system [*Paillard*, 1998]. Insolation forcing was still important in all of these, although in some cases its role in the glacial-interglacial cycles was reduced to little more than phase-locking of internal oscillations.

An alternative approach brought to bear on the glacial-interglacial cycle question was to represent key processes within the climate system in an explicit and mechanistic fashion. The element suspected to play the predominant role was that of the cryosphere [*Calder*, 1974] (including its interaction with other components of the climate system). On this basis, *Weertman* [1976] modelled the (northern hemisphere) cryosphere as a simple equilibrium ice sheet atop a plastic crust. Although significant changes in ice volume were found when this model system was forced with variable (summer 50°N) insolation, no clear 100 ka cycle was produced. Models comprising just atmospheric, ocean, or coupled ocean-atmosphere components similarly failed [*Brickbat et al.*, 1999; *Short et al.*, 1991; *Suarez and Held*, 1976], as did coupling an atmospheric component to the ice sheet [*Pollard*, 1978]. However, the introduction of a realistic time scale for isostatic bedrock adjustment, either explicitly or mechanistically through representation of mantle elasticity or viscoelasticity allowed an ice volume signal with a clear ~100 ka period to be obtained [*Birchfield et al.*, 1981; *Deblonde and Peltier*, 1991; *Pollard*, 1982; *Oerlemans*, 1980, 1982]. Having achieved this, the next area of deficiency in predicted ice volume (compared to the marine δ^{18}O record) concerned the glacial terminations, which tended to be rather sluggish and with incomplete deglaciation occurring. Additional mass wasting parameterizations were therefore introduced to correct for this such as that of ice calving [*Clark and Pollard*, 1998; *Deblonde and Peltier*, 1990, 1991, 1993; *Hughes*, 1992; *Oerlemans*, 1991; *Pollard*, 1983]. In contrast, simulating glacial inception was much less problematic, with adequate representation of continental topology often sufficient to allow the initiation of ice sheets during periods of low summer insolation [*Birchfield et al.*, 1982; *Deblond and Peltier*, 1990, 1991, 1993; *Ledley and Chu*, 1995; *Tarasov and Peltier*, 1997]. Recent studies have also highlighted the potential importance of vegetation-albedo feedbacks in this process [*de Noblet et al.*, 1996; *Gallimore*

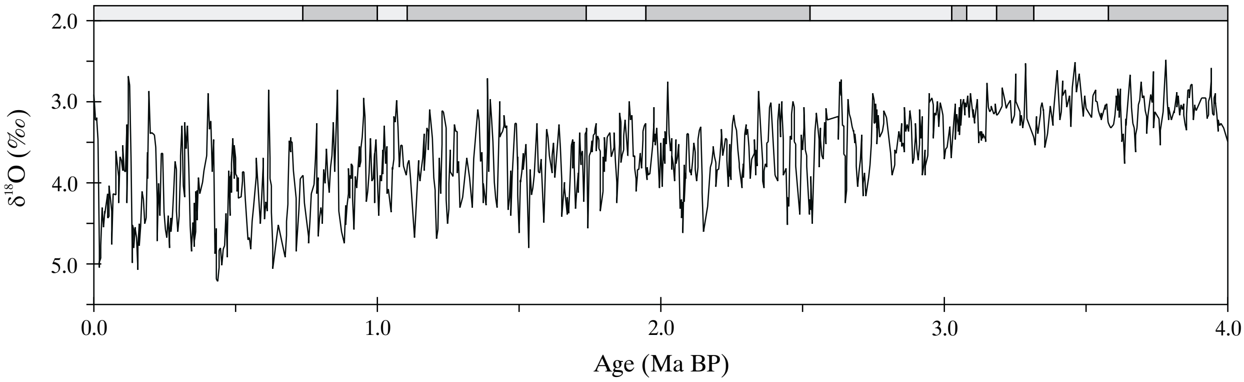

Figure 1-2 The benthic $\delta^{18}O$ record of Ocean Drilling Program site 659 [*Tiedemann et al.*, 1994]. Shown at top are the approximate occurrences of the different magnetic polarity epochs over the length of this record.

and Kutzbach, 1996]. Building upon the promising response obtained by interactions between ice sheets and the underlying bedrock models have gradually attained increasing complexity as additional climate components (such as full atmospheric energy balance models and representations of ocean heat transport and storage) have been added. In particular, considerable advances have been made in our understanding of glacial-interglacial climate dynamics through the development of models of 'intermediate complexity' such as those of Deblonde, Peltier and co-workers [*Deblonde and Peltier*, 1990, 1991, 1992 1993; *Peltier and Marshall*, 1995; *Tarasov and Peltier*, 1997] and the LLN model of André Berger and co-workers [*Berger and Loutre*, 1997a,b; *Berger et al.*, 1990, 1993, 1998, 1999; *Li et al.*, 1998a,b; *Loutre and Berger*, 2000]. However, even relatively advanced models such as these fall noticeably short of being able to fully account for the 100 ka glacial-interglacial cycles. Clearly there must be some important climatic factor still missing.

The climatic fluctuations of the last ~800 ka are only a part of a longer-term evolution in the dynamics of the Earth's climate, which has seen substantial change over the course of much of the late Cenozoic [*Driscoll and Haug*, 1998; *Raymo and Ruddiman*, 1992; *Ruddiman and Raymo*, 1988]. Figure 1-2 shows part of a marine $\delta^{18}O$ record covering the last 5 Ma [*Tiedemann et al.*, 1994]. Again taking (benthic) $\delta^{18}O$ primarily as a proxy for global volume it can be seen that up until about ~3.1 Ma BP, climate appeared relatively stable, with little variability in global ice volume (probably similar to that of the present interglacial). After this point there was a clear downward trend, with the amplitude of fluctuations steadily increasing. This continued to around 2.5 Ma BP when the first major northern hemisphere glacial event occurred [*Shackleton et al.*, 1984]. A relatively extended period ensued thereafter, with ice ages reoccurring with a period of about 41 ka and with maximum ice volume perhaps half that of the more recent 100 ka cycles [*Clark and Pollard*, 1998]. Finally, somewhere during the interval 1.5 to 0.7 Ma BP there was a transition to the establishment of 100 ka glacial-interglacial cycles. In an attempt to characterize the nature of this final transition a wide variety of spectral and statistical techniques have been brought to bear. These have ranged from relatively simple spectral [*Mudelsee and Schulz*, 1997; *Pisias and Moore*, 1981] and bispectral methods [*Hagelberg et al.*, 1991; *Rutherford and D'Hondt*, 2000], through multitaper-based techniques [*Birchfield and Ghil*, 1993; *Mann and Lees*, 1996; *Park and Maasch*, 1993; *Saltzman and Verbitsky*, 1992], to probability density functions [*Maasch*, 1988; *Matteucci*, 1990; *Mudelsee and Stattegger*, 1997] and more recently, wavelet analysis [*Bolton et al.*, 1995; *Lau and Weng*, 1995]. However, these techniques have often been at odds with each other regarding the details of the rate of change and timing of the mid point of the transition. Statistical methods also generally fail to illuminate the underlying physical processes responsible for the change in the dynamics of the climate system at this time, although there have been suggestions that a key role was played by the tropics [*Rutherford and D'Hondt*, 2000].

Various explanations have been offered to account for aspects of the inferred evolution of the Earth's climate system over the late Cenozoic. For the initial onset of ice age cycles around 2.5 Ma BP, favourite among these has been tectonic changes, particularly the emergence of the Isthmus of Panama with possible associated disruption of ocean circulation patterns [*Hay*, 1996], and the deepening of the Fram and Denmark Straits [*Hay*, 1993, 1996]. However, the timing of these events place them too early to have had a direct effect, with the results of ocean and atmospheric circulation models often not supporting a significant role [*Hay*, 1996; *Maslin et al.*, 1998; *Raymo and Ruddiman*, 1992]. Uplift of the Tibetan plateau may also have had an influence in producing climatic conditions conducive to the growth of ice sheets through its distorting influence on atmospheric circulation in the northern hemisphere [*Raymo and Ruddiman*, 1992; *Ruddiman and Raymo*, 1992]. For the transition from 41 to 100 ka periodicity, a gradual

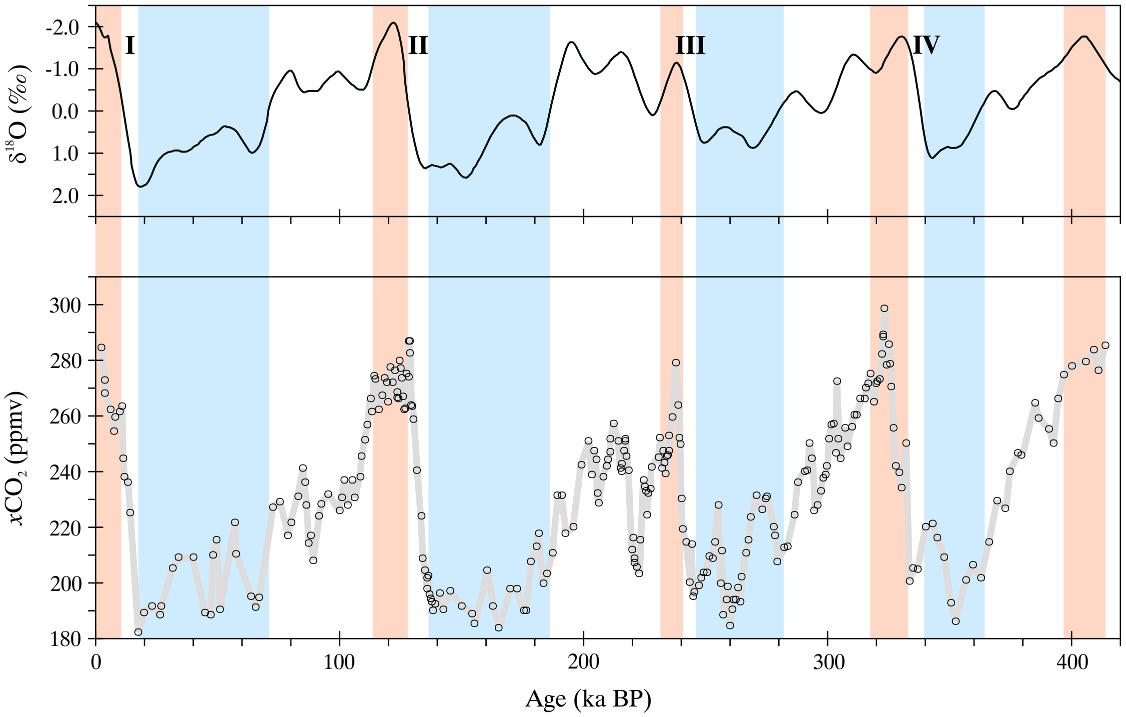

Figure 1-3 Approximate correspondence between glacial-interglacial variations in the concentration of atmospheric CO_2 [*Petit et al.*, 1999] and changes in ice volume (as indicated by the SPECMAP $\delta^{18}O$ record [*Imbrie et al.*, 1984]). Interglacials are highlighted in red with deep glacial periods in blue.

transformation of continental regolith has been proposed, with the formation of ice sheets characterized by much greater height and volume only enabled by the eventual erosion of the underlying sediment substrate down to the bedrock [*Clark and Pollard*, 1998; *Clark et al.*, 1999]. However, such explanations tend to be difficult to critically assess and are not entirely convincing as sole agents. Once again, one must suspect that an additional key component of the climate system has not yet been accounted for.

Past records of atmospheric composition, in the form of microscopic bubbles trapped within the crystalline structure of ice buried in the ice caps of both hemispheres, has sparked a revolution in thinking regarding the long-term dynamics of the climate system. Ice cores recovered from Greenland and Antarctica during the early 1980s and analysed for air bubble CO_2 content showed that atmospheric CO_2 levels at the time of last glacial were some ~30% lower than during the late Holocene [*Neftel et al.*, 1988; *Oeschger et al.*, 1984]. Cores were soon extracted from much greater depths, extending the record first back beyond the last interglacial period (the Eemian) [*Barnola et al.*, 1987; *Jouzel et al.*, 1993; *Lorius et al.*, 1990] and then finally, four complete glacial-interglacial cycles were revealed by the Vostok core [*Petit et al.*, 1999]. Results demonstrated that the pattern was regularly repeated, with relatively high CO_2 levels (~280 ppmv) during interglacials and low levels (~190 ppmv) during the deepest glacial periods (Figure 1-3). On the basis that the presence of CO_2 in the atmosphere effectively retards the loss from the Earth to space of radiation at infrared wavelengths [*IPCC*, 1990], it was immediately recognized that such past variability in CO_2 concentrations might have played an important role in the ice age cycles [*Barnola et al.*, 1987; *Broccoli and Manabe*, 1987].

The potential importance of variations in CO_2 concentrations in determining the envelope of the ice age cycles has been demonstrated by numerous modelling studies. For instance, the addition of a CO_2-dependent forcing to one of the earliest insolation-driven climate models produces a significant improvement in the evolution of simulated ice volumes [*Pisias and Shackleton*, 1984]. Other abstracted models confirmed that relatively realistic ~100 ka cycles could be generated by accounting for the influence of CO_2 [*Lindzen*, 1986; *Saltzman*, 1987, 1990, *Saltzman and Maasch*, 1988; *Saltzman and Verbitsky*, 1994]. Mechanistic (intermediate complexity) climate models also exhibited an evolution in ice volume over the course of the 100 ka glacial-interglacial cycles significantly more in line with paleoclimate reconstructions upon the addition of external CO_2 forcing [*Berger et al.*, 1998, 1999; *Li et al.*, 1998a; *Loutre and Berger*, 2000]. This improvement can be demonstrated more quantitatively through spectral analysis. Without applied variability in CO_2 forcing, model spectral power centred about a period of ~100 ka is in fact split into two peaks corresponding to periods of ~95 and ~125 ka [*Ridgwell et al.*, 1999], closely following the character of eccentricity [*Muller and MacDonald*, 1997a,b,c]. There is also considerable (unwanted) power centred around the ~413 ka eccentricity component. In contrast, model response where changes in CO_2 levels are accounted for exhibit a single peak corresponding to ~100 ka with little power at lower frequencies, consistent with the spectral characteristics of marine $\delta^{18}O$ records [*Ridgwell et al.*, 1999].

The potential importance of CO_2 also extends to the evolution of the climatic system over the late Cenozoic. Uplift of the Tibetan plateau over this period may have resulted in increased chemical weathering and/or increased net organic carbon burial, producing a gradual draw-down in atmospheric CO_2 [*France-Lanord and Derry*, 1997; *Raymo*, 1994; *Raymo and Ruddiman*, 1992; *Raymo et al.*, 1988]. This is illustrated once again by climate models driven by a long-term reduction in CO_2 forcing component, which are able to reproduce both the onset of ~41 ka ice age cycle around ~2.5 Ma BP, together with the transition between 41 and 100 ka periodicity with an associated increase in cycle amplitude [*Saltzman and Maasch*, 1991; *Saltzman and Verbitsky*, 1992, 1993, 1994].

What processes at work within the earth system then drive the observed glacial-interglacial variability in the concentration of atmospheric CO_2 … ?