Chapter 2

Planetary Machinery: The Dynamics of the Earth System Prior to Significant Human Influence

The properties and processes of the non-human dominated Earth System vary across a wide range of space and time scales. Nevertheless, the Earth System has functioned within domains characterised by well-defined limits and periodic patterns. Interconnections among physical, chemical and biological processes and between land, ocean and atmosphere, across both space and time, are ubiquitous and critical for the functioning of the System. Forcings and feedbacks are difficult to distinguish as one becomes the other in the cyclical dynamics of the System. Rapid, abrupt changes can occur as the Earth System reorganises into a new state.

2.1 The Natural Dynamics of the Earth System

This chapter focuses on the nature of the Earth System before human activities became an important feature of the system, that is, prior to the beginning of the Industrial Revolution (Fig. 2.1). Much of the Earth System research that has been carried out in recent decades has sought to understand the backdrop of biogeochemical cycling and climate processes against which all current and future anthropogenic changes must be evaluated. Central to this analysis is the evaluation of the response of biological systems to physical and chemical changes in the Earth System and the role of biological systems in biogeochemical and biophysical processes within the Earth System. Global change research over the past decade has demonstrated that the biosphere is an active and important contributor to the functioning of the Earth System. The persistent notion that the Earth System, especially the climate, is driven largely by the physics of coupled ocean-atmospheric dynamics, with very little role for biology, has been effectively dispelled by the discovery of many concrete mechanisms by which both the marine and terrestrial biospheres interact with physical and chemical processes, and indeed, even help to control some critical Earth System functions.

In this chapter attention is drawn to the ways in which the biogeochemical and biological systems interact with the hydrological cycle and climate over space and time. The examination of biogeochemical systems assumes familiarity with the global cycles of carbon, nitrogen, phosphorus and sulphur. These are not dealt with in detail here. Complete descriptions of these cycles and their most critical processes are available in a number of recent texts (e.g., Schlesinger 1999; Jacobson et al. 2000), in review articles (e.g., Schimel et al. 1995; Vitousek et al. 1997; Smil 2001), and in syntheses in the IGBP series of books (Tyson et al. 2002; Brasseur et al. 2003; Fasham 2003; Kabat et al. 2004; Pedersen et al. 2003). Here, rather, the focus is on examples of some of the most exciting and critical recent findings that give insight into how Earth works as an integrated whole.

Studying the dynamics of the Earth System in a non-human dominated state is not straightforward. As will be made clear later in Chap. 3, many critical processes in Earth System functioning are now significantly influenced by human actions, and observing them directly now could give an incorrect or misleading picture of how the Earth functioned prior to being significantly influenced by human activities. Consequently, this chapter relies heavily on two sources of information: (*i*) palaeo-records, which provide data from time periods where human activities had no or only minimal impact on global-scale processes and which provide the opportunity to evaluate the natural dynamics and variability of the System, and (*ii*) contemporary research in those areas of Earth System functioning where human influences are still thought to be relatively small. The timeframe considered here is the last one million years of the evolution of the Earth System, as this is the period against which the very recent era of significant human influence is most appropriately considered. At a few points in the chapter events earlier than one million years ago are mentioned, but only to help place more recent events in context.

In addition, this chapter introduces a style of analysis that is used throughout this volume. Initially, attention is focused on individual aspects of the Earth System. The functioning of these is described in some detail leaving aside, for the moment, the systems-level perspective. In essence, the reader is asked to take a magnifying lens and examine various segments of the Earth System individually. Then, at the end of each chapter, the reader is asked to put the magnifying glass down and look at the entire object – the Earth System – as a whole, in order to see how the individual segments examined contribute to the functioning of the System.

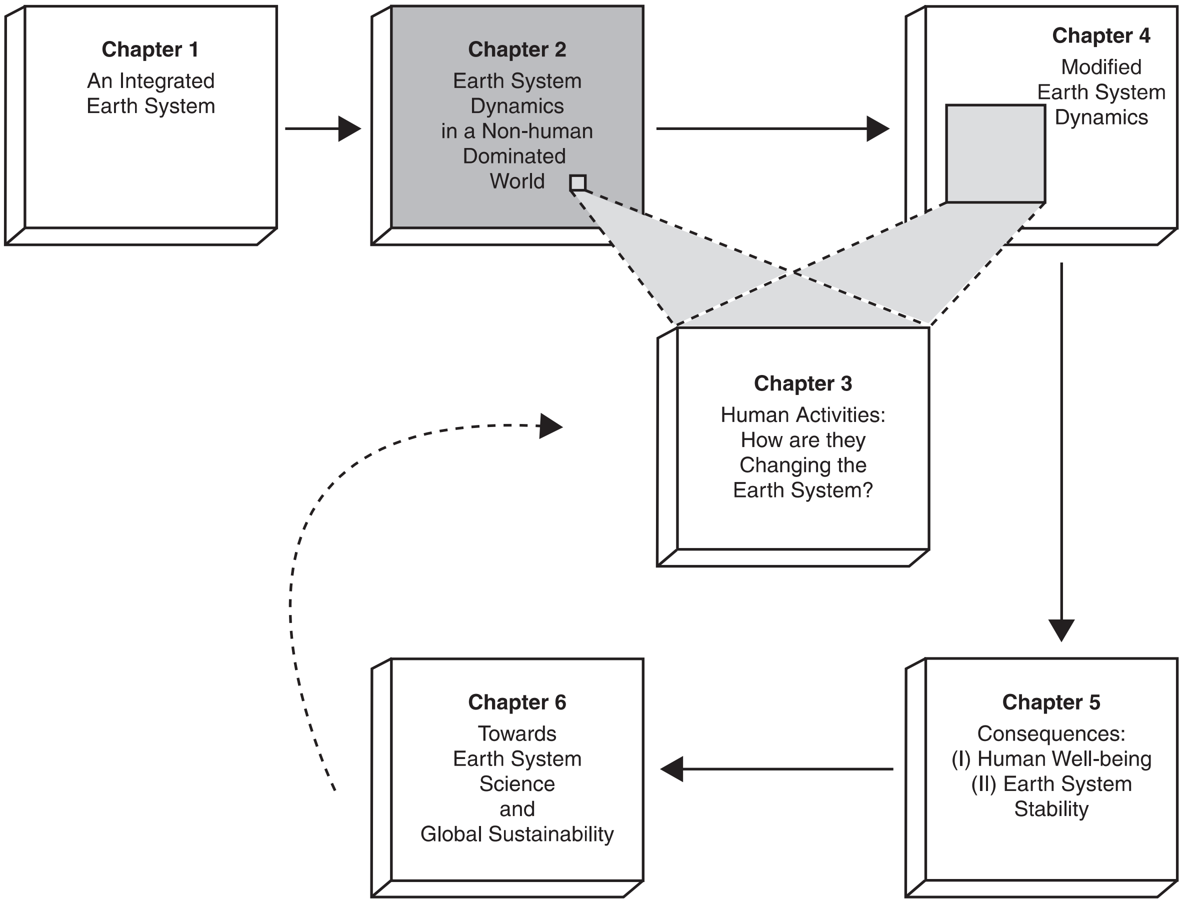

Fig. 2.1. Chapter 2 focus: Earth System functioning prior to significant human influence

2.2 New Insights in Temporal Variability of the Earth System

Recent research has illustrated the considerable natural variability and temporal dynamics of the Earth System. It has made clear that temporal change is a reality of the Earth System, and that static equilibria are unlikely to be a part of the System on almost any time scale and certainly not over the last 400 000 years. In the following sections, some of the insights gained by the great variety of palaeo-records that have been collected and evaluated over the past decade are considered.

2.2.1 The Long-Term Envelope of Natural Self-Regulation

The geological record shows that the functioning of the Earth System has varied continuously on all time-scales (Fig. 2.2). Changes in the Earth's orbit lead to changes in the latitudinal distribution of incoming solar radiation. The orbital parameters responsible for these changes have known periodicities, ~19 000 years and ~23 000 years for precession, ~40 000 years for obliquity and ~100 000 years for eccentricity. The changes in climate to which these orbital parameters give rise are far reaching and their periodicities can be detected in the record of climate variability contained in many environmental archives. As was pointed out in Chap. 1, climate changes are not linearly related to the external forcing. Interactions between biological, chemical and physical components of the Earth System, in response to subtle shifts in external forcing, have often given rise to non-linear changes that are abrupt and out of all proportion to the changes in incoming solar radiation. Nor are the climate changes necessarily synchronous with the orbital changes to which they ultimately respond, for the combination of internal thresholds, differing response times of Earth System components and strong, non-linear interactions can lead to lags between the onset of external changes and the responses of the Earth System.

Not all the past changes in climate that are detectable in the palaeo-record can be ascribed to orbitally driven changes. Many of the changes in temperature and

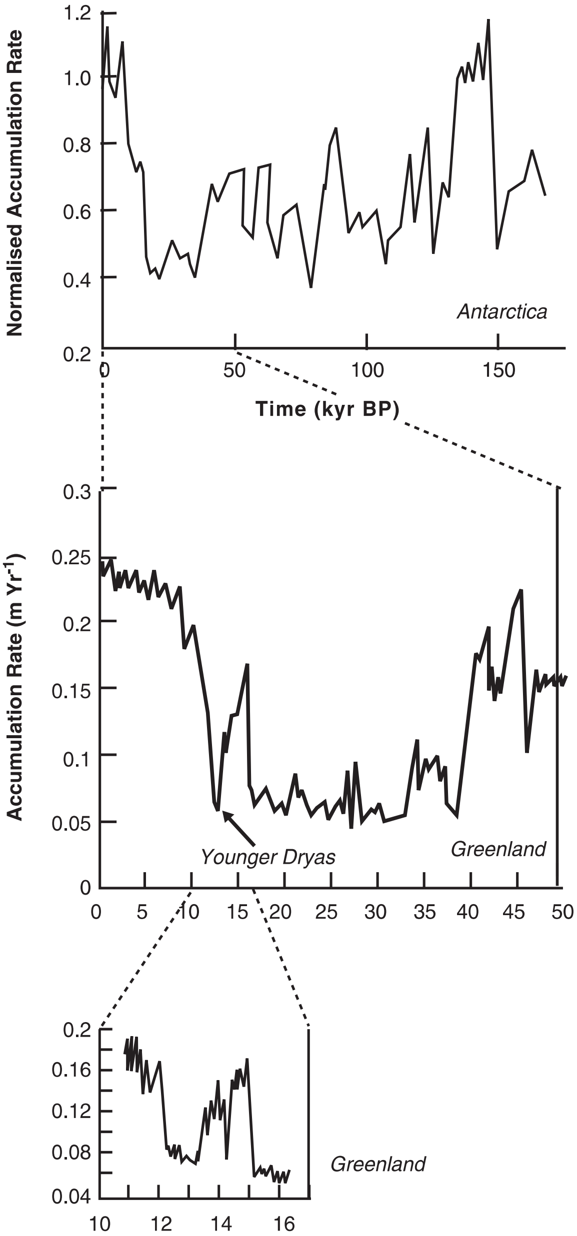

Fig. 2.2. Natural variability in Earth System functioning, from top to bottom: historic measurements of glacial ice accumulation rates, with insets focusing on the Younger Dryas cold interval and the very rapid termination of the last glaciation (adapted from Jacobson et al. 2000)

precipitation that are consistently recorded in environmental archives occur on shorter timescales, ranging from annual to millennial. Volcanicity influences climate on the shortest, mainly sub-decadal, timescales, but many other factors interact to drive the variability that has characterised the Earth's climate on sub-orbital forcing timescales, including short term changes in solar activity, ocean circulation and the terrestrial biosphere. The important point here is that regardless of the extent to which human activities may lead to changes in the Earth System, the functioning of the System will continue to vary in the future. Moreover, future changes, like those in the past, are likely to be characterised by highly non-linear responses to forcing, irrespective of the extent to which this is natural or anthropogenic. Documenting and understanding past variability, therefore, has a vital role to play in understanding present and predicting future change in Earth System functioning. This section focuses on the last 400 000 to 500 000 years, as this time period allows appraisal of four full glacial-interglacial cycles; these dynamics have been the normal operating mode of the Earth System throughout the later stages of human evolution.

The four-cycle Vostok ice core record from Antarctica, spanning the last 420 000 years (Fig. 1.3; Petit et al. 1999), provides the single most compelling template for multi-millennial scale natural variability in the geologically recent past. Of the many noteworthy features of the Vostok record, two provide an essential point of departure for any attempt to place contemporary trends into the longer-term context of natural variability. First, the atmospheric trace gas and isotopically inferred temperature records show that, over the whole of the last four glacial-interglacial cycles, values have oscillated within recurrently similar extreme values. Secondly, the changes in temperature and trace gas concentrations show a high degree of coherence throughout the sequence. Taken together, these observations demonstrate that the vast transformations involved in swings from interglacial to full glacial conditions have all taken place within a strongly self-limiting system; moreover, they show that the self-regulation of the system involves complex interactions in which atmospheric greenhouse gases play a significant part as climatic amplifiers and through essential feedback mechanisms. It is in the context of demonstrable self-regulation, involving maximum global atmospheric concentrations over almost half a million years of about 280 ppmv for CO_2 and 750 ppbv for methane, that any evaluation of contemporary values rising beyond 360 and 1 700, respectively, must be placed. These contemporary values are already significantly in excess of the peaks recorded in the Vostok series even when they are smoothed to replicate the processes affecting the trace gas record in the Vostok ice (Raynaud et al. 2003) (Box 2.1).

2.2.2 Millennial-Scale Oscillations and Abrupt Changes

While the Vostok record provides an essential long-term perspective, it fails to resolve the changes that have taken place on shorter time-scales. For these, archives that provide information with greater temporal resolution are

Box 2.1. The Ice Record of Atmospheric Greenhouse Trace Gases: Reliability and Dating

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Air trapped in glaciers and ice sheets is unique as it provides a clear record of the changes in greenhouse trace gas (CO_2, CH_4, N_2O) levels during the past. Not all glaciers and ice sheets provide an equally reliable record of greenhouse gas concentrations. Where melting occurs, gas content and gas composition may be altered by chemical reactions taking place in aquatic systems or by physical gas exchange between the gaseous and the aquatic sections.

Under dry and cold conditions of polar areas, essentially in Antarctica and Greenland, the top layer of the ice sheets (the first 50 to 130 m) results from the compaction of the surface snow through sintering. In this porous firn layer air readily enters the open spaces and records essentially the same composition as the atmosphere. Below this zone the air in the firn is static and mixes only by molecular diffusion. An equilibrium between molecular diffusion and gravitational settling is reached for each gas component (Craig et al. 1988; Schwander 1989). As a consequence, the air, just before being trapped at the base of the firn column, dates back several decades due to the slow diffusion through the firn pores and has a composition that departs slightly from the atmosphere because of the gravitational fractionation. The magnitude of this fractionation is well known, allowing an accurately corrected ice core record to be constructed.

Physi- or chemi-sorption of gases (especially CO_2) at the surface of the snow and firn grains, and subsequent expulsion of the attached gas molecules after recrystallisation of the grains in the ventilated top layer of firn may induce uncertainty into ice records of trace gases. Selective fractionation of the atmospheric ratios may also occur during the last stage of the closing of channels leading to the bubble close-off (Bender 2002). However, this effect does not significantly affect the concentrations of major trace gases. Despite these possibilities, no significant modifications of greenhouse trace gas concentrations during the trapping phase have been identified. This is demonstrated by the consistency between trace gas concentrations measured in air from the firn and the gas record directly measured in the atmosphere (Battle et al. 1996; Etheridge et al. 1996) and the generally good match of atmospheric and ice core data (Fig. 2.3).

Slow chemical reactions may alter CO_2 concentrations after the gas has been trapped in ice. This has been observed in Greenland where high concentrations of impurities in the ice may lead to significant *in situ* CO_2 production via acid-carbonate interactions and oxidation of organic material (Anklin et al. 1997; Delmas 1993; Haan and Raynaud 1998). Antarctic records provide the most reliable data of changes in global atmospheric CO_2 (Raynaud et al. 1993). Carbon dioxide measurements made several years apart on the same core show no significant changes. Antarctic results are consistent between sites to within a few parts per million by volume despite the coring sites having different ice accumulation rates, temperatures and concentrations of impurities.

At depth, air bubbles progressively disappear and air hydrates form as the ice molecular structure encapsulates the air molecules in the so-called brittle zone (in which recovered ice commonly contains a high density of cracks and fractures). Results obtained from the brittle zone of a single ice core have to be considered with caution as the presence of air hydrates in the deeper parts of long ice cores may induce artifacts in the record. However, multi-site data may be used with more confidence as the brittle zone usually does not have the same age in cores from different sites. Providing that appropriate extraction procedures are used, the agreement between records from different sites or measurements performed on the same core several years after the initial measurements confidently indicates that there are no significant artifacts linked with the air-hydrate occurrence in ice (Raynaud et al. 1993).

Bacterial activity has the potential to alter trace gas composition and its isotopic signature. In polar regions the bacterial concentration is low and bacterially induced alteration of the trace gas composition has yet to be confirmed. However, polar ice cores sporadically show high N_2O values that may originate from *in situ* bacterial production (Flückiger et al. 1999; Sowers 2001) but the significance of any resultant bacterial alteration of the record has yet to be demonstrated.

Dating ice-core records presents challenges. As a consequence of the air trapping process, the air bubbles found at the bottom of the firn column were closed off at different times. Consequently a given ice sample does not have an exact age reflecting its last contact with the atmosphere, but rather an age distribution. The width of the age distribution is as low as seven years at high accumulation/high temperature sites but can be several centuries for Antarctic low accumulation/low temperature sites (Schwander and Stauffer 1984). Furthermore, because the enclosure process occurs 50 to 130 m below surface, the gas is younger than the surrounding ice and the difference in age between ice and gas depends on the temperature and accumulation rate at the site. It can vary between a few hundred to a few thousand years under present day conditions and becomes larger under ice age conditions.

A critical question in global change science is the establishment of the extent to which anthropogenic atmospheric changes over the last few centuries have been unprecedented

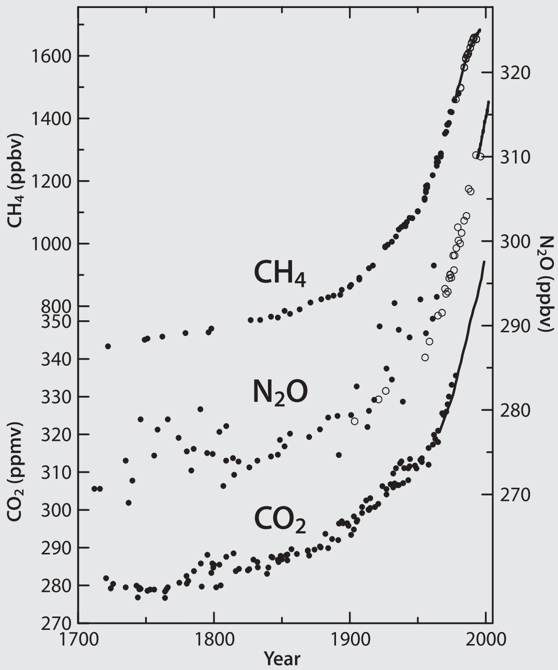

Fig. 2.3. Greenhouse trace gas records since AD 1700 (adapted from Raynaud et al. 2003). The ice core measurements overlap with direct atmospheric measurements in the contemporary period (*solid lines*)

◀

over the last 400 000 years. The record of atmospheric gas composition is smoothed during the air trapping process. Since in the case of the Vostok record this smoothing averages over centuries, it may be questioned whether an anthropogenic signal can be observed in the Vostok data. A simulation to obtain a smoothed Vostok-like record of the present anthropogenic CO_2 increase (Raynaud et al. 2003) shows that such an increase would be imprinted in the record through a CO_2 peak reaching concentrations higher than 315 ppmv with a very slow return toward the pre-industrial level. Such a CO_2 signal is not visible in the Vostok record (Fig. 2.4), although the time resolution of the record does not exclude a pulse-like atmospheric CO_2 signal of a few decades duration with concentrations as high as today. However, this would require both a large carbon release within a few decades (of the order of 200 Gt C) and an equally large and rapid uptake. Such an oscillation is not compatible with the present understanding of the global carbon cycle.

An important question is whether the time resolution of the ice record is precise enough to resolve the leads or lags between greenhouse gases and climate signals. The main uncertainties in this respect arise in connection with the age differences between enclosed air and the surrounding ice. In regard to the onsets of the last two glacial-interglacial transitions, the best-resolved records indicate an uncertainty of about hundred to a few hundred years and an Antarctic warming leading the CO_2 increase by a few hundred years (Monnin et al. 2001; Caillon et al. 2003). In the case of rapid signals like those of the Dansgaard/Oeschger events (cf. Sect. 2.2.2), the uncertainty in age difference is reduced to 10–20 years (Leuenberger et al. 1999; Severinghaus et al. 1998).

Despite the uncertainties and caveats discussed above, ice-core data provide an excellent record of past changes; the record can be used with confidence and provides the most direct and accurate evidence for past atmospheric change yet obtained. The atmospheric greenhouse gas record measured in ice cores is a smoothed temporal record whose accuracy is currently of the order of ±5 ppmv for CO_2 and ±10 ppbv for CH_4.

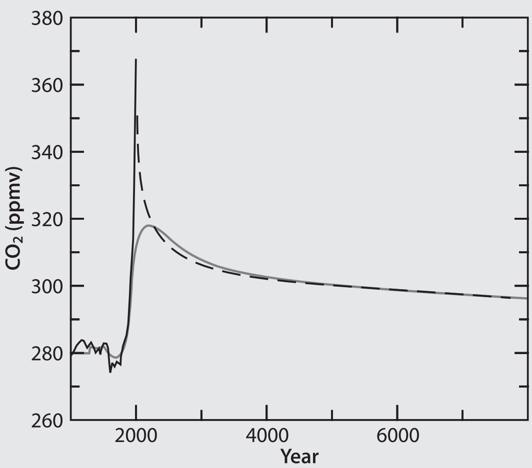

Fig. 2.4. Simulation of the minimum smoothed Vostok-like CO_2 record (in *grey*) that would result from the hypothetical incorporation of the present anthropogenic CO_2 increase (in *black*) in an ice core record (Raynaud et al. 2003)

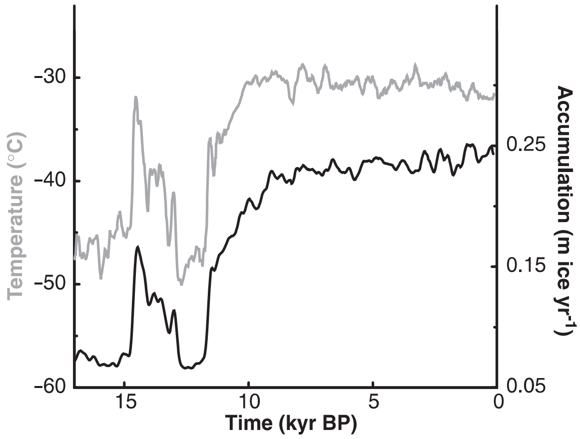

Fig. 2.5. Ice accumulation and oxygen isotope (interpreted as temperature) records from the GISP2 (central Greenland) ice core for the period between the present and 18 000 years ago (Alley et al. 1993; Alverson and Oldfield 2000), showing the abrupt climate shift at the termination of the Younger Dryas cold event some 11 600 years ago. In this record the event is manifested as a warming estimated to be as much as 15 °C, accompanied by a doubling in annual precipitation volume, that occurred in less than a decade

required. The ice cores from central Greenland provide a detailed, well-substantiated and repeatable record spanning the last glacial cycle of around 100 000 years. The rapid oscillations in inferred temperature (Dansgaard/Oeschger Cycles, see Fig. 2.5) recorded during the glacial part of the record often show over half the amplitude of the full glacial/interglacial cycle (Grootes et al. 1993). Apparently synchronous palaeo-oceanographic changes have been widely detected in the northern hemisphere (e.g., Behl and Kennett 1996; McManus et al. 1999; van Kreveld et al. 2000; see Fig. 2.6) and there are an increasing number of continental archives demonstrating parallel patterns of variability on land (e.g., Chen et al. 1997; Allen et al. 2000; Wang et al. 2001; Fang et al. 1999).

In Antarctica relatively high resolution records covering significant parts of the same time interval are, or will soon become, available from the Byrd Station, Taylor Dome, Law Dome (Indermuhle et al. 1999; Raynaud et al. 2000) (Fig. 2.7) and the first stages of analysis of the Dome C (Concordia) core (Flückiger et al. 2002). Now that data from the two hemispheres have been synchronised using common variations in the methane records (Blunier et al. 1998; Raynaud et al. 2000, 2003), several new insights have emerged. Although both sets of polar records show strong evidence for millennial-scale oscillations during the last glacial period in almost every parameter measured, the record from the opposite poles is often out of phase and, for some of the major oscillations, it is in antiphase. Moreover, during the glacial termination, the main warming trend in Antarctica precedes any rapid temperature increase in the northern hemisphere.

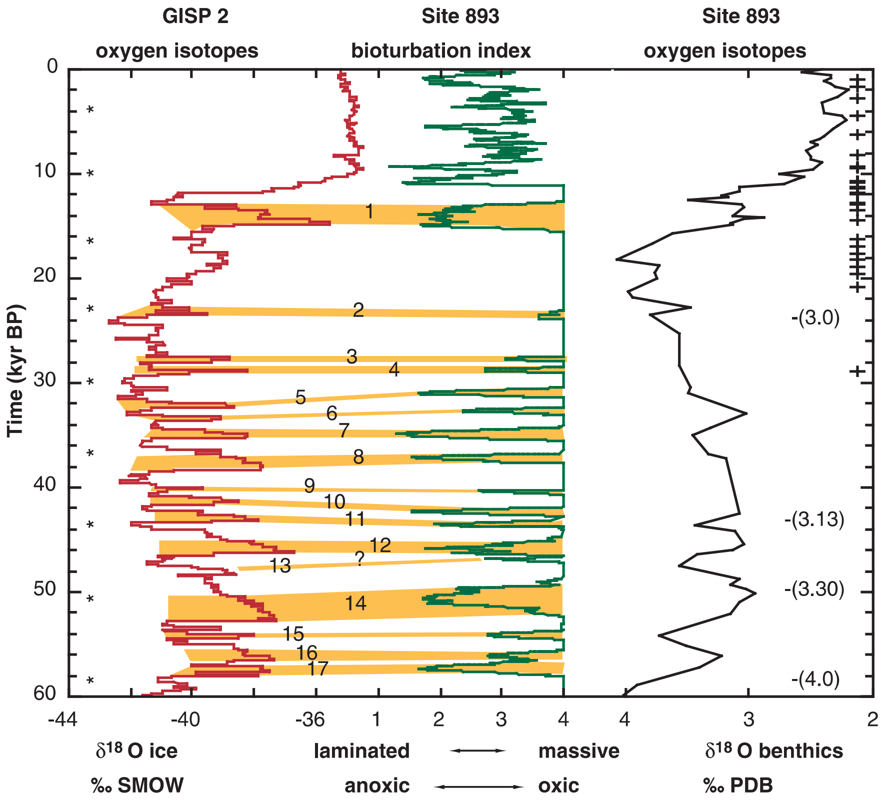

Fig. 2.6.
Low latitude expression of millennial scale climate oscillations taken from GISP2 oxygen isotopes, Santa Barbara basin (Site 893) bioturbation index and high-frequency variations in the $CaCO_3$ record of 70KL (Behl and Kennett 1996). Comparison of site 893 bioturbation index and benthic foraminiferal $\delta^{18}O$ records with $\delta^{18}O_{ice}$ time series from GISP2, showing the excellent correlation of site 893 anoxia (lamination) events to 16 of 17 of the warm interstadials of GISP2. Bioturbation index is presented as a 49 cm (ca. 300–400 years) running average to dampen high-frequency variation and to match the resolution of the GISP2 record. Chronologies for GISP2 and site 893 were independently derived. Radiocarbon age control points (+) and SPECMAP data used for the site 893 age model are shown to the right. Numbers in () refer to standard data of the SPECMAP stratigraphy. The base of each core interval in Hole 893A is indicated by *arrows* to the left

These observations further refine the perspective on past global changes, for they show that:

- major switches in the earth's climate system occurred on much shorter time scales than the glacial/interglacial cycles;
- the recorded changes were often rapid and of high amplitude;
- the changes demonstrate widespread spatial coherence, but, when characterised with sufficient temporal resolution, they are not globally synchronous; and
- complex inter-hemispheric leads and lags occur that require feedback mechanisms for amplifying and propagating changes.

In terms of present day and future implications, these observations are especially important, for they raise the possibility of anthropogenically induced global changes triggering positive feedbacks capable of provoking sudden, dramatic switches in climate comparable to those that have occurred in the past.

Aspects of the broad pattern of change presented above call for closer attention, specifically the rapidity with which the Earth's climate system may undergo major rearrangement. The best-documented period of rapid major change falls at the end of the glacial period, some 11 600 years ago. At mid to high latitudes in the northern hemisphere, the rapid warming at the opening of the Holocene is the final, decisive step in a sequence of oscillations. It represents the culmination of a suite of changes that appear to begin with the first clearly detectable warming trend in the record from Antarctica some 6 000 years earlier. Many lines of evidence point to a rapid warming at the opening of the Holocene, with records from central Greenland indicating that dramatic changes occurred within only a few decades at most (Alley et al. 1993; Alley 2000; Fig. 2.8). Studies of the opening of the Holocene from a wider range of sites may well provide the strongest empirical evidence available for the speed with which the Earth's climate system can respond given a sufficiently powerful combination of external forcing and internal amplification. They may also shed light on the rate at which ecological systems can respond to such rapid changes (Amman and Oldfield 2000; Birks et al. 2000).

2.2.3 Climate Variability in Interglacial Periods

Most of the high variability in inferred temperature outlined above is characteristic of glacial intervals and terminations, but the Earth is currently in a major interglacial that has lasted for over eleven millennia. It is, therefore, not surprising that an increasing amount of attention has been devoted to characterising climate during the last, Eemian interglacial (Marine Isotope Stage 5e). Depending somewhat on definition and on the chronology adopted, this interglacial spanned http://www.springer.com/978-3-540-40800-0

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