Challenges of a Changing Earth: Past Perspectives, Future Concerns

R.S. Bradley
Climate System Research Center, Department of Geosciences, University of Massachusetts, Amherst, MA, 01003-5820, U.S.A

K. Alverson
PAGES International Project Office, Bärenplatz 2, CH 3011 Bern, Switzerland

T.F. Pedersen
Oceanography, Earth and Ocean Sciences, 6270 University Boulevard, University of British Columbia, Vancouver, B.C. Canada V6T 1Z4

8.1 Introduction

Paleoclimatic research has revealed an astonishing picture of past changes in the earth system. Over the last 2 million years, climate has varied widely from ice ages to warm interglacials. Between these extremes global sea-level varied by up to 130m, alternately exposing and submerging land bridges that provided gateways between continents for the migration of early humans. Ice sheets grew to such an enormous size, they depressed the earth's crust under their weight and forced airmasses around them. So much water was sequestered on the continents that the chemical composition of the oceans was altered, affecting all the organisms that lived in the seas. As the ice sheets grew, the world's terrestrial and marine ecosystems changed, in both distribution and composition. Continental interiors became drier, wind speeds increased and large areas of wind-blown loess accumulated. As ecosystems were altered, the composition of the atmosphere changed repeatedly, with low levels of important greenhouse gases during glacial episodes and higher levels in interglacial periods. The evidence for these changes has been carefully extracted from ice cores and sedimentary records on land and in the ocean. Advances in technology have enabled longer and better cores to be recovered, and more detailed and more precise analytical techniques to be applied to the records. Better chronological control has allowed more precise estimates of the timing of changes in different regions to be made, enabling leads and lags in the system to be established and rates of change to be examined. In addition to reconstructions of climate system parameters, paleo-data have also yielded information about the *causes* of past changes, focusing attention on mechanisms within the climate system that translate the forcings into responses that may vary from one region to another. Computer models of the climate system have elaborated on these mechanisms and helped to quantify the nature of interactions between different regions and sub-systems.

Research on glacial-interglacial timescales has thus revealed the dramatic changes that took place as man evolved from *homo erectus* to *homo sapiens*. Changes in climate over more recent intervals of time have been no less significant for human society. The origins of agriculture were associated with abrupt changes in climate in the Middle East during the post-glacial Younger Dryas interval. Archeological research provides numerous examples of societal disruptions related to climate variability during the Holocene, reminding us that agriculturally-based societies remain vulnerable to abrupt and persistent climatic anomalies, even today. As we focus on climatic changes on inter-annual and inter-decadal timescales over recent centuries, it is increasingly clear that important modes of climate variability, such as ENSO and the NAO, have not been an unchanging feature of the climate system over time, and there is no reason to expect they will remain constant in frequency or amplitude in the future.

All of these studies remind us that our modern perspective on the climate system, derived from detailed instrumental observations over (at best) the last century or two, provides a totally inadequate perspective on its real variability. *The message from the paleo-records is that change is normal and the unexpected can happen.*

8.2 Understanding earth system variability

To understand the full variability of the climate system requires a comprehensive network of well-dated, quantitative paleoclimate data. Compared to

contemporary environmental observational networks, the network of paleo-records is still sparse and in many cases poorly resolved in time. Where high resolution records have been recovered, significant advances in our understanding of how the climate system operates have often been made possible. It is essential that more such records be recovered, for the task of deciphering the past is far from over. In particular, a comprehensive understanding of variability on societally-relevant timescales (years to several decades) will require an enormous expansion in paleo-research. Prediction of ENSO activity, for example, will not be fully achieved as long as the full spectrum of ENSO variability remains unknown. So far, the paleo-record provides hints that the modal frequency of ENSO variability (determined by instrumental observations) that the world has experienced over the last century has not been stable. Rather, the ENSO system may have operated at a lower frequency in the recent past (Figure 6.10). There is also evidence that there were periods in the past when ENSO variability may have essentially disappeared, or at least changed in character to a state quite different from that which we now take as its normal mode. Furthermore, it is clear that ENSO teleconnection patterns, that affect rainfall and temperature around the world, have changed over time, yet we have only a rudimentary understanding of how or why such changes have occurred. Predictive models based on limited instrumental data may be able to generate scenarios of unusual ENSO behavior in the future, but confidence in such predictions will be limited unless there is sound evidence that such conditions are plausible, as demonstrated by records from the past.

8.2.1 Paleoclimate data and models

Models are useful tools to understand the complexities of past and future climate variations, but they are no substitute for reality. Unlike models of the past, paleo-records are integrators of forcings and feedbacks, incorporating all the processes operating on them. Global climate models can never be relied upon to give a definitive description of the natural variability of the true climate system since models cannot estimate variability associated with processes or feedbacks that are not present in the models themselves. The potential non-linearities of small-scale processes that are not resolved, dynamical feedbacks that are not accurately represented, and numerous potential surprises in the global climate system will forever limit the ability of models to accurately represent the true variability of the climate system. In fact, paleo-data offer the best

prospect of validating the low-frequency behavior of models. They add a critical element to the climate change detection and attribution problem that is not possible from a comparison of 20th century model simulations and instrumental observations alone. Paleo-data allow us to look at potential forcing mechanisms prior to the era of anthropogenic forcing, potentially validating or testing model-based estimates of climate sensitivity. For example, estimates of the sensitivity of climate to solar irradiance forcing, estimated empirically from paleo-data have provided validation of model-based estimates. In this way, the magnitude of "natural" forcing, upon which anthropogenic forcing is superimposed, can be assessed. Furthermore, "natural" forcings may produce a spatial response in the climate system similar to the signal of anthropogenic (greenhouse gas) forcing, confounding the detection of significant anthropogenic climate effects. Understanding these responses is thus necessary in anthropogenic signal detection.

8.3 Nonlinear dynamics in the earth system

Throughout this volume, we have seen examples of how the paleo-record and associated modeling give insight into processes operating within and between earth system components, and into relationships between forcing mechanisms and system responses. An important theme that appears common to many different temporal and spatial scales is the nonlinear nature of climatic and environmental changes. Once critical thresholds have been passed, recovery of the system to its former state may take a long time, and indeed the former state may not be achieved.

8.3.1 Earth system thresholds

The definition of 'abrupt' change is necessarily subjective, since it depends on sample interval and the pattern of longer term variation within which the change is embedded. Nonetheless, rapid response to gradual forcing is a ubiquitous feature of past climatic and environmental change on all time and space scales, and must be expected to continue into the future. Many examples of threshold dynamics in paleoenvironmental reconstructions and models that are relevant to the future are presented in this book. Some selected examples include:
• The upper and lower bounds within which atmospheric CO_2 concentration has varied over the past four glacial cycles appear to be thresholds within the global carbon cycle (Chapter 2). The ~200ppmv minimum during glacial times may

represent reduced photosynthetic efficiency, below which the global biosphere is restricted in its ability to further lower atmospheric CO_2 levels (Chapter 5, Section 5.3). The ~280 ppmv maximum during interglacials, though not fully understood, is probably controlled by oceanic processes. This limit has been drastically exceeded during the Anthropocene (Chapter1, figure 1.6) with as yet not fully understood consequences for the planet.

• The waxing and waning of massive continental glaciers during the Quaternary is reflected in a rich history of sea level variability (Chapter 3, Figure 3.2a). One simple but plausible model captures a great deal of this variability, simply by assuming a threshold response of the earth system to known high latitude insolation changes (Chapter 3, Figure 3.2b). On millennial timescales, the stadial/interstadial climatic transitions which punctuate glacial periods are modelled as being initiated when fresh water fluxes in the Northern North Atlantic cross a critical threshold amount required to shut down the global thermohaline circulation (Chapter 3, Section 3.3).

• Large regions of the modern ocean, despite ample nutrients, have very low marine productivity. Experiments have shown that with a supply of iron above some critical threshold (as is thought to have occurred in the past) productivity rises dramatically, providing a potentially large oceanic carbon sink. This 'biological pump' may have played a key role in past variations in atmospheric carbon dioxide concentrations (Chapter 4, Section 4.3)

• With some exceptions, the past record shows that many species are able to shift their ranges at a threshold rate of 200 to 2000 m a^{-1} (Chapter 5, Section 5.4). If future climate change causes the potential range of species to shift faster than their threshold rate, this (combined with effects of a fractured, human-dominated landscape) will very likely lead to extinctions.

• Explosive volcanic eruptions that propel particles and gases high into the stratosphere may, if large enough, lower temperatures at the surface to the point that additional feedbacks (involving snow and sea-ice) may amplify the radiative effect of the aerosols, and cause the initial perturbation to persist (Chapter 6, section 6.11).

• Acidification of lakes in recent decades has been shown to be due primarily to industrial pollution and to lie outside of the range of natural variability (Chapter 7, Figure 7.3). The single most important factor determining vulnerability to acidification is the chemical buffering capacity of individual lake catchment systems (Chapter 7, Section 7,4). Chemical buffering serves to maintain stability of lake pH under natural variations in acid input. Given too large a pertubation however, the threshold buffering capacity may be overrun, resulting in rapid acidification and consequent environmental degradation occur.

8.3.2 Hysteresis

Hysteresis is a non-linear dynamical feature common to past climate and environmental processes, across the full range of temporal and spatial scales. In many systems, abrupt shifts associated with the crossing of critical threshold such as those described above, are either difficult or impossible to reverse. Figure 8.1 shows three selected examples of such hysteresis behavior. The upper panel shows an example from the past which is thought to have affected the entire earth system for thousands of years - shown here as thermohaline circulation shutdown by fresh water forcing in a numerical model. Even after reducing fresh water forcing (such as that which triggered the Younger Dryas cold event) models suggest that it may take hundreds of years for the thermohaline circulation to return to its previous state. The second example, shown in the middle panel, is much smaller scale, and taken from the more recent past when natural and human effects interacted. Nutrient loading from fertilizer input in the 1970's caused catastrophic decline of charophyte vegetation and associated ecosystem change in this Dutch lake. In order to reverse this environmental degradation the nutrient loading of the lake had to be decreased far below the level that triggered the environmental catastrophe in the first place. In the lower panel, we show a schematic of the earth system as a whole. The horizontal axis shows the increases in atmospheric CO_2, combined with systemic human impacts on regional ecosystems, that are now driving the system over a critical threshold which separates the Holocene from the Anthropocene (Chapter 1). The degree of hysteresis in this transition is unknown, but certainly not zero.

Thus, any strategy to manage the earth system, or its components needs to account for an understanding of system behavior provided by past records. As discussed in Chapter 6, section 12, an understanding of such system behavior can not possibly be provided by predictive models alone. Rather, it must be gleaned from the past record. Policies which will benefit from a better understanding of past system dynamics and the inherent dangers of reaching critical thresholds in the climate system include those focused on:

• reducing greenhouse gases in an attempt to reduce associated global warming (Chapter 2)

• understanding, monitoring, and perhaps
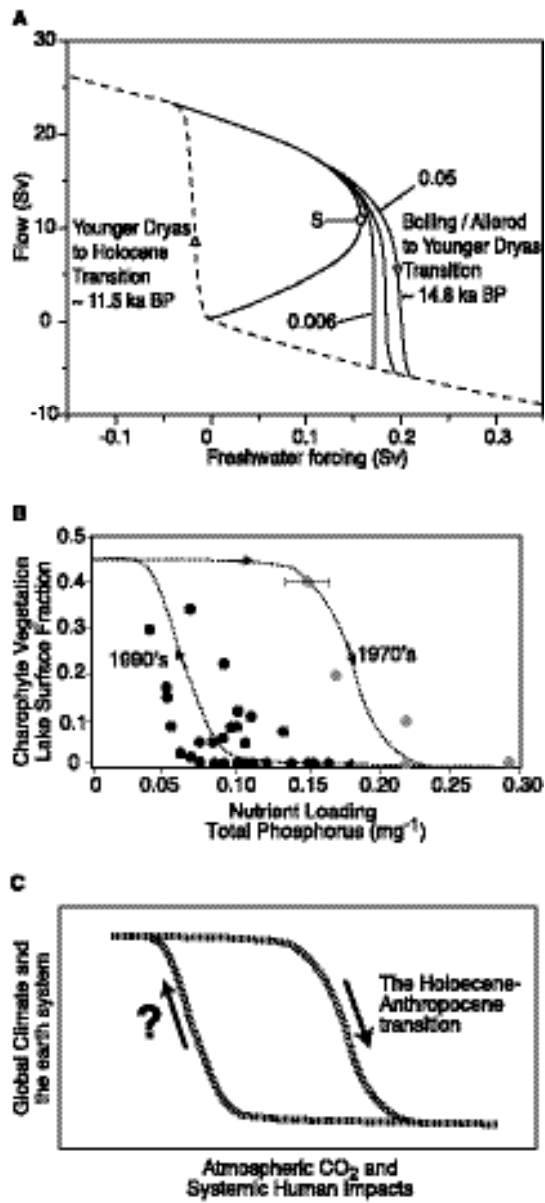
Fig. 8.1 Three examples of hysteresis in components of the earth system on vastly different spatial and temporal scales. Such non-linear behavior is common in records of the past, and must be expected in the future.

preventing changes in regional climate associated with variability of the thermohaline circulation (Chapter 3)

- sequestering fossil fuel carbon in either terrestrial or oceanic reservoirs (Chapter 4)
- developing natural reserves to maintain biodiversity and ensure species survival (Chapter 5)
- detecting and attributing global and regional change to natural and/or anthropogenic forcing (Chapter 6)
- managing lake catchments, coastal zones and landcover in order to protect them for future generations. (Chapter 7)

8.4 Is the past irrelevant to the future?

It might be argued that future changes in the climate system resulting from the dramatic rise in anthropogenic greenhouse gases, will render evidence from the past irrelevant. This is not so. Times of rapid change in the past provide critical insights into how system responses and interactions can be expected to occur. For example, the rates at which various species migrate in response to climate change are primarily constrained by paleodata (Chapter 5, section 5.3). These parameters are critical for management strategies that seek to maintain biodiversity in the future.

Furthermore, there are periods in the past when conditions were warmer or drier than today (at least regionally) and these can be examined to assess how environments may change in the near future. For example, numerous high latitude records from the northern hemisphere point to the early Holocene as a time when summer temperatures were warmer than in the last millennium. It would be useful to know how permafrost responded to such conditions, what effect higher temperatures had on methane flux from northern wetlands, and what Arctic Ocean ice cover was like at that time. Of course, the driving force for such warmer conditions was not a high level of CO_2, so a precise analog should not be expected, but nevertheless, the environmental consequences of warmer summer temperatures (whatever their cause) are of interest as we prepare for a warmer future.

8.5 Human vulnerability to future climate change

Without water, civilization cannot exist. We are well reminded of this by the recently-documented collapse of Akkadian society in the Middle East during a prolonged arid episode 4,200 years ago, and the demise of the Maya in Central America some 1100 years ago when the region turned dry (Chapter 1, Figure 1.5; Chapter 7, Figure 7.11).

Changes in the hydrological cycle in east central Africa during the last millennium (Chapter 1, Figure 1.5) have similarly driven societal upheavals (Chapter 6) – moist conditions indicated by century-long high lake stands in what is now Kenya supported three episodes of pronounced prosperity over the last 600 years, but the inhabitants of the region migrated away toward climatically more hospitable areas during a trio of prolonged dry intervals that punctuated this time interval.

The last millennium has witnessed the severe impact of drought on civilizations elsewhere. Some 600,000 people died of starvation in northern India during the period 1790-1796 as a direct result of limited monsoon rainfall and low soil moisture. During such drought events, dust from the desiccated soils is carried by southerly winds onto the Tibetan Plateau north of the subcontinent. The airborne dust either settles onto snow-covered surfaces on the Plateau or is washed out of the atmosphere by precipitating snow. Progressive accumulation and compaction of seasonal dust-bearing snow layers gives rise to the Tibetan glaciers that mantle the high annulus of the Plateau. The dust accumulation history preserved in these ice deposits therefore yields an annual-resolution archive of the soil moisture deficit across northern India. The striking drought of 1790-96 is but one arid event recorded in this archive. Episodes of marked dust deposition have occurred intermittently over the past 600 years indicating that collapse of the monsoon is not an unknown occurrence in the region.

All these examples of unusual climatic conditions in the paleoclimatic record, have certain attributes in common: they were *abrupt* (and therefore unexpected); they were *unprecedented* in magnitude (in the experience of those societies affected), and they were *persistent* (lasting long enough that societies were unable to easily accommodate the change). Often, this led to people migrating from the affected region, as in the example noted earlier. But in the highly populated, internationally regulated world of today, such a response to climatic disruptions is unlikely to be an option and thus, if such climatic events were to recur again, the scene is set for societal disruptions on a massive scale. Furthermore, additional factors must be considered. The impact of droughts on agriculture can be mitigated by irrigation, providing that water reserves, primarily groundwater, are available. Agriculture in many parts of the world has flourished over the past century precisely because groundwater has been heavily exploited for agrarian purposes, thereby supporting an ever-increasing population. But groundwater is a critical

buffer against episodic drought. Will such buffers be able to offset the next collapse of the monsoon in northern India, or mega-drought in the western and central U.S.? The answer almost certainly is no. The fossil groundwater that has been mined in Gujarat State is now almost exhausted; the water table over much of the region has dropped by over two hundred *meters* in much of the area. Similar problems are apparent in areas with more developed agricultural systems. In northwestern Texas, the High Plains Aquifer that has supported intensive agriculture in the region for more than a century has no more than a 30-year supply of water left at current rates of usage – the groundwater that accumulated over the course of the late Holocene has been nearly exhausted in the mere blink of a geological eye. The situation is as serious in many other parts of the world: southern Alberta, Canada, has diminishing stocks of groundwater; much of the sub-surface supply in middle eastern countries is being exhausted at rapid rates, leading to the desiccation of oases that had until recently supplied water for centuries. Another dimension to this issue exists in mountainous regions. The summer ice-melt that has sustained dry-season river flow for centuries in countries like Peru is now being seriously threatened by the recession of alpine glaciers (Chapter 6) as temperatures continue to rise in most mountainous regions of the world.

Some of the general circulation models that are used to peer over the horizon suggest that as the concentrations of greenhouse gases in the atmosphere continue to increase, areas such as northwest India and the southwestern US will be drier in future. Because the fossil groundwater reserves that underlie these areas have been severely depleted, despite the relatively wet periods of much of the last century (Chapter 6), there is little prospect of future buffering of drought. Few options exist for substitution of groundwater with surface flow. As a result, acute impacts on societies in these regions can be anticipated, and need to be taken into account in climate-change policy decisions at local through international scales.

Where does this leave us? Not only are we living in unusual times in terms of global-scale anthropogenic climate change, but we have been unwittingly pre-conditioning the future by weakening our ability to adapt to *both* natural and human-induced change. Combining studies of the past with observations from the present and predictions of the future is yielding sobering messages, and they need to be heeded; we ignore them at our peril.