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The value of paleoclimate research in our changing climate

An editorial comment

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> Whoever wishes to foresee the future must consult the past…
> —Niccoló Machiavelli (Discourses On the First Ten Books of Titus Livius, 1517)

The paper by Etkin (2010) in this issue of Climatic Change reframes results from Antarctic ice cores in the context of systems theory, and comments on the utility of the past in predicting future climate change. Etkin's discussion touches on three fundamental questions that I will explore in the following springboard editorial essay.

1) What is the value of paleoclimate research for helping understand future climate changes?
2) What are key challenges in paleoclimate research?
3) Are we in a new state of the climate system completely different from the dynamics of the last million years?

1 The value of the past climate in predicting the future climate

Paleoclimate research has the potential to provide unique contributions to our understanding of the climate system and our ability to predict future climate change. I will discuss four benefits of paleoclimate research: (1) it informs our understanding of the complex dynamics of the climate system; (2) it provides tests and evaluations of global climate models; (3) it places recent climate change in the broader context of the Earth's history; and (4) it provides potential analogs for times of rapid climate change similar to today.

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Paleoclimate research enables the characterization of the structure, dynamics, and processes inherent in the Earth's climate system. The climate system consists of nested and interlinked subsystems with complex interactions, positive and negative feedbacks, and nonlinear and transient responses (Snyder et al. 2010). There is no single threshold in the climate system, but rather many interdependent interactions and thresholds for different processes under different conditions and rates. Much of our understanding of these complex dynamics has come from reconstructions of how the climate system has responded to a variety of large changes in the past. Studies have combined simple models with paleoclimate reconstructions to test key assumptions about the dynamics of the climate system. Recent paleoclimate reconstructions with high time resolution disproved previous assumptions of gradualism and changed our understanding of the potential for rapid climate change. For example, reconstructions of changes in the North Atlantic Ocean's meridional overturning circulation have shaped our understanding of the potential in the climate system for multiple stable states (equilibria) and path dependence (hysteresis) between system states (Rahmstorf 2002).

Paleoclimate reconstructions can be used to evaluate and test climate models. In some cases, complex climate models are run using past conditions and are directly compared to paleoclimate reconstructions. For example, the Paleoclimate Modeling Intercomparison Project[1] is comparing the results for nine global climate models run for the mid-Holocene (6,000 years ago) and for the last glacial maximum (~21,000 years ago; e.g., Braconnot et al. 2007; Otto-Bliesner et al. 2009). However, such direct comparisons of detailed model results and paleoclimate reconstructions are only possible for the few times in the Earth's past where there has been extensive and detailed spatial reconstructions. There are additional methods that use a broader set of paleoclimate reconstructions to evaluate climate models and test the accuracy and stability of model assumptions. For example, climate sensitivity can be used as a coarse summary metric to compare climate model behavior with the aggregate behavior of the Earth in the past. Climate sensitivity is the change in equilibrium global average surface temperature in response to a doubling of the atmospheric concentration of carbon dioxide. Several studies have used a variety of evidence from different parts of Earth history to provide estimates of climate sensitivity, for examples see Knutti and Hegerl (2008) and Snyder et al. (in preparation).

Paleoclimate research places anthropogenic climate change within the broader context of the Earth's climate history. How do recent climate changes compare to the "natural" (pre-industrial era) variability of the Earth system? How unusual are the current magnitudes and rates of change of greenhouse gas concentrations? How unusual is the current rate of change of temperature? Answers to these questions can be investigated using the paleoclimate record. For example, proxy records for temperature in the Northern Hemisphere over the past two millennia have been analyzed to show the uniqueness of recent temperature increases (Jansen et al. 2007; Mann 2007). In another set of research, carbon dioxide concentrations have been reconstructed for the past 800,000 years from gas trapped in ice cores from Antarctica

[1]For more information see the following website: http://pmip2.lsce.ipsl.fr/.

(Lüthi et al. 2008). The observed pre-industrial range is 172–300 ppm (parts per million), and the current concentration in 2010 is about 387 ppm.[2]

Paleoclimate research also can provide examples from the past of periods of rapid climate change. I discussed previously how paleoclimate research enables a characterization of the climate system's complex structure and dynamics. But how will the climate behave in periods of rapid change like the current human-forced changes in climate? To explore this question, specific periods of known rapid change have been studied for insight. One such period was the Younger Dryas (∼12,000 years ago): a time when the rapid warming of the last deglaciation was interrupted with a brief period of rapid cooling that returned near-glacial conditions to the higher latitudes of the Northern Hemisphere. The prevailing theory is that this rapid change was due to changes in the Atlantic meridional overturning circulation discussed previously (Rahmstorf 2002). Another period of rapid change is the Paleocene-Eocene Thermal Maximum (∼56 million years ago): a time when the Earth suddenly warmed around 6°C over only 20,000 years, carbon dioxide concentrations rose dramatically, and numerous deep-sea species went extinct due to anoxic deep water (Kennett and Stott 1991). Several mechanisms for this rapid, large increase in greenhouse gas concentrations and global temperature are still being tested, including melting of deep-sea methane clathrates, volcanic activity and outgassing, and oxidation of sediments rich in organic matter (Jansen et al. 2007). Understanding gained from reconstructions of these periods of rapid change informs our projections of how the climate system could respond to the rapid changes humans are making to the Earth system.

2 Key challenges in paleoclimate research

Given the significant role paleoclimate research can play in shaping our ability to predict future climate changes, it is important to understand the key challenges and limitations of such research. For paleoclimate research to be effective in improving our ability to predict the risks of climate change, it must include rigorous consideration of uncertainty and robust statistical methods. Paleoclimate research can be greatly enhanced through collaborations between applied statisticians and climate scientists. I will explore three vital considerations in paleoclimate research: uncertainty analysis, timescale, and causation. Inadequate consideration of these challenges can result in misinterpretation, overconfidence, and biased conclusions about the climate system.

2.1 Key challenges in paleoclimate research: uncertainty analysis

The paleoclimate record is attractive because it has large perturbations in a variety of important variables and has long time series. Paleoclimate reconstructions, however, also have increased uncertainty in the proxy reconstructions, in the dating

[2]For current atmospheric carbon dioxide measurements see the Mauna Loa Observatory website: http://www.esrl.noaa.gov/gmd/ccgg/trends/co2_data_mlo.html.

of the proxy records, and in the forcing factors driving the climate system. Given the potential for large errors in paleoclimate reconstructions, it is imperative that any investigation includes rigorous considerations of uncertainty and tests of the robustness of any inferences to the inherent uncertainty and assumptions.

2.1.1 Sources of uncertainty

Because direct measurements of the climate system variables are unavailable, paleoclimate reconstructions are based on proxies for most quantities of interest. A proxy is an observable entity that is thought to vary in a deterministic way with the quantity of interest. For a given proxy reconstruction, there are several potential sources of uncertainty. For example, there is uncertainty from the measurement of the proxy itself, including from cleaning and extraction procedures. In addition, post-depositional processes might have altered the proxy.

The proxy calibration also entails considerable uncertainty. Estimates of variation in the proxy calibration are available from lab and field experiments, but there also is structural uncertainty in the fundamental assumptions of the proxy method. The proxy calibration process assumes that the relationship found today will hold for the different climatic and chemical conditions of the past. However, evolution and other environmental changes could produce different relationships in the past than found in the present. Another assumption is that the only variable that would cause changes in the proxy value is the particular variable of interest, because otherwise changes in other variables could bias the inferences (social scientists call this effect "omitted variable bias"). Structural uncertainty can be inferred from comparisons between different proxies as well as from expert elicitation. It is important to include estimates of structural uncertainty to reflect the full range of potential uncertainty in proxy reconstructions (Moss and Schneider 2000), but it is rarely done in practice.

Additionally, there is often time averaging of the sample, both from natural processes of deposition and proxy formation as well as from the sampling processes. For example, before gas is trapped in air bubbles in ice, the gas is able to mix and a given air bubble usually includes gas samples with ages spanning around 500 years and the gas is on average 2,500 to 6,000 years younger than the ice around it (Bradley 1999). In comparisons of different records, it is important for all records to have similar time-averaging and temporal resolution. Ignoring such variations can lead to inaccurate statistical interpretations of the relationships between the records. An interesting example comes from reconstructions of carbon dioxide over the last 400 million years: leaf fossils reflect annual carbon dioxide values whereas the chemistry of fossil soils reflect carbon dioxide values averaged over thousands of years (Jansen et al. 2007; Royer 2006). Comparisons of such proxies must include statistical tools that directly include the different time averaging inherent in the different reconstructions.

Lastly, uncertainty in creating absolute age scales for the samples is a key uncertainty in paleoclimate reconstructions that involve comparisons between different locations. It is imperative that comparisons between records include the uncertainty in matching which parts of each record occurred at the same point in time. Many ages scales are developed using the "orbital tuning" method of matching the record's deep-sea oxygen isotope ratio (from benthic foraminifera) with a global reconstruction of deep-sea oxygen isotopes. Such a method has an estimated 95% credible interval of ±10,000 years (Huybers and Wunsch 2004; Martinson et al.

1987). Thus, dating uncertainty is a significant limitation, especially for comparisons of periods of rapid change or analyses of leads and lags of different variables. Few studies have analyzed the effects of dating uncertainty and even fewer have propagated the dating uncertainty in their reconstructions and analyses. In my own work, Richard Samsworth and I have developed a technique to estimate the contribution of such uncertainty to inter-record comparisons using nonparametric regressions, enabling such uncertainty to be propagated in a full uncertainty analysis (Snyder 2010a, submitted for publication).

2.1.2 Statistical challenges

These uncertainties combined with other features of paleoclimate reconstructions lead to important statistical challenges. Properties of the data can lead to biased estimates and overconfidence with traditional statistical methods. The following discussion summarizes a few examples of useful statistical and uncertainty analytics that can be applied to address key challenges in paleoclimate research. Such methods are necessary for rigorous inferences to be draw from paleoclimate reconstructions. These methods also enable transparent and robust representations of uncertainty in conclusions.

There frequently is significant uncertainty in both the dependent and independent variables in regression analyses of paleoclimate variables, as well as unclear directions of causation (challenges of causation will be discussed in more detail below). Left unaddressed, uncertainty in the independent variables will lead to biased coefficient estimates in regression analyses. Several tools are available to address these issues, including one method called "SIMEX" that uses simulation extrapolation to correct the coefficient estimates (Carroll et al. 1995; Cook and Stefanski 1994).

Paleoclimate records often have significant autocorrelation over time, and unaddressed autocorrelation leads to inflated significance estimates in regression analyses. It is necessary to use a generalized least squares method that includes an autoregressive model to account for the correlation of reconstructions over time. However, such methods usually assume equal time steps, and thus records need to be interpolated to equal time spaces. More complex functional relationships of correlation over time could be employed that would not require equal time steps.

Lastly, spatial correlation is also an important consideration in paleoclimate reconstructions. The field of spatial statistics is a rich resource for this challenge, but it is limited due to the traditional assumptions of space-time models and the scarcity of data across time and space (e.g., Banerjee et al. 2004). Hierarchical models also are useful tools to represent the structure of the data used in most reconstructions (e.g., Clark and Gelfand 2006).

Paleoclimate reconstructions also are limited in their spatial coverage and their temporal resolution. The nonrandom and limited samples make generalizations from specific proxy records uncertain. There are statistical tools available to explore this uncertainty. One straightforward method is to repeat the analyses many times with random resampling from within the proxy records. The variation in results from such a bootstrap analysis reflects the uncertainty introduced from the specific sample of records. The limited samples are another reason for the importance of cross-validating analyses by leaving out random sections of the data and testing how much the results vary. Both of these techniques, bootstrapping over records and internal cross-validation tests, need to be more frequently employed in paleoclimate investigations.

2.1.3 Examples of uncertainty analysis

My own research on reconstructions of climate changes over the past million years provides an example of how some of these analytical tools can be applied to paleoclimate reconstructions. I employ a Bayesian hierarchical model (Gelman and Hill 2007) to investigate patterns of sea surface temperature (SST) change over time, over latitude, and between 54 different ocean cores over the last million years (Snyder 2010a, submitted for publication). Hierarchical models are able to simultaneously analyze patterns of commonality and variability within and between SST records, as well as how those patterns change over time. The method optimizes the sharing of information across cores and through time (Gelman and Hill 2007), which enables significance tests of a larger variety of variables than in traditional approaches. I also find that including statistical methods for the dating uncertainty, autocorrelation, and bootstrap resampling increases the robustness of the results. For example, this research is able to discern a potential "universal curve" of SST response over latitude that does not vary over the past 400,000 years, which is useful to climate theory and evaluations of climate models. The universal curve is found to be independent of the specific set of cores, modeling assumptions, proxy methods, and dating uncertainty.

In another study, I propagate multiple sources of uncertainty in proxy records into a new reconstruction of global average temperature over the last 800,000 years (Snyder 2010b, submitted for publication). The estimated uncertainty interval explicitly includes uncertainty from dating, limited spatial coverage of the records, and structural uncertainty from various assumptions. The new reconstruction would have been far less useful to climate research and climate model evaluation had it been merely median estimates. The ability to produce probability distributions representing the uncertainty in reconstructions is essential for paleoclimate research to have broad impacts.

In Snyder et al. (in preparation), we combine evidence from various proxy records to estimate new probability distributions of climate sensitivity over the last 500,000 years. Climate sensitivity is a critical parameter for assessing the risks of future climate change. The main goal of the research is to constrain the upper and lower bounds of uncertainty in climate sensitivity. Exploration of all the uncertainties listed previously is essential for estimating a robust distribution for climate sensitivity. We find that accounting for biases in the regression method using SIMEX significantly increases the final estimates of climate sensitivity. For example, the simple act of ignoring the uncertainty in the independent variable in a regression can cause underestimation by over 20% of climate sensitivity.

2.2 Key challenges in paleoclimate research: timescale

One of the most important lessons from paleoclimate research is the importance of timescale. Timescale determines whether something is considered in equilibrium. A key strength of paleoclimate research is that ocean heat uptake is roughly at equilibrium on most timescales considered. Thus, results can be interpreted as equilibrium states of the climate system and not snap shots of transient responses.

In contrast, modern observations are limited to transient changes as we continue to modify the climate.

It is essential for comparisons of different records to include the same definitions of equilibrium states. Different timescales can interpret the same system state as stable or unstable. The question of interest should drive whether an equilibrium or transient relationship is most relevant. For example, climate sensitivity is the change in average global surface temperature in response to a doubling of atmospheric carbon dioxide *after the system has reached equilibrium* (over several thousand years). Climate sensitivity does not directly quantify the transient temperature response of the Earth system to changes in radiative forcing from greenhouse gases. Therefore, climate sensitivity does not give direct projections for the transient climate changes we will experience over the next hundred years, but it does provide a ballpark estimate of expected warming at equilibrium (on the scale of thousands of years). A separate summary statistic called "transient climate response"[3] was defined to compare the transient responses of different climate models to specific increases in carbon dioxide. It is much more difficult to quantify transient responses than equilibrium responses from paleoclimate research due to the available time resolution, time averaging of the record, and uncertainty in dating.

The importance of timescale is apparent in Etkin's (2010) state diagram that includes information from both equilibrium climate system states and transient climate system states. The ice core data over the past 420,000 years is considered to represent equilibrium global climate states of Antarctic temperature and carbon dioxide levels. In contrast, the modern data have a higher temporal resolution and capture a transient, unstable state of increased carbon dioxide without sufficient time for the feedbacks to cause the full resulting increase in temperature. One possible interpretation of this diagram is that we are experiencing new system dynamics. Another interpretation is that with sufficient time to reach equilibrium in response to changes in carbon dioxide, the Antarctic temperature response will behave similarly to previous events which implies similar system dynamics. It is important to note that this state diagram does not include a third important climate parameter: changes in the radiative balance of the Earth due to aerosol particles. The net effect of anthropogenic aerosol emissions (including the warming effects of soot aerosols) have caused significant cooling of the Earth in the industrial era and are another reason why the system dynamics would appear to have changed when only temperature and carbon dioxide are considered.

Timescale also is important in understanding correlations of climate changes across time and space. Over some timescales, parts of the Earth are nearly synchronous in their climate changes (strong positive correlation): the North and South cool and warm together. Over other timescales, however, the same regions can respond in opposite directions (strong negative correlation): when the North cools, the South warms. Alley et al. (2003) illustrates this effect by comparing Greenland and Antarctic ice core records from the last 100,000 years using different frequency filters. They find that over long timescales there is a significant positive correlation between the two records. The North and South poles go in and out of glacial and

[3]The "transient climate response" is defined as the globally averaged surface temperature change at the time of doubling atmospheric carbon dioxide following a 1% per year transient carbon dioxide experiment (Hegerl et al. 2007).

interglacial periods together, reflecting globally synchronous climate changes over long timescales. When a filter is applied to remove the lower-frequency components and isolate the higher-frequency components of the records (less than 20,000 years), the records switch to having a strong and significant negative correlation. During millennial-scale climate events, the North and South regions exhibit anti-phasing: one cools when the other warms. These high-frequency climate changes are often a result of changes in ocean circulation that alters North-South heat transfer, thus explaining the negative correlation between the North and South. It is important to remember that correlation results are highly sensitive to the chosen timescale.

Timescale also determines whether a change is considered an internal feedback or an external forcing. For example, conventional definitions of climate sensitivity consider changes in water vapor, clouds, sea ice, and ocean circulation all to be internal feedbacks in the climate system. In contrast, changes in ice sheets, vegetation, and dust are considered external forcings to the climate system. In reality, one could distinguish the first set as relatively fast feedbacks (century scale) in contrast to the second set as relatively slow feedbacks (millenium scale), and the timescale of interest is driving the distinction. Indeed, a long perspective of the carbon cycle (on the order of millions of years) would include chemical weathering as an internal negative feedback lowering carbon dioxide levels.

2.3 Key challenges in paleoclimate research: causation

The study of climate science is limited by the inability to perform controlled, repeated experiments with our planet.[4] Paleoclimate research is fundamentally limited because we can observe only correlations and must infer causal relations. Leads and lags are hard to discern from the available records due to dating uncertainty. Also, it is quite difficult to isolate the causes of key climate changes in the Earth's history, and even some major features remain largely unexplained.

For example, there is still significant disagreement on what caused the 100,000-year glacial-interglacial quasi-cycles of the past million years. The ice ages of the late Pleistocene are remarkable for their quasi-periodic nature and repeated pattern of long slow cooling and abrupt warming. The predominant theory in paleoclimatology explaining the timing of these repeated "saw-toothed" cycles is changes in the geometry of the Earth's orbit, collectively known as the "Milankovitch cycles" (Berger 1978; Hays et al. 1976; Milankovitch 1941). However, theories regarding Milankovitch cycles are merely a statistical association, and not a physical explanation. The orbital changes in the Milankovitch cycles cause a seasonal and latitudinal redistribution of the solar radiation received at the Earth's surface, but a small change in the annual global average of radiation received. How do such redistributions of energy cause such large climatic changes? Many different mechanisms have been proposed to be the amplification driving the 100,000-year quasi-cycle, including changes in ice sheet dynamics, ocean processes, and greenhouse gases (e.g., Berger et al. 1999; Clark et al.

[4]Detection and attribution research has been developed as a rigorous process for investigating the cause of the climate changes of the past century. Detection and attribution research involves a combination of climate models, observational data, and sophisticated statistics, see Hegerl et al. (2007) for more details.

2006; de Garidel-Thoron et al. 2005; Imbrie et al. 1993; Shackleton 2000). All require high nonlinearity in the climate system to create the large glacial cycles. Schneider and Thompson (1979) conclude that it is likely that no single physical process can be identified as predominant in this amplification, but rather it is due to the interactions of a number of processes on a variety of timescales.

An interesting example of the challenges of causation comes from climate sensitivity research. How will the Earth respond to the human-caused increases in atmospheric greenhouse gases? Over the past million years, there was not a single external change in greenhouse gases that then caused changes in the Earth's climate. Instead, there were minor changes in orbital forcing externally, and as a result the greenhouse gases, ice sheets, atmospheric dust, vegetation, and the climate of the Earth all changed together. There is significant debate over which might have led or lagged, but most agree there was interactive causation in the complex climate system between the different radiative forcings. Thus, analyses of paleoclimate records are limited to quantifying the correlation relationship between temperature and carbon dioxide in the Earth's history.

3 Are we in a new state of the climate system?

I will conclude with some brief comments on Etkin's (2010) argument that we have entered a new state of the climate system. As I stated previously, the dramatic deviation seen in Etkin's state-space diagram is mainly due to two factors: 1) comparing transient states to equilibrium states; and 2) cooling due to dramatic changes in aerosols by humans. However, the question of whether we are in a new state of the climate system remains a very interesting and provocative question. Indeed, Crutzen and Stoermer (2000) argued that we have entered a new geologic epoch, called the "Anthropocene," where the climate system is now controlled mostly by humans. There is debate over whether this human control of the climate began in the last 200 years or as many as 8,000 years ago (Ruddiman 2003), but there is nearly unanimous agreement among climate change researchers that that humans are now the major change agent influencing the climate system on decadal to century time scales (Solomon et al. 2007).

The question remains, however, whether we should expect the climate dynamics to operate in the future as they have in the past or whether the dynamics have fundamentally changed. For example, it is not certain that climate sensitivity is a constant value over time. A recent modeling study found that climate sensitivity might be state dependent. Hargreaves et al. (2007) found that most (80%) ensembles of a climate model (MIROC3.2) found a higher climate sensitivity value for today than for the last glacial maximum. It is important to note that these results could be highly model dependent, but the results are reflective of the uncertainty in our understanding.

In addition, the changes to the climate system by humans are happening at a rate rarely encountered over geologic time. Greenhouse gas concentrations will potentially reach values that have not been experienced by the Earth for millions of years. Given the uniqueness of these conditions, it is likely that there will be surprises going forward that are different from what we have observed in the past.

I agree that we are entering a "new and unfamiliar region of state space," as Etkin remarks. I contend that our situation does not make paleoclimate research irrelevant, but on the contrary, proves its value in contextualizing current climate changes and understanding core climate dynamics. Paleoclimate research plays an essential role in characterizing the risks of future climate change that can result from human activities.

4 Concluding remarks

Now is an important and exciting time for research in paleoclimatology to provide unique contributions to our understanding of the climate system. It is particularly a prime opportunity for applied statisticians and paleoclimatologists to collaborate. Large databases have collected thousands of proxy records for easy accessibility, but such databases are a severely under-explored resource. Many vital questions remain unanswered and need further applied statistical tools. Important statistical challenges include dating uncertainty, proxy calibration, and spatiotemporal correlation models. Future research should explore spatial reconstructions over a variety of global, regional, and local spatial scales and a variety of time scales. There are also important questions of leads and lags between different variables that can be addressed only by analyses that take into account fundamental dating uncertainty. In addition, research that combines paleoclimate reconstructions and simple and complex climate models has the potential to further evaluate climate models and deepen our understanding of key climate dynamics. However, for paleoclimate research to be most effective in improving our ability to predict future climate changes, it must include robust consideration of uncertainty and rigorous statistical methods. The past does not dictate the future, but understanding the past does improve our ability to understand and project what risks the future may hold. In the words of historian Blair Worden, "what should they know of the present who only the present know?"

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