ASSESSING CLIMATE STABILITY

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Examination of systemic characteristics can improve assessments of the global climate system's vulnerability to abrupt change and growing instabilities already suggest an urgency for precautionary action.

> *We have the wrong model of what's going on in the world of climate. It's not global warming we should be concerned about, but the likelihood that the long period of relative climatic stability—a 10,000-year period in which all of human civilization happened to develop—may be ending. Its replacement will be a period of profound cooling. The leading indicator of such an event—the freshening of the waters of the North Atlantic—is already happening. Perhaps as soon as 10 years from now, Europe might look a lot like Canada, and the climate of California could begin to resemble North Africa.*
>
> — Peter Schwartz, Global Business Network,
> *Inevitable Surprises: Thinking Ahead in a Time of Turbulence*

In the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report, Working Groups (WGs) I and II reviewed the state of knowledge regarding certain low-probability–high-consequence changes in climate (Houghton et al. 2001; McCarthy et al. 2001). Figure 2 in the WG II Summary for Policy Makers (SPM) identifies "risks from future large-scale discontinuities" as one of five "reasons for concern" arising from projected future climate change. The SPM states

> Projected climate changes during the twenty-first century have the potential to lead to future large-scale and possibly irreversible changes in Earth systems resulting in impacts at continental and global scales. These possibilities are very climate scenario–dependent and a full range of plausible scenarios has not yet been evaluated. Examples include significant slowing of the ocean circulation that transports warm water to the North Atlantic [and] large reductions in the Greenland and West Antarctic Ice Sheets. . . . The likelihood of . . . these changes in Earth systems is not well-known, but is probably low; however, *their likelihood is expected to increase with the rate, magnitude, and duration of climate change. . . .*

In the 4 years that have elapsed since the review of scientific literature that led to these summary state-

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ments, more has been learned concerning the dynamics and impacts of ongoing climate change. Data on the increased rate and magnitude of climate change have been addressed in recent publications and the probability that some of these large-scale discontinuities could occur—or are already underway—may have changed accordingly. For instance, the World Meteorological Organization now reports that 2003 was the third-warmest year since 1860. The fact that the four warmest years in weather-keeping history have occurred in the last 6 years tells us that the changes in the earth's temperature, like the well-documented change in atmospheric concentrations of greenhouse gases (GHGs), is accelerating. It is now evident that during the period of secular warming that began in the 1970s, changes have occurred in the Atlantic meridional circulation. Dickson et al. (2002) report evidence for a rapid freshening over the past four decades. Curry et al. (2003) expand upon these observations with their demonstration of a systematic reduction in salinity at high latitudes in both hemispheres that is coincident with a large increase in upper-ocean salinity at low latitudes. They suggest that these changes in the Atlantic Ocean, particularly those at low latitudes, cannot be explained solely by the recent protracted high state of the North Atlantic Oscillation, but are instead consistent with those expected with a warmer Earth. Their interpretation of these data is further supported by observed changes in salinity and temperature in the Pacific and Indian Oceans and the Mediterranean Sea.

The multidecadal trend in Arctic sea ice loss summarized in the IPCC reports continues; the summer extent of sea ice in 2002 was the lowest in five decades of records (Serreze et al. 2003), and the preliminary data for 2003 (Fetterer and Knowles 2004) are similar. Notable also are the diminution of young ice in the Beaufort Sea, and the extensive loss of sea ice along the northeastern coast of Greenland. Rigor et al. (2002), who suggest that an increase in the rate of ice export from the central Arctic basin can explain half of the observed loss in sea ice extent, discuss the linkages of Arctic sea ice distribution and retention processes.

Were all of Greenland to melt, the global sea level would rise 11 m (Houghton et al. 2001). While this would be virtually impossible with any seriously considered climate change scenario for the next century, it is now evident that Greenland is losing ice more rapidly than thought likely only a few years ago (9% per decade; Parkinson et al. 1999). In addition to changes in sea ice in the last several years, the summer melt line in Greenland has crept upslope beyond 2000 m. Summer melt pools are now a common feature along the southwest coast at 1000–2000-m elevation (Schiermeier 2004). In addition to surface melt, glacial ice loss is occurring as surface meltwater follows crevasse fissures to great depths within the glacier (Zwally et al. 2002), increasing the potential for sudden slippage of the margins of this great mass of ice. The implications of these recent changes in Greenland were recently reviewed by Hansen (2004).

Surprisingly rapid and nonlinear aspects of ice loss are also evident in Antarctica. The loss of Larsen Ice Shelf A in 1995 (Rott et al. 1996) was followed by the dramatic collapse of Larsen Ice Shelf B in 2002, a month after extensive surface melt pools were observed. Percolation of surface meltwater led to fragmentation of > 5000 km^2 of ice in a few weeks' time. Prior to this breakup, an ice shelf had persisted in this locality for the last 12,000 years. Warming ocean conditions, leading to a thinning of the Larsen Ice Shelf and increased crevasse fracturing, are now thought to have set the stage for unstable conditions (Shepherd et al. 2003). The loss of these ice shelves may result in more rapid flux of glacial ice from the continental surface to the sea (Schiermeier 2004).

ASSESSING CLIMATE STABILITY. How do we judge if a system is unstable and prone to rapid changes in state? Modelers have great difficulty treating the likelihood of nonlinear discontinuities and phase-state changes in projections of future climate change. That we have reached thresholds (or will soon) in forcing factors (e.g., GHG concentrations) that could precipitate dramatic climate impacts has been estimated (Albritton et al. 2001, their Fig. 2). There is, however, large uncertainty in where the thresholds actually lie, and relying on smooth projections of temperature change or GHG concentrations may not provide sufficient warning. Rapid transformations and the reorganization of systems can occur out of proportion to the prevailing forcing, and, hence, assessing the stability of the climate system, itself, can generate additional information regarding the sensitivity to change.

Therefore, in addition to focusing on the amount of change, it is important to assess derivatives—the *rates* of change in forcing factors and in systemic responses (warming and patterns of weather). One must also study variance as an outcome in itself, rather than merely a statistical "nuisance" to be factored out with running multiyear averages. While measuring variance (e.g., swings in weather to greater extremes) has been central to assessing the biological and economic consequences of climate change (Albritton et al. 2001), measuring variance as a property of the climate system, assessing how far oscillations in the system depart from prevailing norms, provides an additional indicator of stability and sensitivity to change.

We suggest a group of parameters that can help assess systemic stability and the propensity for change, and provide our own assessment of stability based on the state of those parameters today. We suggest that the examination of these systemic characteristics can improve the assessment of vulnerability of the global climate system to "surprises," baseline shifts, and abrupt change, and find that growing instabilities in the climate system already counsel urgent, precautionary action to significantly and rapidly reduce human-induced forcing on the climate system.

ABRUPT CHANGES IN THE PAST AND SCENARIOS FOR THE FUTURE. Ice cores reveal that climate has often changed abruptly (NRC 2001), and that "cold reversals," lasting from a few years to centuries, have interrupted warming periods. Smith et al. (2002) consider the accuracy of climate simulations of these discontinuities and reveal the following underlying concern: "errors must be considered along with . . . uncertainty related to climate chaos, which occurs because of non-linear interactions in the global climate system." Ensemble simulations have greatly advanced the projections of temperature and precipitation patterns, as well as our understanding of the potential for a slowdown in thermohaline circulation (Dai et al. 2001). Other models incorporate feedbacks—such as future alterations in ocean and soil sinks for carbon, further acceleration of the hydrological cycle, and altered albedo—that might cause the climate to warm faster than earlier projections have suggested (Cox et al. 2000). Meanwhile some simulations (and policy projections) underestimate current and near-future states, because they are driven by CO_2 levels rather than the global warming potential of all GHGs.

MEASURING INSTABILITY. In addition to rates of change, other characteristics that can help assess climate stability include the magnitude and pattern of variance in temperature and precipitation; the number of significant outliers (events beyond two standard deviations from the mean); ocean temperatures, pressure gradients, and wind speeds; and the contemporaneous changes occurring in multiple components of the global climate system (ice cover, the biosphere, troposphere, stratosphere, and ocean—its heat content, salinity, and circulation patterns), whose interactions provide important feedbacks and stabilizing mechanisms for the earth's climate.

First, changes in the *rate of warming*—changes in the first derivative (temperature versus time)—can be compared to historical records, and from the 1970s through the 1990s, the rate of warming increased (Karl et al. 2000; Houghton et al. 2001). Excerpting from Karl et al. (2000),

> warming since 1976 is clearly greater than the mean rate of warming averaged over the late 19th and 20th Centuries. It is less certain whether the rate of temperature change has been constant since 1976 or whether the recent string of record-breaking temperatures represents yet another increase in the rate of temperature change. . . . [T]he probability of observing the record temperatures is more likely with higher average rates of warming, around 3-degrees C per century. . . . This means that over the past two and one-half decades, we have already experienced the rate of warming projected to continue throughout the next Century. . . . [T]hese results imply that if the climate continues to warm at present rates of change, more events like the 1997 and 1998 record warmth can be expected.

With the four warmest years in the instrumental record having occurred in the last 6 years (WMO 2004), there is little doubt that this acceleration continues. Year-end data (2003) from Mauna Loa, Hawaii, indicate the rate of the buildup of carbon dioxide is also increasing. At 379 parts per million, the rate of change is now 3 ppm yr^{-1}, up from 1.8 ppm yr^{-1} for the past several decades, and 1 ppm yr^{-1} prior to that; from preindustrial levels of 280 ppm. (Are the sources rising faster or are ocean and terrestrial sinks becoming saturated?)

Second, changes in the *variance* in weather associated with heat build up in the atmosphere and the oceans (WMO 2004)—which can have greater impacts than warming, per se—are characteristic of an unstable system. Weather patterns have become more variable over the last half-century, with more frequent and more intense extremes, including more prolonged droughts and more intense rainfall events (> 2 in. day^{-1}; Karl et al. 1995; Easterling et al. 2000). Changes in the timing and localities of precipitation are also occurring (Houghton et al. 2001). In the 1990s, wide swings from norms were observed, with anomalies—especially warmer winters, and even colder cold spells—falling more frequently outside of the 30-year climatology (Dischel 2002).

Outlier events. In the past 5 years extreme precipitation events and heat waves, and sequences of extremes (droughts followed by heavy rains), have been responsible for the unprecedented loss of human life worldwide. Hurricane Mitch in Honduras in 1998, with over 11,000 lives lost, severe rains in Venezuela in 1999, and intense flooding and three cyclones over 6 weeks in Mozambique stand out as outliers and events with long-lasting impacts on development. The pace of outliers appears to be quickening; in 1 year (summer 2003–summer 2004) the following occurred: temperatures and impacts associated with the surprisingly intense 2003 European summer heat wave far exceeded any of the model projections (Kalkstein and Greene 1997); intense rains on the island of Hispaniola in May 2004 registered 5 ft of rain in 36 h and killed over 3300; 520 tornadoes battered the middle of the United States in May 2004; 16 in. of rain fell on Guam in 24 h (27 June 2004), shattering the daily rainfall record of 3.16 in. set in 1962; and we just ended the sixth consecutive year of drought (perhaps the most severe in 500 years) in the western United States. Only hindsight will reveal if the current spate of such outlier events continues; the rate of these significant anomalies is certainly another derived indicator to monitor.

Climate change impacts also tend to cluster in the face of more erratic conditions—intense heat waves and accompanying droughts, for example, harm humans directly and also harm wildlife, damage crops, and sustain wildfires. The rising costs associated with weather volatility (Houghton et al. 2001) provide another derived indicator of the state of the climate system (see below).

Ice core records from the end of the last glacial maximum indicate that increased variability preceded the sudden change of 2°–3°C that occurred within a decade, and culminated in the Younger Dryas cold reversal (Mayewski and White 2002; NRC 2001). Greater scrutiny of high-resolution ice core records is warranted to assess the historical connections between variability and sensitivity to abrupt change.

Considering *temperature and pressure gradients,* data presented by Smith et al. (2002) indicate sea surface warming over the past 150 years in all oceans, save for the North Atlantic (with equivocal findings in the North Pacific). Surface winds have increased over the Pacific (Graham and Diaz 2001), and from 1998 to fall 2004 the Pacific basin was in an anomalous state—the "cold east" and "warm west"—creating "the perfect ocean for drought" (Hoerling and Kumar 2003).

The freshening and associated pressure gradient in the North Atlantic is of growing concern (as mentioned above), and the plausible contributing factors include the a) melting of Greenland ice (Parkinson et al. 1999), b) thinning of north polar ice (Rothrock et al. 1999), and c) increased flow from Siberian rivers (Semiletov et al. 2000; Peterson et al. 2002), from melting glaciers, and/or increased winter precipitation falling as rain at high latitudes. Dai et al. (2001) project further cooling of the North Atlantic, which must be interpreted in the context of variability associated with the North Atlantic Oscillation (see Hoerling et al. 2002; Thompson and Wallace 2001; Hurrell et al. 2001).

It is now also evident that the Southern Ocean has warmed at middepth in the last half century (Gille 2002), and that warmer bottom water at great depths all across the North Pacific Ocean may be linked to changes in the Southern Ocean (Fukasawa et al. 2004). Understanding the role of changes in the deep ocean (Levitus et al. 2000), the chemical composition and heat budgets in the troposphere and stratosphere, and their impacts on circumpolar, vortex winds (coupled with surface winds) needs greater assessment. North Atlantic temperature and pressure changes alter transatlantic wind speeds, and the gradient buildup over the past decade has immediate implications for weather patterns in Europe, eastern Canada, and the northeast United States. The long-term implications of the ocean surface freshening and atmospheric changes for the stability and position of the thermohaline circulation are unknown; on the one hand, there is less ice to melt than at the end of the last glacial maximum (see Broecker 1997). On the other hand, rain from warmer, more saline tropical oceans (Curry et al. 2003) is adding significantly to the freshening, and since 1950 a portion of the North Atlantic Deep Water overflow has slowed (Hansen et al. 2001).

The anomalous conditions in the North Atlantic and the Pacific may continue to generate colder winters in the Northern Hemisphere, with more prolonged and severe droughts (or some other pattern of variance); or, under the pressure of continued ice melting, more rain at high latitudes, and atmospheric changes, thermohaline circulation could shift suddenly, producing global-scale changes in weather, water distribution and winds, with major implications for agriculture, disease spread, and conflict over resources (especially water), as envisioned by the Pentagon (Schwartz and Randall 2003). With CO_2 outside the envelope, it has been in for at least 420,000 years (Petit et al. 1999), we are truly in uncharted waters.

Changing atmospheric composition of trace gases is just one of *multiple contemporaneous factors* now forcing the global climate. Alterations in land use/land cover, large-scale changes in natural systems as a result of extreme weather events (e.g., droughts and wildfires), changes in the composition and temperature distribution of the stratosphere, acceleration of the hydrological cycle (Trenberth 1999), and shrinking of the cryosphere (Anisimov and Fitzharris 2001) are all occurring contemporaneously. Cryosphere instability is of overriding concern. In addition to changes in polar ice, the melting of montane glaciers in temperate and tropical regions is accelerating. Greenland ice may be responding more quickly to warming than previously had been projected (Schiermeier 2004), and all of the changes in the cryosphere affect albedo, with the potential to further accelerate warming.

Taken together, these changes will alter feedback dynamics, thereby increasing the possibilities for nonlinear interactions and destabilizing feedbacks. As components shift, interactions and fluxes among them may change in magnitude or even direction, or previously unappreciated internal linkages may become manifest.

Finally, one impact measured by the IPCC—the *economic costs* related to more severe and volatile weather—deserves mention as an integral indicator of volatility. Costs associated with disasters rose from an average of $4 billion per year in the 1980s to $40 billion annually in the 1990s (1999 dollars; Vellinga and Mills 2001), and the United Nations Environmental Programme projects that, if current trends continue, the losses will to rise to $150 billion per year within this decade. While coastlines have become more populated and values of built structures on coastal property have risen, the number of extreme weather events has also risen in both hemispheres [see the online Emergency Events Database (EMDAT); www.em-dat.net/]. In 2002, 2003, and 2004 the costs continued to rise, and the mounting costs of weather volatility and extremes has created considerable concern in the reinsurance industry (companies that insure the insurers).

DISCUSSION. While it is not possible to predict when sudden phase-state changes will occur, it is possible to address properties of systems and the forces to which they are being subjected. Changes in some properties may increase systemic sensitivity to forcings and act to trigger subsequent ripples and waves. Internal conditions may be "ripe" for amplifying the stresses, leading to reinforce new harmonics and their persistence via a network of interactions that can drive the system into a chaotic state or into a new equilibrium. Shifts in the connections that are already understood (and included in models), or previously unappreciated internal connections, can produce surprises, because we underestimate the enormous number and complexity of interconnections among abiotic components and biotic communities of organisms—the mosaics of habitats that comprise self-sustaining, complex adaptive systems.

Systems are formed under a range of recurrent and periodic, and even random, stresses; but the stresses fall within envelopes spanning decades to hundreds of thousands of years. Today, ecosystems and the climate system are being challenged by new disturbances, new patterns of disturbance, and by forcing factors outside the range they have endured for at least 420,000 years (Petit et al. 1999), and most likely for the past two million years. The parameters addressed above are relevant to the diversity of components, and feedbacks and self-regulating interactions that dampen disturbances, and provide resilience that assures the stability of systems. Stability of the climate is the overriding question today, and it may not depend solely on the level of greenhouse gases. Though difficult to contemplate, scenarios for very different future climates stem from a National Academy of Sciences study, *Abrupt Climate Change: Inevitable Surprises*, published in January 2001. The Pentagon study takes this a step further, addressing the implications of a rapid climate change for conflicts over resources—oil, water, fisheries—thus, for global security (Schwartz and Randall 2003). There are additional questions regarding the implications for water quality and availability, for food safety and security, and for the distribution of opportunistic pests and pathogens (whose populations can rise rapidly in disturbed environments) that can radically transform forests and coral reefs; for example, habitat itself (Epstein et al. 2003).

Simultaneous changes in multiple components of the climate system, in the face of new stresses and new patterns of temperature and precipitation, suggest that feedbacks and buffers that were built up over millennia are being overwhelmed, increasing the potential for nonlinear responses. The nature of the response will undoubtedly depend on how the changes and fluxes interact with the periodic, naturally occurring phenomena (and perhaps internally stabilizing oscillations) such as El Niño–Southern Oscillation (Kerr 2004).

Multiple climate outcomes are possible with "business as usual" and increasing emissions of fossil fuel combustion products: 1) continued atmospheric warming with increasing weather volatility; 2) a significant surprise (e.g., dramatic and a more rapid than expected loss of Greenland ice); and 3) abrupt change to a) a much warmer state (e.g., from the positive feedback of methane released at high latitudes due to thawing permafrost; Stokstad 2004), b) a "cold shift" in the Northern Hemisphere from a shift in thermohaline circulation, or c) a rapid acceleration in the rise of sea level (from enhanced loss of continental ice from Greenland or Antarctica).

These outcomes are not mutually exclusive, and all three (plus others) are plausible and could occur, in some measure, simultaneously. The first trajectory is already altering the earth's ecosystems, is directly responsible for the loss of human life, and has significant economic and security implications. The second type of "climate shock" has the potential to galvanize public attention and mobilize political will. The third would be truly disastrous for human life, property, and infrastructure in many nations.

CONCLUSIONS. Just as we underestimated the rate at which climate would change, we have underestimated the rate at which biological systems would respond to that change (Root et al. 2003; Parmesan and Yohe 2003), and the costs associated with the increased severity of weather extremes accompanying that change (Banuri et al. 2001; WMO 2004). Given the patterns of extremes, even those beyond several standard deviations from the mean, we may have misjudged the "shape of the curve"—that is, the behavior of the system and the distribution of events as the mean shifts. Our inability to project abrupt shifts and large-scale changes with the most advanced general circulation models should not deflect us from assessing the potential for abrupt change. Given the pace of warming today, the anomalies in the World Ocean, the acceleration of the hydrological cycle, the associated increase in weather variability, and the growing instabilities in the cryosphere, the authors suggest that we are already observing signs of instability within the climate system. The current "business as usual" emission trajectories will likely lead to greater variability, more extremes, and more costly impacts for natural and socioeconomic systems, even with the current rate of change in the average global temperature.

Stabilization of CO_2 at 450 or 550 ppm may possibly avoid some critical adverse thresholds; but, there is no assurance that the rate of change of greenhouse gas buildup in the interim will not force the system to oscillate erratically and yield significant and punishing surprises, or even force the system to jump into another equilibrium state. Gradually leaning far over to the side in a canoe may not tip it; but rapid movements and wide, erratic swings from one side to the other can tip the balance.

Kreibel et al. (2001) argue that, in the face of observable instabilities, insufficiencies in modeling nonlinear events can no longer justify delays in precautionary action. While the climate community endeavors to improve models and projections of future climate change, the stark reality is that climate changes judged unlikely only a few years ago are now unfolding. The community of scientists, nongovernmental organizations, United Nations agencies, governments, and corporate leaders that are aware of these new risks should be inspired to explore every means to rapidly reduce global emissions of greenhouse gases and help create the framework and incentives for stabilizing the climate *and* stimulating healthy and sustained economic growth. Perhaps we have also underestimated the health, ecological, and economic benefits of such a clean energy transition.

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