Warm Climate Surprises

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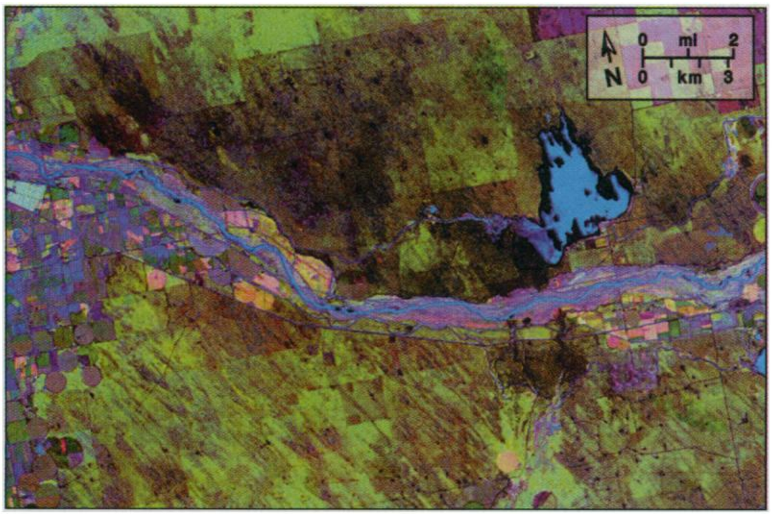
Over the last decade, paleoclimatic data from ice cores and sediments have shown that the climate system is capable of switching between significantly different modes, suggesting that climatic surprises may lie ahead (*1*). Changes of several degrees in glacial surface air and sea temperatures over large expanses of the high northern latitudes apparently occurred multiple times within years to decades (*2*, *3*) and have been attributed to abrupt shifts in oceanic thermohaline circulation (*4*). These high-latitude events are likely linked to abrupt climatic shifts at low latitudes (*5*, *6*). Most attention in the growing area of abrupt climatic change research continues to be focused on the large changes observed during glacial periods, when large quantities of glacial meltwater were available to influence ocean circulation and climatic change. In contrast, the current warm interglacial climate is often characterized as relatively stable, leaving the impression that climates of the future are likely to be more or less well behaved. There also seems to be a widespread belief that the full range of natural interannual- to centennial-scale climate variability is well represented in the instrumental record of the last century. The weight of the paleoclimatic evidence now being collected, however, suggests that these comforting conclusions of benign warm climate variability may be incorrect.

Hints of significant decadal to centennial climate variability during the Holocene (that is, the last 10,000 years) have appeared routinely in the literature over the last 20 years, but efforts to map coherent patterns of this variability, and to define causal mechanisms, have lagged behind similar efforts focused on glacial variability. This dichotomy stems in part from the lower signal-to-noise ratio associated with many warm climate events and from the lack of clearly understood forcing mechanisms in the absence of large Northern Hemisphere ice sheets. Ironically, it was not until recent ice core drilling uncovered evidence for major abrupt changes during the last interglacial (120,000 to 130,000 years ago) that interest in variability during warm climates began increasing (*7*). Now, as the record of the last interglacial becomes more uncertain owing to apparent stratigraphic complexities in the deep Greenland ice cores (*2*), attention is returning to the current Holocene interglacial.



A pattern of change. Enhanced LANDSAT Thematic Mapper (TM) principal components image developed by georegistering and processing data acquired on 12 August and 15 October 1985. Dark parabolic landforms adjacent to the South Platte River in northeastern Colorado are currently stabilized dunes found to have been mobile at least four times during the Holocene. [Courtesy of R. Yuhas and A. Goetz, Center for the Study of Earth from Space (CSES/CIRES), University of Colorado, Boulder, Colorado]

The Holocene is a fertile ground for climate research. Advances in geochronology and paleoclimatic reconstruction have aided the generation of an increasing number of well-dated paleoclimatic time series that resolve decade- to century-scale climatic events. It is now clear that climate variability in many regions of the world, including Greenland, was significantly greater during the last 10,000 years than during the last 150 years (*5*, *8–12*). Most Holocene events were smaller in magnitude than their glacial counterparts, but many were still large enough to dwarf changes seen in the instrumentally based climate record of the last 150 years. More importantly, many of these past Holocene events appear to have been large enough that, if they were to recur in the future, they would have major impact on humans.

In contrast with their glacial counterparts, the biggest potential warm-climate surprises are likely to be linked with the continental hydrologic cycle. Major century-scale shifts in monsoon strength appear to have characterized large parts of Africa during the Holocene (*5*). Changes in moisture availability were also large in North America. Large areas of the Great Plains were mobilized in the form of eolian dunes during multiple intervals in the Holocene, most likely coincident with changes in ground-water and lake levels in regions now heavily farmed (*8*). There is little doubt that these episodes of drought were more severe and persistent than any recorded since Europeans came to North America (including the "dust bowl" droughts of the mid–20th century) and that other parts of the continent experienced drought and flood events significantly more extreme than any recorded in the instrumental period (*10*). Decades- to centuries-long droughts were apparently more common in California before this century (*11*) but are not well understood. Droughts unprecedented with respect to the last 400 years have also been implicated in the demise of ancient New World civilizations (*9*).

The paleoclimatic record leaves little doubt that warm interglacial climates are, even in the absence of any human forcing, capable of generating significant decade- to century-scale climatic surprises. We are beginning to be able to map the patterns of these variations, but unraveling their causes remains a major challenge and will require significant advances in the theory of climate change (*13*). Solar and volcanic forcing may play important roles in driving the observed patterns of change, but their influences (particularly amplifying feedbacks) require further investigation. One clue to the causes of Holocene variability may be that the frequency and magnitude of El Niño–Southern Oscillation events experience long-term variations, both small (*14*) and large (*15*). Exciting new Holocene data from the North Atlantic also suggest that ocean thermohaline circulation may be capable of significant abrupt warm climate changes (*16*).

The primary goal of climate research is to enhance our predictive ability. Clearly, this ability must include the capacity to simulate the full range of variability observed in the paleoclimatic record. Even

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in the absence of significant greenhouse warming, a major challenge will be to anticipate future climate surprises of the type recorded in the paleoclimatic record of the last 10,000 years. This period included significant shifts in climate forcing, warmer Northern Hemisphere summer temperatures, and perhaps our best observational record of significant climatic change (*17*). If the climate system turns out to be highly sensitive to elevated atmospheric trace gas concentrations, then we may be confronted with modes of climate variability without precedent. This possibility further highlights the need to expand our testing of predictive models against the varied patterns of significant paleoenvironmental change, just as we now exercise our modeling ability against the relatively small variability of the 20th century. Major warm climate surprises of the type apparent in the Holocene interglacial paleoclimatic record may be our biggest worry in the years to come.

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Cancer Risk of Low-Level Exposure

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It is time to scientifically challenge the old tenet stating that cancer risk is always proportional to dose, no matter how small. This seemingly blasphemous statement is based on new approaches that allow testing of the hypothesis that cancer risk is linearly proportional to dose with no threshold, the basis of much regulatory and assessment documentation. We hear much these days about the need for all assessments and regulations for risk to be based on sound and solid science. This has not been the case for physical and chemical cancer risks to humans.

For both physical and chemical exposure to agents that are thought to increase cancer risk, it has been traditional to state that responsible evaluations and recommendations should assume that all exposures, no matter what the amount, carry an associated cancer risk. This assumption allows estimation, for example, of the lifetime cancer risk of a single ionization or the risk from intake of a single molecule of a putative carcinogen. It further leads to the concept of a collective dose, where all the ionizations are added up in all the people, and the product [for example, person–roentgen equivalent man (rem) or person-sievert (Sv)] is related to (multiplied by) a cancer risk factor to give a potential population body count (*1*). Such a calculation is the origin of predictions, for example, that so many persons will die from radon exposure, or so many cancers will result from treating apples with a chemical.

As an extreme extrapolation, consider that everyone on Earth adds a 1-inch lift to their shoes for just 1 year. The resultant very small increase in cosmic ray dose (it doubles for every 2000 m in altitude), multiplied by the very large population of the Earth, would yield a collective dose large enough to kill about 1500 people with cancer over the next 50 years. Of course no epidemiological confirmation of this increment could ever be made, and although the math is approximately correct, the underlying assumptions should be questioned. Most of the environmental risks we now face from present or proposed activities probably are of this magnitude, and many of our policies say that prudence requires us to reduce these small values even further. We do not seem to have a realistic process whereby we can uniformly both protect the public health and avoid seemingly frivolous prevention schemes.

A large part of the problem is that all cancer risk assessments are derived from studies of cohorts exposed to very high levels of insult (*1, 2*). The conservative assumption is to connect the high-level risk values to the zero intercept and describe the slope of the resulting line as a "risk coefficient," fatal cancers per unit of dose. The radiation risk issue is the most thoroughly studied, but a similar situation also exists for the case of chemical exposures (*3*). However, it is now possible to evaluate the results of low levels of exposure and to apply newly developed analytical and biological tools and thereby test whether this type of extrapolation is warranted.

Historically, the stochastic or probabilistic radiation linearity issue began some seven decades ago when Nobel laureate H. J. Müller demonstrated that mutations in fruit flies increased linearly with exposure dose (*4*). (It was not actually linear; he said that "...the number of recessive lethals does not vary directly with x-ray energy absorbed, but more nearly with the square root of the latter...we should have to conclude that these mutations are not caused directly by a single quanta of x-ray energy absorbed at some critical spot.") The smallest doses, about 0.25 gray (1 gray = 100 rad), were quite high by today's standards. Linearity was later related to radiation cancer risk during the era of atmospheric weapons testing (*5*). This concept was expanded to apply to chemicals in the Delany Amendment of 1958, where any compound found carcinogenic in any test system at any level of exposure could not be added to foods sold to the public. We have since learned that some natural products and many normal foods (nitrosoamines and smoked or charred meat, peanut butter, and aflatoxin) contain compounds that are carcinogenic at high concentrations.

Radiation exposure is ubiquitous throughout the planet and is higher in some areas than in others (*1*). Interestingly, when cancer mortality in populations in higher natural background regions is compared with that of comparable populations living in low-background regions, there is no cancer incidence increase in the higher background areas (*6*). In fact, most of the studies show the opposite, giving support to a concept of hormesis, a beneficial effect of a

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