Atmospheric carbon dioxide is expected to double by A.D. 2050, raising global temperatures 2 to 3°C. A model for climatic deviations is presented, based upon paleoclimatic experience 5,000 to 8,000 years ago, when midlatitude temperatures were 1.5 to 2.5°C higher. The economic prognosis includes a United States barely able to meet its own agricultural needs and a substantial overall reduction of world food supplies. The revolutionary implications for contemporary sociopolitical alignments suggest an urgent need for long-range planning and more, historically oriented research.

ADAPTATION TO GLOBAL ENVIRONMENTAL CHANGE*

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THE concept of adaptation is a biological one, but it has long been borrowed and applied by the social sciences. "Cultural adaptation" derives from its evolutionary counterpart and implies long-term, nongenetic adjustment of cultures to their environments [3]. Although objective measures of adaptive success are difficult to define in cultural terms, adaptation, as a strategy for survival, provides a practicable focus for empirical study. Individual cultures represent adaptive systems [8], characterized by a set of behaviors that reflect cognitive identification of the environment and that adjust in response to external and internal changes [29]. Historically, traditional cultures have been to some degree interlinked at the regional, if not the continental, level. Today, as a result of international exchange networks, contemporary societies are globally interlinked in an open system of increasingly interdependent adaptive systems.

Recent climatic anomalies provide examples of the significance of small-scale environmental variability: the exceptionally cold winters of 1976–79 in parts of North America and Europe exacerbated dependence upon imported petroleum, while a sequence of bad harvests in the Soviet Union required massive grain imports. At a higher order of variability, the Dust Bowl years served to reverse two generations of adaptive development on the Great Plains, setting in train important internal migrations. Instances of medium-scale variability, involving perturbations or low-threshold equilibrium shifts lasting a few centuries or millennia, can also be identified in the historical record [16, 30, 31]. Although systematic economic and demographic evaluation has rarely been attempted, the results of a Clark University project devoted to the recent Sahel drought, the Dust Bowl, and historical Mesopotamia [21] promises new insights in regard to small- and medium-scale variation. There have also been significant changes during the later prehistoric record, particularly along the polar and arid margins of the *oikoumene* [13, 26]. But large-scale environmental flux of the amplitude experienced during the Pleistocene has not affected major population centers during the past ten millennia [9].

Until quite recently, geographers have generally remained oblivious to the temporal dynamism of adaptive systems. The major exception has been the traditional concern with human impacts upon the environment [36, 50]. But even here geographical concerns were largely dormant until the ecological movement of the 1960's created a disciplinary atmosphere more favorable to environmental research. Somewhat belatedly, attention was focused upon the dramatic transformation of recent centuries—the cultural degradation whereby natural ecosystems have been drastically simplified and their stability maintained at an increasingly high cost of artificial intervention [4, 41]. This trajectory of intensifying

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environmental transformation has created a metastable equilibrium, the component interbalance of which is becoming conditional upon persistent net economic growth. Examples can readily be cited from developing countries, where agricultural productivity on precarious soilscapes can be maintained only by high capital investment. Closer to home, mention can be made of high-cost settlement in zones prone to an exceptional recurrence of natural extremes [7]. A major perturbation, such as global economic disruption, or gross environmental change, is increasingly likely to reduce the plasticity of at least some of the major adaptive components to a degree that the viability of the global network may be seriously threatened.

Atmospheric Carbon Dioxide Projections

The grave economic strains of the growing energy crisis, exacerbated by the international petroleum cartel, represent a medium-range, potential perturbation. No less disturbing is a different but related environmental mechanism with fundamental, long-range implications. The readjustment of the global carbon cycle [*42*] that began during the mid-nineteenth century continues to increase the level of atmospheric carbon dioxide [*23, 27, 34, 49*]. The voracious need of industrial societies for energy continues to release vast quantities of previously fixed carbon dioxide from fossil fuels into the atmosphere [*33, 42, 43*]. At the same time, the rapid deforestation of large land surfaces to accommodate expanding populations has almost crippled the ability of autotrophic terrestrial organisms to adjust through increased photosynthetic production rates [*1, 5, 42, 53, 55*]. As a result, the carbon dioxide released by combustion exceeds the capacity of the hydrosphere to absorb it. Many diverging estimates have been offered as to the long-term rate of atmospheric carbon dioxide increase. Even the most conservative of these see a 50 percent increase by A.D. 2050, and several, reasonably convincing projections imply a doubling of atmospheric carbon dioxide by some time in the period A.D. 2040 to 2060 [*23, 33, 42, 46*].

The uncertainties in modeling the potential flux along the ocean-atmosphere and atmosphere-biosphere interfaces are considerable [*23, 33*]. Major problems are our incomplete bio- and geo-chemical understanding of carbon dioxide flux in the oceans and the persistent uncertainties concerning the capacity of vegetation and soil to absorb increasing quantities of carbon dioxide. Nonetheless, barring an unlikely, large-scale reversal in energy consumption patterns and land use practices, long-term global planning must anticipate a doubling of atmospheric carbon dioxide within less than a century.

Climatic Prediction

The climatic implications of such a change involve more variables than a box model for the global energy budget can account for. Vertical mixing and horizontal energy flux in the oceans, as well as changes in atmospheric water vapor, cloud cover, and albedo remain problematical, and the potential role of both positive and negative feedback mechanisms cannot yet be anticipated [*38*]. The provisional concensus is that the augmented greenhouse effect will raise mean temperatures in the lower troposphere by at least 2 or 3°C [*33, 42*], although change will be minimal in the tropics but somewhat greater in middle and higher latitudes [*33, 35*]. Such a restructuring of atmospheric energy gradients represents a major planetary change of an amplitude surpassing any experienced during the past ten millennia.

The closest paleoclimatic parallels for such conditions would be the warmest phases of certain Pleistocene interglacials [*10, 25, 45*], during which many world biomes were changed in terms of demarcation as well as physiognomic and generic detail, but without promoting a major change in the regimen of the Greenland and Antarctic ice sheets. However, paleoclimatic reconstructions for the interglacials are insufficiently detailed to provide a useful model for potential climatic anomalies during the mid-twenty-first century. The best analogy, consequently, is the mid-Holocene Altithermal or Hypsithermal of 8,000 to 5,000 years ago. At that time mean temperatures were 1.5 to 2.5°C higher than today in middle latitudes as well as at high elevations.

The implications of higher mid-Holocene temperatures include a longer growing season and poleward extension of the tree line in Alaska [*20*], Canada [*40*], and northern Europe [*20, 26*], together with an upward shift of montane eco-zones in Europe [*26*], the western U.S.A. [*32*], southeastern Australia [*6*], and elsewhere. Rainfall increased throughout the Sahara [*11, 13*], in East Africa [*13, 14, 17*], Arabia [*37*], the Thar Desert [*47*], the Kalahari and Karoo of southern Africa [*13, 18*], and across Australia [*6*], although there were several marked dry spells within this generally moist time span. Conditions in tropical South America may have been similar, but field evidence is not yet available. In the American Midwest and on the Great Plains, climate was distinctly drier than today, with expansion of prairie at the expense of forest in Minnesota, Illinois, and Missouri [*12, 28, 52, 54*]. Climate was at least as dry as today in the basins—but not in the mountains—of the West, judging by low lake levels [*48*]; trends in northern Mexico have yet to be determined. Also lacking are properly dated pollen or lake sequences of this age in Southern Russia, Central Asia, and Mongolia, although a shrunken, saline lake in the then nonforested Van Basin of eastern Anatolia [*51*] suggests that continental positions comparable to the western and central United States may also have been drier in Eurasia. Such an interpretation finds strong support in the extensive Caspian Basin, with a sea level 25 m lower than in historical times during the mid-Holocene [*23*]. The Mediterranean Basin experienced no climatic disruptions [*15*], but southernmost Africa was drier [*18*], and unpublished pollen studies by V. Markgraf suggest that the foothills of the Argentinian Andes were also drier.

The basic mid-Holocene pattern is as follows: (a) substantially augmented growing seasons in cool environments now marginal for agriculture; (b) distinctly drier climate in most midlatitude arid, semiarid, and subhumid regions, with an inherent trend to desertification, including the major wheat- and corn-producing belts of the United States and the Soviet Union; and (c) moderately increased precipitation in the tropical and subtropical arid zone, primarily in what are now pastoral and irrigated lands of Africa, Arabia, India-Pakistan, and Australia, but excepting the more productive mediterranean environments of Europe and South Africa. This pattern is reasonably consistent (spatially and temporally) and well documented, and it provides a usable, qualitative working model for expected climatic zonation during the mid-twenty-first century (Figure 1). Quantitative data are far more speculative but may involve negative deviations of 20 or 30 percent in the hydrological balance of middle latitudes and positive anomalies of 30 to 50 percent in lower latitudes. Because mid-Holocene temperature deviations were perhaps half of those expected for the twenty-first century, the upper range of these crude estimates is the more probable.

Economic Prognosis

The agricultural implications suggested by the mid-Holocene model (Figure 1) for the twenty-first century are mixed and, in certain important ways, negative overall [*24, 42, 44*]. Dust Bowl conditions would become commonplace on the Great Plains, with an increased incidence of drought in the Midwest. A substantial part of the present winter-wheat belt would have to revert to grazing, with large-scale replacement of the corn-soybean production of Illinois, Iowa, and Missouri by winter wheat. The corn belt would shift, climatically, to Wisconsin, Minnesota, and Canada, where podsolized soils are poorer and drainage less than ideal. Irrigation waters in the West would be substantially reduced and less reliable. Overall United States crop acreage and average yields would plummet, and corn—with its attendant livestock industry—would be widely replaced by wheat of

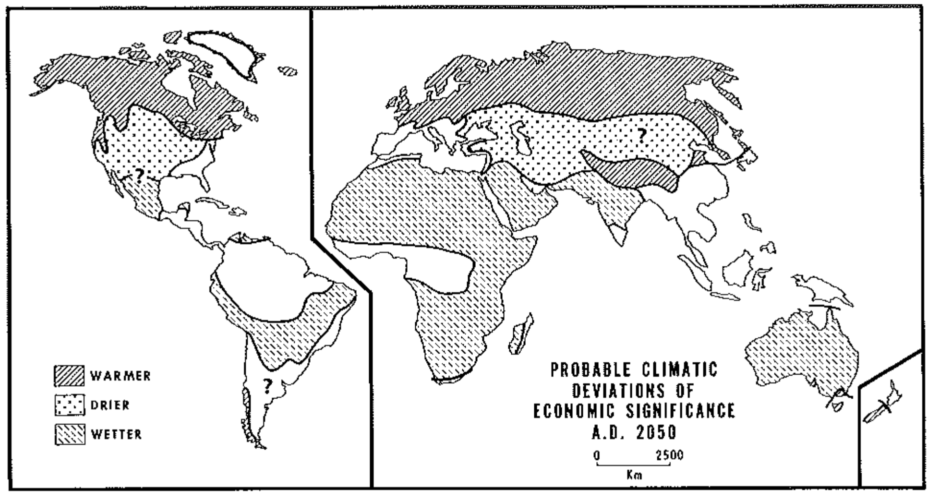

Figure 1. Probable climatic deviations of economic significance A.D. 2050, based upon patterns of 8,000 to 5,000 years ago.

substantially lower productivity. Similar problems can be expected to plague food production in the Ukraine and Central Asia. By comparison, the potential expansion of agriculture onto the marginal soils of the mixed coniferous forest belt of Canada and northern Europe would be relatively insignificant.

Increased moisture in the low-latitude deserts and semi-arid zone of Africa, Asia, Australia, and parts of South America would primarily affect the productivity of low-efficiency pastoral economies, only locally supplemented by agriculture. Even increased yields in the subsistence-agriculture belt of the Old and New World tropics would not add substantially to the world food supply, probably serving only to accelerate demographic expansion. In effect, long-range benefits could be assured only by a protracted program of carefully tailored agricultural modernization, soil amelioration, and large-scale irrigation schemes—all of which require heavy and sustained capital investment in countries lacking both industrial capacity and energy resources.

In the world oceans, a surface layer of warmer water would increase vertical stability and so reduce both upwelling and biological productivity. No model is yet available for potential effects on the major midlatitude fishing grounds, but the impact may be as substantial, in a negative sense, as the warming of coastal waters and ice break-up will certainly be of positive import in subpolar areas.

One related issue that has also been raised concerns increased, possibly catastrophic melting of the residual Greenland and Antarctic ice sheets [*23, 24*]. One of the erroneous assumptions here is that, because Pleistocene interglacial shorelines can commonly be identified well above those of the present, there was greater melting of the present ice sheets, returning more water to the world ocean. Instead, however, continuous records of deep-sea sedimentation identify only two brief intervals when ocean surface waters were even slightly warmer than those of the mid-Holocene, and even here the salinities indicated argue for a world glaciological balance not substantially different from that of the moment [*45*]. Also, during mid-Holocene times, absolute sea level remained very much within its present, limited range of fluctuation, from 0.5 m above to 2.5 m below that of today [39]. The observed vertical divergencies are a result of crustal readjustments as well as long-term tectonic trends [19]. The second dubious assumption is that of Antarctic ice surges, an interesting theory that finds no confirmation in the geological record. It is therefore improbable that a catastrophic rise of sea level will inundate the world's more fertile coastal, deltaic, and alluvial plains. Expected changes in the coastline will continue to be minor and less important than local tectonics and catastrophic storms.

Despite this skepticism in regard to projected shoreline change, the overall qualitative scenario outlined here for the world food supply is decidedly negative, even allowing for substantial negative feedback within both the environmental and the adaptive systems. In particular, the United States, now the world's major food exporter, will barely remain self-sufficient, while the Soviet Union will be heavily dependent upon food imports. Unless demographic trends in low-latitude, Fourth World nations are reversed, and agricultural productivity at least doubled, Canada's and Australia's sustained capacity to export will be quite inadequate to meet world demand for food.

There is then every reason to believe that a continuation of present environmental trends will spell an economic crisis of global proportions within the lifetimes of our children and grandchildren. The negative impacts of such cumulative change will affect some countries, such as the two present superpowers, the United States and the Soviet Union, far more than others, creating severe tensions in the global sociopolitical network. At the same time, it will selectively affect certain regions or economic sectors of individual nations, particularly as resources become inadequate to maintain controlled ecosystems, suggesting further confrontations within existing socioeconomic subsystems. The pending crisis of the twenty-first century can thus be expected to take three forms:

(a) A substantial reduction of the world food supply, at a time of maximum demographic pressures upon global resources and shrinking energy reserves;
(b) selective decline of productivity among the major economic and food-producing nations, implying a fundamental readjustment between developed and developing world regions; and
(c) differential impacts within undersupplied nations of special complexity, suggesting severe internal disruptions within existing socioeconomic fabrics, e.g., between the haves and have-nots.

Discussion

To what extent can human ingenuity, improved technology, and long-range planning hope to compensate for the dislocations that threaten society or at least to ameliorate their negative affects?

The spatial and temporal interrelationships between those primary components that define the global ecosystem impose a set of constraints to indefinite economic expansion. A century of accelerating growth did indeed suggest that technological innovations were potentially unlimited. But the ominous proportions of the pending world energy deficit, which became apparent in 1973, now make it seem unlikely that adequate resources will be available to support the research necessary for further quantum leaps in technology. Consequently, present and future environmental constraints will impose real boundary conditions on productivity and expansion in terms of cost-benefit decisions.

A diachronic examination shows that complex, urbanized cultural systems, both traditional and industrialized, are to some extent buffered from environmental vicissitudes by multiple "layers" of technology, social organization, and exchange networks. Their adaptive strategies emphasize stability, the maintenance of a set of socioeconomic priorities, cultural norms, and value systems that define a familiar cognitive universe. Some societies, such as those of the developed, western capitalist nations, aspire beyond equilibrium to unrestricted upward, socioeconomic mobility. In any event, environmental vicissitudes such as destructive storms, floods, or droughts, are interruptions to the normal stream of events and are to be overcome by returning as soon as possible to the set ways of every day, without serious reevaluation of future strategies. The cultural system that shields both the society and the individual manifests an innate lack of systemic pliancy. Unlike those of the simplified environmental systems to which they are linked, the instability thresholds of complex cultural systems tend to be high, in no small part because negative feedback mechanisms are numerous. But, in probability terms, the same multiplicity of components also increases the chance of a concatenation of negative inputs. For example, the unexpected coincidence of poor leadership, external political stress, internal economic factors, and environmental perturbation can trigger a catastrophic train of mutually reinforcing events that the system may not be able to absorb.

Viewed over a span of five millennia, Mesopotamia [2] and Egypt [*11, 16*] exemplify the inherent diachronic dynamism of an adaptive system characterized by a particular social and natural environment. These historical trajectories are marked by cyclic alternation between centuries when population and productivity increased in apparent response to effective hierarchical control and other centuries when demographic decline and political devolution occurred. Periodic minor and diverse crises were overcome by temporary structural shifts, whereas major crises led to reorganization of the political and economic superstructures, leaving intact the basic environmental and sociocultural components of the infrastructure. Consequently, although social and political identities have repeatedly changed since the time of Sumer and Old Kingdom Egypt, the fundamental adaptive system of floodplain irrigation agriculture continues to survive in modern Iraq and Egypt.

It appears, then, that elaborate cultural systems enjoy centuries of adaptive equilibrium, with or without sustained growth, followed by discontinuities. Such discontinuities are apparently marked by reevaluation of adaptive strategies while the cultural system undergoes structural elaboration or significant changes among its fundamental components, with or without a transformation of identity. In the long-range view, elaborate cultural systems are dynamic rather than stable, as structural changes are repeatedly required to ensure viability or even survival.

It requires no elaboration to demonstrate that short-term strategies are the rule rather than the exception in modern democracies, where the timetable of elections dictates cost-benefit analyses. Even the "five-year" economic plans of one-party socialist states are short range and exceeded only by military projections. The United States lacks a comprehensive energy plan after five years of high-level discussions, and government leaders have so far been unable to convince the American people that an energy crisis exists, let alone to make them understand what conservation means. At this rate, societies around the globe are likely to stumble through the mounting crises that spell out exactly the sort of concatenation of negative inputs that requires drastic systemic readjustment for survival.

If this does indeed happen, environmental change in the twenty-first century is bound to have revolutionary results in economic, political, demographic, and social terms. Spatial economic gradients will be reversed and existing political configurations will disappear, with radical redefinition of the bases of world power. Demographic repercussions will surpass those of the Black Death in fourteenth-century Europe, on a global rather than regional scale. In the wake of such fundamental realignments, unknown in any previous period of human history, some sociocultural systems will disintegrate and lose their identities, as the price for rudimentary survival.

The alternative is multi-level, long-range planning in both national and international contexts. The carbon dioxide problem is closely linked with that of energy conservation, and it calls for immediate and draconian, comprehensive programs, both to decelerate the combustion of fossil fuels and to develop nonpolluting sources for sustained energy yields.

The worldwide trend to deforestation must be arrested, and systematic reforestation of suitable, agriculturally marginal lands begun. The demographic pressures leading to deforestation, particularly in tropical environments, must be brought under control. Optimal photosynthetic productivity of oceanic phytoplankton must be assured. Substantial progress in these several directions during the next two to five decades could greatly reduce carbon dioxide release from fossil fuels, as well as the destruction of modern carbon dioxide reservoirs, while increasing the absorption of atmospheric carbon dioxide by the biosphere and hydrosphere. In such an eventuality the environmental change for mid-century might yet be averted or at least slowed and so reduced in magnitude as to remain within the scope of normal systemic readjustment.

In order to achieve a measure of success in such a long-range program, the academic and professional community has a major responsibility for education at all levels. Politicians must be convinced that the welfare of future generations is more important than next year's election prospects. Bold ten- and fifty-year plans must be conceived and implemented to achieve the requisite goals of education, conservation, and agricultural readjustment. Leading political spokesmen must eschew their demagogic urges against academic research that may seem esoteric in the short run, but that, like paleoclimatology and culture history, provides invaluable diachronic experience in the dynamics of environmental and cultural systems. The collision course between environmentalists and conservation principles must be averted and a fresh set of common goals defined. The middle and especially the upper economic classes must be convinced that material comforts need to be significantly curtailed. Finally, at all levels of society, there must be a pragmatic reallocation of national priorities in all spheres from microeconomics to national policy. Then and only then can a nation hope to have significant input in international efforts by example rather than by admonishment.

At the international level, alternative ways of energy generation and biospheric conservation must be debated with an appropriate sense of urgency. But no number of paper-generating supranational committees can hope to turn the tide.

A prerequisite to change is public conviction of the need to change. Education is the key to this transformation, and the academic, religious, and political communities must assume a far greater role in this process, both through the formal education process and by public discussion of the alternatives from which we must choose today and the outcome of which will confront the generation of tomorrow. To avoid yet another ideological movement, more concerned with slogans than information, there must also be a great deal more research on climatic, energy, and agricultural themes that emphasizes historical experience, simulation of future trends, and better understanding of contemporary processes and interrelationships. Only when a cultural system accepts new information that is consonant with its value systems can there be successful behavioral readaptation.

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