Global Warming: What It Is, What Is Controversial About It, and What We Might Do in Response to It

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I. INTRODUCTION TO GLOBAL WARMING AND ITS CONTROVERSIES

If global warming were to occur in the future as projected by the computer models of climate, major disruptions would take place in many aspects of our environment. Sea level rise and changes in the patterns of rainfall and temperature inland might lead to massive destruction of many kinds of ecosystems. Many species would become threatened or endangered. Legally protected natural areas would be threatened by inundation or would become inappropriate habitats for the organisms they were meant to protect. Fresh water would become an even scarcer resource than it is today, while salt water would intrude inland. Coastal wetlands, caught between the rising sea and housing developments, could become even rarer than they are today.

Increases in the need for water in agriculture and urban use would conflict with the maintenance of natural areas. Effects would not be limited to natural ecosystems, but would affect agriculture, commercial forestry and fisheries, as well as outdoor recreation. Urban and suburban settlements and industrial complexes would be affected. Settlements near the ocean shore might be undercut or flooded as the sea level rises, raising questions of responsibility and liability.

These are some possible outcomes, but whether global warming is likely to occur remains controversial. Those outside scientific fields that study such environmental problems are often confused by statements that reach the media for and against the possibility of

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this rapid climatic change. Given the possible dire consequences, it seems valuable for those involved with environmental law to understand the basic issues: what scientists mean by global warming; what are the legitimate scientific controversies about the likelihood of its occurrence; and what the time frame for impacts might be. This information may help determine what would be prudent courses of action to follow in the development of legislation and other policy mechanisms. The purpose of this article is to provide a basis from which those interested in environmental law can begin to understand and plan legal responses to a possible global warming.

A. *What Is Global Warming?*

Global warming refers to a variety of complex climatic changes that would accompany a rapid increase in the concentration of certain gases in the atmosphere known as greenhouse gases. These gases are: water vapor, carbon dioxide, methane, nitrous oxide, and CFCs (chloro-fluoro-carbons).[1]

How do greenhouse gases affect climate? These gases are small molecules that are transparent to visible light, but opaque to some longer wavelengths known as infrared radiation (also sometimes called informally "heat radiation"). To understand how the greenhouse effect works, it is necessary to understand a little about the properties of light.[2] Light is classified according to its wavelength. The higher the energy the light possesses, the shorter the wavelength. The spectrum of light from high to low energy level is classified as follows: gamma radiation, X-ray radiation, ultraviolet radiation, visible light (what humans can see), infrared radiation and radio waves. The dominant wavelengths of light emitted by a surface vary with the surface temperature—the hotter the temperature, the shorter the predominant wavelengths. The major players in global warming are the sun (the source of the energy) and the Earth (the target of the energy). Because the sun's surface is very hot, most of its radiation is in the visible and near infrared spectrum. The much cooler surface of the Earth radiates primarily in the longer infrared.

1. CFCs are also the culprit in the destruction of the upper atmospheric ozone layer, and this overlap confuses many people about the distinction between global warming and the ozone problem. These are two separate global environmental problems. It is simply a curious coincidence that the chemical which can destroy upper atmosphere ozone also happens to be an important greenhouse gas.

2. More information about the greenhouse effect can be found in D. BOTKIN & E. KELLER, ENVIRONMENTAL STUDIES: EARTH AS A LIVING PLANET (1987).

The analogy of the greenhouse is helpful in understanding the effect of greenhouse gases on the Earth's atmospheric temperature. The glass of a greenhouse is transparent to visible light and opaque to infrared light. Therefore, much of the incoming visible light from the sun passes through the glass and warms the interior surfaces. The surfaces in the greenhouse reradiate in the infrared, which the glass then absorbs. The glass becomes warmer and radiates in the infrared both up into the air outside the greenhouse and back down into the greenhouse. The energy reradiated warms the interior of the greenhouse. Greenhouse gases in the Earth's atmosphere have the same effect as the glass in a greenhouse. The gases allow visible light to reach and heat the surface, and absorb and reradiate the infrared energy emitted from the Earth's surface. Another reason that a greenhouse is warmer than the outside is that the walls and roof prevent convective loss of heat. The greenhouse gases do not have this effect on the surface of the Earth.

B. *Greenhouse Effect Controversies*

Global warming has become a subject of intense controversy, with its proponents, the most well known of which are Dr. James Hansen of NASA's Goddard Space Flight Center, New York[3] and Stephen Schneider of the National Center for Atmospheric Research,[4] and opponents, the best known of which is Dr. William Nierenberg, Director Emeritus of Scripps Institute of Oceanography.[5] Greenhouse effect controversies focus on how a complex atmosphere on a complex planet—one with liquid water, life, and plate tectonics—will respond to a single change. The greenhouse gas phenomena itself—transparency to visible light and opaqueness to infrared light—is not controversial. In fact, the method used to measure the concentration of carbon dioxide in the atmosphere makes use of the infrared absorbing capacity of that gas in specific wavelengths. Light-absorbing characteristics of each kind of chemical compound are used routinely in astronomy and in analytical chemistry to determine the occurrence and concentrations of com-

3. *See, e.g.*, Hansen, Lacis, & Ruedy, *Comparison of Solar and Other Influences on Long-term Climate*, in CLIMATE IMPACT OF SOLAR VARIABILITY 135 (K. Schatten & A. Arking eds. 1990).

4. *See, e.g.*, S. SCHNEIDER, GLOBAL WARMING: ARE WE ENTERING THE GREENHOUSE CENTURY? (1989).

5. F. SEITZ, K. BENDETSEN, R. JASTROW, & W. NIERENBERG, SCIENTIFIC PERSPECTIVES ON THE GREENHOUSE PROBLEM (1989); S. IDSO, CARBON DIOXIDE AND GLOBAL CHANGE: EARTH IN TRANSITION (1989); Roberts, *Global Warming: Blaming The Sun*, 246 SCIENCE 992 (1989).

pounds on the Earth and on distant astronomical objects. No scientist questions that greenhouse gases are transparent in the visible spectrum and opaque in certain wavelengths of the infrared spectrum.

Water is by far the most abundant of the greenhouse gases. Its concentration varies from 0 to 2%, and it absorbs nearly six times as much solar energy as all other gases combined.[6] The concentration of carbon dioxide is today approximately 0.036% of the volume of the atmosphere. The other greenhouse gases are present in even smaller concentrations. How can these trace gases, present in extremely small concentrations in the atmosphere compared to water, have any significant effect on the climate? Doesn't the greenhouse effect of water vapor overwhelm the effects of the trace gases? No, primarily for two reasons. First, each chemical compound has unique light absorbing characteristics. Carbon dioxide absorbs in different parts of the infrared spectrum than water. Heat energy can pass through an atmosphere without carbon dioxide in infrared wavelengths bands to which water is transparent. Carbon dioxide prevents emissions through some bands of the light spectrum in which water is transparent, metaphorically "closing" an atmospheric window. Due to differing chemical properties, the other greenhouse gases close other "atmospheric windows."

The second reason that trace greenhouse gases can have an effect in spite of the larger concentration of water is that these gases condense to a liquid and freeze at lower temperatures than water and therefore remain as gases at higher altitudes. Carbon dioxide at higher altitudes can absorb and reradiate energy that has passed through water vapor at lower altitudes. Carbon dioxide has "the last say," in comparison to water, as to what heat energy can escape the atmosphere.

Why is there any need for the Earth's surface to lose heat through the atmosphere? The answer is that the Earth's surface tends toward an energy steady state determined by the amount of radiant energy received from the sun and infrared energy emitted from the surface. All other factors being equal, an increase in greenhouse gas concentration will result in less energy lost to space. As a result, the surface temperature will rise. However, the total amount of energy radiated by an object increases as its surface temperature rises (just as, for example, a light bulb that is on feels hot

6. Byers, *The Atmosphere up to 30 Kilometers*, in THE EARTH AS A PLANET 300 (G. Kuiper ed. 1954).

at a distance while a light bulb that is off does not). As the temperature at the surface rises, more energy is emitted until a new steady state is reached. This is the response of the Earth to the greenhouse effect stated in its simplest form.

Scientists generally agree that the concentration of greenhouse gases in the atmosphere is increasing. The major reason for the acceptance of this fact is the development over the last several decades of programs to measure the concentration of greenhouse gases in the atmosphere. The most notable measurements are those that have been gathered continually since 1957 at Mauna Loa Observatory in Hawaii.[7] These data show that since 1957 the concentration of carbon dioxide has increased from approximately 330 parts per million (ppm) to 360ppm, or almost 1 ppm per year.[8]

Before these measurements were available, the idea that human actions could change the atmosphere seemed incredible and was viewed with skepticism by many scientists. For example, in the 1930s one scientist, Callendar, compared nineteenth century and twentieth century measurements of the concentration of carbon dioxide in the atmosphere, which at that time had been done infrequently and at sporadic locations.[9] He suggested that an apparent increase could be accounted for by the amount of fossil fuels burned since the beginning of the industrial revolution. Critics dismissed this possibility on the grounds that it must be due simply to poor measurements made in the nineteenth century.

Curiously, although the Mauna Loa measurements are among the most important to the entire global warming story, there have been many occasions when this measurement program has nearly been cancelled by the U.S. Government, which operates the facility today through the National Oceanic and Atmospheric Administration. These and similar monitoring programs are invaluable, but have little status and not much funding security. Legislation that would secure existing programs and expand national and international capabilities for such monitoring is vital to monitor global warming.

Today, increases in atmospheric concentrations of greenhouse

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7. Ekdahl & Keeling, *Atmospheric Carbon Dioxide and Radiocarbon in the Natural Carbon Cycle*, in CARBON AND THE BIOSPHERE 51 (G. Woodwell & E. Pecan eds. 1973).

8. D. BOTKIN, DISCORDANT HARMONIES: A NEW ECOLOGY FOR THE 21ST CENTURY 173 (1990).

9. Callendar, *The Artificial Production of Carbon Dioxide and its Influence on Temperature*, 64 Q. J. ROYAL MET. SOC'Y. 223 (1938); Callendar, *Can Carbon Dioxide Influence Climate?*, 4 WEATHER 310 (1949).

gases are attributed primarily to human activities. The increase in carbon dioxide is attributed to burning of fossil fuels and to land clearing, especially of forests and soils, especially when these occur in tropical areas that are among the world's largest remaining storehouses of organic matter.[10] CFCs are manufactured gases. Their buildup in the atmosphere is the result of industrial and residential use of these gases, primarily in refrigeration and as propellants in spray cans. The causes of increased methane in the atmosphere are more obscure. Methane is produced naturally by bacteria that live in habitats that lack oxygen. These habitats are found in wetlands, in the digestive tracts of termites, and in the stomachs of cattle and other ruminants who then vent these gases. Any one of these could be an increasing source of methane. For example, it has been speculated that deforestation increases the abundance of dead wood, which in turn has led to an increase in the number of termites. Growth in cattle populations also may be increasing methane concentration. A global warming would melt permafrost areas and could lead to the emission of methane from northern marshlands. Methane is also a main component of natural gas whose increased use may result in increased releases into the atmosphere. While all these are possible, no one knows which ones are primarily responsible for observed increases in methane in the atmosphere.

If scientists agree that greenhouse gases are increasing and that the greenhouse gas effect is real, why is there any controversy about the possibility of global warming? The answer is that the atmosphere is a complex and dynamic system. Furthermore, the interactions of the atmosphere, oceans, land surfaces, and life create an even more complex system than the atmosphere alone. All of these components form our planetary life support system that is sometimes called the "biosphere."[11] We know very little about how this system operates. The study of it is very new, and despite the rhetoric about global warming, only a small fraction of our nation's research dollars goes toward improving our understanding of the biosphere.

The controversies about global warming have to do with how the biosphere as a whole will respond to an increase in the concentration of greenhouse gases and how these increases will change the

10. Woodwell, Whittaker, Reiners, Likens, Hall, Delwiche, & Botkin, *The Biota and the World Carbon Budget*, 199 SCIENCE 141 (1977).

11. For a discussion of the concept of the biosphere, see Botkin, *Science and The Global Environment*, in MAN'S ROLE IN CHANGING THE GLOBAL ENVIRONMENT 3 (D. Botkin, M. Caswell, J. Estes & A. Orio eds. 1989).

entire temperature and precipitation characteristics of the biosphere.

One crucial controversy has to do with the effect of global warming on water vapor. If the Earth's surface were to warm, the rate of water evaporation would increase. Lakes, rivers, and oceans would evaporate more water, as would forests, grasslands, and farms. There would be more water vapor in the atmosphere than at present. The controversy is whether this additional evaporated water would increase or decrease the Earth's average atmospheric temperature. If the water remained as vapor, it would act as additional greenhouse gas and lead to a further warming of the Earth. The water vapor could also condense into clouds. The clouds would reflect much of the sunlight, allowing less energy to reach the Earth's surface and the Earth might cool. Therefore, a cloudier atmosphere might compensate for an increase in the concentration of greenhouse gases or even lead to an overall cooling of the Earth. Which scenario will happen continues to be controversial.

Another controversy concerns the interaction between the atmosphere and the oceans. Ocean currents could distribute the heat energy from the atmosphere in ways that might delay global warming. Only very recent global climate models include such ocean components.

A third important controversy concerns vegetation. Rapid climate change would lead to changes in vegetation over wide areas. For example, rapid changes in temperature and rainfall would favor shorter-lived grasses as forests would decline over large areas. Vegetation can affect the atmosphere in four ways that can in turn affect weather and climate. Changes in vegetation affect how much light is reflected, how much water is evaporated from the surface, how fast winds flow at the surface, and how much carbon is removed annually from the atmosphere. If global warming occurs, changes in vegetation might cause positive or negative feedbacks, further increasing or compensating for the greenhouse effect. How these changes would in turn affect climate is not well understood.

II.
TOWARD A SOLUTION TO THE CONTROVERSY

How can scientists resolve the question of how the biosphere will respond to a rapid change in greenhouse gas concentrations? There are three kinds of evidence that can help us estimate the chances that there will be a global warming: evidence from the past, the present, and, through computer models and mathematically based theory, projections into future.

A. *Studying the Earth's History*

Remarkable advances have been made in the reconstruction of the history of the Earth's climate and historical concentrations of greenhouse gases in the atmosphere.[12] Reconstruction of the concentration of atmospheric carbon dioxide and the Earth's average surface temperature during the past 150,000 years show a surprisingly strong correspondence between the two. When the concentration of carbon dioxide in the atmosphere was low, the average Earth temperature was also low. When the concentration of carbon dioxide was high, the temperature was high. Suggestive as these may seem, the evidence is simply circumstantial and does not prove that changes in the concentration of carbon dioxide caused the change in temperature. Even the opposite could be true—that changes in temperature led to changes in carbon dioxide concentrations in the atmosphere.

The study of the Earth's more recent past provides another source of data concerning possible changes in the Earth's average temperature. Weather records collected in the last one hundred years suggest that there has been an average increase in global temperatures of about 0.4°C (approximately 1°F) during the past century.[13] However, there are problems even with this direct evidence.

Seventy percent of the Earth's surface is water, yet most weather records are collected from land stations. Air temperature near the ocean surface has been measured primarily by personnel on ships—typically the first mate reading a thermometer on deck once a day. These measurements represent a sporadic and statistically unreliable sample of ocean temperatures. Over time, changes in the construction of ships may have affected temperature records. As ships have become larger, the average height above the ocean surface at which measurements are made has increased. During World War II average air temperatures near the ocean surface seemed to increase because those making the temperature measurements were reluctant to spend as much time outside on deck as they had before.

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12. Barnola, Raynaud, Korothevich, & Lorius, *Vostok Ice Core Provides 160,000-year Record of Atmospheric CO_2*, 329 NATURE 408 (1987). *See also* Rosenfeld & Botkin, *Trees Can Sequester Carbon, or Die, Decay, and Amplify Global Warming: Possible Positive Feedback Between Rising Temperature, Stressed Forests, and CO_2*, 19 PHYSICS AND SOC'Y 5 (1990).

13. Kerr, *The Global Warming is Real*, 243 SCIENCE 603 (1989).

Typically temperature measurements were taken from an open porthole and were affected by the interior temperature of the ship. Thus measurements on ships may include unknown biases or artifacts that may suggest changes that in fact did not occur or they may hide changes that did occur. In addition, it is unlikely that temperature measurements concentrated along shipping lanes are representative of the entire ocean.

Weather records on the land may also suffer from artifacts. In the past, the location of a weather station was determined by local convenience, rather than an interest in obtaining a statistically valid global measurement. Most weather stations were established in cities and towns or near the outskirts of urban areas. As the urban areas increased in size, temperatures recorded at weather stations have increased because of an urban "heat-island" effect—a city is warmer than its surroundings.[14] Observed temperature increases might simply be an artifact of urbanization. Studies of historic temperature records attempt to correct for these errors.[15] The most recent analysis indicates that this "heat-island" effect would be minor and account for only a 0.06°C (about 0.12°F) increase in average temperatures in the United States.[16]

A recent analysis of satellite remote sensing information shows no statistically significant change in the average temperature of the Earth during the past twenty years. These data fail to shed more light on the issue, because two decades are too short a time to detect a trend.[17]

Although approximately 1°F of warming has taken place in the last century,[18] historic measurements fail to demonstrate definitively that global warming is occurring. The last century provides statistically too short a time. While the observed warming is consistent with the more conservative projections of global climate models, it could also be the result of other factors, such as changes in the intensity of sunlight.[19]

14. Karl & Jones, *Urban Bias in Area-averaged Surface Air Temperature Trends*, 70 BULL. AM. METEOROLOGICAL SOC'Y 265 (1989).

15. Hansen & Lebedeff, *Global Surface Air Temperatures: Update Through 1987*, 15 GEOPHYSICAL RES. LETTERS 323-26 (1988).

16. Kerr, *supra*, note 13.

17. Spencer & Christy, *Precise Monitoring of Global Temperature Trends from Satellites*, 247 SCIENCE 1558 (1990).

18. *See* Roberts, *supra* note 5, at 993.

19. *Id.* at 992-93.

B. *Evidence from Our Neighboring Planets*

Another source of evidence comes from observations of the atmospheres of our neighboring planets, Mars and Venus. The atmospheres of Mars and Venus are chemically different from the Earth's, primarily because of the effect of life on the Earth's atmosphere during the past 3.5 billion years.[20] The atmosphere of the Earth is high in oxygen and low in carbon dioxide, while the atmospheres of Venus and Mars are just the reverse. The average temperature of the surface of Venus is 450°C.[21] Due to the composition of the Earth's atmosphere, the Earth would have a much cooler average temperature than Venus if it were situated the same distance from the sun as Venus. The Earth would also have a cooler average temperature than Mars if the Earth were placed the same distance from the sun as Mars. This comparison shows that a planet's average temperature does respond globally to the concentration of greenhouse gases in its atmosphere. However, the comparisons to our neighboring planets are limited because unlike the Earth, Mars and Venus lack life, liquid water, and plate tectonics. The question remains: how would a complex biosphere on a planet with these three characteristics respond to an increase in greenhouse gases?

C. *Forecasting the Future: Computer Models of Climate*

Given the limitations on the use of the Earth's ancient and recent history and the limited usefulness of observations of neighboring planets, science has turned to theoretical models that will allow us to project the response of the Earth's biosphere to an increase in the concentration of greenhouse gases. Because the atmosphere is so complex, such theories can only be expressed through complex computer models which themselves have become a major source of controversy. There are currently less than ten major models of the Earth's climate. These are called "general circulation models" or "GCMs."[22] These models project an increase of 1.5° to 4°C (about

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20. Lovelock & Margulis, *Atmospheric Homeostasis by and for the Biosphere: The Gaia Hypothesis*, 26 TELLUS 2 (1974); J. LOVELOCK, GAIA, A NEW LOOK AT LIFE ON EARTH (1979).

21. S. SCHNEIDER, *supra* note 4, at 19.

22. Major general circulation models frequently cited include those developed at Oregon State University (OSU model), Princeton University, and NASA Goddard Space Flight Center (GISS model). *See, e.g.*, Hansen, Russell, Rind, Stone, Lacis, Lebedeff, Ruedy, & Travis, *Efficient Three-Dimensional Global Models for Climate Studies: Models I and II*, 111 MONTHLY WEATHER REV. 609 (1983); Hansen, Fung, Lacis, Rind, Lebedeff, Reudy, & Russell, *Global Climate Changes as Forecast by Goddard Institute*

3° to 8°F) in the average surface temperature of the Earth during the next century due to the greenhouse effect.

These models are so complex that they can be used only on the faster and largest "super" computers. At present, several months of computer time are required on these machines to run these models one century into the future. Projections for the next one hundred years are considered to be of most importance for present policy decisions.

However complex as the GCMs are, they still seem to be crude approximations of nature. For example, a unit of one of these models is very large—on the order of 5° latitude and longitude on a side. At this scale, Great Britain is too small to appear. The Great Lakes and Rocky Mountains of North America also do not appear in the models. The state of California occupies only a few grid elements. Regional effects that are crucial to the determination of local climate simply cannot be represented in these models.

The models also suffer from an oversimplification of biosphere components. These models divide the entire atmosphere into only three vertical components. The models treat soil as a simple structure rather than a complex system that can change with and affect the climate. Vegetation does not appear as a dynamic feature that responds to and can affect the atmosphere. The models also generally ignore ocean waters and currents that can affect climate by absorbing carbon dioxide and heat.

To summarize, the general circulation models are as complex as modern computers can handle. Yet they are crude approximations of the Earth's surface. Consequently, the question must be asked whether the projections made with these models are good enough to serve as a basis for substantive policy. The answer, as unsatisfying as it may be, is that we have no choice but to set policy based on the best available knowledge. At this point, our best knowledge is based on insights from the past, observations from neighboring planets, general circulation models, and numerous opinions advanced by scientific experts.

III.
CHOOSING ACCEPTABLE RISKS

There is a tendency in our society to believe that science can give

for Space Studies' Three-Dimensional Model 293, 93 J. GEOPHYSICAL RES. 9341-64 (1988); Schlesinger & Mitchell, *Climate Model Simulations of the Equilibrium Climatic Response to Increased Carbon Dioxide*, 25 REV. GEOPHYSICS 760 (1987).

complete, final, and exact answers to all questions, given enough time and research dollars. This is a dubious expectation for any science, and especially unlikely in the study of the biosphere. In part this is because the environment is always changing.[23] As an example, during the last 150,000 years the average surface temperature of the Earth has changed continually and the changes show little regularity. There seems to be some inherent randomness in the changes in the biosphere. As a result, even the best understanding of this system would allow one to make projections only to probabilities. In addition, the primitiveness of our knowledge about the biosphere means that answers we could give today are only approximations. Our understanding of how the biosphere works is like the understanding of the human body by a medieval physician. We have only a faint inkling of the intricate causes and effects within our planetary life support system.

Given the uncertainties in our knowledge and the inherent randomness of the environment, how can we arrive at reasonable societal policies about global warming? In recent years we have become accustomed to weather reports that give the chance of rain. Similarly we must view the projections of global warming in terms of probabilities. The question becomes: how certain will the onset of global warming have to be before we will be willing to adopt policy to deal with it? What level of risk of global warming are we willing to accept?

IV.
POSSIBLE IMPACTS OF GLOBAL WARMING

We can only choose a level of risk that we consider acceptable if we understand the consequences of global warming—the impacts on the environment, especially on life in the environment. The important focus for environmental law must be on the possible impacts of global warming and the probabilities of their occurrence.

To arrive at a perspective on global warming we must consider its possible impacts. But our abilities are extremely limited. Scientists have only just begun to investigate possible impacts of global warming, and at this time only a tiny fraction of federal research dollars is allocated to this issue. (Most of the funding has been from the Environmental Protection Agency.) In general, if global warming were to occur a variety of consequences would follow. It would

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23. D. BOTKIN, DISCORDANT HARMONIES: A NEW ECOLOGY FOR THE 21ST CENTURY (1990).

lead to increases in temperatures that would be especially pronounced in mid-latitudes. Drier soil conditions would affect agriculture, forests, grasslands, and agricultural and urban water demand. An increase in the variability of climate could cause increases in severe droughts on one hand and increases in episodes of severe storms and flooding on the other. A rise in sea level resulting from the melting of polar ice and thermal expansion of water would affect coastal resources including fisheries, wetlands, and human habitation along coasts.[24] Changes in climate could threaten endangered species and raise new concerns about conservation of biological diversity and about national laws and international agreements affecting biological conservation. The more specifically these consequences are defined, the more specific and effective the solutions can be to any potential problems.

A. *Impacts of Global Warming on Forests*

Forests are one of our most valuable renewable natural resources. They benefit humankind not only as commercial timber resources, but also as watersheds for water supply to much of our nation, habitat for wildlife and many endangered species, and as a site for recreation of many kinds. The economic value of forests results from these multiple uses. Timber production alone is a multi-billion dollar a year business in the United States. The four major regions of U S. timber production include: the Northwest, the Great Lake States, New England, and the Southeast. As an example of this economic importance, estimates state that the timber industry provides an annual value of $20 billion for three of the Great Lake States: Minnesota, Michigan, and Wisconsin.[25]

In addition, forests play an important role in the biosphere, and provide us with major "public service" functions which are only slowly becoming apparent. Forests provide the major biological storehouses of carbon and are believed to play an important role in maintaining lower atmospheric carbon dioxide levels. For national economic and environmental reasons we must determine as best as we can the likely impact of rapid climatic change on our forests.

Projections of the effects of global warming on forests depend on studies of the Earth's history, computer models, and the opinions of experts. Evidence from the past involves the correlation between

24. Titus, *Sea Level Rise*, in THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES 324 (J. Smith & D. Tirpak eds. 1989).

25. Personal communication with Henry Webster, State Forester, Michigan State Department of Natural Resources (June, 1989).

fossil deposits of vegetation and reconstructions of past climate. The best fossil evidence for this purpose is the deposits of pollen in lakes and wetlands. Pollen is made of small grains with a hard outer coating. The shape of a grain and patterns on the coating are distinctive for most species, and the outer coating is inert and persists for a very long time. Trees emit pollen which are then widely dispersed by winds. Some pollen falls into lakes and wetlands where it accumulates with mud and other organic matter of the same period. The organic matter can be dated using radioactive carbon-14, so that a core of material removed from the bottom of a lake can be used to determine what species of trees were abundant and where they were abundant at each major time period during and since the last glacial episode. For example, pollen records show that the geographic distribution of trees shifted south during the last ice age. In North America, some species migrated to the southeast and some to the southwest.[26]

The correlation between past geographic range of a tree species and past climate can be used to project future distributions of trees under global warming. For example, these correlations suggest that climate zones in the mid-latitudes of eastern North America will move northward several hundred kilometers over the next century[27] at approximately 10 times the rate characteristic of the Holocene and Pleistocene periods.[28] Present vegetation in this area may be replaced by species characteristic of more southern regions. Analyses based on pollen records are useful in providing a general idea of changes in the ranges of trees, but they cannot tell us the rate at which existing forests will respond to climate change. For this we must turn to another method, computer simulation.

Computer aided projections suggest that global warming may have surprisingly rapid and severe effects on forests of mid and high latitudes, with some forests projected to change within the next decade or two.[29] If global warming were to occur as projected by global circulation models, forests in many areas would undergo

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26. Davis, *Pleistocene Biogeography of Temperate Deciduous Forests*, 13 GEOSCIENCE & MAN 13, 15 (1976); Davis, *Quaternary History and the Stability of Forest Communities*, in FOREST SUCCESSION: CONCEPTS AND APPLICATIONS, 132, 137 (D. West, H. Shugartand & D. Botkin eds. 1981).

27. Davis & Zabinski, *Rates of Dispersal for North American Trees: Implications for Response to Climatic Warming*, in CONSEQUENCES OF THE GREENHOUSE EFFECT FOR BIOLOGICAL DIVERSITY, (R. Peters ed., in press).

28. S. SCHNEIDER, *supra* note 4, at 64-65.

29. Smith, *Great Lakes*, in THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES 121 (J. Smith & D. Tirpak eds. 1989).

rapid and severe changes, beginning with a die-back of existing species, followed, where conditions were appropriate, by an influx of species from drier and warmer habitats. If this were to happen there would be major impacts on all uses and benefits of the forests. Such effects could become noticeable by the turn of the century.

Some experts have suggested that an increase in atmospheric carbon dioxide concentration would have several beneficial effects on forests. It is well known that plants grow better in air with an increased concentration of carbon dioxide. This condition is employed in some greenhouses to increase yields of hothouse crops. A possible reduction in water use by vegetation might accompany an increase in the atmospheric concentration of carbon dioxide. Plants open pores called stomata in their leaves to allow carbon dioxide to enter and water to leave. When carbon dioxide increases in the air, these pores need to be open a shorter time. Closing them reduces water loss. Increases in carbon dioxide in the air might make vegetation more efficient in water use. However, computer projections of forest growth indicate that the beneficial effects of an increase in carbon dioxide will be very small compared to the impacts of drought and heat, and will probably not compensate for the impact of global warming on forests.[30]

B. *Effects on Endangered Species*

Rapid changes in climate and forests could threaten species with extinction and increase the risk to those presently endangered. As an example, computer projections suggest that the present management program to conserve the Kirtland's warbler, an endangered species that nests only in jack pine woodlands where these grow on sandy soils in Michigan,[31] may not be sufficient to save this species from extinction if global warming were to occur.[32] Current management involves 40,000 acres on which controlled fires are set periodically to clear the woodlands and create warbler habitat. This program is the result of cooperation among the State of Michigan Department of Natural Resources, the Federal Fish and Wildlife Service, and the Audubon Society, and is an important example of a constructive approach to biological conservation.[33] Modifications

30. D. Botkin & R. Nisbet, *Response of Forests to Global Warming and CO_2 Fertilization*, REPORT TO EPA (1990).

31. H. MAYFIELD, THE KIRTLAND'S WARBLER 9-10 (1960).

32. Botkin, Woodby, & Nisbet, *Kirtland's Warbler Habitats: A Possible Early Indicator of Climatic Warming*, 56 BIOLOGICAL CONSERVATION 63 (1991).

33. J. BYELICH, M. DECAPITA, G. IRVINE, R. RADTKE, N. JOHNSON, W. JONES, H.

in this program may be necessary if global warming occurs. Similar difficulties might arise for other endangered or threatened species that depend on forest habitats, such as the spotted owl of the northwest, whose habitat, already threatened by logging of old-growth forests, might be further endangered by forest die-backs that could accompany global warming. (It is important to emphasize that computer projections for the impact of global warming on the forests of the northwest have not been made, so our insights into the possible timing or degree of such a die-back are highly speculative at this time.)

Because human actions have fragmented forests in many parts of the world, they exist today as "ecological islands"—artificial islands of one kind of ecosystem surrounded by human altered land.[34] As a result, natural migratory responses to rapid environmental changes are not possible. Before human alteration of vast areas of land, species could migrate freely over large areas in response to climate change. Today, if that sort of migration is to occur, we will have to assist it by creating migration corridors between these "ecological islands." Such corridors could be extensions of urban parkland or could be easements through private lands in cities as well as in rural areas.

Given the importance of forest habitats to many species, including endangered ones, the importance of forest products to civilization, the public service functions of forests, and the recreational and aesthetic values people attach to forests, it seems merely prudent to take action in response to any significant probability that global warming will occur.

C. *Rising Sea Levels and Coastal Environments*

Global warming would lead to an increase in the rate of sea level rise for two reasons. First, as the oceans warm, their waters would expand. Second, as the air temperature rises, glaciers would melt, increasing the amount of water in the oceans. Estimates of the potential rise in sea level vary widely, but a reasonable range is the one reported by EPA to be between a 0.5 to 2 meters (roughly 2 to 7 feet) sea level rise by year 2100.[35] The sea level rise would affect both natural and developed areas. According to the analysis by

MAYFIELD & W. MAHALAK, KIRTLAND'S WARBLER RECOVERY PLAN (1985) (available from U.S. Fish & Wildl. Serv.).

34. Peters & Darling, *The Greenhouse Effect and Nature Reserves*, 35 BIOSCIENCE 707 (1985).

35. Titus, *supra* note 24, at 319.

EPA, a one meter rise would inundate between 25 to 80% of the United States' coastal wetlands, and between 40 and 73% could be lost,[36] as could 5,000 to 10,000 square miles of unprotected shoreland. It has been estimated that a rise in sea level of one-half meter could inundate one-third of coastal wetlands in the United States.[37] Remaining wetlands would suffer changes in salinity. Widespread reduction in existing wetlands could lead to declines in waterfowl, with effects on sport hunting and on the conservation of endangered species.

Before human settlement and global warming, a sea level rise would have occurred slowly enough to allow species of wetland vegetation to become established in new inland marshes. The speed with which global warming induced sea level rise might occur might overwhelm natural migration rates of coastal vegetation. In addition, today, the area inland is typically covered with concrete or is drained, filled, and subject to other intense land uses. For example, in California, approximately 90% of coastal wetlands have been destroyed by development and other human activities. The remaining 10% lies generally between the ocean and highly developed areas. With a rapid rise in sea level, many of these wetlands, now protected under Section 404 of the Clean Water Act of 1977,[38] would be inundated. It is noteworthy that, while section 404 discourages wetland development, it does not discuss the possibility of the need of land for wetland migration. As the sea level rises, salt water will also move inland into the estuaries and rivers, which could affect breeding habitats of some sport and commercial fish and lead to declines in the reproduction of these species. In addition, changes probably would occur in the near-shore ocean currents, which would lead to changes in the distribution of species of fish. It is unclear what the overall effect would be on commercial fisheries, but one can expect that any rapid change is likely to have short-term negative consequences. There is some basis to suggest that global warming will lead to El Niño-like conditions, which could have complex effects on marine life.

Such rapid changes in sea level would lead to legal dilemmas. The EPA report to Congress points out that an attempt to establish a policy to prevent all further development of wetlands would raise

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36. T. Armentano, R. Park & C. Cloonan, *Impacts on Coastal Wetlands Throughout the United States*, in GREENHOUSE EFFECT, SEA LEVEL RISE, AND COASTAL WETLANDS, EPA-230-05-86-013 (J. Titus ed. 1988).

37. Titus, *How It Might Be: Sea Levels*, 15 EPA J. 14 (1989).

38. 33 U.S.C. § 1344 (1988).

unresolved constitutional issues about due process.[39] Another possibility is to allow development under a binding agreement that such development would "revert to nature" if threatened with inundation. The State of Maine has established coastal dune regulations along these lines.[40]

Protecting the developed areas along the coast would cost between $73 and $111 billion. Most of the damage would occur in the Southeast, although there could be important effects elsewhere. In developed coastal areas, existing sea walls might fail, and their reconstruction plus the need for new sea walls to protect inland developed areas would lead to pressures for new public construction projects. A report on the impact of global warming on natural ecosystems of California states that "[a] rise in sea level of one-third meter could erode beaches from 67 to 133 meters in California, but because many are not this wide, substantial loss of marine intertidal zones, wetland habitat, and recreational sites are likely in urban areas with seawalls."[41]

D. *Global Warming and Water Resources*

Global warming would lead to an increase in water demand and a decrease in available water. The climate models predict rainfall less reliably than temperature. Some projections suggest rainfall will increase while others suggest rainfall will decrease. But even those projections that suggest that rainfall will increase also suggest that rising temperatures will increase water evaporation from forests, grasslands, and cropland to such an extent that the water lost from soils would exceed the amount added from additional rainfall. As a result, much of the land will become drier. The effects of a drier climate will be felt in commercial as well as agricultural and urban water use. Surface runoff would decrease, leading to a decline in stream and river flow and a decline in lake levels. This could lead to more frequent episodes of river water levels too low for transport of goods by boats as occurred recently on the Mississippi river. Conflicts over water resources for agricultural and urban use would be especially acute.

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39. Titus, *supra* note 24, at 355.

40. Titus & Greene, *Appendix*, in U.S. Environmental Protection Agency, EPA-230-05-89-050 app. (J. Smith & D. Tirpak eds. 1989); *See also* J. Titus, T. Henderson & J. Teal, *Sea Level Rise and Wetlands Loss in the United States*, 6 NATIONAL WETLANDS NEWSLETTER 4 (1984).

41. Botkin, Nisbet, Bicknell, Woodhouse, Bentley, & Ferren, *Climate Change and Natural Ecosystems of California*, in CLIMATE CHANGE AND CALIFORNIA (J. Knox & M. Dowling eds., in press).

Increased competition for water use could create an increased conflict between the maintenance of natural ecosystems and the needs of agriculture and urban development. For example, as sea level rises, increased fresh water flow would be required to maintain fresh and brackish water ecosystems along the coasts, but this water demand would conflict with agricultural pressures.[42] Such problems would be especially severe in California which already has serious conflicts over water supplies. Pressures to build new reservoirs would create additional conflicts between nature conservation and demands for societal uses of water.

As an example, consider the possible conflicts that might arise over the conservation of Mono Lake, already the subject of many court proceedings. In the 1980s, the Mono Lake watershed provided seventeen percent of the water supply for the city of Los Angeles. Water diversions had eliminated all but a small fraction of runoff into the lake, with resulting rapid decline in lake level and threats to the lake ecosystem and birds that depend on the lake as a breeding ground and a feeding habitat during migration.[43] Under the present climate, this issue might be resolved through alternative water sources for the city of Los Angeles, but the conflict will be exacerbated as these sources provide less water, the population and water demand of Los Angeles increase, and other jurisdictions claim rights to the water sources now used by the city. If global warming occurs, legal conflicts over Mono Lake might continue and worsen, rather than be resolved.

Conservation problems of dry-land lakes would occur widely. As another example, the Aral Sea in the Soviet Union, in some ways an analog of Mono Lake, has been allowed to undergo severe reduction in area and an increase in salinity, with a resulting destruction of the natural ecosystem and an increase in air pollution from the salt dusts deposited by the drying salt waters. Environmental problems of the Aral Sea would worsen under global warming.

Given the great increase in environmental awareness in many nations, it is unlikely that damage to large salt lakes would occur during a global warming without a major public debate. Such a debate could easily lead to new legal conflicts.

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42. Botkin, Woodby, & Nisbet, *Kirtland's Warbler Habitats: A Possible Early Indicator of Climatic Warming*, 56 BIOLOGICAL CONSERVATION 63 (1991); Titus, *How It Might Be: Sea Levels*, 15 EPA J. 14 (1989).

43. D. BOTKIN, W. BROECKER, L. EVERETT, J. SHAPIRO, & J. WIENS, THE FUTURE OF MONO LAKE (California Water Resources Center, University of California, Riverside, Report No. 68 (1988)).

E. *Global Warming and Crops*

Some argue that global warming will not pose a threat to agriculture because the distribution of crops could be altered to match temperature changes. Some have suggested that global warming will have beneficial effects, leading to the greening of Siberia and northern Canada. This is an oversimplified view that overlooks some crucial impacts. As pointed out earlier, global warming would lead to a drier soils. As soils dry, crops will require an increase in irrigation. Limitation in the availability of water is already a worldwide concern that would be exacerbated by global warming. The first problem to be faced by farmers if global warming occurs is in finding sufficient irrigation water.

The EPA forecasts dire consequences for crops if global warming occurs. For example, in California, crop yields could be reduced by 20 to 40%, depending on crop type and location. Corn production is estimated to decrease between 14 and 31%; tomatoes between 5 and 15%.[44] In the warmer parts of the southeast of the United States, agricultural yields might decline by as much as 91% and between 10 and 57% of the farmland might be taken out of production.[45]

Some agricultural experts have suggested that the positive effect of carbon dioxide on plants will benefit crops, leading to an increase in production that will at least compensate for decreases due to changes in temperature. This is only likely if temperature and moisture impacts remain small while the fertilization effect is large.

In addition to increased temperatures, the increases in the variability of climate could also have negative effects on agriculture. For example, corn, soybeans, wheat, and sorghum are sensitive to high temperatures, especially when flowers are formed.[46] An increase in climate variability could lead to an increasing chance of high temperatures during this part of the growing season, with a resulting decline in crop yields even if there were little overall increase in average temperatures. Increases in the chance of early and late frosts also could lead to a decrease in crop yields.[47]

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44. Rosenzweig & Riebsame, *Great Plains*, in THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES 271 (J. Smith & D. Tirpak eds. 1989).

45. Titus, *Southeast*, in THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES 183, 230 (J. Smith & D. Tirpak eds. 1989).

46. Shaw, *Estimates of Yield Reductions in Corn Caused by Water and Temperature Stress*, in CROP REACTION TO WATER AND TEMPERATURE STRESSES IN HUMID, TEMPERATE CLIMATES 49 (C. Raper & P. Kramer eds. 1983).

47. Mearns, *Variability*, in THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES 600 (J. Smith & D. Tirpak eds. 1989).

Global warming could also change the distribution and abundance of crop pests. These changes could increase overwintering of insect pests in some areas, leading to an increase in crop destruction by these pests.[48]

At the present we live in a fortunate time where the best climates for agriculture tend to occur where the best soils occur, as in the North American midwest. With the onset of global warming, the best climates for agriculture may shift so that they occur over poorer soils. In North America, a northward movement of climate would place good agricultural climates over Canada where, due to the effects of ice age glaciers, soils are not in general as fertile as they are in the midwest of the United States.

Even if global warming did not lead to a net worldwide decline in crop production, it would affect competition among nations in crop production, shifting the best production northward. This could have a negative effect on United States crop production.

V.
IMPLICATIONS FOR ENVIRONMENTAL LAW

If global warming were to occur, it would lead to massive changes in the environment that would require many responses by our society and would undoubtedly affect many aspects of environmental law. The question that confronts us now is how much faith to put into the possibility of global warming. In this article I have suggested that the only reasonable basis for evaluation is an estimation of acceptable risks, and this requires consideration of possible impacts on all aspects of life on the Earth, including impacts on natural ecosystems, endangered species, as well as the management of biological resources with direct economic uses including forests, agriculture, fisheries, wildlife, and rangeland. When planning for the future, lawmakers will have to seriously consider the possible impacts of global warming on all aspects of the natural ecosystem and human activity.

Present projections of impacts suggest that global warming would have severe effects that might become evident soon after the turn of the century. It would seem merely prudent for those involved in the development of environmental law to begin now to investigate alterations in laws affecting the environment. There are two dangers which lawmakers must avoid: the first is paying too little attention

48. Rosenzweig & Daniel, *Agriculture*, in THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES 368 (J. Smith & D. Tirpak eds. 1989).

to the possibility of global warming; the second is treating the concern with global warming as a fad and developing superficial responses in the interest of political expediency rather than from a basis in careful consideration of the impacts.

The legal options can be separated into two classes: those directed at eliminating the causes of global warming, and those aimed at mitigating the effects of global warming. We should begin now to consider how we should change laws that affect the environment in order to reflect our concern with global warming. If we want to attempt to slow global warming, then we need to begin to consider our options at once. At this time there is little in the way of thoughtful, considered approaches, while hastily put together programs appear to be growing.

Various legal responses could help avoid global warming. For example, legislation is needed to secure funding of programs to monitor key global environmental variables as is now done for the concentration of carbon dioxide on Mauna Loa, and to improve our understanding of how the biosphere works. Legislation should also be directed at reducing the net atmospheric concentration of greenhouse gases. Such legislation could include programs in energy conservation, use of alternative energy, and prudent, large scale tree planting. Additional legal responses are needed to arrange for and lighten the effects of global warming. For example, modification is needed of laws concerning protection of natural areas and conservation of biological diversity. We need to allow for adjustment of habitats including park and preserve boundaries and provide migration corridors. Land use and development regulations should be reconsidered, especially in areas at high risk of change during global warming, such as coastal areas. Legislation will also be needed to deal with increasing demands for a decreasing supply of water. The key question for implementing any of the legal responses is the timing. What work should begin now before clear evidence that global warming is upon us? The potential impacts of global warming seem severe enough to warrant immediate, careful consideration of the possible legal responses.

A. *International Laws and Agreements*

Global warming is a worldwide problem that raises many international legal issues. Today developed nations produce the greatest quantity of greenhouse gases and consequently need to alter their practices to reduce output of these gases. However, developing nations are becoming a key focus for international efforts to reduce the production of greenhouse gases. As economists have pointed out, developing nations did not share in the benefits from the burning of fossil fuels until recently, and many are just now reaching the point where they could profit from the use of these fuels. For example, China and India are likely to use large amounts of fossil fuels in the near future. These nations would seem to have little motivation to slow their use of fossil fuels simply to meet what might appear to be a concern of the industrialized nations. If we are to achieve a worldwide reduction in the use of fossil fuels, then there must be development of some parity in this reduction, and it may be necessary for the industrialized nations to provide compensation to the developing nations in response to their reduction in the use of fossil fuels.[49]

Conservation organizations have also placed special focus on the importance of tropical rain forests both in global climate dynamics and for purposes of biological conservation. However, there are difficulties in achieving conservation of these forests. Most of these forests exist in developing nations. Economists have questioned why these nations would be motivated to conserve their tropical forests, which are major economic resources, for what may appear to be abstract and distant concerns. New approaches toward international law will be needed if progress is to be made on this issue. There are already interesting precedents, such as "debt-for-nature" programs. In these programs, part of the national debt of a nation is retired with funds raised by conservation organizations. In exchange, the nation creates a new tropical forest nature preserve of a specified size and location. It is not clear how well such mechanisms will work over the long term, and especially how well such legally designed parks will avoid illegal logging and clearing. In the Philippines, tropical forest preserves on the island of Palawan are reputed to be undergoing extensive logging in spite of their "protected" status.

The Montreal Protocol, an agreement to reduce the use of CFCs as a way of protecting the atmospheric ozone layer, is an important precedent in international cooperation on a major global environmental issue. Since CFCs affect both the ozone layer and global warming, this is an especially important precedent. Other important international precedents exist in biological conservation such as the International Whaling Commission and treatises that control

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49. Pearce, *Sustainable Futures: Some Economic Issues*, in CHANGING THE GLOBAL ENVIRONMENT: PERSPECTIVES ON HUMAN INVOLVEMENT 309 (D. Botkin, M. Caswell, J. Estes & A. Orio, eds. 1989).

migratory birds. These precedents can be instructive when formulating future international agreements to deal with global warming.

VI.
CONCLUSION

Global warming refers to complex climatic changes, including a rise in temperature and changes in the amount and patterns of rainfall and in the variability of weather, that would accompany a rapid increase in the concentration of greenhouse gases in the atmosphere. If global warming were to occur in the future as projected by the computer models of climate, major disruptions would take place in many aspects of our environment which in turn would require certain legal responses to deal with the changes.

It is therefore necessary to decide now what importance to attach to this possibility. In this article I suggest that the best way to evaluate the importance of global warming is by examining the potential impacts and determining a level of acceptable risk. The important focus for environmental law must be on the possible impacts of global warming and the probabilities of their occurrence.

In deciding when action needs to be taken, it is helpful to understand what is and is not controversial about global warming. The major scientific controversies concern: (1) whether the observed increase in the average temperature during the past century is the result of global warming or other phenomena; (2) whether an increase in temperature will increase cloud cover, that could lead to a subsequent cooling of the Earth; and (3) whether existing computer models of climate are too crude to be trusted, or whether, since they are the only existing quantitative tool, they must be relied on at present.

If global warming occurs, it would lead to the following: increases in temperatures that would be especially pronounced in mid-latitudes; drier soil conditions that would affect agriculture, forests, and grasslands; an increase in the variability of climate that could mean increases in severe droughts and concomitant increases in natural fire frequencies; increases in episodes of severe storms and flooding; and a rise in sea level that would affect coastal resources including fisheries, and human habitation along coasts.

If global warming occurs, many environmental laws will have to be rewritten, and it is only prudent that those interested in this process begin now to consider what is wise and useful to do.