Paleoclimate: The History of the Earth System

The USGCRPbudget includes $27 million in FY 2001 for the study of the Earth's amazingly complex climate and environmental history (see Table 9). This element of the USGCRP focuses on providing a quantitative understanding of how the environment has changed in the past and defining the envelope of natural environmental variability within which the effects of human activities on the planet's biosphere, geosphere, and atmosphere can be assessed.

Paleoenvironmental records are derived from a wide variety of natural archives—such as: lake and ocean sediments, tree rings, wind-blown deposits, coral, and ice cores—as well as historical documents. Chemical, isotopic, and ecological analyses of these records have demonstrated that the natural climate system has varied locally and globally over a far greater range than can be inferred from relatively short-term instrumental records. In most locations, instrumental records might provide 100 years of climate data, whereas an ice core might provide an annual climate record of 10,000 to 30,000 years (more than 400,000 years in Antarctica).

Understanding the natural environmental changes of our planet on long timescales (years to millennia) provides the context for understanding today's climate dynamics and elucidating the effects of natural versus anthropogenic influences. Reconstructing past climate records offers an enhanced understanding of mechanisms that control the Earth's climate system and, together with insight from numerical modeling exercises, provides a foundation for anticipating how the planet might respond to future environmental perturbations.

Recent Accomplishments

- Recent progress in synthesizing various proxy records of past climates enables placement of 20th century climate warming within a longer-term perspective. Recent results indicate that much of the variability during the past 1,000 years prior to the rise in emissions of greenhouse gases from human activities (beginning in about 1850) can be attributed to pulses of volcanism or changes in the output of the Sun's energy. Neither of these mechanisms—or natural climate variability in the ocean-atmosphere system—can explain the late 20th century rise in the globally averaged surface temperature. Greenhouse gases appear to emerge as the dominant forcing during the 20th century. According to proxy temperature records, the 1990s appear to have been the warmest decade (and 1998 the warmest year) in the past 1,000 years.
- A partnership between two sets of researchers has resulted in the acquisition of ice core and meteorological data from the Sajama ice cap in Bolivia. This research has provided a record of glacial versus interglacial tropical climate dynamics over the past 25,000 years and is contributing to a better understanding of past and present tropical Pacific climate variability.

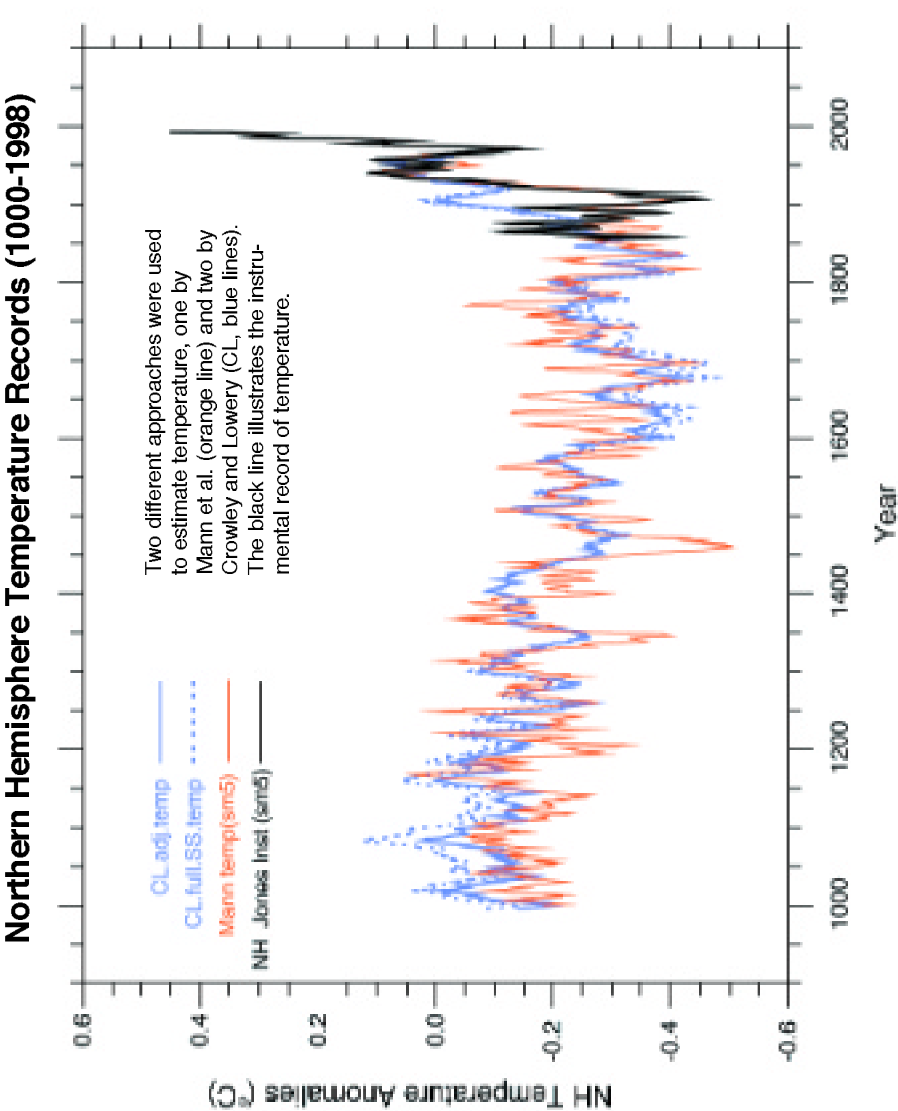

Figure 6. Northern Hemispher e Temperature Records for the Past 1,000 Years

(See page 41 for additional information)

Table 9
Paleoclimate: The History of the Earth System

FY 2001 Budget by Agency
(discretionary budget authority in $millions)

DOC/NOAA Scientific Research	2.3
DOI/USGS	4.0
NSF	19.5
Smithsonian Institution	1.6
TOTAL	**27.4**

FY 2001 Plans

The USGCRPwill focus on acquisition of new paleoenvironmental data, enhancing paleoclimate modeling, and improving access to both data and models. Goals include:

- Constructing new long-term climate and environmental records for parts of North and South America by successfully obtaining and analyzing eight new long, continuous sediment cores—four from the Great Salt Lake in the United States and four from Lake Titicaca in Bolivia. This will be accomplished by using a newly acquired drilling system for obtaining sediment cores from beneath large lakes. These sediments are the primary source of long-term paleoenvironmental records from continental areas. Acquisition and study of such sediments has been the object of years of planning and coordination work.
- Increasing overall paleoclimate modeling activities by 30-50 percent by improving computing capabilities and providing model access to additional users. Data-model comparisons will be an important part of these activities. This paleo-modeling effort will be complementary to, and compatible with, the extensive climate simulation efforts for modern climate.
- Doubling the overall volume of publicly accessible paleoclimate data holdings, expanding the utility of these data to facilitate their application by a wider range of users, and expanding data access to 10 percent more users.

INTERNATIONAL CONNECTIONS

The USGCRP addresses an important set of national objectives; it also participates in a series of international efforts directed toward improving understanding of change on global and regional scales. The resulting databases, when aggregated, provide essential inputs to the increasingly complex coupled models that enable scientists to improve analysis and prediction of global change. Regular interaction between the USCGRPand these international scientific efforts also results in substantial feedback to our assessment of the impacts of global change and their consequences for the North American continent. Some examples of USGCRPinternational connectivity of special relevance for scientific areas that the USGCRPexpects to emphasize in the coming year are described below.

International Global Change Research Programs

At the global level the **International Geosphere-Biosphere Programme (IGBP)** has as its primary goal describing and understanding the interactive physical, chemical, and biological processes that regulate the Earth system. The IGBP will convene a major International Open Science Meeting in July 2001 to review the progress of IGBP research; synthesize results achieved; and set directions for future IGBP research in areas such as global atmospheric chemistry, global change and terrestrial ecosystems, and land-use and land-cover change.

The **World Climate Research Programme (WCRP)** is directed at improving scientists'understanding of the Earth's climate system and climate processes and, through such studies, determining the extent to which climate can be predicted and the extent to which humankind influences climate. The WCRP's Global Energy and Water Cycle Experiment (GEWEX) will be of increasing importance to U.S. scientists as the USGCRPincreasingly emphasizes research on changes in the global water cycle as a primary determinant of the Earth's climate.

The **International Human Dimensions Programme (IHDP)** coordinates multidisciplinary international collaborative scientific programs that examine the causes and environmental consequences of people's individual and collective actions as well as the potential efficacy and impact of various general adaptation and mitigation strategies. The IHDP also works to identify emerging research opportunities and provides synthesis reports and policy-oriented summaries to contribute a scientific basis for individual and collective decisionmaking.

Regional Activities

At the regional level, the **International Research Institute for Climate Prediction (IRI)** prepares, issues, and distributes interannual climate forecasts, such as forecasts of El Niño events, derived from global and regional ocean-atmosphere coupled models. The primary audience is countries that are especially vulnerable to global change and the major interannual events associated with such change. IRI forecasts are of special value in sectors such as agriculture, health, and water resources.

The **Inter-American Institute forGlobal Change Research (IAI)** is an intergovernmental treaty organization established in 1994 to promote collaborative research to understand and predict the integrated impact of present and future global changes. The IAI has established a network of more than 200 collaborating institutions throughout the

Americas, involving nearly 1,000 scientists. The results of IAI projects to date have demonstrated that high-quality, peer-reviewed science, along with capacity building, can produce broad benefits.

The **Asia-Pacific Network for Global Change Research (APN)** made notable progress in 1999 and was able to increase substantially its support for climate research and studies of the human dimensions of global change. U.S. scientists are substantially involved in APN research programs.

Bilateral Cooperation

U.S. scientists involved in global change research also work closely with their counterparts in many other countries on a bilateral basis. The USCGRP strongly encourages such direct scientific cooperation. Of special note is the growing cooperation between U.S. and Japanese scientists in several areas of mutual interest.

In 1999, the Seventh **U.S.-Japan Workshop on Global Change Research** focused on Precipitation Systems and Their Variability in the Asia-Pacific Region. This workshop resulted in several recommendations for follow-up, some of which are being pursued actively this year. The eighth in this series of workshops, which will address Global Change and Environment, will be convened in November 2000 at NIH. Special areas of emphasis for this workshop will be climate change and air pollution impacts on human health, and health impacts of stratospheric ozone depletion and greater exposure to harmful solar radiation.

International Interactions in Support of Observations and Monitoring

USGCRP scientists are actively engaged in several efforts to expand and improve U.S. capabilities to observe and monitor the Earth system in support of global change research. At the international level, the **Committee on Earth Observational Satellites (CEOS)** provides a forum through which the United States and other countries that are conducting Earth remote-sensing programs coordinate their activities. This forum is of special importance now because of the successful launch of a series of U.S. Earth remote-sensing satellites in 1999. Cooperative arrangements with the European Space Agency (ESA) and the National Space Development Agency of Japan (NASDA) also are valuable in this area.

The **Integrated Global Observing Strategy (IGOS)** Partnership brings together CEOS; the International Group of Funding Agencies for Global Change Research (IGFA); the IGBP and WCRP; and United Nations agencies involved in in situ ocean, atmosphere, and terrestrial observing systems to promote effective interaction and complementarity between remote sensing and in situ observing systems for global change research and prediction.

International Scientific Assessment

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) to assess available scientific, technical, and socioeconomic information in the field of climate change. A substantial number of USGCRP-supported researchers are contributing to the IPCC's Third Assessment Report on the science of climate change; climate change impacts, adaptation, and vulnerability; and mitigation of climate change.

RECENT ASSESSMENTS AND REPORTS ON GLOBAL CHANGE

Intergovernmental Panel on Climate Change. *Climate Change 1995: The Science of Climate Change*. Contribution of Working Group I to the Second Assessment Report of the IPCC. Cambridge, U.K.: Cambridge University Press, 1996.

Intergovernmental Panel on Climate Change. *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*. Contribution of Working Group II to the Second Assessment Report of the IPCC. Cambridge, U.K.: Cambridge University Press, 1996.

Intergovernmental Panel on Climate Change. *Climate Change 1995: Economic and Social Dimensions of Climate Change*. Contribution of Working Group III to the Second Assessment Report of the IPCC. Cambridge, U.K.: Cambridge University Press, 1996.

Intergovernmental Panel on Climate Change. *The Regional Impacts of Climate Change: An Assessment of Vulnerability*. Special Report of the IPCC. Cambridge, U.K.: Cambridge University Press, 1997.

Intergovernmental Panel on Climate Change. *Aviation and the Global Atmosphere*. Special Report of the IPCC. Cambridge, U.K.: Cambridge University Press, 1999.

Intergovernmental Panel on Climate Change. *Land Use, Land-Use Change, and Forestry*. Special Report of the IPCC. Cambridge, U.K.: Cambridge University Press, 2000

Intergovernmental Panel on Climate Change. *Emissions Scenarios*. Special Report of the IPCC. Cambridge, U.K.: Cambridge University Press, 2000.

Intergovernmental Panel on Climate Change. *Methodological and Technological Issues in Technology Transfer*. Special Report of the IPCC. Cambridge, U.K.: Cambridge University Press, 2000.

National Research Council. *Global Environmental Change: Research Pathways for the Next Decade*. Washington, D.C.: National Academy Press, 1999.

National Research Council. *Reconciling Observations of Global Temperature Change*. Washington, D.C.: National Academy Press, 2000.

United Nations Environment Programme (UNEP). *Synthesis of the Reports of the Scientific, Environmental Effects, and Technology and Economic Assessment Panels of the Montreal Protocol: A Decade of Assessments for Decision Makers Regarding the Protection of the Ozone Layer: 1988-1999*. Nairobi, Kenya: UNEP, 1999. (Copies of this report are available from the Web site of the UNEPOzone Secretariat at: http://www.unep.org/ozone or http://www.unep.ch/ozone.)

United Nations Environment Programme (UNEP). *Environmental Effects of Ozone Depletion: 1998 Assessment*. Nairobi, Kenya: UNEP, 1998. (Copies of this report are available at the following Web site: http://sedac.ciesin.org/ozone/docs/UNEP98/UNEP98.html.)

U.S. Global Change Research Program. *A U.S. Carbon Cycle Science Plan*. Report of the Carbon and Climate Working Group, 1999.

U.S. Global Change Research Program. *1999 Newly Available Agency Data Sets That are Significantly Global Change Related*. Report of the USGCRPData Management Working Group. (This report is available on the Global Change Data and Information System Web site at: http://globalchange.gov/data/datasets-1999.html.)

World Meteorological Organization, United Nations Environment Programme, NOAA, NASA, and European Commission. *Scientific Assessment of Ozone Depletion: 1998*. (This report may be ordered on the UNEP Web site at: http://www.unep.org/ozone or http://www.unep.ch/ozone.)

FIGURE CAPTIONS

Figure 1: Asymmetric Trends in Arctic and Antarctic Sea-Ice Extent

General circulation model (GCM) experiments that simulate future climate conditions assuming a gradual increase in atmospheric CO_2 show various hemispheric asymmetries in global sea ice extent. Some suggest that Arctic sea ice will decrease significantly, whereas Antarctic sea ice will decrease substantially less or even increase. Scientists at the NASAGoddard Space Flight Center have found observational evidence that there is a current asymmetry in global sea ice changes. In particular, they found that the areal extent of sea ice decreased by 2.9 +/- 0.4% per decade in the Arctic and increased by 1.3 +/- 0.2% per decade in the Antarctic from November 1978 through December 1996. These results are based on measurements from passive microwave instruments on the Nimbus 7 and three defense Meteorological Satellite Program spacecraft. The assymetry in sea ice trends is intriguing and indicates that climate in the southern polar region may have very different dynamics from the climate in the northern polar region.

Source: NASAGoddard Space Flight Center. D.J. Cavalieri, P. Gloersen, C.L. Parkinson, J.C. Comiso, and H.J. Zwally, Laboratory for Hydrospheric Processes/Code 971.

Figure 2a: Polar ozone loss is now evident in both hemispheres, raising concern that climate change could delay the recovery of stratospheric ozone

Figure 2a is a graph of total column ozone (in Dobson units) as a function of time since 1970, as obtained from several NASAand NOAAsatellites. The points plotted represent a monthly average of total column ozone for March in the Northern Hemisphere (NH) and October in the Southern Hemisphere (SH). The plotted points also represent an average of data obtained from 63 to 90 degrees latitude (defined as the polar region) in each hemisphere. In the SH polar springtime (October), stratospheric ozone began a steep decline in 1980 that has continued almost smoothly, leading to steady, severe loss over the last decade. In the NH springtime, the situation is different. Stratospheric ozone levels were fairly constant during the 1980s, with a significant decline not beginning until 1990. The NH decline also exhibits greater interannual variability. Both SH and NH responses are due to the increase in human-supplied chlorine to the stratosphere from ozone-destroying industrial chemicals now banned by the Montreal Protocol and its amendments and adjustments. The years with severe NH polar ozone loss are strongly correlated with NH winters of colder than average stratospheric temperatures, with the cold persisting until the sunlight returns in the springtime. These are the usual conditions in SH, but until recently have been uncommon the NH. An emerging explanatory paradigm is that greenhouse gas forcing has been cooling the NH polar lower stratosphere through dynamical and radiative mechanisms. This interaction of stratospheric chemistry and climate change could delay the expected recovery of stratospheric ozone by a number of decades.

Source: NASA

Figure 2b and 2c: Stratospheric ozone is depleted, as the level of active chlorine (ClO) rises, along the flight track of NASA's ER-2 high-altitude airborne laboratory

Figure 2b and 2c are two plots of measurements made by the instruments on board NASA's ER-2 high-altitude aircraft. These observations were made during field campaigns designed to explore in detail the health of the stratospheric ozone layer in the Antarctic, the Airborne Antarctic Ozone Experiment (AAOE, 1987), and in the Arctic, the SAGE III Ozone Loss and Validation Experiment (SOLVE, 1999-2000).

Figure 2b shows ozone and chlorine monoxide concentrations in the lower stratosphere (number of ozone (O_3) and chlorine monoxide (ClO) molecules per billion molecules of air (in blue and red, respectively) plotted against Greenwhich mean time during the AAOE ER-2 flight of September 16, 1987. Chlorine monoxide is the catalytically active radical responsible for severe polar ozone loss in the polar springtime. As the aircraft flight track crosses into the Antarctic polar vortex, the concentration of ClO goes up by a factor of 10 while ozone concentration decreases by more the 60% during this same period of the flight. The anti-correlation between ozone and ClO concentrations, exhibited in both the large-scale changes and the smaller fluctuations, is a strong indication that anomalous chlorine chemistry is responsible for the ozone depletion.

In Figure 2c, a similar plot has been constructed for an ER-2 flight in the Arctic during the SOLVE campaign conducted on March 11, 2000. Again we see the anti-correlation between ozone and ClO, this time as the plane flies into the Arctic polar vortex. With advances in measurement capability, we can now see additional important atmospheric species, chlorine nitrate ($ClONO_2$), the important reservoir molecule that stores the human-supplied chlorine in a form not directly destructive to ozone, and chlorine peroxide (Cl_2O_2), the dimer of ClO that is the source of the destructive ClO when the sunlight returns to the polar regions in the spring. These new observations, a benefit of technological advances since AAOE, help form a more complete picture of the complex chemistry of polar ozone loss, and have confirmed that this chemical ozone loss occurs in the Arctic.

Atmospheric chlorine, a result of human emissions, has been available in the atmosphere for many years, and conversion from the innocuous reservoir forms (such as chlorine nitrate) to the destructive radical forms (ClO) in the early polar spring has been a regular feature of springtime Antarctic chemistry. However, the extremely cold stratospheric temperatures, a necessary ingredient for this conversion, have also started in recent years to become a more regular feature in the Arctic springtime. This development, a possible consequence of increasing greenhouse gases, has the potential for significant impacts on the larger population of the Northern Hemisphere.

Source: NASA

Figure 3: TRMM Measures Sea Surface Temperature Through Clouds

This image was acquired over the tropical Atlantic Ocean and U.S. East Coast regions from Aug. 22 - Sept. 23, 1998. Cloud data were collected by the Geostationary Operational Environmental Satellite (GOES). Sea Surface Temperature (SST) data were collected aboard the NASA/NASDA Tropical Rainfall Measuring Mission (TRMM) satellite by the TRMM Microwave Imager (TMI). TMI is the first satellite microwave sensor capable of accurately measuring sea surface temperature through clouds, with results shown in this scene.

For years scientists have known there is a strong correlation between sea surface temperature and the intensity of hurricanes. But one of the major stumbling blocks for forecasters has been the precise measurement of those temperatures when a storm begins to form. In this scene, clouds have been made translucent to allow an unobstructed view of the surface. Notice Hurricane Bonnie approaching the Carolina Coast (upper left) and Hurricane Danielle following roughly in its path (lower right). The ocean surface has been falsely colored to show a map of water temperature—dark blues are around 75°F, light blues are about 80°F, greens are about 85°F, and yellows are roughly 90°F.

A hurricane gathers energy from warm waters found at tropical latitudes. In this image we see Hurricane Bonnie cross the Atlantic, leaving a cooler trail of water in its wake. As Hurricane Danielle followed in Bonnie’s path, the wind speed of the second storm dropped markedly, as available energy to fuel the storm dropped off. But when Danielle left Bonnie’s wake, wind speeds increased due to temperature increases in surface water around the storm.

As a hurricane churns up the ocean, it’s central vortex draws surface heat and water into the storm. That suction at the surface causes an upwelling of deep water. At depth, tropical ocean waters are significantly colder than water found near the surface. As they’re pulled up to meet the storm, those colder waters essentially leave a footprint in the storm’s wake which might last as long as two weeks. Forecasters can quantify the difference in surface temperatures between this footprint and the surrounding temperatures and use that information to better predict storm intensity. If another storm intersects with this cold water trail, it is likely to lose significant strength due to the fact that the colder water does not contain as much potential energy as warm water.

Source: TRMM Project, Remote Sensing Systems, and Scientific Visualization Studio, NASAGoddard Space Flight Center
Image may be viewed at:
http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=2918

Figure 4: Partitioning of Fossil-Fuel-Derived Carbon

Annual sources and sinks of atmospheric CO_2 as determined from atmospheric measurements of CO_2 and its isotopic ratio $^{13}C/^{12}C$. Red: fossil fuel combustion; blue: net uptake by the oceans (sometimes a source); green: net uptake by terrestrial ecosystems (a source due to tropical deforestation is included in these numbers); gray: the measured atmospheric increase, which is the sum of fossil fuel combustion and the exchanges with the oceans and terrestrial biosphere. The atmosphere increases every year.

Sources: Francey et al., Nature 373, 326-330 (1995); Tans et al. (private communication), updated from Ciais et al., Science 269, 1098-1102, (1995); see also www.cmdl.noaa.gov (Carbon Cycle Greenhouse Gases).

Figure 5: Potential Change in Wildfire Over the Conterminous U.S. Under Climate Change

The potential change in biomass consumed by fire is shown for two future climate scenarios as simulated by the MC1 dynamic general vegetation model. The future climate scenarios are from the Hadley Centre (HADCM2SUL) and the Canadian Climate Centre (CGCM1). Shown is the difference in the average annual carbon consumed by wildfire over the past 100 years compared to that simulated over the next 100 years under each scenario. The simulations indicate that climate change could lead to increased wildfire over much of the western U.S. The green colors show a reduction in biomass consumed by fire (kg dry matter per m^2/yr, while the yellows to reds indicate an increase in biomass consumed. Both the Hadley and Canadian future climate scenarios produce increases in biomass consumed in the West, particularly the Southwest and interior dry forests of the Great Basin. Increased precipitation under both scenarios throughout much of the West produces more vegetation, which adds fuel to relatively dry ecosystems. Occasional dry years, thus produce more and larger fires in the drier Southwest and Great Basin ecosystems. Increased drought stress in the Southeast forested region under the Canadian scenario also results in more and larger fires in that region. These fire impacts could begin occurring within the next few decades.

MC1 (MAPSS-CENTURY, version 1, Daly et al. 2000) is a dynamic general vegetation model, combining shifting vegetation distribution from the MAPSS biogeography model (Mapped Atmosphere-Plant-Soil System, Neilson 1995) with carbon and nutrient dynamics from the CENTURY biogeochemistry model (Parton et al. 1987). MC1 also contains a state-of- the-art, process-based fire model (Lenihan et al. 1998), which calculates fuel loads, moisture levels, and wildfire as a function of climate and vegetation characteristics. These results are for "potential dynamic vegetation" only and do not include land-management activities, such as fire suppression, forest harvest, or conversion to agriculture.

Source: Ronald P. Neilson (USDAForest Service); Dominique Bachelet, James M. Lenihan and Raymond J. Drapek (Oregon State University).

Bachelet, D., Neilson, R. P., Lenihan, J. M., and Drapek, R. J. (in review), "Climate Change Effects on Vegetation Distribution and Carbon Budget in the U.S." Submitted to: *Ecosystems*. (This journal paper is one of several submitted as a group to Ecosystems as background documents to the USGCRPNational Climate Assessment.)

References:

Daly C., Bachelet D., Lenihan J.M., Neilson R.P., Parton W., and Ojima D. 2000. Dynamic simulation of tree-grass interactions for global change studies. *Ecological Applications* 10(2) 449-469.

Lenihan J.M., Daly C., Bachelet D., and Neilson, R.P.. 1998. Simulating broad-scale fire severity in a dynamic global vegetation model. *Northwest Science* 72:91-103.
Neilson R.P. 1995. A model for predicting continental scale vegetation distribution and water bal-

ance. *Ecological Applications* 5(2):362-385.

Parton W.J., Schimel D.S., Cole C.V., and Ojima D. 1987. Analysis of factors controlling soil organic levels of grasslands in the Great Plains. *Soil Science Society of America* 51:1173-1179.

Figure 6: Northern Hemisphere Temperature Records for the Past 1,000 Years

Comparison of different Northern Hemisphere temperature reconstructions for the last 1000 years. Two different approaches were used to estimate temperature, one by Mann et al. (orange line) and two by Crowley and Lowery (CL, blue lines). The solid blue line is the best CLestimate; the dashed line represents an estimate incorporating lower resolution data that are not as reliable. The black line illustrates the instrumental record of temperature. Regardless of which approach was adopted, all reconstructions (plus two others for midlatitude summers) agree that late 20th century temperatures are the highest in at least the last 1000 years.

Source: Figure from Thomas J. Crowley and Thomas S. Lowery, "How Warm Was the Medieval Warm Period?" *Ambio*, Vol. 29, No. 1, Feb. 2000, pp. 51-54 (Royal Swedish Academy of Sciences). Figure also uses data from: (1) Mann, M.E., Bradley, R.S., and Hughes, M.K., 1999, "Northern Hemisphere Temperatures During the Past Millennium: Inferences, Uncertainties, and Limitations," *Geophys. Res. Lett*., 26, 759-762; and (2) Jones, P.D., New, M., Parker, D.E., Martin, S., and Rigor, I.G., 1999, "Surface Air Temperature and its Changes Over the Past 150 Years," *Rev. Geophys.*, 37, 173-199.