

whether proposed response strategies, such as reductions in emissions or efforts to enhance natural carbon sequestration processes, would produce economic or other effects more detrimental than the effects of climate change itself.

Science-based information is required to inform public debate on the wide range of climate and global change issues necessary for effective public policy and stewardship of natural resources. Developing the needed information will require addressing a wide-ranging set of fundamental science questions, significantly improving observations and data management, and implementing highly credible and transparent mechanism for conveying research results in ways that are useful for decisionmakers and the public.

### 1. The Issues for Science and Society

Environmental systems on Earth are changing constantly. The climate system is highly variable, with conditions varying significantly over the span of seasons, years, decades, and longer timescales. Fluctuations in the amount of energy emitted by the Sun, slight deviations in the Earth's orbit, volcanic injections of gases and particles into the atmosphere, and natural variations in ocean temperatures and currents, all cause variability and changes in climate conditions.

Against the backdrop of these natural forces, humans have become agents of environmental change, at least on timescales of decades to centuries, even as living standards for billions of people have improved tremendously. Emission of greenhouse gases and pollutants and extensive changes in the land surface (both tied to widespread development of modern living standards) have potential consequences for global and regional climate. They also influence air quality, the Earth's protective shield of stratospheric ozone, the distribution and abundance of water resources and many plant and animal species, and the ability of ecosystems to provide life-supporting goods and services.

The challenge is that discerning whether human activities are causing observed climatic changes and impacts requires detecting a small, decade-by-decade trend against the backdrop of wide temperature changes that occur on shorter timescales (seasons to years). A sound base of observations, as well as a solid understanding of how the Earth's environmental systems respond to different natural and human forces, is essential to detecting and attributing climate change to any specific cause. Currently, measurements taken at the Earth's surface, in various layers of the

atmosphere, in boreholes, in the oceans, and in other environmental systems such as the cryosphere (frozen regions) indicate that the climate is warming. Further, in *Climate Change Science: An Analysis of Some Key Questions* (NRC, 2001a), the National Research Council (NRC), the operational arm of the National Academy of Sciences (NAS), concluded that "the changes observed over the last several decades are likely mostly due to human activities, but we cannot rule out that some significant part of these changes is also a reflection of natural variability." The NRC report elaborates on this point:

Because of the large and still uncertain level of natural variability inherent in the climate record and the uncertainties in the time histories of the various forcing agents (and particularly aerosols), a causal linkage between the buildup of greenhouse gases in the atmosphere and the observed climate changes during the 20th century cannot be unequivocally established. The fact that the magnitude of the observed warming is large in comparison to natural variability as simulated in climate models is suggestive of such a linkage, but it does not constitute proof of one because the model simulations could be deficient in natural variability on the decadal to century time scale. The warming that has been estimated to have occurred in response to the buildup of greenhouse gases in the atmosphere is somewhat greater than the observed warming. At least some of this excess warming has been offset by the cooling effect of sulfate aerosols, and in any case one should not necessarily expect an exact correspondence because of the presence of natural variability.

Apparently contradicting the evidence of warming are inconsistencies in the observational record, particularly related to the differences between temperature trends measured at the surface and measurements taken from satellite observations of the lower- to mid-troposphere, which show no significant warming trends in the last two decades of the 20th century. Reconciling these differences and improving observational capabilities remains an important challenge with significant potential implications for decisionmaking.

But the issues extend beyond those of "detection and attribution" to projecting how climate and other related environmental conditions could change in the future. Confidence in such projections is tied to knowledge of basic climate processes and natural variability, the ability of climate models to represent accurately these processes, and the ability of models to represent

interactions of natural processes and any human-induced changes in the climate system.

Improving the capability to project future climate conditions would be of significant economic and social value. Consider, for example, the benefits of improved forecasts of the onset of the El Niño-Southern Oscillation (ENSO). ENSO is a large-scale climate oscillation in the equatorial Pacific Ocean that changes phase every few years. Its effects reverberate through the global climate system to affect precipitation and temperature in many regions of the world. Armed with a basic understanding of the processes involved, scientists intensified systematic observations and improved their models, and by the late 1990s could successfully forecast some conditions months in advance. While much additional work is required to improve ENSO forecasts, some climatic features can now be accurately predicted, with significant societal benefits. In the United States, decisionmakers are able to better estimate energy requirements, prepare for storms, manage water resources, anticipate where damage recovery efforts will be required, and foresee other potential impacts. In countries in South America, Africa, and other regions of the world, resource planners and managers are applying model results to develop agricultural plans, anticipate potential food surpluses and shortages, and prepare for other impacts. Such as planning has already reduced suffering and saved crops that would have otherwise been lost to drought and other ENSO effects.

Improving the ability to project long-term trends in climate and related conditions is important to understanding the effects of different types and amounts of natural and human forcing, such as that due to different levels of greenhouse gas and aerosol emissions. Therefore, anticipating how possible future forcing could affect the climate requires development of complex computer models that incorporate the many features of the climate system and their interactions. Such models have been under construction for decades, and require ongoing observations and research into basic processes to fuel their continued improvement. Already, large-scale features of climate can be simulated, but many significant uncertainties remain to be addressed. Current models project significantly different increases in the global average surface temperature, from approximately 1 °C during the 21st century to more than 5 °C during the