1 Introduction

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LOCAL IMPACTS AND RESPONSES TO CLIMATE CHANGE AND VARIABILITY

This book presents results from six research projects on the impacts of and responses to climate change and climate variability. The projects have been carried out over the course of more than three years as part of the US Global Change Research Program (US GCRP). Six separate research groups concentrated on a diverse set of topics – from changes in wildland fire dynamics to water use in agriculture, to air quality impacts on human health, to reliability of urban infrastructure systems – all under a wide range of climate, socioeconomic and management scenarios.

The six projects present integrated assessments of the impacts of climate change, and adaptive and mitigating responses to it at urban and regional scales. These assessments have contributed to knowledge of localized experiences of climate change, how it affects different sectors, how different stakeholders perceive its implications and are adapting to it, and how decision support systems can serve to promote dialogues between researchers, stakeholders and policy makers.

A key feature that unites the chapters in this book is their emphasis on the development of approaches for integrated assessments of the potential consequences of climate variability and change on the United States. Specific emphasis is given to assessments that integrate observed and anticipated dynamics ‘horizontally’ and ‘vertically’. Horizontal integration means analysis that brings together under a unified framework studies of impacts on, and responses by different sectors, such as water management, agricultural production and fisheries. Vertical integration means analysis from the level of climate systems through to socioeconomic impacts and responses.

Each of the six studies focuses on a finer geographic scale than is customary in integrated assessment research. Instead of broad global or continental-scale impacts, the research investigates consequences of climate change and variability at sub-national scales – such as individual river basins

and mountain ranges or specific metropolitan areas. All six studies explore major trends of both human-induced and natural climate change and variability for the subsequent 25 to 100 years. Their purpose is to generate insights into climate change impacts that are best assessed at those fine geographic scales and that are of potentially significant environmental, social and/or economic importance. Specific interest lies in impacts which, when considered jointly, are likely to identify important interactions that would alter conclusions about the vulnerability of a locality or resource to climate change (US GCRP 2004). The result of this research is a rich set of insights into methodologies for integrated assessments and a set of guides for investment and policy making.

The findings from the projects have clear policy relevance – they are targeted at the levels at which impacts of climate change and climate variability are felt most acutely and at which the interests and capacities for change lie (Wilbanks and Kates 1999). In several instances, the research projects have made extensive use of insights of stakeholders to facilitate information exchange and make findings relevant to the groups and communities who are ultimately expected to act on the findings that the research results generate. Where appropriate, stakeholder participation was made an integral part of the research projects – from problem definition to data collection and model development, to interpretation of results and response strategies. In the process, stakeholder involvement advanced knowledge both among stakeholders and researchers. In several cases, the projects began to leverage existing capacities and provided avenues for the research results to find application in actual environmental investment and policy making in the light of climate change and climate variability.

The following section briefly reviews the causes and ramifications of climate change and variability. Next we discuss responses that may be chosen to reduce anthropogenic impacts on the climate and to prepare for continued climate change and variability, and the roles that stakeholders may play in assessment of climate impacts and identification of responses. Following this discussion of climate impacts and responses, we place the chapters of this book in the broader context of impact assessment research.

A PRIMER ON CLIMATE CHANGE AND VARIABILITY

Physical and Biogeochemical Processes

Earth's climate is regulated, in part, by the presence of gases and particles in the atmosphere which are penetrated by short-wave radiation from the sun and which trap the longer-wave radiation that is reflecting back from Earth.

Collectively, those gases are referred to as greenhouse gases (GHGs) because they can trap radiation on Earth analogous to the glass of a greenhouse and have a warming effect on the globe. The main GHG is water, which affects the overall energy budget of the globe and – working like a steam heating system – funnels energy through the hydrological cycle across regions. Among the other most notable GHGs are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and chlorofluorocarbons (CFCs). Their sources include fossil fuel combustion, agriculture (e.g. releasing carbon from soils or methane from rice paddies and livestock) and industrial processes.

Each GHG has a different atmospheric concentration, mean residence time in the atmosphere, and different chemical and physical properties. As a consequence, each GHG has a different ability to upset the balance between incoming (solar) radiation and outgoing long-wave radiation. This ability to influence Earth's radiative budget is known as climate forcing. While some constituents of the atmosphere tend to reflect outgoing radiation back to Earth, the presence of aerosols in the atmosphere – released, for example, from coal burning power plants – leads to reflection of incoming radiation and thus has a cooling effect that may partly offset the warming effect of greenhouse gases (Wigley 1999).

Climate forcing varies across chemical species in the atmosphere. Spatial patterns of radiative forcing are relatively uniform for CO₂, CH₄, N₂O and CFCs because these gases are relatively long-lived and as a consequence become more evenly distributed in the atmosphere. In contrast, patterns of spatial radiative forcing of short-lived constituents, such as aerosols and ozone, are closely aligned with their sources of emissions (Wigley 1999).

Steep increases in atmospheric GHG and aerosol concentrations occurred since the Industrial Revolution. Those increases are unprecedented in Earth's history. As a result of higher GHG concentrations, global average surface temperature has increased by about 0.6°C during the 20th century with the 1990s as the warmest decade and 1998 the warmest year in the instrumental record since 1861 (IPCC 2001). These average global changes mask larger regional variations. For example, higher latitudes have warmed more than the equatorial regions (OSTP 1997).

A change in average temperatures may serve as a useful indicator of changes in climate, but it is only one of many ramifications of higher GHG concentrations. Since disruption of Earth's energy balance is neither seasonally nor geographically uniform; effects of climate disruption vary across space as well. For example, there has been a widespread retreat of mountain glaciers during the 20th century. Scientific evidence also suggests that there has been a 40 percent decrease in Arctic sea ice thickness during late summer to early autumn in recent decades and considerably slower decline in winter sea ice thickness, while Northern Hemisphere spring and

summer ice extent have decreased by about 10–15 percent since the 1950s (IPCC 2001).

Large-scale efforts are under way to explore the complex causal relationships between human activities and climate change, to put the various pieces of the climate change puzzle together on computers, and to explore likely future climate conditions under alternative assumptions about biogeochemical mechanisms and human activities (IPCC 2001). A range of projections has emerged from these computer models, which indicate that global averaged surface temperature is likely to increase by 1.4–5.8°C over the period 1990–2100, making the projected rate of warming much larger than the observed changes during the 20th century and very likely larger than rates of warming for at least the last 10 000 years, as indicated by data derived from the paleoclimate record (Wigley 1999; IPCC 2001). Relative to any fixed threshold, the frequency of daily, seasonal and annual warm temperature extremes will likely increase and the frequency of daily, seasonal and annual cold weather extremes will likely decrease. As in the recent past, changes in temperature could be accompanied by larger year-to-year variations in precipitation, regionally distinct rates of snow and ice cover changes, and changes in sea level (Klein and Nicholls 1999; IPCC 2001).

Climate change models increasingly show climate responses that are consistent across very differently specified models, and responses that are consistent with recent observations. These models, combined with long-term historical analyses and field experiments, indicate that humanity has indeed embarked on a real-world climate change experiment of monumental proportions. Although increasingly sophisticated, the climate models on which predictions are based continue to suffer from uncertainties in many underlying biogeochemical processes and our fundamental inability to adequately anticipate future human responses to climate change. Moreover, the models' specifications make it difficult to reflect potential discontinuities of climate processes and instead often only portray gradual changes (Schelling 1992; Kay and Schneider 1994). Examples of discontinuities include rapid changes in the direction of ocean currents that funnel significant amounts of energy among continents and fundamentally affect regional temperature, sea levels and precipitation patterns. A gradual increase in temperature may result in local climate conditions that are unfavorable to some local species, triggering a change in species composition. Changes in species composition may affect diverse ecosystem features such as soil properties or pollination of fruit trees or crop species, local food supply and livelihoods, impact water regimes and spread of disease, and trigger changes in society and the economy.

Implications for Natural and Managed Ecosystems

Higher temperatures can lead to dramatic changes in the snowfall and snowmelt dynamics in mountainous watersheds and lead to more rapid, earlier and greater spring runoff (Gleick 1987; Jeton et al. 1996; Leung and Wigmosta 1999). This effect was already identified, for example, in the 1980s for watersheds in California (Burn 1994; Lettenmaier et al. 1994; Lins and Michaels 1994).

The net loss of snow and ice cover, combined with an increase in ocean temperatures and thermal expansion of the water mass in oceans, resulted in a rise of global average sea level between 0.1 and 0.2 meters during the 20th century, which is considerably higher than the average rate during the last several millennia (Barnett 1984; Douglas 2001; IPCC 2001). However, the rate and extent of sea level rise varies across the globe, with some areas losing heights relative to the sea, such as the UK and Western France, while others, such as Scandinavia and Scotland, are emerging (Doornkamp 1998). In some cases anthropogenic land subsidence – e.g. from mining, natural gas or ground water extraction – significantly speeds up the potential effects of climate change-induced relative rise of sea levels (Gampolati et al. 1999).

The impacts of changes in ocean temperatures, sea levels and coastal storm patterns are broad and include displacement and loss of wetlands, inundation of low-lying property, increased erosion of the shoreline, expansion of flood zones, and salinization of surface water and groundwater. Since many large cities and their built infrastructure are located on the coast, impacts from sea level rise on urban areas and their hinterlands will be significant.

Increasingly, public moneys will need to be directed towards protection of coastal aquifers and other public water supply systems (Nicholls et al. 1999). Locally, new infrastructure is put in place to protect coastal zones from inundation. Hard structures influence banks, channels, sediment deposits and morphology of the coastal zone, leading to a loss of coastal ecosystems (Sorenson et al. 1984; Weggel 1989; Gleick and Maurer 1990; Leatherman 1994). For example, estimates of the fixed costs for dikes or levees built to protect against a one-meter rise in sea level range from \$150 to \$800 per linear foot (1990 dollars) (ASCE 1992). Beach nourishment, one of the most popular soft protection strategies, may solve the fundamental problem of diminishing sediment resources, especially during the early onset of erosion (Yohe and Neumann 1997). However the long-term effectiveness of beach nourishment remains uncertain due to an incomplete understanding of coastal processes and their responses to future climate change (Neumann et al. 2000; Ruth and Kirshen 2001).

Changes in heat fluxes through the atmosphere and oceans, combined with changes in reflectivity of the earth's surface and an altered composition

of GHGs and particulates in the atmosphere, may result in altered frequency and severity of climate extremes around the globe (Easterling et al. 2000; Meehl et al. 2000). For example, it is likely that there has been a 2–4 percent increase in the frequency of heavy precipitation events in the mid and high latitudes of the Northern Hemisphere over the latter half of the 20th century, while in some regions, such as Asia and Africa, the frequency and intensity of droughts have increased in recent decades (IPCC 2001). Furthermore, the timing and magnitude of snowfall and snowmelt may be significantly affected (Frederick and Gleick 2000), influencing, among others, erosion, water quality and agricultural productivity.

The proportion of total precipitation from heavy precipitation events has grown at the expense of moderate precipitation events (White and Howe 2002). As a result, flood magnitude and frequency tend to increase. Flooding is one of world's most costly and destructive natural disasters. It can seriously damage the built environment, paralyze transportation, interrupt energy distribution, impair wastewater plants, disrupt safe water supplies, pose threats to the health of species and humans, and even cause deaths or severe injury. For example, flooding in the UK during autumn 2000 caused an estimated £1 billion of damage and brought chaos to many parts of England and Wales (Zoleta-Nantes 2000). Floods in poor districts of Manila, Philippines, exposed people to respiratory infections, skin allergies and gastro-intestinal illnesses, with children most at risk (IPCC 2001)

The US, on average, is well-endowed with water. However fresh water can be a scarce resource virtually anywhere in the US at some time, especially in the urban areas of the arid and semiarid West (Alcamo et al. 2003). Despite the fact that detailed regional impacts of global climate change on future water supplies are notoriously uncertain (Frederick and Gleick 2000), consensus exists that climate change will affect the demand as well as the supply of water. It may substantially affect irrigation withdrawals (Doll and Siebert 2001). Net irrigation requirements per unit of irrigated area generally would decrease across much of the Middle East and northern Africa, whereas most irrigated areas in India and northern China would require more water (Boland 1997). The most sensitive areas in municipal water use to climate change are increased personal washing and increased use of water in gardens and for lawns (IPCC 2001). Industrial use for processing purposes is relatively insensitive to climate change. Demands for cooling water, in contrast, may be noticeably affected by climate change (Cruise et al. 1999; Frederick and Gleick 2000).

Climate change is also likely to affect water quality. Potential negative implications of climate change include lower flows, higher water temperatures, and increased storm surges. Lower flows in rivers will lead to increases in salinity levels to downstream water users and increase peak concentrations of metals and chemical compounds (IPCC 2001). Higher water temperatures

alone would lead to increases in concentrations of some chemical species but decreases in others, and would also encourage the growth of algal blooms, which can lead to oxygen deficits in the water, and thus directly affect riverine ecosystems and indirectly the economies which depend on them (Frederick and Gleick 2000).

Increases in the number of days with more intense precipitation could increase the agricultural and urban pollutants washed into streams and lakes, further reducing oxygen levels (Frederick and Gleick 2000). However current understanding of the hydrological impacts is insufficient to determine whether climate change would improve or worsen low-flow conditions. The direction as well as the magnitude of the climate impacts on lake quality from changes in precipitation and evaporation rates is also uncertain (Frederick and Gleick 2000), and as a consequence the direct and indirect impacts on urban areas, as well as the needs for planning and investments are uncertain as well.

Impacts on the Health of Species

Sea level rise and even modest changes in the frequency, severity and distribution of tropical storms and hurricanes, for example, may have substantial impacts on coastal wetland patterns and processes, many of which are part of urban ecosystems. These impacts will combine with other human uses of wetlands, for example, agriculture, industry and settlements as well as the harvesting of plants and animals (Barth and Titus 1984; Carter 1988; Day et al. 1993; Michener et al. 1997). Fragmentation of landscapes, combined with changing climate conditions, may reduce diversity of indigenous species and prove an increasing challenge to the ability of natural resource managers to maintain viable habitats and species populations (Peters and Darling 1985; Peters and Lovejoy 1992). Disruptions of existing ecosystem processes may be the result, for example, of disruption of seed dispersal, limitations on foraging ranges, infringement on species migration corridors, or increased competition with exotic species (Fahrig and Paloheimo 1988).

Cities are often the ports of first entry of exotic species – introduced deliberately for agricultural production, ornamental uses or as pets, and inadvertently introduced in ballast waters of ships, or with agricultural and other products. The conditions for longer-term establishment of populations of exotic species may improve with climate change, in part because present ecosystems become increasingly stressed and because the conditions that favored their presence at their place of origin may now be found in their new destination. Since different species are likely to respond differently to climate change, changes in species composition may result (Graham 1988); and even though the extent to which disturbance in general affects invasion of ecosystems by species previously considered exotic (Lodge 1993), the

abundance and diversity of exotic species is expected to increase (Sweeney et al. 1992).

Changes in precipitation and temperature regimes of urban areas also can lead to increased runoff of fertilizers and pesticides from intensively managed agricultural lands, parks and lawns; increased release of detergents and solvents from households and industry as a result of overwhelmed combined sewer overflow systems and water treatment plans; as well as runoff of oils and other petroleum products from roads, filling stations and parking lots during periods of heavy downpours. Hurricane-induced storm surges can have deleterious effects on inland freshwater and brackish wetlands and low-lying terrestrial areas because of the salt water, sediments and organic material that these surges carry inland (Blood et al. 1991; Knott and Matore 1991). Elevated salt levels may persist for more than a year, causing significant long-term changes in plant communities (Hook et al. 1991).

Climate asserts a significant influence on human health, as is evident by the geographic distribution and seasonal fluctuations of many diseases and causes of mortality (Tromp 1980). The connection between climate and human health strongly suggests that climatic change may alter the incidence and distribution of a wide range of diseases (Stone 1995) and mortality causes (Martens 1998). Public health researchers have, however, only recently begun to investigate the potential impacts of climate change and to identify adaptation strategies to reduce public health vulnerabilities to climate variability and change (Longstreth 1991; Kovats et al. 1999; Patz et al. 2000a; Patz et al. 2000b; WHO 2000; Watson and McMichael 2001).

Changes in temperature and precipitation regimes, as well as in the frequency of extreme weather events will combine to affect morbidity and mortality. From a societal perspective, changes in extreme events may be an even larger concern than changes in climatic averages (Katz and Brown 1992; Changnon 2000). Recent research indicates that the frequency of extreme heat-stress events in the US may already have increased (Gaffen and Ross 1998). The recognition of likely future increases in extreme temperature events in combination with the well-established sensitivity of mortality to temperature extremes has resulted in expanded public health research to examine the effects of climate change on temperature-related mortality.

Mid-latitudinal climates exhibit strong cyclical temperature and mortality patterns (Lerchl 1998). Higher temperatures are commonly associated with lower mortality rates and, conversely, lower temperatures associated with higher mortality rates. The seasonal nature of mortality rates has been observed, for example, in heart failure-related morbidity and mortality (Steward et al. 2002), coronary heart disease (Pell and Cobbe 1999), and incidence of stroke (Lanska and Hoffmann 1999; Oberg et al. 2000). Some research indicates that the magnitude of the seasonal mortality oscillation may be dampening due to advances in medicine and the ability of humans to

control their microenvironments (Seretakis et al. 1997; Lerchl 1998). Other researchers, however, find no evidence of a decline in the oscillation of seasonal mortality (Van Rossum et al. 2001).

Exposure to temperature extremes, such as those experienced during heatwaves and cold spells, is associated with rapid increases in mortality (Huynen et al. 2001). For example, more than 700 deaths in Chicago were attributed to the July 1995 heatwave (Semenza et al. 1996). Extreme heat events increase requirements on the cardiovascular system to produce physiological cooling which, in turn, may lead to excess deaths (Kilbourne 1997). In particular, infants, the elderly, individuals with pre-existing illnesses, the poor, the overweight and individuals living in urban areas are vulnerable to heat-related morbidity and mortality (Blum et al. 1998; Smoyer et al. 2000; CDC 2002; NWS 2002).

Extreme cold temperature events are also associated with increases in mortality rates, controlling for influenza (Kunst et al. 1993; Eurowinter Group 1997). Sharp increases in mortality during cold events have been identified, mainly due to thrombotic and respiratory disease (Donaldson and Keatinge 1997). Other mechanisms through which cold affects mortality include increases in blood pressure, blood viscosity and heart rate. Coronary and stroke mortality have been shown to be associated with cold temperatures in the US (Rogot and Padgett 1976). In Russia mortality is found to increase by 1.15 percent for each 1°C drop in temperature (Donaldson et al. 1998). A study of the impacts of temperature and snowfall on mortality in Pennsylvania found exposure to snow and temperatures below -7°C (19°F) to be dangerous to health (Gorjanc et al. 1999).

The effects of extreme temperature events on mortality are not solely determined by physiological variables, but also by the degree of acclimation of the local population to the regional climate regime (Kalkstein and Davis 1989; Kalkstein and Greene 1997; Smoyer 1998; Keatinge et al. 2000; Curriero et al. 2002). Acclimation entails the adaptation of communities to their environmental surroundings including behavioral patterns, societal fashions and customs such as dress and siestas, the thermal attributes of the local built infrastructure, availability of air conditioning and the health system's familiarity and ability to deal with weather-induced health conditions. In fact, research suggests that the sensitivity of mortality to extreme heat events has been decreasing over time, possibly as a result of societal adaptation (Davis et al. 2002).

The wide range of climatic environments inhabited by humans demonstrates our enormous ability to buffer ourselves from harsh macroenvironments. As an example, in Yakutsk, eastern Siberia – the coldest city in the world – no association is present between mortality rates and extremely cold temperatures (Donaldson et al. 1998). Yet, while acclimation enables a population to become less vulnerable to the prevalent weather

events, the population remains susceptible to weather events that occur relatively infrequently (events at the tails of the probability distribution). Therefore, the changes in the frequency of extreme events accompanying climate change need to be examined in order to identify adaptation strategies such that the population can adapt to the characteristics of the new climate regime.

Studies investigating the impacts of climate on human health often employ a place-based approach in consideration of the importance of local acclimation in determining a population's morbidity and mortality (Martens 1998; Smoyer 1998). Place-specific mortality responses to changes in temperature have been found to be present even after controlling for differences in meteorological, demographic and economic variables (Smoyer et al. 2000). In general, mortality rates of populations in cool climates are more sensitive to heat events, whereas populations in warmer climates have mortality rates more sensitive to cold events (Curriero et al. 2002). To illustrate, Keatinge finds that for every 1°C decrease in temperature below 18°C (64.4°F) mortality rates in south Finland increases by only 0.27 percent while in Athens, Greece mortality rates increase by 2.15 percent (Keatinge 1997). Likewise, Kalkstein and Davis (1989) evaluate temperature-related mortality rates in 48 US cities and find considerable variation in heat threshold levels with, for example, heat thresholds in Phoenix and Las Vegas equal or exceeding 109°F (43°C) whereas in Boston and Pittsburgh the thresholds are below 86°F (30°C). A city-level study examining minimum mortality temperatures in 11 large US cities finds temperature differences of up to 15°F (8°C) between cities (Curriero et al. 2002).

Elevated temperatures not only result in heat stress – most notably among the elderly and urban poor – but also exacerbate local air pollution and thus air quality-related respiratory health problems. While one portion of society may increase their demand for air conditioning, potentially contributing to local energy shortages and urban heat island effects, others may increasingly suffer.

Though the intragenerational health effects of climate change may on occasion be notable, a host of non-climate related issues do play a major, if not overwhelming role in the health of a population (Smoyer et al. 2000). These non-climate related issues include changes in a population's age structure and ethnic diversity; economic prosperity; access to air conditioning, fresh water and health care; and integrity of social networks. Increased mobility too may lead to the spread of diseases irrespective of climate change.

Interrelationships Between Local and Global Climatic Conditions

Changes in land cover and land use affect local climatic conditions. For example, urban and other land use changes account for as much as half of the

observed increases in the diurnal temperature range in the US (Kalnay and Cai 2003). Asphalt and concrete for roads, buildings and other structures necessary to accommodate growing populations absorb – rather than reflect – the sun's heat. The displacement of trees and shrubs eliminates the natural cooling effects of shading and evapotranspiration. Emission from energy conversion in power plants and combustion engines, especially when combined with reduced vegetation and larger areas with darker surfaces (Taha and Meier 1997) can raise air temperatures in a city by 2–8°F (1–3°C) (WMO 1984) and even change local temperature and precipitation patterns. The resultant 'heat island effect' is different from global warming, though it may exacerbate, and be exacerbated by climate variability and trends. Temperature increases and precipitation changes may stimulate further increases in energy use for cooling purposes, water pumping and more (US EPA 2000), and result in increased emissions of greenhouse gases, precursors of urban smog and contributors to changes in local environmental conditions.

Heat island effects have been observed most notably in urban areas. Changes in urban vegetation cover and albedo can be measured from space, using remote sensing, and correlated with climatologic information from urban weather stations. Time-series analyses, comparative time trends at one or more urban stations, comparisons along urban transects or among urban, suburban and rural stations, as well as between measurements on weekdays and weekends have helped document urban heat island effects for mega-cities across the US, including the New York Metropolitan area, Philadelphia, Washington DC, Pittsburg, Buffalo, Cleveland, Albany, Atlanta and Los Angeles (Bornstein and Lin 2000). Empirical evidence of urban heat island effects also exists for Turkey (Tayanc and Toros 1997), Austria (Böhm 1998), South Africa (Hughes and Balling 1996), Japan (Hadfield 2000), Singapore (Wong et al. 2003) and elsewhere. Although the name of urban heat island implies that it is solely an urban problem, research has shown urban heat islands are also becoming prevalent in small cities (Pinho and Orgaz 2000) and suburbs (Stone and Rodgers 2001).

Research into heat island effects suggests that heat island intensity decreases with increasing wind speed and increasing cloud cover (Ackerman 1985; Travis et al. 1987; Kidder and Essenwanger 1995; Figuerola and Mazzeo 1998; Magee et al. 1999; Morris et al. 2001; Unger et al. 2001). Heat island intensity most likely increases in the summer or warm half of the year (Schmidlin 1989; Klysik and Fortuniak 1999; Philandras et al. 1999) and tends to increase with increasing size of settlements and/or population (Park 1986; Yamashita et al. 1986; Hogan and Ferrick 1998; Torok et al. 2001). However several challenges to these generalizations have been mounted. For example, the greatest urban–rural difference detected in Birmingham, UK occurs in spring and autumn (Unwin 1980). Reykjavik, Iceland shows a tendency for negative heat island intensities (rural areas warmer than urban

areas) in summer and only weak development at other times of the year (Steinecke 1999). A larger rate of growth of Prague's urban heat island has been detected since the 1920s in winter and spring than in summer (Brazdil and Budikova 1999).

Heat island phenomena affect the environment and population in a number of ways, including through increased demand for cooling energy, degradation of air quality, threats to public health, the triggering of adverse meteorological events and indirectly promoting urban sprawl. Increased energy demand for cooling and air conditioning are a direct result of higher ambient temperatures and decreased air quality. Increased energy demand, coupled with increasing energy prices, can result in greater costs to consumers. It is estimated that as much as 15 percent of the electricity consumed for cooling within Los Angeles is utilized for the sole purpose of offsetting the effects of the urban heat island (Rosenfeld and Romm 1996). The annual energy cost of urban heat islands alone within the US is estimated to be approximately \$10 billion (Rosenfeld and Romm 1996).

Degradation of air quality, a result of increased emissions and higher ambient temperatures, may manifest itself in elevated concentrations of volatile organic compounds (VOCs), ground-level ozone and other air pollutants which may adversely affect the health of species, including humans (Cardelino and Chameides 1990). For example, ground-level ozone negatively impacts photosynthesis, inflames lung tissues and aggravates a range of respiratory ailments such as asthma. Researchers at the Lawrence Berkeley National Laboratory (LBNL) have estimated that each 1°F (0.6°C) rise in temperature over 70°F (21°C) increases the potential for ozone formation in Los Angeles by approximately 3 percent (US DOE 1996).

Heat islands may impact precipitation events either over or downwind of communities. Naturally occurring storms often intensify as they pass through cities. Moderate rainstorms may turn into full-blown thunder and lightning storms. The urban heat island in Atlanta, Georgia, for example, creates thunderstorms south of the city, which could cause urban flooding (NASA 1999). Urban heat islands have also been credited for torrential rains that wreaked havoc in Tokyo, Japan (Hadfield 2000).

Extreme temperature episodes, poor air quality and adverse meteorological conditions combine to worsen the habitability and comfort of human settlements in urban areas and may thus push people further away from those places. Yet, at the same time, complex and subtle relations among environmental conditions in urban and suburban areas may evade decision makers. For example, complex interactions of nitrogen oxides (NO_x) and urban ozone (O₃) may help reduce the potentially negative impacts of O₃ on plant growth in urban areas, while higher cumulative O₃ exposures and associated damages may result in suburban and rural areas with lower NO_x

concentrations (Gregg et al. 2003). As a result, urban heat island effects may make the problem of sprawl more intractable.

CLIMATE CHANGE AND RESPONSE STRATEGIES

Climate change may have many positive and negative, direct and indirect impacts on environmental, economic and social systems, and those impacts vary across space, time and various segments of an economy and society. Human settlement and resource use history is in large part characterized by adaptations to local environmental conditions. However, the scale and rate at which climate is changing poses new challenges for human response. Even if climate change impacts on socioeconomic systems are, by themselves, less than the combined non-climate impacts, their marginal effect could be significant, and they could noticeably compound existing stresses on resources, infrastructures and the institutions that govern their development and use.

To date the climate change debate has concentrated mainly on direct, negative impacts on current generations. Global response strategies have been identified to address what has been perceived, in essence, as a global problem. However, greater attention is being given recently to adaptation strategies, especially those that are beneficial even without climate change, and that lay the footprint for future development that is robust in the light of climate change. This section briefly reviews some of these strategies, concentrating on two broad categories – efforts to mitigate the greenhouse effect and measures to adapt to climate change. Both acknowledge that humans are not passive victims of climate change, and that simply insuring against adverse effects avoids the moral dimensions of climate change while jeopardizing the solvency of the insurance industry (Doornkamp 1998). The timing and extent of both mitigation and adaptation strategies are influenced by the tensions between the perceived needs, on the one hand, to resolve remaining uncertainties about climate change and, on the other hand, to be precautionary (Pearce 1991; Lemons and Brown 1995). The section closes with a discussion of the roles of stakeholders in climate impact assessment and identification of mitigation and adaptation strategies.

Mitigation

The United Nations Framework Convention on Climate Change (FCCC), which took effect in 1994, establishes as its goal the stabilization of GHG concentrations in the atmosphere ‘at a level that would prevent dangerous anthropogenic interference with the climate system’ (FCCC 1992). Towards

that goal, parties to the convention are obliged to develop national inventories of GHG sources and sinks, to promote and cooperate in the development and diffusion of technologies that can prevent GHG emissions, to promote conservation and enhancement of GHG sinks and reservoirs, to cooperate in preparing for adaptation, to share information, and to promote education, training and public awareness. In addition, industrialized countries are asked to provide developing countries with financial resources to meet their commitments under the Framework Convention. In their 1997 annual meeting in Kyoto, the parties signed a protocol laying out mechanisms to achieve the Framework Convention's goals (FCCC 1997).

Common to the various mechanisms laid out in the Framework Convention is the intent to provide incentives to countries for reducing emissions beyond their own targets and to collaborate internationally to globally achieve cost-effective emissions reductions. Specific focus is given to economic incentives, such as marketable emissions permits, and to new institutions, such as the Global Environment Facility (GEF) to foster environmentally friendly development.

Promotion of technological change plays a crucial role in the climate change and development context (Edmonds et al. 2000). On the one hand, some changes in technology help boost output and reduce cost of fossil fuels, or energy end use devices. These changes tend to increase GHG emissions. On the other hand, efficiency improvements and increases in knowledge tend to decrease GHG emissions and cost of mitigation. The issue is further complicated by the fact that efficiency improvements and increases in knowledge are often related to production rates. Higher production and sales generate revenues for investment in new technology, and more experience is often gained as cumulative production increases (Yelle 1979; Ruth 1993). Furthermore, as relative prices of products change and development occurs, consumer preferences are likely to change. Substitution among inputs into production and among consumer goods and leisure activities – all of which are related to where people live – are key determinants of GHG emissions (Jorgenson et al. 2000). Yet little attention is paid in current international agreements to the indeterminacy of the net effects of technology change, technology transfer and changes in preferences for GHG emissions.

A slew of other instruments are already available in many countries to achieve specific emissions goals, or help leverage the effectiveness of market-based climate change policies. Among these instruments are environmental labeling requirements for electricity sources, demand side management, tax credits and accelerated depreciation schedules, planning and siting preferences for renewable energy facilities, renewable energy portfolio standards, land reclamation and reforestation policies, trace gas collection requirements for landfills, and more. Many of these instruments have originally been implemented to achieve goals such as improvements of energy security,

achievements of higher ambient air quality, maintenance of ecosystem health and species diversity, or increased energy efficiency of households and firms. Coordination of their use may help further leverage GHG emission reductions (Dernbach 2000).

The Framework Convention's call for climate change mitigation has spurred a flurry of activities in government, industry and academia to identify for individual sectors of the economy how targets can be met and what the associated costs and benefits of alternative mitigation strategies are (Gwilliam 1993; Bernstein et al. 1999; Ruth et al. 2000). The debate quickly zeroed in on no-regrets strategies – strategies that are considered beneficial even if climate change were not an issue. Soon the debate proceeded to address how multiple policy instruments, ranging from taxes and subsidies to enhanced research and development efforts and regulatory instruments, could be applied simultaneously to more effectively improve efficiencies and reduce emissions (Ruth et al. 2000). More recently, the debate broadened to emphasize the wider range of social and environmental cost of energy use, aside from narrowly defined economic costs of energy conversion, GHG emissions and mitigation efforts (see for example Berry and Jaccard 2001). Solutions are being sought that transcend narrowly defined technological fixes and place technology policy in the broader context of development of adequate local capacity and essential support systems (Ruth et al. 2000). It is in this context that the relationships between urban development and climate change are being explored.

While social scientists and policy makers have begun to place climate change in the broader context of socioeconomic growth and development, natural scientists have begun to emphasize that non-CO₂ GHGs have caused most of the observed warming and that it may be more practical to reduce their emissions rather than emissions of CO₂, thus achieving climate goals more cost effectively (Hansen et al. 2000). How the confluence of these trends may be shaping climate change policy in the future is explored in more detail below, following a brief overview of the role of adaptation in dealing with climate change vulnerabilities.

Adaptation

Adaptation has often been perceived as the antidote to mitigation. Mitigation places emphasis on human capabilities to revert human-induced environmental trends. Adaptation, in contrast, means adjusting to climate change in order to reduce vulnerabilities of society and ecosystems, and is frequently perceived as an admission of an inability to noticeably revert climate change in a timely manner.

While successful mitigation depends on international cooperation, successful adaptation depends on local financial, technological and human

resources. By the same token, mitigation has global benefits and adaptation has local benefits. As a consequence, mitigation has frequently been promoted as *the* proper response to the global issue of climate change. Yet, pursuit of adaptation strategies is neither an admission that climate change cannot be reverted, nor need it be a mere treatment of symptoms instead of eradication of the cause of the problem. As we discuss in more detail below, mitigation and adaptation can go hand in hand, and spending scarce resources on appropriate policy and investment strategies may successfully advance both mitigation and adaptation. Both also are closely related to land use, urban development and associated socioeconomic and technological issues.

Adaptation strategies can range from sharing or bearing losses, to actively reducing or preventing vulnerabilities. Some adaptations may occur as reactions to specific climate events, such as installations of pumps in basements and tunnels in response to increased rainfall, or increased chlorination of drinking water to prevent spread of diseases at higher temperatures. Others may be anticipatory, such as implementing early warning systems for extreme weather events, adjusting agriculture and forest management practices, genetically engineering crops, redesigning bridges to reduce scour at high-flow events, laying power lines underground to minimize susceptibility to wind and ice storms, or establishing habitat corridors for migratory species (Frankhauser 1996).

Much like some mitigation strategies, various adaptations to climate can generate benefits to society even if climate does not change. Benefits are derived from reducing susceptibilities to extreme weather events (Burton 1996) and correcting economic inefficiencies (Toman and Bierbaum 1996). Examples include changes in settlement patterns along rivers and coastlines that can help maintain healthy ecosystems that provide habitat for species, contribute to water retention and act as flood controls. In some instances retreat from susceptible areas may not be possible, making protection through biological barriers such as reforested mangrove forests, or artificial barriers such as sea walls, all the more relevant (Al-Farouq 1996).

The complex interrelations among climate, ecosystem health and socioeconomic development seem to call for a sophisticated set of strategies to address undesired outcomes. The fact that social and economic systems change rapidly with noticeable responses by the climate and ecosystems requires special focus on those geographic areas and sectors of an economy and society that are among the key drivers behind those changes. Consequently, the following section concentrates on urban systems.

The Roles of Stakeholders

In integrated assessments of the effects of climate change, the term ‘science’ applies to more than the knowledge of the workings of physical processes. It

applies also to the interaction of social systems with ecosystems. As several of the studies discussed in this volume demonstrate, the impacts likely to be experienced in various locales will be determined by the adaptive and mitigative behavior of residents, policy makers and natural resource system managers – the many stakeholders in the public, private and non-profit realms.

If, as the US EPA program that funded these studies (STAR) intends, science is to achieve results, the science of integrated assessments of impacts of climate change at urban and regional scales – *as well as* the studies through which that science is developed – needs to be informed by stakeholders.

The type and extent of interactions between researchers and stakeholders and the extent to which the latter were integrated with the research projects over the period of time in which they were conducted varied from project to project, depending on research design. In some projects stakeholder input was critical to development of the research tools and decision support systems (DSSs).

Striking the right balance between stakeholder-involved science and stakeholder-informed science, without compromising the science itself, or using science to support agendas of select stakeholder groups, will be key to the future success of integrated assessments and decision support systems. This new kind of science will likely be guided by a high degree of social motivation, must meet the highest scientific standards, and will require a different organization, management and financial structure than is common in traditional environmental science. Several of the projects described in this book involved dozens of researchers and in some cases more than a hundred stakeholders – all with very different educational and professional backgrounds. All experienced long lead times to form effective research groups, faced severe budget constraints, and continued to run up against deadlines as new complexities in climate variability, climate change, impacts and response strategies were unveiled.

The managerial and leadership skills needed to insure project success is neither being taught to the next generation of scientists nor is it well-documented. Unrealized opportunities exist to build on the experiences laid out in this volume – and by similar projects around the world – to foster the dialog between science and society, and in the process of doing so to advance upon both.

OUTLINE OF THIS BOOK

The global climate change debate to date has heavily focused on anthropogenic emissions of greenhouse gases and the impacts of changing atmospheric concentrations of these gases on the stability of the climate system. Improved understanding of global climate change is used to point

towards necessary mitigation strategies to avoid adverse feedbacks from climate variability and change to human living conditions and ecosystem processes. Goals for global reduction in greenhouse gas concentrations are being translated into international policies to guide national and regional development.

More recently, efforts have been increased to explore adaptation strategies that may reduce or avoid impacts of climate variability and change on local economies and ecosystems. Mechanisms to foster the implementation of adaptation strategies are being explored, and in the process of these recent developments, social science and planning-oriented analyses and modeling have expanded to complement biogeochemical models of climate change. While many of these developments are still driven by global concerns, the studies presented in this book focus heavily on local impacts and actions to improve quality of life through improvements in economic, social and ecosystem health.

The following chapter presents an assessment by Hugo Hidalgo and his co-workers of the impacts of climate change on water allocation, water quality and salmon production in the San Joaquin river basin, the most agriculturally intensive region in California's Central Valley. The study cuts across spatial scales, ranging from region-specific water runoff simulations, which are captured by soil moisture accounting models and snow accumulation and ablation models, to the large-scale drivers of climate change, reflected in the runs of General Circulation Models. A water allocation model is used to capture and simulate monthly impacts on irrigation, water storage and associated activities. The results point towards critical relationships between precipitation and temperature, on the one hand, and water availability and quality especially for smaller reservoirs, on the other hand.

Chapter 3 concentrates on interactions among wildland fires, climate change and variability, as well as societal dynamics in the Southwest US. Not only does the study in this chapter build on cutting-edge research into the dynamics of fires, the ecosystems within which those fires occur and the communities affected by fires, it also builds on the knowledge held by stakeholders in the region to inform wildland fire management. The integrated assessment combines stakeholder participation with geographic information systems and models to identify physical, biological and socioeconomic conditions at the scale of individual mountain ranges, and derives alternative management options for a variety of 'what-if' scenarios. Interface design, information presentation and communication of uncertainties in data, model structures and functional relationships are shown to be particularly critical for successful implementation of DSSs as means of conducting research and promoting interaction between researchers and stakeholders. The chapter points towards further research that is needed on the nature and quality of interaction between researchers and stakeholders both during the development

and use of integrated assessments and DSSs to learn about, adapt to and mitigate the impacts of climate change.

Chapter 4 presents an integrated assessment of multiple-sector impacts on a Midwestern US watershed, produced by predicted changes in climate. The research used historical data, models, and standard and innovative analysis tools in conducting the assessment and was guided by early stakeholder input. The impact assessment focused on locations in the Mackinaw River watershed in Illinois. The project lays out sector specific responses to climate change; identifies relationships between and among sectors at each site, and among all sites; applies the impact analysis paradigm to identify and quantify local impacts produced by climate change; suggests mechanisms that produce an adaptive response to climate change while developing sector/system resilience to climate change impact; and integrates project results with a web-based decision support interface.

Chapter 5 presents an integrated assessment of the ecological and economic impacts of climate change on dryland grain production systems of the Northern Plains region of the US. The study explicitly captures adaptation actions as an endogenous driver, accounting for the fact that adaptation is typically not marginal but a clear deviation from past action. Special focus is given to the spatial and temporal variability in biophysical and economic conditions that result from different adaptation strategies.

In contrast to the preceding chapters, the remaining two studies of this book concentrate on urban systems. The research presented in Chapter 6, by Patrick Kinney and co-workers, focuses on potential public health impacts of climate change in the New York metropolitan area. This study presents an integration of global climate modeling with meso-scale meteorological modeling, land use/land cover change modeling and multi-scale air quality modeling to provide information about public health risks associated with changes in ambient air quality.

The Climate's Long-term Impacts on Metro Boston (CLIMB) project of Chapter 7 explores the potential impacts of climate change and variability on six major urban infrastructure systems and services: water supply and demand, water quality, flood control from riverine flooding and sea level rise, transportation, energy and public health. Analysis of each system and its services have been carried out under a wide range of climate, socioeconomic and technological scenarios, all of which are consistent across the sector-specific assessments and are integrated to explore adaptation options that help improve system performance. Like the research projects of the preceding chapters, the CLIMB project offers guidelines for environmental investment and policy strategies under a wide range of future scenarios. Like the companion studies in this book, the CLIMB project points towards future research and modeling needs to reduce uncertainties about climate impacts and responses. And, as in other chapters, it becomes clear that climate change

has both positive and negative effects on the system under investigation. Some of the negative effects may be quite dramatic, others – especially when addressed by adequate adaptation strategies – may turn out to be rather benign.

Despite remaining uncertainties about future climate, socioeconomic and technological conditions, a set of responses can be identified to help reduce impacts of climate change and variability. Many of the strategies described in the following chapters are robust – are largely unaffected by the detailed assumptions about the climate, biophysical or socioeconomic conditions – and make good environmental and economic sense even in the absence of climate change. The concluding chapter returns to these lessons in more detail.

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