White Paper

Tribal Climate Change Adaptation Options: A Review of The Scientific Literature

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Disclaimer:

This White Paper is based on a review of the scientific literature and summaries the physical changes in the climate due of Climate Change, the vulnerabilities of natural resources to these effects, and adaptation options that may be relevant to tribes in EPA Region 10. This White Paper does not represent the official EPA position on these topics, nor does it represent EPA policy or guidance. This White Paper is intended to be a 'living' document and will be updated and revised, as needed, in response to the needs of the R10 tribes, and to incorporate the most recent information on Climate Change in the scientific literature.

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1. Introduction

a. Purpose

Tribal Nations will likely be one of the most heavily impacted populations in North America by Climate Change due to several factors including an intimate, long-standing relationship with the land, limited and relatively non-diverse economies, poor energy security and transportation options, and the practice of subsistence activities in many communities. These characteristics of Tribal Nations make them more vulnerable or sensitive to the impacts of Climate Change. The most likely tribal resources effected by Climate Change are ecosystems, natural resource, human health and energy production and use. The purpose of this White Paper is to summarize information in published scientific literature that identify physical changes in the climate due to Climate Change, to identify vulnerabilities of tribal resources to Climate Change, and to identify adaptation options that tribes in Region 10 could implement to minimize the possible adverse effects to their life style and well being. This White Paper is intended to be a ‘living’ document and will be updated and revised, as needed, in response to the needs of the tribes, and to incorporate the most recent information on Climate Change adaptation in the scientific literature.

The impacts of Climate Change, as predicted by various models, includes increasing air temperatures, changing precipitation patterns, increasing severity of drought in arid climates, more frequent extreme weather events, earlier snow melt in the mountains, and rising ocean levels. These climatic impacts have the potential to adversely affect the biodiversity and function of ecosystems, availability and quality of natural resources, productivity of agriculture and forestry, human health, and societal infrastructure. A dynamic interaction exists between people and ecosystems and natural resources. People both directly and indirectly drive change in ecosystems and natural resources, and the changes in ecosystems and natural resources cause changes in human well-being. The effects of Climate Change are already being experienced in various regions of the world by various people, and the effects of Climate Change are predicted to increase as concentrations of man-made greenhouse gases (GHGs) in the atmosphere continue to increase. Adaptation is widely recognized in the literature as a tool to minimize the effects of Climate Change on ecosystems and natural resources.

b. Overview of Climate Change

“Climate” refers to long-term weather patterns, over periods of 30 years or more, that are typical of a region. When changes occur in the climate that a region experiences over a long period of time, it is called “Climate Change”. Scientific research has documented that the earth’s atmosphere has been warming since the pre-industrial period of the mid-18th century due to increasing concentrations of GHGs in the atmosphere. Naturally, the earth absorbs a portion of the sunlight it receives, which then heats the planet, and reflects some of the sunlight back into space. As the earth is heated by the sunlight, it also radiates a portion of this heat back into the atmosphere in the form or infrared radiation. Greenhouse gases warm the earth system by absorbing a portion of the outgoing radiation from the planet and re-radiating some of the absorbed radiation back towards the Earth’s surface. As the overall energy of the system increases, the surface and lower atmospheric temperatures increase, too. Many greenhouse gases occur naturally, and without them the earth surface would be on average 60 degrees Fahrenheit colder (Wallace and Hobbs, 2006).

The major greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and various halocarbons. Water vapor also acts as a greenhouse gas, but since human activities contribute inconsequentially to its atmospheric concentration, it is neglected as a greenhouse gas and instead considered as part of the climate system feedbacks. Aerosols (also called particulate matter, PM, or particles) are another anthropogenic influence. In contrast to greenhouse gases which warm the planet, most aerosols reflect incoming solar radiation and act as a cooling agent. Black carbon (for our purposes, equal to "elemental carbon" and "light absorbing carbon") efficiently absorbs solar radiation and warms the atmosphere (IPCC, 2007a).

Individual greenhouse gases and aerosols differ in their effectiveness. For example, each methane molecule is 20 times for effective at warming the atmosphere than each carbon dioxide molecule. However, since carbon dioxide is present in higher concentrations and lasts longer in the atmosphere, it is a more important greenhouse gas than methane. Current emissions of carbon dioxide will be influencing our climate long after current methane emissions (IPCC, 2007a).

The variable lifetimes of greenhouse gases and aerosols in the atmosphere have a couple very important implications for mitigation strategies. Emission reductions for short-lived gases like methane will slow the rate of warming in a matter of years to decades. Emission reductions for carbon dioxide, while more important in the long run, will not be evident for several decades. Thus, immediate implementation of technology to reduce warming agents like methane and black carbon can give societies some "breathing room" while strategies for reducing all agents including carbon dioxide are being put in place. In addition, most greenhouse gases mix uniformly across the globe and present a classic tragedy of the commons, while black carbon aerosol has a short enough atmospheric life time that emissions from a region warm that area more than the rest of the globe (Menon et al., 2002). Even areas with relatively low global emissions, such as the four states in Region 10, have some – albeit small – influence on their own corner of the world. This is especially the case for black carbon in the Arctic since its effect is magnified by deposition on snow and ice (Hansen and Nazarenko, 2004).

Studies that rigorously quantify the effect of different external influences on observed changes conclude that most of the recent global warming is very likely due to human generated increases in GHG concentrations. The Intergovernmental Panel on Climate Change (IPCC) concluded that it is unequivocal that the average temperature of Earth's surface has warmed recently, and it is very likely (greater than 90% probability) that most of this global warming is due to increased concentrations of human generated greenhouse gases. A large number of climate model simulations show that natural factors alone cannot explain the observed warming in the second half of the 20th century of Earth's land masses and oceans, or that of the North American continent. On the other hand, simulations that include human factors are able to reproduce important large-scale features of the recent changes. Several lines of evidence, including the correlation between GHG emissions, atmospheric CO_2 concentrations, and average global surface temperature, point to a strong human influence on climate. Although these individual lines of evidence vary in their degrees of certainty, when considered together they provide a compelling and scientifically sound explanation of the changes to Earth's climate, including changes in surface temperature, ice extent, and sea level rise, observed at global and continental scales over the past few decades (IPCC, 2007a).

In addition to average temperatures, recent work shows that human activities have also likely influenced extremes in temperature. Many indicators of climate extremes, including the annual numbers of frost days, warm and cold days, and warm and cold nights, show changes that are consistent with warming. For example, there is evidence that human-induced warming may have substantially increased the risk of extremely warm summer conditions in some regions. Discernible human influences extend to additional aspects of climate, including the recent decreases in Arctic sea ice extent, patterns of sea level pressure and winds, and the global-scale pattern of land precipitation (IPCC, 2007a).

c. Adaptation

"Adaptation" is defined as an adjustment in natural or human systems to a new or changing environment. Adaptation to Climate Change refers to adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Planned adaptation, or proactive adaptation, refers to strategies adopted by society to manage systems based on an awareness that conditions are about to change or have changed, such that action is required to meet management goals (IPCC, 2001b).

Several concepts related to adaptation are important to fully appreciate the need for successful anticipatory adaptation to climate-related stresses, as well as the opportunities and barriers to adaptation. The first of these is *vulnerability*. Vulnerability is typically viewed as the propensity of a system or community to experience harm from some stressor as a result of (a) being *exposed* to the stress, (b) its *sensitivity* to it, and (c) its *potential or ability to cope* with and/or *recover* from the impact. Key vulnerabilities can be assessed by exploring the magnitude of the potential impacts, the timing (now or later) of impacts, the persistence and reversibility (or irreversibility) of impacts, the likelihood of impacts and confidence of those estimates, the potential for adaptation, the distributional aspect of impacts and vulnerabilities (disadvantaged sectors or communities), and the importance of the system at risk. Of particular importance here is a system's *adaptive capacity*: the ability of a system or region to adapt to the effects of climate variability and change. How feasible and/or effective this adaptation will be depends on a range of characteristics of the ecological system, such as topography and micro-refugia, soil characteristics, biodiversity; pre-existing stresses, such as the presence of invasive species or loss of foundation species or fragmentation of the landscape; the status of the local ecosystem, *e.g.*, early to late successional and its intrinsic "inertia" or responsiveness; and on characteristics of the social system interacting with, or dependent on, the ecosystem (CCSP, 2008b, Chapter 3).

Ecosystems provide many goods and services that are of vital importance for the functioning of the biosphere, and provide the basis for the delivery of tangible benefits to human society. According to the Millennium Ecosystem Assessment (2003), these services can be divided into four categories: provisioning (e.g., food, fiber, and fuel), regulating (e.g., air and water quality maintenance, climate regulation), and cultural (spiritual and aesthetic values), and supporting (e.g., carbon sequestration, soil formation and retention, nutrient cycling, water cycling). Many ecosystems are vulnerable to adverse effects due to Climate Change. Such vulnerable ecosystems will likely produce poorer quality goods and services than ecosystems that are resilient to Climate Change.

The purpose of adaptation strategies is to reduce the risk of adverse outcomes through activities that increase the resilience of ecological systems to Climate Change stressors. A stressor is defined as any physical, chemical, or biological entity that can induce an adverse response. Resilience refers to the amount of change or disturbance that can be absorbed by a system before the system is redefined by a different set of processes and structures. Potential adverse outcomes of Climate Change may vary for different ecosystems, depending on their sensitivity to climate stressors and their intrinsic resilience to climate change. The “effectiveness” of an adaptation option that is designed to boost ecosystem resilience will thus be case-dependent, and can be measured only against a desired ecosystem condition or natural resource management goal.

2. Impacts of Climate Change

The following sections focus on potential Climate Change impacts to North America and the United States. For current and predicted climate change impacts specific to the Pacific Northwest, see Appendix A, an excerpt from "State of Climate Modeling: Contribution to Region 10's Action Plan for Energy and Climate Change" (Elleman et al., 2007).

a. Rising Global Temperature

Global climate is warming, as is now evident from direct observations of increases in global average air and ocean temperatures, inferences from widespread melting of snow and ice, rising global average sea level, and other indicators. As determined by the IPCC (IPCC, 2001a), the globally averaged temperature rise over the last 100 years (1906–2005) is 1.33 ± 0.32 °F when estimated by a linear trend. The rate of global warming over the last 50 years (0.23 ± 0.05 °F per decade) is almost double that for the past 100 years (0.13 ± 0.04 °F per decade). In addition, as assessed by the IPCC (IPCC, 2001a), it is very likely that average Northern Hemisphere temperatures during the second half of the 20th century were warmer than any other 50-year period in the last 500 years, and it is likely that this 50-year period was the warmest Northern Hemisphere period in the last 1,300 years. Land regions have warmed faster than the oceans—about double the ocean rate after 1979 (more than 0.49 °F per decade). The greatest warming is at high northern latitudes during spring and winter.

Like global average temperatures, U.S. average temperatures also increased during the 20th and into the 21st century, according to federal statistics. The last decade is the warmest in more than a century of direct observations in the U.S. Average temperatures for the contiguous U.S. have risen at a rate near 0.6 °F per decade in the past few decades. But warming is not distributed evenly across space or time. The number of U.S. heat waves has been increasing since 1950, though it should be noted that the heat waves associated with the severe drought of the 1930s remain the most severe in the U.S. historical record. There have also been fewer unusually cold days during the last few decades, and the last 10 years have seen fewer severe cold waves than for any other 10-year period in the historical record, which dates back to 1895 (IPCC, 2001a).

The IPCC (IPCC, 2001a) concluded that continued greenhouse gas emissions at or above current rates are expected to cause further warming and to induce many changes during the 21st century that will very likely be larger than those of the 20th century. For the next 20 years, a globally averaged warming of about 0.3 to 0.4 °F per decade is projected for a range of scenarios of greenhouse gas emissions. Through about 2030, there is little difference in the warming rate projected using a variety of emissions scenarios. Possible future variations in natural factors, such as a large volcanic eruption, could introduce variations to this long-term warming projection. Even if atmospheric greenhouse gas levels remained constant, the globally averaged warming would continue to be nearly 0.2 °F per decade during the next two decades because of the time it takes for the climate system, particularly the oceans, to reach equilibrium.

By the mid-21st century, the effect of the choice of emission scenario becomes more important in terms of the magnitude of the projected warming, with model projections of increases in globally averaged temperature of approximately 2 to 3 °F for several of the IPCC scenarios. According to the IPCC (IPCC, 2007b), all of North America is very likely to warm during this century, and to warm more than the global average increase in most areas. Nearly all the models assessed by the IPCC project that the average warming in the U.S. will exceed 3.6 °F, with 5 out of 21 models projecting that average warming will exceed 7.2 °F by the end of the century. The largest warming in the U.S. is projected to occur in winter over northern parts of Alaska. In regions near the coasts, the projected warming during the 21st century is expected to be less than the national average. According to CCSP (CCSP, 2008a), abnormally hot days and nights and heat waves are very likely to become more frequent, and cold days and cold nights are very likely to become much less frequent over North America.

b. Precipitation, runoff, drought

According to historical records, the total annual precipitation over the contiguous U.S. has increased at an average rate of 6% per century from 1901 to 2005, with significant variability over time and by region. The greatest increases in precipitation were in the northern Midwest and the South. The contiguous U.S. has had statistically significant increases in heavy precipitation, primarily during the last three decades of the 20th century and over the eastern parts of the country. In keeping with the overall precipitation trends, most of the U.S. has experienced decreases in drought severity and duration during the second half of the 20th century. However, a severe drought has affected the southwestern U.S. from 1999 through 2007. The southeastern U.S. has also recently experienced severe drought. On a longer time scale, reconstructions of droughts using tree rings and geological evidence show that much more severe droughts have occurred over the last 2,000 years than those that have been observed in the instrumental record, notably, the Dust Bowl drought of the 1930s and extensive drought in the 1950s (IPCC, 2007b).

Streamflow in the eastern U.S. has increased 25% in the last 60 years. However, it has decreased by about 2% per decade in the central Rocky Mountain region over the past century. The annual peak of streamflow in snowmelt-dominated western mountains is now generally occurring at least a week earlier than in the middle of the 20th century. Winter stream flow is increasing in basins with seasonal snow cover. The fraction of annual precipitation falling as rain (rather than snow) increased in the last half century(IPCC, 2007b).

Most climate models project an increase in winter precipitation in the northern tier of states and a decrease in portions of the Southwest during the 21st century. Summer precipitation is projected to decrease in the Northwest of the contiguous U.S. and increase in Alaska; it is uncertain whether summer precipitation will increase or decrease over large portions of the interior U.S. In northern regions of North America, the magnitude of precipitation increase is projected to be greatest in autumn, whereas winter precipitation is projected to increase by the largest fraction relative to its present amount. A majority of climate models generally show winter increases in northern regions and summer decreases in western and southern regions. In the 21st century, precipitation over North America is projected to be less frequent but more intense. This increase in storminess is projected to be accompanied by greater extreme wave heights along the coasts (IPCC, 2007b).

c. Extreme Weather Events

Whether they have become drier or wetter, many land areas have likely experienced an increase in the number and intensity of heavy precipitation (5 cm of rain or more) events. About half of the increase in total precipitation observed nationally has been attributed to the increase in intensity of storms. Heavy precipitation events are the principal cause of flooding in most of the U.S. The general warming trend observed in most of the U.S. was also accompanied by more frequent hot days, hot nights, and heat waves. Furthermore, higher temperatures along with decreased precipitation have been associated with observations of more intense and longer droughts over wider areas since the 1970s. Within the U.S., the western region has experienced longer and more intense droughts, but these appear also to be related to diminishing snow pack and consequent reductions in soil moisture. In addition to the factors above, changes in sea-surface temperatures and wind patterns have been linked to droughts (IPCC, 2007b).

d. Snowpack and Ice

The snow-covered area of North America, during the period of November to January, increased from 1915 to 2004, due to increases in precipitation. However, spring snow cover in mountainous regions of the western U.S. generally decreased during the latter half of the 20th century. The IPCC (IPCC, 2007b) determined that this latter trend is very likely due to long-term warming, with potential influence from decadal-scale natural variability. In Alaska, where the warming has been particularly pronounced, the permafrost base has been thawing at a rate of up to 1.6 inches per year since 1992.

The date that rivers and lakes freeze over has become later (average rate of 5.8 ± 1.6 days per century) and the ice breakup date has happened earlier (average rate of 6.5 ± 1.2 days per century), according to an analysis of 150 years of available data for the Northern Hemisphere. In addition to these changes in seasonal ice and snow, glaciers have been losing mass in the northwestern U.S. and Alaska, with losses especially rapid in Alaska after the mid-1990s (IPCC, 2007b).

Snow cover is projected to continue to decrease as the climate warms. According to the IPCC (IPCC, 2007b), results from multiple model simulations indicate that an Arctic Ocean free of summer ice is likely by the end of the century, with some models suggesting that this could occur as soon as 2040. Glaciers and terrestrial ice sheets are projected to continue to lose mass as increases in summertime melting outweigh increases in wintertime precipitation. This will contribute to sea level rise. Widespread increases in thaw depth are projected over most permafrost regions.

e. Ocean levels and pH

There is strong evidence that global average sea level gradually rose during the 20th century, after a period of little change between A.D. 0 and A.D. 1900, and is currently rising at an increased rate. The global average rate of sea level rise from 1993 to 2003 was 0.12 ± 0.03 inches per year, significantly higher than the 20th century average rate of 0.067 ± 0.02 inches per year. Two major processes lead to changes in global mean sea level on decadal and longer time scales, and each currently account for about half of the observed sea level rise: expansion of the ocean volume due to warming, and the exchange of water between the oceans and land reservoirs of water, including glaciers and land ice sheets (IPCC, 2007b).

U.S. sea level data from at least as far back as the early 20th century show that along most of the U.S. Atlantic and Gulf Coasts, sea level has been rising 0.8 to 1.2 inches per decade. The rate of relative sea level rise varies from a few inches per decade along the Louisiana Coast (due to sinking land) to a drop of a few inches per decade in parts of Alaska (due to rising land). The IPCC (IPCC, 2007b) projects that global sea level will rise between 7 and 23 inches by the end of the century (2090–2099) relative to the base period (1980–1999). According to the IPCC, the average rate of sea level rise during the 21st century is very likely to exceed the 1961–2003 average rate. Storm surge levels are expected to increase due to projected sea level rise. Combined with non-tropical storms, rising sea level extends the zone of impact from storm surge and waves farther inland, and will likely result in increasingly greater coastal erosion and damage. Potential accelerations in ice flow of the kind recently observed in some Greenland outlet glaciers and West Antarctic ice streams could substantially increase the contribution from the ice sheets to sea level, a possibility not reflected in the aforementioned projections. Understanding of these processes is limited and there is no consensus on their magnitude and thus on the upper bound of sea level rise rates.

Between 1750 and 1994, the oceans absorbed about 42% of all emitted carbon dioxide (CO_2). As a result, the total inorganic carbon content of the oceans increased by 118 ±19 Gigatons of carbon over this period and is continuing to increase. This increase in oceanic carbon content caused calcium carbonate ($CaCO_3$) to dissolve at greater depths and led to a 0.1 unit decrease in surface ocean pH from 1750–1994. The rate of decrease in pH over the past 20 years accelerated to 0.02 units per decade. A decline in pH, along with the concomitant decreased depth at which calcium carbonate dissolves, will likely impair the ability of marine organisms to use carbonate ions to build their shells or other hard parts (IPCC, 2007b).

3. Criteria to Determine Vulnerabilities to Climate Change

There are seven criteria identified in the IPCC fourth assessment report on Climate Change (IPCC, 2007b) that may be used to identify key vulnerabilities in ecosystems and other natural systems to Climate Change. These criteria are: magnitude, timing, persistence and reversibility, likelihood and confidence, potential for adaptation, distribution, and the importance of a vulnerable system.

Magnitude

Impacts of large magnitude are more likely to be evaluated as ‘key’ than impacts with more limited effects. The magnitude of an impact is determined by its scale (e.g., the area or number of people affected) and its intensity (e.g., the degree of damage caused). Therefore, many studies have associated key vulnerabilities or dangerous anthropogenic interference primarily with large-scale geophysical changes in the climate system. Various aggregate metrics are used to describe the magnitude of climate impacts. The most widely used quantitative measures for climate impacts are monetary units such as welfare, income or revenue losses, costs of anticipating and adapting to certain biophysical impacts such as a large sea-level rise, and estimates of people's willingness to pay to avoid (or accept as compensation for) certain climate impacts.

Another aggregate, non-monetary indicator of magnitude is the number of people affected by certain impacts such as food and water shortages, morbidity and mortality from diseases, and forced migration. Climate impacts are also quantified in terms of the biophysical end-points, such as agricultural yield changes and species extinction numbers or rates. For some impacts, qualitative rankings of magnitude are more appropriate than quantitative ones. Qualitative methods have been applied to reflect social preferences related to the potential loss of cultural or national identity, loss of cultural heritage sites, and loss of biodiversity.

Timing

A harmful impact is more likely to be considered 'key' if it is expected to happen soon rather than in the distant future. Climate Change in the 20th century has already led to numerous impacts on natural and social systems, some of which may be considered 'key'. Impacts occurring in the distant future which are caused by nearer-term events or forcings (i.e., 'commitment'), may also be considered 'key'. An often-cited example of such 'delayed irreversibility' is the disintegration of the West Antarctic ice sheet: it has been proposed that melting of ice shelves in the next 100 to 200 years may lead to gradual but irreversible deglaciation and a large sea-level rise over a much longer time-scale. Debates over an 'appropriate' rate of time preference for such events (i.e., discounting) are widespread in the integrated assessment literature, and can influence the extent to which a decision-maker might label such possibilities as 'key'.

Another important aspect of timing is the rate at which impacts occur. In general, adverse impacts occurring suddenly (and surprisingly) would be perceived as more significant than the same impacts occurring gradually, as the potential for adaptation for both human and natural systems would be much more limited in the former case. Finally, very rapid change in a non-linear system can exacerbate other vulnerabilities (e.g., impacts on agriculture and nutrition can aggravate human vulnerability to disease), particularly where such rapid change curtails the ability of systems to prevent and prepare for particular kinds of impacts.

Persistence and reversibility

A harmful impact is more likely to be considered 'key' if it is persistent or irreversible. Examples of impacts that could become key due to persistence include the emergence of near-permanent drought conditions and intensified cycles of extreme flooding. Examples of climate impacts that are irreversible, at least on time-scales of many generations, include changes in regional or global biogeochemical cycles and land cover, the loss of major ice sheets; the shutdown of the meridional overturning circulation, the extinction of species, and the loss of unique cultures. The latter is illustrated by small Island Nations at risk of submergence through sea-level rise and the necessity for the Inuit of the North American Arctic to cope with recession of the sea ice that is central to their socio-cultural environment.

Likelihood and confidence

Likelihood of impacts and our confidence in their assessment are two properties often used to characterize uncertainty of Climate Change and its impacts. Likelihood is the probability of an outcome having occurred or occurring in the future; confidence is the subjective assessment that any statement about an outcome will prove correct. Uncertainty may be characterized by these properties individually or in combination. An impact characterized by high likelihood is more apt to be seen as 'key' than the same impact with a lower likelihood of occurrence. Since risk is defined as consequence (impact) multiplied by its likelihood (probability), the higher the probability of occurrence of an impact the higher its risk, and the more likely it would be considered 'key'.

Potential for adaptation

To assess the potential harm caused by climate change, the ability of individuals, groups, societies and nature to adapt to or ameliorate adverse impacts must be considered. The lower the availability and feasibility of effective adaptations, the more likely such impacts would be characterized as 'key vulnerabilities'. The potential for adaptation to ameliorate the impacts of Climate Change differs between and within regions and sectors. There is often considerable scope for adaptation in agriculture and in some other highly managed sectors. There is much less scope for adaptation to some impacts of sea-level rise such as land loss in low-lying river deltas, and there are no realistic options for preserving many endemic species in areas that become climatically unsuitable. Adaptation assessments need to consider not only the technical feasibility of certain adaptations but also the availability of required resources (which is often reduced in circumstances of poverty), the costs and side-effects of adaptation, the knowledge about those adaptations, their timeliness, the incentives for people to actually implement them, and their compatibility with individual or cultural preferences.

Distribution

The distribution of climate impacts across regions and population groups raises important equity issues. The literature concerning distributional impacts of Climate Change covers an increasingly broad range of categories, and includes, among others, income, gender and age, in addition to regional, national and sectoral groupings. Impacts and vulnerabilities that are highly heterogeneous or which have significant distributional consequences are likely to have higher salience, and therefore a greater chance of being considered as 'key'.

Importance of the vulnerable system

A salient, though subjective, criterion for the identification of 'key vulnerabilities' is the importance of the vulnerable system or system property. Various societies and peoples may value the significance of impacts and vulnerabilities on human and natural systems differently. For example, the transformation of an existing natural ecosystem may be regarded as important if that ecosystem is the unique habitat of many endemic species or contains endangered charismatic species. On the other hand, if the livelihoods of many people depend crucially on the functioning of a system, this system may be regarded as more important than a similar system in an isolated area (e.g., a mountain snowpack system with large downstream use of the melt water versus an equally large snowpack system with only a small population downstream using the melt water).

4. Climate Change Vulnerabilities

a. Ecosystems and Biodiversity (IPCC, 2007, chapter 19)

There is high confidence that Climate Change will result in extinction of many species and reduction in the diversity of ecosystems. Climate Change vulnerability of ecosystems and species is partly a function of the expected rapid rate of Climate Change relative to the resilience of many such systems. However, multiple stressors are significant in ecosystems, as vulnerability is also a function of human development, which has already substantially reduced the resilience of ecosystems and makes many ecosystems and species more vulnerable to Climate Change through blocked migration routes, fragmented habitats, reduced populations, introduction of alien species and stresses related to pollution.

There is very high confidence that regional temperature trends are already affecting species and ecosystems around the world, and it is likely that at least part of the shifts in species observed to be exhibiting changes in the past several decades can be attributed to human-induced warming. Thus, additional climate changes are likely to adversely affect many more species and ecosystems as global mean temperatures continue to increase. For example, there is high confidence that the extent and diversity of polar and tundra ecosystems is in decline and that pests and diseases have spread to higher latitudes and altitudes.

Each additional degree of warming increases disruption of ecosystems and loss of species. Individual ecosystems and species often have different specific thresholds of change in temperature, precipitation or other variables, beyond which they are at risk of disruption or extinction. Looking across the many ecosystems and thousands of species at risk of climate change, a continuum of increasing risk of loss of ecosystems and species emerges in the literature as the magnitude of Climate Change increases, although individual confidence levels will vary and are difficult to assess. Nevertheless, further warming is likely to cause additional adverse impacts to many ecosystems and contribute to biodiversity losses.

Several simulations indicate that, over the 21st century, warming will lengthen growing seasons, sustaining forest carbon sinks in North America, despite some decreased sink strength resulting from greater water limitations in western forests and higher respiration in the tropics. Impacts on ecosystem structure and function may be amplified by changes in extreme meteorological events and increased disturbance frequencies. Ecosystem disturbances, caused either by humans or by natural events, accelerate both loss of native species and invasion of exotics. It is projected that the areal extent of drought-limited ecosystems will increase by 11%/ºC warming in the continental U.S. By the end of the 21st century, ecosystems in the north-east and south-east U.S. will likely become carbon sources, while the western U.S. remains a carbon sink.

b. Forests

Overall forest growth in North America will likely increase modestly (10-20%) as a result of extended growing seasons and elevated CO2 over the next century, but with important spatial and temporal variations. A 2ºC temperature increase in the Olympic Mountains in Washington would cause dominant tree species to shift upward in elevation by 300 to 600m, causing temperate species to replace sub-alpine species over 300 to 500 years. For widespread species such as lodgepole pine, a 3ºC temperature increase would increase growth in the northern part of its range, decrease growth in the middle, and decimate southern forests (IPCC, 2007, chapter 14).

Across North America, impacts of Climate Change on commercial forestry potential are likely to be sensitive to changes in disturbances from insects, diseases and wildfires. Warmer summer temperatures are projected to extend the annual window of high fire ignition risk by 10-30%, and could result in increased area burned of 74-118% in Canada by 2100. The tendency for North American producers to suffer losses increases if Climate Change is accompanied by increased disturbance, with simulated losses averaging $1 billion to $2 billion/yr over the 21st century. Increased tropospheric ozone could cause further decreases in tree growth. Risks of losses from Southern pine beetle likely depend on the seasonality of warming, with winter and spring warming leading to the greatest damage. Warmer winters with more sporadic freezing and thawing are likely to increase erosion and landslides on forest roads, and reduce access for winter harvesting (IPCC, 2007, chapter 14).

Due to changes in summer precipitation and temperature, the area burned by fire regionally (in the U.S. Columbia Basin) is projected to double or triple (medium scenario, (A1B)), from about 425,000 acres annually (1916-2006) to 0.8 million acres in the 2020s, 1.1 million acres in the 2040s, and 2.0 million acres in the 2080s. The probability that more than two million acres will burn in a given year is projected to increase from 5% (1916-2006) to 33% by the 2080s. Fire regimes in different ecosystems in the Pacific Northwest have different sensitivities to climate, but most ecosystems will likely experience an increase in area burned by the 2040s. Year-to-year variation will increase in some ecosystems (Littell, et al., 2009).

Due to climatic stress on host trees, mountain pine beetle outbreaks in the Pacific Northwest are projected to increase in frequency and cause increased tree mortality. Mountain pine beetles will reach higher elevations due to a shift to favorable temperature conditions in these locations as the region warms. Conversely, the mountain pine beetle will possibly become less of a threat at middle and lower elevations because temperatures will be unfavorable for epidemics. Other species of insects (such as spruce beetle, Douglas-fir bark beetle, fir engraver beetle, and western spruce budworm) will possibly also emerge in areas that are no longer suitable for the mountain pine beetle. The amount of habitat with climate ranges required for pine species susceptible to mountain pine beetle will likely decline substantially by mid 21st century. Much of the currently climatically suitable habitat is in places unlikely to have future climatic conditions suitable for pine species establishment and regeneration, and established trees will be under substantial climatic stress. The regeneration of pine species after disturbance will likely be slowed, if the species can establish at all (Littell, et al., 2009).

The area of severely water-limited forests will increase a minimum of 32% in the 2020s, and an additional 12% in both the 2040s and 2080s (Figure 11, medium scenario, (A1B)). Douglas-fir productivity varies with climate across the region and will potentially increase in wetter parts of the state during the first half of the 21st century but decrease in the driest parts of its range. Geographic patterns of productivity will likely change; statewide productivity will possibly initially increase due to warmer temperatures but will then decrease due to increased drought stress. It is important to note that changes in species mortality or regeneration failures will possibly occur before the point of severe water limitation is reached (Littell, et al., 2009).

c. **Freshwater and Water Resources**

Freshwater resources will be affected by Climate Change across Canada and the U.S., but the nature of the vulnerabilities varies from region to region. In certain regions, including the Columbia River, surface and/or groundwater resources are intensively used for often competing agricultural, municipal, industrial and ecological needs, increasing potential vulnerability to future changes in timing and availability of water.

Surface water

Higher evaporation related to warming tends to offset the effects of more precipitation, while magnifying the effects of less precipitation. Warming, and changes in the form, timing and amount of precipitation, will very likely lead to earlier melting and significant reductions in snowpack in the western mountains by the middle of the 21st century. In projections for mountain snowmelt-dominated watersheds, snowmelt runoff advances, winter and early spring flows increase (raising flooding potential), and summer flows decrease substantially. Over-allocated water systems of the western U.S. and Canada, such as the Columbia River, which rely on capturing snowmelt runoff, will be especially vulnerable (IPCC, 2007, chapter 14).

April 1 snow water equivalent (snow water content) is projected to decrease by an average of 28% to 29% across the state of Washington by the 2020s, 37% to 44% by the 2040s and 53% to 65% by the 2080s compared with the 1916 – 2006 historical mean. By the 2080s, seasonal streamflow timing in snowmelt-dominated and transient rain-snow watersheds in the Pacific Northwest would shift significantly due to the decrease in snowpack and earlier melt. Snowmelt-dominated watersheds will likely become transient, resulting in reduced peak spring streamflow, increased winter streamflow and reduced late summer flow. Transient basins will likely experience significant shifts, becoming rain-dominant as winter precipitation falls more as rain and less as snow. Watersheds that are rain dominated will likely experience higher winter streamflow because of increases in average winter precipitation, but overall will experience relatively little change with respect to streamflow timing. These changes are important because they determine when water is available and how it must be stored (Littell, et al., 2009).

The Yakima Valley is an example of an area in Washington that relies heavily on irrigation to raise crops. Crops in the Yakima Valley, most of which are irrigated, represent about a quarter of the value of all crops grown in Washington. The watershed's reservoirs hold 30% of streamflow annually and rely heavily on additional water storage in winter snowpack to meet water demand for agriculture. As in other watersheds across Washington, climate change is projected to cause decreases in snowpack and changes in streamflow patterns, making active management of water supply critical for minimizing negative impacts. Agricultural production increases caused by warming temperatures will likely be undermined by lack of water for irrigation. Due to increases in temperature and changes in the timing and quantity of snowmelt and runoff, the irrigation season in the Yakima Valley will likely be shorter, the growing season will likely be earlier by about two weeks, and crop maturity will likely be earlier by two to four weeks by the 2080s (Littell, et al., 2009).

Groundwater

With climate change, availability of groundwater is likely to be influenced by withdrawals (reflecting development, demand and availability of other sources) and recharge (determined by temperature, timing and amount of precipitation, and surface water interactions). Simulated annual groundwater base flows and aquifer levels respond to temperature, precipitation and pumping – decreasing in scenarios that are drier or have higher pumping and increasing in a wetter scenario. In some cases there are base flow shifts - increasing in winter and decreasing in spring and early summer. For aquifers in alluvial valleys of south-central British Columbia, temperature and precipitation scenarios have less impact on groundwater recharge and levels than do projected changes in river stage (IPCC, 2007, chapter 14).

Water quality

Simulated future surface and bottom water temperatures of lakes, reservoirs, rivers, and estuaries throughout North America consistently increase from 2 to 7°C (based on a doubling of CO_2 concentrations), with summer surface temperatures exceeding 30°C in Midwestern and southern lakes and reservoirs. Warming is likely to extend and intensify summer thermal stratification, contributing to oxygen depletion. A shorter ice-cover period in shallow northern lakes could reduce winter fish kills caused by low oxygen. Higher stream temperatures affect fish access, survival and spawning (e.g., west coast salmon) (IPCC, 2007, chapter 14).

Climate Change is likely to make it more difficult to achieve existing water quality goals. For the Midwest, simulated low flows used to develop pollutant discharge limits (Total Maximum Daily Loads) decrease over 60% with a 25% decrease in mean precipitation, reaching up to 100% with the incorporation of irrigation demands. Restoration of beneficial uses (e.g., to address habitat loss, eutrophication, beach closures) under the Great Lakes Water Quality agreement will likely be vulnerable to declines in water levels, warmer water temperatures, and more intense precipitation. Decreases in snow cover and more winter rain on bare soil are likely to lengthen the erosion season and enhance erosion, increasing the potential for water quality impacts in agricultural areas (IPCC, 2007, chapter 14).

Freshwater fisheries

Cold-water fisheries will likely be negatively affected by climate change; warm-water fisheries will generally gain; and the results for cool-water fisheries will be mixed, with gains in the northern and losses in the southern portions of ranges. Salmon, which prefer cold, clear water, are likely to experience the most negative impacts. Arctic freshwaters will likely be most affected, as they will experience the greatest warming. Many warm-water and cool-water species will shift their ranges northward or to higher altitudes. In the continental U.S., cold-water species will likely disappear from all but the deeper lakes, cool-water species will be lost mainly from shallow lakes, and warm-water species will thrive except in the far south, where temperatures in shallow lakes will exceed survival thresholds. Species already listed as threatened will face increased risk of extinction, with pressures from climate exacerbated by the expansion of predatory species like smallmouth bass. While temperature increases may favor warm-water fishes like smallmouth bass, changes in water supply and flow regimes seem likely to have negative effects (IPCC, 2007, chapter 14).

Climate plays a crucial role in salmon ecology at every stage of their life cycle. Key limiting factors for freshwater salmon reproductive success depend on species, their life history, watershed characteristics, and stock-specific adaptations to local environmental factors. The critical Climate Change impacts on salmon in the Pacific Northwest include the following (Littell, et al., 2009):

- Rising stream temperature will reduce the quality and quantity of freshwater salmon habitat substantially. Since the 1980s the majority of waters with stream temperature monitoring stations in the interior Columbia Basin have been classified as stressful for salmon (where annual maximum weekly water temperatures exceed 60°F). Water temperatures at these stations are projected to become increasingly hostile for salmon under both medium (A1B) and low (B1) emissions scenarios. The duration of temperatures[15] causing migration barriers and thermal stress in the interior Columbia Basin are projected to quadruple by the 2080s. Water temperatures for western Washington stations are generally cooler, and projected increases in thermal stress are significant but less severe - the duration of temperatures greater than 70°F will increase but such temperatures are still projected to be relatively rare for all but the warmest water bodies in Washington.

- In the major river systems of Puget Sound and lower elevation basins in the interior Columbia Basin, flood risk will likely increase, which in turn increases the risk of streambed scouring of spawning habitat. In snowmelt-dominated watersheds that prevail in the higher altitude catchments and in much of the interior Columbia Basin, flood risk will likely decrease. Summer low flows will decrease in most rivers under most scenarios, leading to reduced habitat capacities for rearing juveniles that must spend at least one summer in freshwater.
- Consequences of these changes will vary with different populations and with where they spend the different parts of their life cycles. Salmon populations that typically inhabit freshwater during summer and early fall for either spawning migrations, spawning, or rearing will experience significant thermal stress. For spawning migrations, effects of warming are projected to be most severe for adult summer steelhead, sockeye, and summer Chinook populations in the Columbia Basin, sockeye and Chinook in the Lake Washington system, and summer chum in Hood Canal. For rearing habitat, impacts of warming will likely be greatest for Coho and steelhead (summer and winter runs) throughout western Washington. Reductions in summer and fall flows will likely negatively impact the rearing capacities and for Coho, steelhead, and stream type Chinook because they all have a life history pattern that requires at least one year of juvenile rearing in freshwater.

d. **Coastal Systems** (IPCC, 2007, chapter 6)

Coastal landforms, affected by short-term perturbations such as storms, generally return to their pre-disturbance morphology, implying a simple, morphodynamic equilibrium. Many coasts undergo continual adjustment towards a dynamic equilibrium, often adopting different ‘states’ in response to varying wave energy and sediment supply. Coasts respond to altered conditions external to the system, such as storm events, or changes triggered by internal thresholds that cannot be predicted on the basis of external stimuli. This natural variability of coasts can make it difficult to identify the impacts of Climate Change.

Climate-related ocean-atmosphere oscillations can lead to coastal changes. One of the most prominent is the El Niño-Southern Oscillation (ENSO) phenomenon, an interaction between pronounced temperature anomalies and sea-level pressure gradients in the equatorial Pacific Ocean, with an average periodicity of 2 to 7 years. Recent research has shown that dominant wind patterns and storminess associated with ENSO may perturb coastal dynamics, influencing (1) beach morphodynamics in eastern Australia, mid-Pacific and Oregon; (2) cliff retreat in California; and (3) groundwater levels in mangrove ecosystems in Micronesia and Australia.

Sea-level rise has accelerated in eastern North America since the late 19th century and further acceleration is expected. For The IPCC Special Report on Emissions Scenarios scenarioA1B, global mean sea level is projected to rise by 0.35 ± 0.12 m from the 1980 to 1999 period to the 2090 to 2099 period. Spatial variability of sea-level rise has become better defined since the IPCC Third Assessment Report (TAR) (IPCC, 2001a) and the ensemble mean for A1B shows values close to the global mean along most North American coasts, with slightly higher rates in eastern Canada and western Alaska, and stronger positive anomalies in the Arctic. Vertical land motion will decrease (uplift) or increase (subsidence) the relative sea level rise at any site.

Superimposed on accelerated sea-level rise, the present storm and wave climatology and storm-surge frequency distributions lead to forecasts of more severe coastal flooding and erosion hazards. The water-level probability distribution is shifted upward, giving higher potential flood levels and more frequent flooding at levels rarely experienced today. If coastal systems, including sediment supply, remain otherwise unchanged, higher sea levels are likely to be correlated with accelerated coastal erosion. Potentially more intense storms and possible changes in El Niño are likely to result in more coastal instability. Damage costs from coastal storm events (storm surge, waves, wind, ice encroachment) and other factors (such as freeze-thaw) have increased substantially in recent decades and are expected to continue rising.

Global mean sea-level rise will generally lead to higher relative coastal water levels and increasing salinity in estuarine systems, thereby tending to displace existing coastal plant and animal communities inland. Estuarine plant and animal communities may persist as sea level rises if migration is not blocked and if the rate of change does not exceed the capacity of natural communities to adapt or migrate. Climate Change impacts on one or more ‘leverage species’, however, can result in sweeping community level changes. Some of the greatest potential impacts of Climate Change on estuaries may result from changes in physical mixing characteristics caused by changes in freshwater runoff. Freshwater inflows into estuaries influence water residence time, nutrient delivery, vertical stratification, salinity and control of phytoplankton growth rates. Increased freshwater inflows decrease water residence time and increase vertical stratification, and vice versa. The effects of altered residence times can have significant effects on phytoplankton populations, which have the potential to increase fourfold per day. Consequently, in estuaries with very short water residence times, phytoplankton are generally flushed from the system as fast as they can grow, reducing the estuary’s susceptibility to eutrophication and harmful algal blooms. Changes in the timing of freshwater delivery to estuaries could lead to a decoupling of the juvenile phases of many estuarine and marine fishery species from the available nursery habitat.

The distribution, production, and many other aspects of species and biodiversity in coastal ecosystems are highly sensitive to variations in weather and climate, affecting the distribution and abundance of the plant and animal species that depend on each coastal system type. Several recent studies have revealed that Climate Change is already impacting biodiversity in some coastal systems. It is clear that responses of intertidal and shallow marine organisms to Climate Change are more complex than simply latitudinal shifts related to temperature increase, with complex biotic interactions superimposed on the abiotic. Examples include the northward range extension of a marine snail in California and the reappearance of the blue mussel in Svalbard.

e. **Mountain Ecosystems** (IPCC, 2007, chapter 4)

Mountain regions (about 20-24% of all land, scattered throughout the globe) exhibit many climate types corresponding to widely-separated latitudinal belts within short horizontal distances. Consequently, although species richness decreases with elevation, mountain regions support many different ecosystems and have among the highest species richness globally. Mountain ecosystems have a significant role in biospheric carbon storage and carbon sequestration, particularly in semi-arid and arid areas (e.g., the western U.S.). Mountain ecosystem services such as water purification and climate regulation extend beyond their geographical boundaries and affect all continental mainlands. Local key services allow habitability of mountain areas, e.g. through slope stabilization and protection from natural disasters such as avalanches and rockfall. Mountains increasingly serve as refuges from direct human impacts for many endemic species. They provide many goods for subsistence livelihoods, are home to many indigenous peoples, and are attractive for recreational activities and tourism. Critically, mountains harbor a significant fraction of biospheric carbon.

Key vulnerabilities

The TAR (IPCC, 2001b) identified mountain regions as having experienced above-average warming in the 20th century, a trend likely to continue. Related impacts included an earlier and shortened snow-melt period, with rapid water release and downstream floods which, in combination with reduced glacier extent, could cause water shortage during the growing season. The TAR suggested that these impacts may be exacerbated by ecosystem degradation pressures such as land-use changes, over-grazing, trampling, pollution, vegetation destabilization and soil losses, in particular in highly diverse regions such as the Caucasus and Himalayas. While adaptive capacities were generally considered limited, high vulnerability was attributed to the many highly endemic alpine biota. Since the TAR, the literature has confirmed a disproportionately high risk of extinction for many endemic species in various mountain ecosystems, such as tropical mountain cloud forests or forests in other tropical regions on several continents, and globally where habitat loss due to warming threatens endemic species.

Impacts

Because temperature decreases with altitude by 5-10°C/km, relatively short-distanced upward migration is required for persistence. However, this is only possible for the warmer climatic and ecological zones below mountain peaks. Mountain ridges, by contrast, represent considerable obstacles to dispersal for many species which tends to constrain movements to slope upward migration. This is expected to reduce genetic diversity within species and to increase the risk of stochastic extinction due to ancillary stresses, a hypothesis confirmed by recent genetic analysis showing gene drift effects from past climate changes. A reshuffling of species on altitude gradients is to be expected as a consequence of individualistic species responses that are mediated by varying longevities and survival rates. These in turn are the result of a high degree of evolutionary specialization to harsh mountain climates, and in some cases they include effects induced by invading alien species.

Where warmer and drier conditions are projected, mountain vegetation is expected to be subject to increased evapotranspiration. This leads to increased drought, which has been projected to induce forest dieback in continental climates, particularly in the interior of mountain ranges, and Mediterranean areas. Even in humid tropical regions, plants and animals have been shown to be sensitive to water stress on mountains. There is very high confidence that warming is a driver of amphibian mass extinctions at many highland localities, by creating increasingly favorable conditions for the pathogenic *Batrachochytrium* fungus.

The duration and depth of snow cover, often correlated with mean temperature and precipitation, is a key factor in many alpine ecosystems. A lack of snow cover exposes plants and animals to frost and influences water supply in spring. If animal movements are disrupted by changing snow patterns, as has been found in Colorado, increased wildlife mortality may result. At higher altitudes, the increased winter precipitation, likely to accompany warming, leads to greater snowfall, so that earlier arriving altitudinal migrants are confronted with delayed snowmelt. Disturbances such as avalanches, rockfall, fire, and wind and herbivore damage interact and are strongly dependent on climate. These effects may prevent recruitment and thus limit adaptive migration responses of species, and are exacerbated by human land use and other anthropogenic pressures.

Ecotonal sensitivity to climate change, such as upper tree lines in mountains, has shown that populations of several mountain-restricted species are likely to decline. The most vulnerable ecotone species are those that are genetically poorly adapted to rapid environmental change, reproduce slowly, disperse poorly, and are isolated or highly specialized, because of their high sensitivity to environmental stresses. Recent findings for Europe, despite a spatially coarse analysis, indicate that mountain species are disproportionately sensitive to Climate Change (about 60% species loss). Substantial biodiversity losses are likely if human pressures on mountain biota occur in addition to Climate Change impacts.

f. Agriculture and Food Production (IPCC, 2007, chapter 5)

The inter-annual, monthly and daily distribution of climate variables (e.g., temperature, radiation, precipitation, water vapor pressure in the air and wind speed) affect a number of physical, chemical and biological processes that drive the productivity of agricultural, forestry and fisheries systems. The latitudinal distribution of crop, pasture and forest species is a function of the current climatic and atmospheric conditions, as well as of photoperiod. Total seasonal precipitation and its variability, are both of major importance for agricultural, pastoral and forestry systems. In general, changes in precipitation and evaporation-precipitation ratios, modify ecosystem function, particularly in marginal areas.

Crops exhibit threshold responses to their climatic environment, which affect their growth, development and yield. Yield-damaging climate thresholds that span periods of just a few days for cereals and fruit trees include absolute temperature levels linked to particular developmental stages that condition the formation of reproductive organs, such as seeds and fruits. Short-term natural extremes, such as storms and floods, interannual and decadal climate variations, as well as large-scale circulation changes, such as the El Niño Southern Oscillation (ENSO), all have important effects on crop, pasture and forest production. Many of the world’s rangelands are affected by ENSO events. The TAR identified that these natural events are likely to intensify with climate change, with subsequent changes in vegetation and water availability. More frequent extreme events may lower long-term yields by directly damaging crops at specific developmental stages, such as temperature thresholds during flowering, or by making the timing of field applications more difficult, thus reducing the efficiency of farm inputs. In dry regions, there are risks that severe vegetation degeneration leads to positive feedbacks between soil degradation and reduced vegetation and rainfall, with corresponding loss of pastoral areas and farmlands.

Multiple stresses, such as limited availability of water resources, loss of biodiversity, and air pollution, are increasing sensitivity to Climate Change and reducing resilience in the agricultural sector through soil erosion. Stalinization of irrigated areas, dryland degradation from overgrazing, over-extraction of ground water, growing susceptibility to disease and build-up of pest resistance favored by the spread of monocultures and the use of pesticides, and loss of biodiversity and erosion of the genetic resource base when modern varieties displace traditional ones. Small-holder agriculturalists are especially vulnerable to a range of social and environmental stressors. Additionally, multiple stresses, such as forest fires and insect outbreaks, increase overall sensitivity.

Plant response to elevated CO_2 alone, without climate change, is positive and was reviewed extensively by the TAR (IPCC, 2001b). Recent studies confirm that the effects of elevated CO_2 on plant growth and yield will depend on photosynthetic pathway, species, growth stage and management regime, such as water and nitrogen (N) applications. On average across several species and under unstressed conditions, recent data analyses find that, compared to current atmospheric CO_2 concentrations, crop yields increase at 550 ppm CO_2 in the range of 10-20% for C3 crops and 0-10% for C4 crops. Many recent studies confirm and extend the TAR findings that temperature and precipitation changes in future decades will modify, and often limit, direct CO_2 effects on plants. For instance, high temperature during flowering may lower CO_2 effects by reducing grain number, size and quality. Increased temperatures may also reduce CO_2 effects indirectly, by increasing water demand. Rain-fed wheat grown at 450 ppm CO_2 demonstrated yield increases with temperature increases of up to 0.8°C, but declines with temperature increases beyond 1.5°C; additional irrigation was needed to counterbalance these negative effects. In pastures, elevated CO_2 together with increases in temperature, precipitation and N deposition resulted in increased primary production, with changes in species distribution and litter composition. Future CO_2 levels may favor C3 plants over C4, yet the opposite is expected under associated temperature increases; the net effects remain uncertain.

g. Human Health (IPCC, 2007, chapters 8)

Overview

Evidence has grown that Climate Change already contributed to the global burden of disease and premature deaths. Climate change plays an important role in the spatial and temporal distribution of malaria, dengue, tick-borne diseases, cholera and other diarrheal diseases; is affecting the seasonal distribution and concentrations of some allergenic pollen species; and has increased heat-related mortality. The projected health impacts of Climate Change are predominately negative, with the most severe impacts being seen in low-income countries, where the capacity to adapt is weakest. Vulnerable groups in developed countries will also be affected. Projected increases in temperature and changes in rainfall patterns can increase malnutrition; disease and injury due to heat waves, floods, storms, fires and droughts; diarrheal illness; and the frequency of cardio-respiratory diseases due to higher concentrations of ground-level ozone.

The main findings of the IPCC TAR (IPCC, 2001b) in regards to the effects of Climate Change on human health were the following:

- An increase in the frequency or intensity of heat waves will increase the risk of mortality and morbidity, principally in older age groups and among the urban poor.
- Any regional increases in climate extremes (e.g., storms, floods, cyclones, droughts) associated with Climate Change would cause deaths and injuries, population displacement, and adverse effects on food production, freshwater availability and quality, and would increase the risks of infectious disease, particularly in low-income countries.

- In some settings, the impacts of Climate Change may cause social disruption, economic decline, and displacement of populations. The health impacts associated with such socioeconomic dislocation and population displacement are substantial.
- Changes in climate, including changes in climate variability, would affect many vector-borne infections. Populations at the margins of the current distribution of diseases might be particularly affected.
- Climate Change represents an additional pressure on the world's food supply system and is expected to increase yields at higher latitudes and decrease yields at lower latitudes. This would increase the number of undernourished people in the low-income world, unless there was a major redistribution of food around the world.
- Assuming that current emission levels continue, air quality in many large urban areas will deteriorate. Increases in exposure to ozone and other air pollutants (e.g., particulates) could increase morbidity and mortality.

Climate Change and Diseases

Many human diseases are sensitive to weather, from cardiovascular and respiratory illnesses due to heat waves or air pollution, to altered transmission of infectious diseases. Synergistic effects of other activities can exacerbate weather exposures (e.g., via the urban heat island effect), requiring cross sector risk assessment to determine site-specific vulnerability. The incidence of infectious diseases transmitted by air varies seasonally and annually, due partly to climate variations. Water-borne disease outbreaks from all causes in the U.S. are distinctly seasonal, clustered in key watersheds, and associated with heavy precipitation, or extreme precipitation and warmer temperatures in Canada. Heavy runoff after severe rainfall can also contaminate recreational waters and increase the risk of human illness through higher bacterial counts. This association is strongest at beaches closest to rivers.

Vector-borne diseases (VBD) are infections transmitted by the bite of infected arthropod species, such as mosquitoes, ticks, triatomine bugs, sandflies and blackflies. VBDs are among the most well-studied of the diseases associated with climate change, due to their widespread occurrence and sensitivity to climatic factors. There is some evidence of climate-change related shifts in the distribution of tick vectors of disease, of some (non-malarial) mosquito vectors in Europe and North America, and in the phenology of bird reservoirs of pathogens. In north-eastern North America, there is evidence of recent micro-evolutionary (genetic) responses of the mosquito species *Wyeomyia smithii* to increased average land surface temperatures and earlier arrival of spring in the past two decades. Although not a vector of human disease, this species is closely related to important arbovirus vector species that may be undergoing similar evolutionary changes.

The strain of West Nile virus (WNV) that emerged for the first time in North America during the record hot July 1999 requires warmer temperatures than other strains. The greatest WNV transmissions during the epidemic summers of 2002 to 2004 in the U.S. were linked to above-average temperatures. Laboratory studies of virus replication in WNV's main *Culex* mosquito vector show high levels of virus at warmer temperatures. Bird migratory pathways and WNV's recent advance westward across the U.S. and Canada are key factors in WNV and must be considered in future assessments of the role of temperature in WNV dynamics. A virus closely related to WNV, Saint Louis encephalitis, tends to appear during hot, dry La Niña years, when conditions facilitate transmission by reducing the extrinsic incubation period.

Lyme disease is a prevalent tick-borne disease in North America for which there is new evidence of an association with temperature and precipitation. In the field, temperature and vapor pressure contribute to maintaining populations of the tick *Ixodes scapularis* which, in the U.S., is the micro-organism's secondary host. A monthly average minimum temperature above -7ºC is required for tick survival. The northern range limit for this tick could shift north by 200 km by the 2020s, and 1000 km by the 2080s (IPCC, 2007b). Harmful algal blooms produce toxins that can cause human diseases, mainly via consumption of contaminated shellfish. Warmer seas may thus contribute to increased cases of human shellfish and reef fish poisoning (ciguatera) and poleward expansions of these disease distributions.

Heat waves and Health

Heat-related morbidity and mortality is projected to increase. Severe heat waves, characterized by stagnant, warm air masses and consecutive nights with high minimum temperatures, will intensify in magnitude and duration over the portions of the U.S. and Canada where they already occur. Across North America, the population over the age of 65 will increase slowly to 2010, and then grow dramatically as the Baby Boomers join the ranks of the elderly – the segment of the population most at risk of dying in heat waves. Late in the century, Chicago is projected to experience 25% more frequent heat waves annually, and the projected number of heat wave days in Los Angeles increases from 12 to 44-95 days.

Climate Change and Air pollution

Since ozone formation is temperature dependent, surface ozone concentration are projected to increase with a warmer climate. Ozone damages lung tissue, causing particular problems for people with asthma and other lung diseases. Even modest exposure to ozone may encourage the development of asthma in children. Ozone and non-volatile secondary particulate matter generally increase at higher temperatures, due to increased gas-phase reaction rates. Many species of trees emit volatile organic compounds (VOCs) such as isoprene, which is a precursor of ozone formation, at rates that increase rapidly with temperature.

For the 2050s, daily average ozone levels are projected to increase by 3.7 ppb across the eastern U.S., with the cities most polluted today experiencing the greatest increase in ozone pollution. One-hour maximum ozone follows a similar pattern, with the number of summer days exceeding the 8-hour regulatory U.S. standard projected to increase by 68%. Assuming constant population and dose-response characteristics, ozone related deaths from climate change increase by approximately 4.5% from the 1990s to the 2050s. The large potential population exposed to outdoor air pollution translates this small relative risk into a substantial attributable health risk.

In some regions, changes in temperature and precipitation are projected to increase the frequency and severity of fire events. Large wildfires release large amounts of fine particulates (PM2.5), causing PM2.5 concentrations to reach levels as high as 10-20 times the national ambient air quality standard (NAAQS) in adjacent populated areas. Wildfires also release large amounts of VOCs and semi-volatile organic compounds, which contribute to the formation of secondary organic aerosols (SOAs). Elevated concentrations of PM2.5 and SOAs cause by wildfires are usually accompanied by an increase in the number of people with respiratory problems, such as asthma and chronic obstructive pulmonary diseases, to seek treatment at a hospital.

Pollen, another air contaminant, is likely to increase with elevated temperature and atmospheric CO_2 concentrations. A doubling of the atmospheric CO_2 concentration stimulated ragweed-pollen production by over 50%. Ragweed grew faster, flowered earlier and produced significantly greater above-ground biomass and pollen at urban than at rural locations. Climate Change has caused an earlier onset of the spring pollen season in the Northern Hemisphere. It is reasonable to conclude that allergenic diseases caused by pollen, such as allergic rhinitis, have experienced some concomitant change in seasonality.

h. Energy Production and Use

Energy production and use are sensitive to changes in the climate. For example, increasing temperatures will reduce consumption of energy for heating but increase energy used for cooling buildings. The implications of climate change for energy supply are less clear than for energy demand. Climate change effects on energy supply and demand will depend not only on climatic factors, but also on patterns of economic growth, land use, population growth and distribution, technological change and social and cultural trends that shape individual and institutional actions.

Energy Production

To date, less research has been undertaken on how climate change may affect energy production. Some of the possible effects are discussed below (IPCC, 2007, chapter 7).

- Hydropower generation is the energy source that is likely to be most directly affected by climate change because it is sensitive to the amount, timing and geographical pattern of precipitation and temperature. Furthermore, hydropower needs may increasingly conflict with other priorities, such as salmon restoration goals in the Pacific Northwest. However, changes in precipitation are difficult to project at the regional scale, which means that climate change will affect hydropower either positively and negatively, depending on the region.
- Infrastructure for energy production, transmission and distribution could be affected by climate change. For example, if a warmer climate is characterized by more extreme weather events such as windstorms, ice storms, floods, tornadoes and hail, the transmission systems of electric utilities may experience a higher rate of failure, with attendant costs.
- Power plant operations can be affected by extreme heat waves. For example, intake water that is normally used to cool power plants become warm enough during extreme heat events that it compromises power plant operations.
- Finally, some renewable sources of energy could be affected by climate change, although these changes are very difficult to predict. If climate change leads to increased cloudiness, solar energy production could be reduced. Wind energy production would be reduced if wind speeds increase above or fall below the acceptable operating range of the technology. Changes in growing conditions could affect biomass production, a transportation and power plant fuel source that is starting to receive more attention.

Hydropower accounts for roughly 70% of the electrical energy production in the Pacific Northwest and is strongly affected by climate-related changes in annual streamflow amounts and seasonal streamflow timing. Heating and cooling energy demand in Washington will be affected by both population growth and warming temperatures. Annual hydropower production (assuming constant installed capacity) is projected to decline by a few percent due to small changes in annual stream flow, but seasonal changes will be ***substantial.*** Winter hydropower production is projected to increase by about 0.5% to 4.0% by the 2020s, 4.0% to 4.2% by the 2040s, and 7% to 10% by the 2080s (compared to water year 1917-2006) under the medium (A1B) emissions scenario. The largest and most likely changes in hydropower production are projected to occur from June to September, during the peak air conditioning season. Summer (JJA) energy production is projected to decline by 9% to11% by the 2020s, 13% to 16% by the 2040s, and 18% to 21% by the 2080s (Littell, et al., 2009).

Energy Use

Changes in temperature due to climate change could affect our demand for energy. For example, rising air temperatures will likely lead to substantial increases in energy demand for air conditioning in most North American cities. On the other hand, energy needed for space-heating may decrease. The net effects of these changes on energy production, use and utility bills, will vary by region and by season. There may also be changes in energy consumed for other climate-sensitive processes, such as pumping water for irrigation in agriculture. Rising temperatures and associated increases in evaporation may increase energy needs for irrigation, particularly in dry regions across the Western U.S. Depending on the magnitude of these possible energy consumption changes, it may be necessary to consider changes in energy supply or conservation practices to balance demand. Many other factors (e.g., population growth, economic growth, energy efficiency changes and technological change) will also affect the timing and size of future changes in the capacity of energy systems (IPCC, 2007, chapter 7).

Despite decreasing heating degree days with projected warming, annual heating energy demand is projected to increase due to population growth. In the absence of warming, population growth would increase heating energy demand in WA by 38% by the 2020s, 68% by the 2040s, and 129% by the 2080s. For fixed 2000 population, projected warming would reduce heating energy demand by 11% to 12% for the 2020s, 15-19% for the 2040s, and 24% to 32% for the 2080s due to decreased heating degree days. Combining the effects of warming with population growth, heating energy demand for WA is projected to increase by 22% to 23% for the 2020s, 35% to 42% for the 2040s, and 56% to 74% for the 2080s. Increases in annual heating energy demand will affect both fossil fuel use for heating and demand for electrical power (Littell, et al., 2009).

Residential cooling energy demand is projected to increase rapidly due to increasing population, increasing cooling degree days, and increasing use of air conditioning. In the absence of warming, population growth would increase cooling energy demand in WA by 38% by the 2020s, 69% by the 2040s, and 131% by the 2080s. For fixed 2000 population, warming would increase cooling energy demand by 92% to 118% for the 2020s, 174-289% for the 2040s, and 371% to 749% by the 2080s due to the combined effects of increased cooling degree days, and increased use of air conditioning. Combining the effects of warming with population growth, cooling energy demand would increase by 165% to 201% (a factor of 2.6-3.0) for the 2020s, 363-555% (a factor of 4.6-6.5) for the 2040s, and 981-1845% (a factor of 10.8-19.5) by the 2080s. Increases in cooling energy demand are expected to translate directly to higher average and peak electrical demands in summer (Littell, et al., 2009).

5. Adaptation Options

a. Ecosystems (CCSP, 2008b, chapter 9)

Managers' past experiences with unpredictable and extreme events such as hurricanes, floods, pest and disease outbreaks, invasions, and forest fires have already led to some existing approaches that can be used to adapt to climate change. Ecological studies combined with managers' expertise reveal several common themes for managing natural systems for resilience in the face of disturbance. A clear exposition of these themes is the starting point for developing best practices aimed at climate adaptation.

There are seven adaptation approaches to manage natural systems for resilience: (1) protection of key ecosystem features, (2) reduction of anthropogenic stresses, (3) representation, (4) replication, (5) restoration, (6) refugia, and (7) relocation. These techniques manipulate or take advantage of ecosystem properties to enhance their resilience to climatic changes. Each of these adaptation approaches ultimately contributes to resilience, whether at the scale of individual protected area units, or at the scale of regional/national systems. The approaches above are not mutually exclusive and may be implemented jointly. The specific management activities that are selected under one or more approaches above should then be based on considerations such as: the ecosystem management goals, type and degree of climate effects, type and magnitude of ecosystem responses, spatial and temporal scales of ecological and management responses, and social and economic factors.

Protect Key Ecosystem Features

Within ecosystems, there may be particular structural characteristics (*e.g.*, three-dimensional complexity, growth patterns), organisms (*e.g.*, functional groups, native species), or areas (*e.g.*, buffer zones, migration corridors) that are particularly important for promoting the resilience of the overall system. Such key ecosystem features could be important focal points for special management protections or actions. For example, managers of national forests may proactively promote stand resilience to diseases and fires by using silviculture techniques such as widely spaced thinnings or shelterwood cuttings. Another example would be to aggressively prevent or reverse the establishment of invasive non-native species that threaten native species or impede current ecosystem function. Preserving the structural complexity of vegetation in tidal marshes, seagrass meadows, and mangroves may render estuaries more resilient. Finally, establishing and protecting corridors of connectivity that enable migrations can enhance resilience across landscapes in national wildlife refuges.

Reduce Anthropogenic Stresses

Reducing anthropogenic stresses is one approach for which there is considerable scientific confidence in its ability to promote resilience for virtually any situation. Managing for resilience often implies minimizing anthropogenic stressors (*e.g.*, pollution, overfishing, development) that hinder the ability of species or ecosystems to withstand a stressful climatic event. For example, one way of enhancing resilience in wildlife refuges is to reduce other stresses on native vegetation such as erosion or altered hydrology caused by human activities. Marine protected area managers may focus on human stressors such as fishing and inputs of nutrients, sediments, and pollutants both inside the protected area and outside the protected area on adjacent land and waters. The resilience of rivers could be enhanced by strategically shifting access points or moving existing trails for wildlife or river enthusiasts, in order to protect important riparian zones.

Representation

Representation is based on the idea that biological systems come in a variety of forms. Species include locally adapted populations as opposed to one monotypic taxon, and major habitat types or community types include variations on a theme with different species compositions, as opposed to one invariant community. The idea behind representation as a strategy for resilience is simply that a portfolio of several slightly different forms of a species or ecosystem increases the likelihood that, among those variants, there will be one or more that are suited to the new climate. A management plan for a large ecosystem that includes representation of all possible combinations of physical environments and biological communities increases the chances that, regardless of the climatic change that occurs, somewhere in the system there will be areas that survive and provide a source for recovery. Employing this approach with wildlife refuges may be particularly important for migrating birds because they use a diverse array of habitats at different stages of their life cycles and along their migration routes, and all of these habitats will be affected by climate change. At the level of species, it may be possible to increase genetic diversity in river systems through plantings or via stocking fish, or maintain complexity of salt marsh landscapes by preserving marsh edge environments.

Replication

Replication is simply managing for the continued survival of more than one example of each ecosystem or species, even if the replicated examples are identical. When one recognizes that Climate Change stress includes unpredictable extreme events and storms, then replication represents a strategy of having multiple bets in a game of chance. With marine protected areas, replication is explicitly used as a way to spread risk: if one area is negatively affected by a disturbance, then species, genotypes, and habitats in another area provide both insurance against extinction and a larval supply that may facilitate recovery of affected areas. The analogy for forests would be spreading risks by increasing ecosystem redundancy and buffers in both natural environments and plantations. It is prudent to use replication in all systems. In practice, most replication strategies also serve as representation strategies (since no two populations or ecosystems can ever be truly identical), and conversely most representation strategies provide some form of replication.

Restoration

In many cases natural intact ecosystems confer resilience to extreme events such as floods and storms. One strategy for adapting to Climate Change thus entails restoring intact ecosystems. For example the restoration of wetlands and natural floodplains will often confer resilience to floods. Restoration of particular species complexes may also be key to managing for resilience—a good example of this would be fire-adapted vegetation in forests that are expected to see more fires as a result of hotter and drier summers. At Blackwater National Wildlife Refuge, the USFWS is planning to restore wetlands that may otherwise be inundated by 2100. In the case of estuaries, restoring the vegetational layering and structure of tidal marshes, seagrass meadows, and mangroves can stabilize estuary function.

Refugia and Relocation
The term *refugia* refers to physical environments that are less affected by Climate Change than other areas (e.g., due to local currents, geographic location, etc.) and are thus a “refuge” from Climate Change for organisms. *Relocation* refers to human-facilitated transplantation of organisms from one location to another in order to bypass a barrier (e.g., an urban area). Refugia and relocation, while major concepts, are actually subsets of one or more of the approaches listed above. For example, if refugia can be identified locally, they can be considered sites for long-term retention of species (e.g., for representation and to maintain resilience) in forests. Or, in national wildlife refuges, it may be possible to use restoration techniques to reforest riparian boundaries with native species to create shaded thermal refugia for fish species. In the case of relocation, an example would be transport of fish populations in the Southwest that become stranded as water levels drop to river reaches with appropriate flows (e.g., to preserve system-wide resilience and species representation).

b. Forest Ecosystems (CCSP, 2008b, chapter 3)

Depending on the environmental context, management goals, and availability and adequacy of modeling information (climate and otherwise), different approaches may be taken to adapt forest ecosystems to Climate Change. The following suite of adaptation options intentionally plans for change rather than resisting it, with a goal of enabling forest ecosystems to naturally adapt as environmental changes accrue. Given that many ecological conditions will be moving naturally toward significant change in an attempt to adapt (e.g., species migration, stand mortality and colonization events, changes in community composition, insect and disease outbreaks, and fire events), these options seek to work with the natural adaptive processes. In so doing, options encourage gradual adaptation over time, thus hoping to avoid sudden thresholds, extreme loss, or conversion that may occur if natural change is cumulatively resisted.

1. Assist transitions, population adjustments, range shifts, and other natural adaptations
Use coupled and downscaled climate and vegetation models to anticipate future regional conditions, and project future ecosystems into new habitat and climate space. With such information, managers might plan for transitions to new conditions and habitats, and assist the transition. For example, managers could move species uphill, plan for higher-elevation insect and disease outbreaks, reduce existing anthropogenic stresses such as air quality or land cover changes, anticipate species mortality events and altered fire regimes, or consider loss of species’ populations on warm range margins and do not attempt restoration there. Further examples might be to modify rotation lengths and harvest schedules, alter thinning prescriptions and other silvicultural treatments, consider replanting with different species, shift desired species to new plantation or forest locations, or take precautions to mitigate likely increases in stress on plantation and forest trees.

2. Increase Redundancy and Buffers
This set of practices intentionally manages for an uncertain but changing future, rather than a specific climate future. Practices that involve spreading risks in diverse opportunities rather than concentrating them in a few are favored; using redundancy and creating diversity are key. Forest managers can facilitate natural selection and evolution by managing the natural regeneration process to enhance disturbances that initiate increased seedling development and genetic mixing, as has been suggested for white pines and white pine blister rust. Managers might also consider

shortening generation times by increasing the frequency of regeneration, and increasing the effectiveness of natural selection by managing for high levels of intra-specific competition; in other words, by ensuring that lots of seedlings get established when stands are regenerated. This diversification of risk with respect to plantations can be achieved, for instance, by spreading plantations over a range of environments rather than within the historic distribution or within a modeled future location. Options that include using diverse environments and even species margins will provide additional flexibility.

A benefit of redundant plantings across a range of environments is that they can provide monitoring information if survival and performance are measured and analyzed. Further, plantations originating as genetic provenance tests, and established over the past several decades, could be re-examined for current adaptations. This diversification of risk could also be achieved using natural regeneration and successional processes. A range of sites representing the diversity of conditions in a forest could be set aside after disturbance events to allow natural regeneration and successional processes to identify the most resistant species and populations. Other examples include planting with mixed species and age classes, as in agroforestry; increasing locations, sizes, and range of habitats for landscape-scale vegetation treatments; assuring that fuels are appropriately abated where vegetation is treated; and increasing the number of rare plant populations targeted for restoration, as well as increasing population levels within them.

3. Expand Genetic Diversity Guidelines

Existing guidelines for genetic management of forest plantations and restoration projects dictate maintenance of and planting with local germplasm. In the past, small seed zones, used for collecting seed for reforestation or restoration, have been delineated to ensure that local gene pools are used and to avoid contamination of populations with genotypes not adapted to the local site. These guidelines were developed assuming that neither environments nor climate were changing—i.e., a static background. Relaxing these guidelines may be appropriate under assumptions of changing climate. In this case, options could be chosen based on the degree of certainty known about likely future climate changes and likely environmental changes (e.g., air quality). If sufficient information is available, germplasm could be moved in the anticipated adaptive direction; for instance, rather than using local seed, seed from a warmer (often, downhill) current population would be used. By contrast, if an uncertain future is accepted, expanding seed zone sizes in all directions and requiring that seed collections be well distributed within these zones would be appropriate, as would relaxing seed transfer guidelines to accommodate multiple habitat moves, or introducing long-distance germplasm into seed mixes. Adaptive management of this nature is experimental by design, and will require careful documentation of treatments, seed sources, and outplanting locations in a corporate data structure to learn from both failures and successes of such mixes.

4. Manage for Asynchrony

Changing climates over paleoecologic timescales have repeatedly reset ecological community structure (species diversity) and composition (relative abundances) as plants and animals have adapted to natural changes in their environments. To the extent that climate acts as a region- and hemispheric-wide driver of change, the resulting shifts in biota often occur as synchronous changes across the landscape. Asynchrony can be achieved through a mix of activities that promotes diverse age classes, species mixes, stand diversities, genetic diversity, etc., at landscape scales. Early successional stages are likely the most successful (and practical) opportunities for resetting ecological trajectories that are adaptive to present rather than past climates, because this is the best chance for widespread replacement of plants. Such ecological resetting is evidenced in patterns of natural adaptation to historic climate shifts.

5. Establish "Neo-Native" Plantations and Restoration Sites

Information from historic species ranges and responses to Climate Change can provide unique insight about species behaviors, ecological tolerances, and potential new habitats. For instance, areas that supported species in the past under similar conditions to those projected for the future might be considered sites for new plantations or "neo-native" stands of the species. These may be well outside the current species range, in locations where the species would otherwise be considered exotic. For instance, Monterey pine (*Pinus radiata*), endangered throughout its small native range, has naturalized along the north coast of California far disjoined from its present native distribution. Much of this area was paleohistoric range for the pine, extant during climate conditions that have been interpreted to be similar to expected futures in California. Using these locations specifically for "neo-native" conservation stands, rather than planning for the elimination of the trees as undesired exotics (which is the current management goal), is an example of how management thinking could accommodate a climate-change context. This option is relevant to both forest plantation and ecological restoration contexts.

6. Promote Connected Landscapes

Capacity to move (migrate) in response to changing climates is key to adaptation and long-term survival of plants and animals in natural ecosystems. Plants migrate, or "shift ranges" by dying in unfavorable sites and colonizing favorable edges, including internal species' margins. Capacity to do this is aided by managing for porous landscapes; that is, landscapes that contain continuous habitat with few physical or biotic restrictions, and through which species can move readily (recruit, establish, forage). Promoting large forested landscape units, with flexible management goals that can be modified as conditions change, will encourage species to respond naturally to changing climates. This enables managers to work with, rather than against, the flow of change. Evaluating and reducing fragmentation, and planning cumulative landscape treatments to encourage defined corridors as well as widespread habitat availability, is a proactive approach.

7. Realign Significantly Disrupted Conditions. Restoration treatments are often prescribed for forest species or ecosystems that have been significantly or cumulatively disturbed and are far outside natural ranges of current variation. Because historical targets, traditionally used as references for restoration, are often inappropriate in the face of changing climates, re-alignment with current process rather than restoration to historic pre-disturbance condition may be a preferred choice. In this case, management goals seek to bring processes of the disturbed landscape into the range of current or anticipated future environments.

c. **Freshwater Resources** (IPCC, 2007, chapter 3)

Climate Change poses a major conceptual challenge to water managers, in addition to the challenges caused by population and land-use change. It is no longer appropriate to assume that past hydrological conditions will continue into the future (the traditional assumption) and, due to Climate Change uncertainty, managers can no longer have confidence in single projections of the future. It will also be difficult to detect a clear Climate Change effect within the next couple of decades, even with an underlying trend.

Changing to meet altered conditions and new ways of managing water are autonomous adaptations which are not deliberately designed to adjust with climate change. Drought-related stresses, flood events, water quality problems, and growing water demands are creating the impetus for both infrastructure investment and institutional changes in many parts of the world. On the other hand, planned adaptations take Climate Change specifically into account. In doing so, water planners need to recognize that it is not possible to resolve all uncertainties, so it would not be wise to base decisions on only one, or a few, climate model scenarios. Rather, making use of probabilistic assessments of future hydrological changes may allow planners to better evaluate risks and response options.

Integrated Water Resources Management (IWRM) should be an instrument to explore adaptation measures to climate change, but so far is in its infancy. Successful integrated water management strategies include, among others: capturing society’s views, reshaping planning processes, coordinating land and water resources management, recognizing water quantity and quality linkages, conjunctive use of surface water and groundwater, protecting and restoring natural systems, and including consideration of climate change. In addition, integrated strategies explicitly address impediments to the flow of information. A fully integrated approach is not always needed but, rather, the appropriate scale for integration will depend on the extent to which it facilitates effective action in response to specific needs. In particular, an integrated approach to water management could help to resolve conflicts among competing water users. In several places in the western U.S., water managers and various interest groups have been experimenting with methods to promote consensus-based decision making. These efforts include local watershed initiatives and state-led or federally-sponsored efforts to incorporate stakeholder involvement in planning processes. Such initiatives can facilitate negotiations among competing interests to achieve mutually satisfactory problem-solving that considers a wide range of factors.

The TAR (IPCC, 2001b) drew a distinction between ‘supply-side’ and ‘demand-side’ adaptation options, which are applicable to a range of systems. In general terms, supply-side options, involving increases in storage capacity or abstraction from water courses, tend to have adverse environmental consequences (which can in many cases be alleviated). Conversely, the practical effectiveness of some demand-side measures is uncertain, because they often depend on the cumulative actions of individuals. There is also a link between measures to adapt water resources and policies to reduce energy use. Some adaptation options, such as desalination or measures that involve pumping large volumes of water, use large amounts of energy and may be inconsistent with mitigation policy.

Information, including basic geophysical, hydro-meteorological, and environmental data as well as information about social, cultural and economic values and ecosystem needs, is also critically important for effective adaptation. Programs to collect these data, and use them for effective monitoring and early warning systems, would constitute an important first step for adaptation. In the western U.S., water-market transactions and other negotiated transfers of water from agricultural to urban or environmental uses are increasingly being used to accommodate long-term changes in demand (e.g., due to population growth) as well as short-term needs arising from drought emergencies.

Adaptation in the water sector involves measures to alter hydrological characteristics to suit human demands, and measures to alter demands to fit conditions of water availability. It is possible to identify four different types of limits on adaptation to changes in water quantity and quality:

- The first is a physical limit: it may not be possible to prevent adverse effects through technical or institutional procedures. For example, it may be impossible to reduce demands for water further without seriously threatening health or livelihoods, it may physically be very difficult to react to the water quality problems associated with higher water temperatures, and in the extreme case it will be impossible to adapt where rivers dry up completely.
- Second, while it may be physically feasible to adapt, there may be economic constraints to what is affordable.
- Third, there may be political or social limits to the implementation of adaptation measures. In many countries, for example, it is difficult for water supply agencies to construct new reservoirs, and it may be politically very difficult to adapt to reduced reliability of supplies by reducing standards of service.
- Finally, the capacity of water management agencies and the water management system as a whole may act as a limit on which adaptation measures (if any) can be implemented. The low priority given to water management, lack of coordination between agencies, tensions between national, regional and local scales, ineffective water governance and uncertainty over future Climate Change impacts constrain the ability of organizations to adapt to changes in water supply and flood risk.

A rather different way of coping with the uncertainty associated with estimates of future Climate Change is to adopt management measures that are robust to uncertainty. Integrated Water Resources Management, for example, is based around the concepts of flexibility and adaptability, using measures which can be easily altered or are robust to changing conditions. These tools, including water conservation, reclamation, conjunctive use of surface and groundwater, and desalination of brackish water, have been advocated as a means of reacting to Climate Change threats to water supply in California. Similarly, resilient strategies for flood management, such as allowing rivers to temporarily flood and reducing exposure to flood damage, are preferable to traditional ‘resistance’ (protection) strategies in the face of uncertainty.

d. **Coastal systems** (IPCC, 2007, chapter 6)

Overview

The capacity of coastal systems to regenerate after disasters, and to continue to produce resources and services for human livelihoods and well-being, is being tested with increasing frequency. This highlights the need to consider the resilience of coastal systems at broader scales and for their adaptive capacity to be actively managed and nurtured.

One constraint on successful management of climate-related risks to coastal systems is the limited ability to characterize in appropriate detail how these systems, and their constituent parts, will respond to Climate Change drivers and to adaptation initiatives. Of particular importance is understanding the extent to which natural coastal systems can adapt and therefore continue to provide essential life-supporting services to society. The lack of understanding of the coastal system, including the highly interactive nature and non-linear behavior, means that failure to take an integrated approach to characterizing climate-related risks increases the likelihood that the effectiveness of adaptation will be reduced, and perhaps even negated. Despite the growing emphasis on beach nourishment, the long-term effectiveness and feasibility of such adaptive measures remains uncertain, especially with the multiple goals explicit within Integrated Coastal Zone Management (ICZM). The question of who pays and who benefits from adaptation is another issue of concern. Public acceptance of the need for adaptation, and of specific measures, also needs to be increased.

Adaptation options

Adaptive capacity is the ability of a system to evolve in order to accommodate climate changes or to expand the range of variability with which it can cope. The adaptive capacity of coastal communities to cope with the effects of severe climate impacts declines if there is a lack of physical, economic and institutional capacities to reduce climate-related risks. But even a high adaptive capacity may not translate into effective adaptation if there is no commitment to sustained action.

ICZM provides a major opportunity to address the many issues and challenges identified above. Since it offers advantages over purely sectoral approaches, ICZM is widely recognized and promoted as the most appropriate process to deal with climate change, sea-level rise and other current and long-term coastal challenges. Enhancing adaptive capacity is an important part of ICZM. The extent to which Climate Change and sea-level rise are considered in coastal management plans is one useful measure of commitment to integration and sustainability. Responses to sea-level rise and Climate Change need to be implemented in the broader context and the wider objectives of coastal planning and management. ICZM focuses on integrating and balancing multiple objectives in the planning process. Generation of equitably distributed social and environmental benefits is a key factor in ICZM process sustainability, but is difficult to achieve. Attention is also paid to legal and institutional frameworks that support integrative planning on local and national scales. Different social groups have contrasting, and often conflicting views on the relative priorities considerations, as well as short and long-term perspectives.

Those involved in managing coastal systems have many practical options for simultaneously reducing risks related to current climate extremes and variability as well as adapting to Climate Change. This reflects the fact that many disaster and Climate Change response strategies are the same as those which contribute positively to present-day efforts to implement sustainable development, including enhancement of social equity, sound environmental management and wise resource use. This will help harmonize coastal planning and Climate Change adaptation and, in turn, strengthen the anticipatory response capacity of institutions. The timeframes for development are typically shorter than those for natural changes in the coastal region, though management is starting to address this issue. Examples include restoration and management of the Mississippi River and delta plain, and management of coastal erosion in Europe. Identifying and selecting adaptation options can be guided by experience and best practice for reducing the adverse impacts of analogous, though causally unrelated, phenomena such as subsidence (natural and/or human-induced) and tsunami. Based on this experience, it is highly advantageous to integrate and mainstream disaster management and adaptation to climate variability and change into wider coastal management, especially given relevant lessons from recent disasters.

There are also important trade-offs in adaptation. For instance, while hard protection can greatly reduce the impacts of sea level and Climate Change on socio-economic systems, this is to the detriment of associated natural ecosystems due to coastal squeeze. Managed retreat is an alternative response, but at what cost to socio-economic systems? General principles that can guide decision making in this regard are only beginning to be developed. Stakeholders will be faced with difficult choices, including questions as to whether traditional uses should be retained, whether invasive alien species or native species increasing in abundance should be controlled, whether planned retreat is an appropriate response to rising relative sea level or whether measures can be taken to reduce erosion. Decisions will need to take into account social and economic as well as ecological concerns. Considering these factors, the U.S. Environmental Protection Agency is preparing sea-level rise planning maps that assign all shores along its Atlantic Coast to categories indicating whether shore protection is certain, likely, unlikely, or precluded by existing conservation policies. In the Humber estuary (UK) sea-level rise is reducing the standard of protection, and increasing erosion. Adaptation initiatives include creation of new intertidal habitat, which may promote more cost effective defenses and also helps to offset the loss of protected sites, including losses due to coastal squeeze.

Current pressures are likely to adversely affect the integrity of coastal ecosystems and thereby their ability to cope with additional pressures, including Climate Change and sea-level rise. This is a particularly significant factor in areas where there is a high level of development, large coastal populations and high levels of interference with coastal systems. Natural coastal habitats, such as dunes and wetlands, have a buffering capacity which can help reduce the adverse impacts of climate change. Equally, improving shoreline management for non-Climate Change reasons will also have benefits in terms of responding to sea-level rise and Climate Change. Adopting a static policy approach towards sea-level rise, conflicts with sustaining a dynamic coastal system that responds to perturbations via sediment movement and long-term evolution.

e. **Agriculture and Food Production** (IPCC, 2007, chapter 5)

Many of the autonomous adaptation options identified before and since the TAR (IPCC, 2001b) are largely extensions or intensifications of existing risk-management or production-enhancement activities. For cropping systems there are many potential ways to alter management to deal with projected climatic and atmospheric changes. These adaptations include:

- altering inputs such as varieties and/or species to those with more appropriate thermal time and vernalization requirements and/or with increased resistance to heat shock and drought, altering fertilizer rates to maintain grain or fruit quality consistent with the climate and altering amounts and timing of irrigation and other water management practices;
- wider use of technologies to ‘harvest’ water, conserve soil moisture (e.g., crop residue retention) and to use water more effectively in areas with rainfall decreases;
- water management to prevent water logging, erosion and nutrient leaching in areas with rainfall increases;
- altering the timing or location of cropping activities;
- diversifying income by integrating other farming activities such as livestock raising;
- improving the effectiveness of pest, disease and weed management practices through wider use of integrated pest and pathogen management, development and use of varieties and

species resistant to pests and diseases, maintaining or improving quarantine capabilities, and sentinel monitoring programs;
- using seasonal climate forecasting to reduce production risk.

If widely adopted, these autonomous adaptations, singly or in combination, have substantial potential to offset negative Climate Change impacts and take advantage of positive ones. For example, practicable adaptations of varieties and planting times to avoid drought and heat stress during the hotter and drier summer months predicted under Climate Change altered significant negative impacts on sorghum (–48 to –58%) to neutral to marginally positive ones (0 to +12%). The benefits of adaptation vary with crops and across regions and temperature changes; however, on average, they provide approximately a 10% yield benefit when compared with yields when no adaptation is used. Another way to view this is that these adaptations translate to damage avoidance in grain yields of rice, wheat and maize crops caused by a temperature increase of up to 1.5 to 3°C in tropical regions and 4.5 to 5°C in temperate regions. Further warming than these ranges in either region exceeds adaptive capacity. The benefits of autonomous adaptations tend to level off with increasing temperature changes while potential negative impacts increase.

A large number of autonomous adaptation strategies have been suggested for planted forests including changes in management intensity, hardwood/softwood species mix, timber growth and harvesting patterns within and between regions, rotation periods, salvaging dead timber, shifting to species or areas more productive under the new climatic conditions, landscape planning to minimize fire and insect damage, adjusting to altered wood size and quality, and adjusting fire-management systems. Adaptation strategies to control insect damage can include prescribed burning to reduce forest vulnerability to increased insect outbreaks, non-chemical insect control (e.g., baculoviruses) and adjusting harvesting schedules, so that those stands most vulnerable to insect defoliation can be harvested preferentially. Under moderate climate changes, these proactive measures may potentially reduce the negative economic consequences of Climate Change.

f. **Human Health** (IPCC, 2007, chapter 8)

Overview

Adaptation is needed now in order to reduce current vulnerability to the Climate Change that has already occurred, and additional adaptation is needed in order to address the health risks projected to occur over the coming decades. Current levels of vulnerability are partly a function of the programs and measures in place to reduce burdens of climate-sensitive health determinants and outcomes, and partly a result of the success of traditional public-health activities, including providing access to safe water and improved sanitation to reduce diarrheal diseases, and implementing surveillance programs to identify and respond to outbreaks of malaria and other infectious diseases. Weak public-health systems and limited access to primary health care contribute to high levels of vulnerability and low adaptive capacity for hundreds of millions of people. Current national and international programs and measures that aim to reduce the burdens of climate-sensitive health determinants and outcomes may need to be revised, reoriented and, in some regions, expanded to address the additional pressures of Climate Change. The degree to which programs will need to be augmented will depend on factors such as the current burden of climate-sensitive health outcomes, the effectiveness of current interventions, projections of where, when and how the burden could change with changes in climate and climate variability, access to the human and financial resources needed to implement activities, stressors that could increase or decrease resilience to impacts, and the social, economic and political context within which interventions are implemented.

The planning horizon of public-health decision-makers is short relative to the projected impacts of Climate Change, which will require modification of current risk-management approaches that focus only on short-term risks. A two-tiered approach may be needed, with modifications to incorporate current Climate Change concerns into ongoing programs and measures, along with regular evaluations to determine a program's likely effectiveness to cope with projected climate risks.

Adaptation Approaches
Climate-based early warning systems for heat waves and malaria outbreaks have been implemented at national and local levels to alert the population and relevant authorities that a disease outbreak can be expected based on climatic and environmental forecasts. To be effective in reducing health impacts, such systems must be coupled with a specific intervention plan and have an ongoing evaluation of the system and its components. The effectiveness of warning systems for extreme events depends on individuals taking appropriate actions, such as responding to heat alerts and flood warnings. Individuals can reduce their personal exposure by adjusting clothing and activity levels in response to high ambient temperatures and by modifying built environments, such as by the use of fans, to reduce the heat load. Weather can partially determine cultural practices that may affect exposure.

Seasonal forecasts can be used to increase resilience to climate variability, including to weather disasters. For example, the Pacific ENSO Application Center (PEAC) alerted governments, when a strong El Nino was developing in 1997/1998, that severe droughts could occur, and that some islands were at unusually high risk of tropical cyclones. The interventions launched, such as public education and awareness campaigns, were effective in reducing the risk of diarrheal and vector-borne diseases.

Health systems need to plan for and respond to Climate Change. There are effective interventions for many of the most common causes of ill-health, but frequently these interventions do not reach those who could benefit most. One way of promoting adaptation and reducing vulnerability to Climate Change is to promote the uptake of effective clinical and public-health interventions in high-need cities and regions of the world. Funding health programs is a necessary step towards reducing vulnerability but will not be enough on its own. Progress depends also on strengthening public institutions; building health systems that work well, treating people fairly and providing universal primary health care; providing adequate education, generating demand for better and more accessible services; and ensuring that there are enough staff to do the required work. Health-service infrastructure needs to be resilient to extreme events. Efforts are needed to train health professionals to understand the threats posed by Climate Change.

g. Energy Production and Use

Overview
Adaptations to effects of Climate Change on energy *use* may focus on increased demands for space cooling in areas affected by warming and associated increases in total energy consumption costs. Alternatives could include reducing costs of cooling for users through energy efficiency improvement in cooling equipment and building envelopes; responding to likely increases in demands for electricity for cooling through expanded generation capacities, expanded interties,

and possibly increased capacities for storage; and responding to concerns about increased peak demand in electricity loads, especially seasonally, through contingency planning for load-leveling. Over a period of several decades, for instance, technologies are likely to respond to consumer concerns about higher energy bills where they occur (Wilbanks et al., 2007).

Many technologies that can enable adaptations to effects on energy *production and supply* are available for deployment. The most likely adaptation in the near term is an increase in perceptions of uncertainty and risk in longer-term strategic planning and investment, which could seek to reduce risks through such approaches as diversifying supply sources and technologies and risk-sharing arrangements (Wilbanks et al., 2007). Renewable energy technologies are expected to play a major role in supplementing or replacing convention fossil fuel energy sources over the next several decades. For a description of the status and potential applications of wind, solar, and biomass renewable energy technologies, see Appendix B.

It seems possible that adaptation challenges would be greatest in connection with possible increases in the intensity of extreme weather events and possible significant changes in regional water supply regimes. More generally, adaptation prospects appear to be related to the magnitude and rate of climate change (e.g., how much the average temperature rises before stabilization is achieved, how rapidly it moves to that level, and how variable the climate is at that level), with adaptation more likely to be able to cope with effects of lesser amounts, slower rates of change, and less variable climate (Wilbanks et al., 2007).

Energy Production and Use in Indian Country (Suagee and MacCourt, 2007)
A tribal government could create an electric utility to perform one or more of the functions performed by traditional electric utilities: generation, transmission and distribution. The mission of a tribal utility might be conceived broadly, such as to make energy-related services and benefits available to reservation residents, with an emphasis on promoting energy efficiency and locally available renewable resources. With such a broad mission, the distribution of electric power might just be a part of the overall package of services. The utility might put an emphasis on programs to help customers install distributed generation facilities, such as roof-top photovoltaic arrays, which could be owned by either the utility or the customers. Or they might be owned by third-party investors who would take advantage of the tax credits. Ownership might be transferred from the utility to the customer over time though a lease-purchase agreement. Similar ownership and financing arrangements could be used for other kinds of investments, such as the battery packs of plug-in hybrid electric vehicles, which could be used to provide "ballast" for intermittent renewable energy sources.

A tribal utility might put an emphasis on providing service to areas that do not presently have access to the power grid, building and operating mini-grids for such areas, which could be stand-alone systems or could be interconnected with the grid. If the tribal utility were to promote the development of such mini-grids, it might want to look at experience in less-developed countries for ideas about how to set prices for power from the mini-grid and policies on interconnection of distributed generation facilities to the mini-grid.

The tribal utility might include a building design assistance program to help customers incorporate energy efficiency and solar design techniques into new construction. New buildings could be not just "zero-net energy" but, rather, net energy producers, pumping more power into the grid than they consume. The utility might recruit joint venture partners from private industry to help provide assistance and to help make investment capital available. The utility could put an emphasis on schools and other educational institutions, and help to design and carry out energy education programs with hands-on aspects .

In deciding among the various functions that a tribe might want to take on, there are many factors to consider, such as the adequacy of the existing utility service, relationship with the current service provider, costs associated with taking over the system, the locally available resource base, and the broader political framework. The broader context includes federal and state legislation, such as: existing state laws that establish renewable portfolio standards for regulated utilities; the federal incentive in section 203 of the 2005 Energy Policy Act for federal agencies to purchase power from tribal renewable energy projects; possible future legislation to create a "cap and trade" program to reduce CO_2 emissions, and various other kinds of incentives for renewables, including tax incentives unavailable to tribes but potentially useful for business partners of tribal utilities .

A tribe might want to do some parts sooner and other parts later. For example, a tribe with a substantial wind power resource might be able to bring that resource into operation and use the revenue stream to subsidize energy efficiency services or the purchase of the existing power grid within the reservation. A tribe might create a utility with a broad mandate but with the expectation that it will start small and expand its range of activities over time. In such phased development, there could be decision points at which tribal council approval is necessary.

Another approach would be to create more than one entity, perhaps one with a conservative mission of providing reliable retail electric power service at reasonable rates and another with a more entrepreneurial mission of bringing renewable energy projects into operation using investment strategies that entail more risk than is consistent with the conservative mission of a distribution utility. In that scenario, the mission of the entrepreneurial entity might be described as including the marketing of risk to investors willing to accept it. In light of the range of benefits that could be realized in tribal communities through renewable energy development and the associated offsets for CO_2 emissions, renewable energy in Indian country should be able to make the grade among investments that are screened for social and environmental responsibility.

6. Planning and Managing Adaptation of Natural Resources

a. Adaptation Management Concepts

In a broad sense, there are three general types of approaches that resource managers can take to managing natural resources for Climate Change. These approaches are: 1) reactive adaptation, 2) planned management responses, and 3) proactive management. The following description of these three approaches, which has been proposed for managing National Forests, is from CCSP, 2008b, chapter 3.

Approach 1: Reactive Adaptation

The extent and severity of an extreme weather or climate event vis-à-vis the ecosystem's ability to naturally adjust to or recover from it, as well as the management agency's ability to quickly marshal the necessary response resources (money, staff, equipment, etc.) when the event occurs, will determine the ultimate impacts on the ecosystem and the cost to the managing agency. Depending on the extent of the impacts on the ecosystem and on the managing agency, future attainment of management goals may also be affected. While unforeseen opportunities may emerge, the cost of such unplanned reactive management is typically larger than if management tools can be put in place in a timely and efficient manner (a common experience with reactive vs. proactive resource or hazard management).

This reactive approach, which does not take into account changing climate conditions, is sometimes used when scientific uncertainty is considered too great to plan well for the future. There is a strong temptation to not plan ahead, because it avoids the costs and staff time needed to prepare for an event that is uncertain to occur. The risk to an agency of initiating expensive and politically challenging management strategies is large in the absence of a strong scientific consensus on vulnerabilities and Climate Change effects. However, not planning ahead also can mean incurring greater cost, and may bring with it great risk later on—risk that results from inefficiencies in the response when it is needed, wasted investments made in ignorance of future conditions, or potentially even greater damages because precautionary actions were not taken.

Approach 2: Planned Management Responses to Changing Climate

This approach to adaptation assumes that adjustments to historical management approaches are needed eventually, and are best made during or after a major climatic event. In this case, the managing agency would identify climate-change-cognizant management approaches that are to be implemented at the time of a disturbance, as it occurs, such as a historically unprecedented fire, insect infestation, or extreme windfall event, hurricanes, droughts and other extreme climatic events. A choice is made to not act now to prepare for climate change, but rather to react once the problem is evident. The rationale, again, could be that the Climate Change impacts are too uncertain to enact or even identify appropriate anticipatory management activities, or even that the best time for action from a scientific as well as organizational efficiency standpoint may be post-disturbance (*e.g.,* from the standpoint of managing successional processes within ecosystems and across the landscape).

Significant cost efficiencies, relative to the reactive approach, may be achieved in this approach, as management responses are anticipated—at least generically—well in advance of an event, yet are implemented only when "windows of opportunity" open. Future constraints to implementing such changes will need to be anticipated and planned for, and, if possible removed in advance for timely adaptation to be able to occur when the opportunity arises. For example, managers could ensure that the genetic nursery stock is available for wider areas, or they could re-examine regulations restricting practices so that, immediately after a disturbance, management can act rapidly to re-vegetate and manage the site. Such an approach may be difficult to implement, however, as crises often engender political and social conditions that favor "returning to the status quo" that existed prior to the crisis rather than doing something new.

Approach 3: Proactive Management

This management approach that is most forward-looking is one that uses current information about future climate, future environmental conditions, and the future societal context of National Forest management to begin making changes to policy and on-the-ground management now and when future windows of opportunity open. Opportunities for such policy and management changes would include any planning or project analysis process in which a description of the changing ecosystem/disturbance regime as climate changes would be used to identify a proactive management strategy.

Relevant information for forest managers may include projections of regional or even local climates, including changes in average temperature, precipitation, changes in patterns of climatic extremes and disturbance patterns (*e.g.,* fire, drought, flooding), shifts in seasonally important dates (*e.g.,* growing degree-days, length of fire season), expected future distribution of key plant species, and changes in hydrological patterns. The ability of climate science to provide such information at higher spatial and temporal resolution has been improving steadily over recent years, and is likely to improve further in coming years. Current model predictions have large uncertainties, which must be considered in making management adaptation decisions. Other relevant information may be species-specific, such as the climatic conditions favored by certain plant or animal species over others, or the ways in which changed climatic conditions and the resultant habitats may become more or less favorable to particular species (*e.g.*, for threatened or endangered species). The overall goals of planned anticipatory management would be to facilitate adaptation in the face of the changing climate.

Again, significant cost efficiencies and maybe even financial gains may be achieved in this approach, as management responses are anticipated well in advance and implemented at the appropriate time. If climatic changes unfold largely consistent with the scientific projections, this approach to adaptation may turn out to be the most cost-effective and ecologically effective (referred to as the "perfect foresight" situation by economists. For example, analyses using forest sector economic models that assume “perfect foresight” have shown that when a diverse set of management options are available to managers under conditions of extensive mortality events from climate change, the economic impacts on the wood product sector, even with large-scale mortality events, are less costly than otherwise.

This approach may not be able to maintain ecosystems that currently exist (as those are better adapted to current climate regimes), but it may be best suited to support natural adaptive processes—such as planning corridor development to facilitate species migration to more appropriate climates, or managing for protection of viable habitats for threatened and endangered species to enhance or extend opportunities for adaptation. Under such a management approach, the specific management targets—such as outputs of particular rangeland and forest products, or maintenance of a particular species habitat—may themselves be adjusted over time, as the opportunities for those ecosystem services diminish under a changing climate and new opportunities for other services may have a greater chance of being met. The inability to maintain ecosystems that currently exist may suggest activities such as long-term seed bank storage with future options for re-establishing populations in new and more appropriate locations. Assessing the potential for this type of change will draw on ecological, economic, and social information. Importantly, such an approach would need to involve managers at various levels to monitor changes in the ecosystem (*i.e.*, observed on the ground); coordinate and make appropriate changes in policies, regulations, plans, and programs at all relevant scales; and modify the on-the-ground practices needed to implement these higher-level policies. This degree of cross-scale integration is not typically achieved at present, and would need to occur in the future to effectively support such an approach to adaptation.

b. Developing an Impact Assessment (CCSP, 2008b, chapter 9)

Today's natural resource planning and management practices were developed under relatively stable climatic conditions in the last century, and under a theoretical notion that ecological systems tend toward a natural equilibrium state for which one could manage. Most natural resource planning, management, and monitoring methodologies that are in place today are still based on the assumption that climate, species distributions, and ecological processes will remain stable, save for the direct impacts of management actions and historical interannual variability. Indeed, many government entities identify a "reference condition" based on historical ranges of variability as a guide to future desired conditions.

Although mainstream management practices typically follow these traditional assumptions, in recent years resource managers have recognized that climatic influences on ecosystems in the future will be increasingly complex and often outside the range of historical variability and, accordingly, more sophisticated management plans are needed to ensure that goals can continue to be met. By transforming management and goal-setting approaches from a static, equilibrium view of the natural world to a highly dynamic, uncertain, and variable framework, major advances in managing for change can be made, and thus adaptation is possible.

Within the context of natural resource management, an impact assessment is a means of evaluating the sensitivity of a natural system to climate change. Sensitivity is defined by the IPCC (2001b) as "the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli." An impact assessment is part of a larger process to understand the risks posed by Climate Change, including those social and economic factors that may contribute to or ameliorate potential impacts, in order to decide where and when to adapt. In the Climate Change community, this process is well established. It begins with an assessment of impacts, followed by an evaluation of an entity's capacity to respond (adaptive capacity). The information on impacts is then combined with information on adaptive capacity to determine a system's overall vulnerability. This information becomes the basis for selecting adaptation options to implement. The resource managers' mental model for this larger decision making process contains similar elements to the climate community's model, but addresses them in a different sequence of evaluation to planning. The managers' process begins with estimating potential impacts, reviewing all possible management options, evaluating the human capacity to respond, and finally deciding on specific management responses. The resource management community implicitly combines the information on potential impacts with knowledge of their capacity to respond during their planning processes.

Impact assessments combine (1) understanding of the current state of the system and its processes and functions, with (2) drivers of environmental change in order to, (3) project potential responses to future changes in those drivers. Knowledge of the current state of the system, including its critical thresholds and coping ranges, provides the fundamental basis for understanding the implications of changes in future conditions. A coping range is the breadth of conditions under which a system continues to persist without significant, observable consequences, taking into account the system's natural resilience. Change is not necessarily "bad," and the fact that a system responds by shifting to a new equilibrium or state may not necessarily be a negative outcome. Regardless of the change, it will behoove managers to adjust to or take advantage of the anticipated change. Several examples of approaches to conducting impact assessments are provided below along with a discussion of the types of tools needed and key issues related to conducting impact assessments.

A Guiding Framework for Impact Assessments

The aim of a framework to assess impacts is to provide a logical and consistent approach for eliciting the information needs of a decision maker, for conducting an assessment as efficiently as possible, and for producing credible and useful results. While impact assessments are routinely done to examine the ecological effects of various environmental stressors, the need to incorporate changes in climate variables adds significantly to the spatial and temporal scales of the assessment, and hence its complexity.

A number of frameworks for impact assessments have been developed. For example, within the international conservation arena, a successful framework for managers has been developed by The Nature Conservancy (2007). The steps in this framework include (1) identifying the management goal and climate threat to that goal; (2) selecting measurable indicators; (3) determining the limits of acceptable variation in the indicators; (4) assessing the current status of the system with respect to meeting management goals, as well as with respect to the indicators; and (5) analyzing data on indicators to decide whether a change in management is required.

Tools to Assess Impacts

The example framework described in the previous section references two key types of tools: models that represent the climate system as a driver of ecological change, and models that embody the physical world to trace the effect of climate drivers through relevant pathways to impacts on management endpoints of concern. There are numerous tools that begin to help managers anticipate and manage for climate change, although characterization of uncertainty could be improved, along with "user friendliness" and the ability to frame management endpoints in a manner that more closely meshes with the needs of decision makers. Fortunately, tool development for impact analysis is one of the most active areas of climate research, and greatly improved tools can be expected within the next few years.

Climate Models

The most widely recognized need for information is the need for climate projections at useable scales—scales much finer than those associated with most general circulation model (GCM) projections. In particular, the resolution of current climate-change projections from GCMs is on the order of degrees of latitude and longitude (200–500 km^2). Projections from regional climate models are finer in resolution (*e.g.,* 10 km^2), but are not available for most regions. All climate projections can be downscaled using methods that take local topography and local climate patterns into account. Although relatively coarse climate projections may be useful for anticipating general trends, the effects of local topography, large water bodies, and specific ecological systems can make coarse predictions highly inaccurate. To be more useful to managers, projections will need to be downscaled using methods that account for local climate patterns. In addition, climate-change projections will need to be summarized in a way that takes their inherent uncertainty into account. That uncertainty arises from the basic model structure, the model parameters, and the path of global emissions into the future. Useful future projections will provide summaries that take this uncertainty into account and inform managers where the projections are more and less certain and, specifically, how confident we can be in a given level of change. Several different approaches exist for capturing the range of projected future climates. It also will be important to work with climate modelers to ensure that they provide the biologically relevant output variables from the model results. For further information on the state of climate models, and their application to predict climate scenarios in the Pacific Northwest, see Appendix C, an except from "State of Climate Modeling: Contribution to Region 10's Action Plan for Energy and Climate Change" (Elleman et al., 2007).

Impact Models to Assess Endpoints of Concern

Climate Change impacts may be defined by two factors, (1) the types and magnitude of climate changes that are likely to affect the target in a given location, and (2) the sensitivity of a given conservation target to climate change. Assessing the types and magnitude of climate changes that a population or system is likely to experience will require climate-change projections as well as projected changes in climate-driven processes such as fire, hydrology, vegetation, and sea level rise. For example, managing forests in a changing climate will require data on projected potential changes to vegetation, as well as detailed data on the current condition of vegetation.

Sensitivity of target organisms to Climate Change depends on several aspects of the biology of a species or the ecological composition and functioning of a system. For example, species that are physiologically sensitive to changes in temperature or moisture; species that occupy climate-sensitive habitats such as shallow wetlands, perennial streams, and alpine areas; and species with limited dispersal abilities will all be more sensitive to Climate Change. Populations with slow growth rates and populations at a species range boundary are also likely to be more sensitive to Climate Change. Species, communities, or ecosystems that are highly dependant on specific climate-driven processes—such as fire regimes, sea level rise, and hydrology—will also be highly sensitive to climate change.

There are many new ecological models that would help managers address climate change, but the most important modeling tools will be those that integrate diverse information for decision making and prioritize areas for different management activities. Planners and managers need the capability to evaluate the vulnerability of each site to Climate Change and the social and economic costs of addressing those vulnerabilities. One could provide this help with models that allow the exploration of alternative future climate-change scenarios and different funding limitations that could be used for priority-setting and triage decisions. Comprehensive, dynamic, priority-setting tools have been developed for other management activities, such as watershed restoration. Developing a dynamic tool for priority-setting will be critical for effectively allocating limited resources.

Establishing Baseline Conditions

To estimate current and potential future impacts, a literature review of expected climate impacts may be conducted to provide a screening process that identifies “what trends to worry about.” The next step beyond a literature review is a more focused elicitation of the ecological properties or components needed to reach management goals for lands and waters. For each of these properties or components, it will be important to determine the key to maintaining them. If the literature review reveals that any of the general climate trends may influence the ecological attributes or processes critical to meeting management goals, then the next steps are to identify baselines, establish monitoring programs, and consider specific management tools and models.

Once the important ecological attributes or processes are identified, a manager needs to have a clear idea of the baseline set of conditions for the system. Ecologists, especially marine ecologists, have drawn attention to the fact that the world has changed so much that it can be hard to determine an accurate historical baseline for any system. The reason that an understanding of a system's long history can be so valuable is that the historical record may include information about how systems respond to extreme stresses and perturbations. When dealing with sensitive, endangered, or stressed systems, experimental perturbation is not feasible. Where available, paleoecological records should be used to examine past ranges of natural environmental variability and past organismal responses to Climate Change.

Historic baselines have the potential to offer insights into how to manage for climate change. Examples of baseline data important for making management decisions and understanding potential effects of Climate Change include species composition and distribution of trees in forests; rates of freshwater discharge into estuaries; river flooding regimes; forest fire regimes; magnitude and timing of anadromous fish runs; and home ranges, migration patterns, and reproductive dynamics of sensitive organisms. However, baselines also have the potential to be misleading. For example, historic baselines are useful only if climate is incorporated into those past baselines and the relationship of vegetation to climate is explored. If a baseline is held up as a goal, and the baseline depends on historic climates that will never again be seen in a region, then the baseline could be misleading. Adjusting baselines to accommodate changing conditions is an approach that would require caution to avoid unnecessarily compromising ecosystem integrity for the future and losing valuable historical knowledge.

Monitoring to Inform Management Decisions

Monitoring is needed to support a manager's ability to detect changes in baseline conditions as well as to facilitate timely adaptation actions. Monitoring also provides a means to gauge whether management actions are effective. Some monitoring may be designed to detect general ecological trends in poorly understood systems. However, most monitoring programs should be designed with specific hypotheses in mind and trigger points that will initiate a policy or management re-evaluation. For instance, using a combination of baseline and historical data, a monitoring program could be set up with predefined thresholds for a species' abundance or growth rate, or a river's flow rate, which, once exceeded, would cause a re-examination of management approaches and management objectives.

A second important feature of any monitoring program is the decision of what to monitor. Ideally several attributes should be monitored, and those that are selected should be chosen to represent the system in a tractable way and to give clear information about possible management options. Otherwise there is a risk of collecting volumes of data but not really using it to alter management. Sometimes managers seek one aggregate indicator—the risk in this is that the indicator is harder to interpret because so many different processes could alter it.

Some systems will require site-specific monitoring programs, whereas others will be able to take advantage of more general monitoring programs. For example, the severity and frequency of forest fires are clearly linked to climate. Thus, managing for changing fire regimes will require assessing fire risk by detecting changes in fuel loads and weather patterns. Detecting climate-driven changes in insect outbreaks and disease prevalence will require monitoring the occurrence and prevalence of key insects, pathogens, and disease vectors. Detecting early changes in forests will also require monitoring changes in hydrology and phenology, and in tree establishment, growth, and mortality.

Using Scenarios as a Means of Managing Under Uncertainty

The high degree of uncertainty inherent in assessments of Climate Change impacts can make it difficult for a manager to translate results from those assessments into practical management action. However, uncertainty is not the same thing as ignorance or lack of information—it simply means that there is more than one outcome possible as a result of climate change. One approach for dealing with uncertainty is to develop a range of responses based on a range of possible climate changes that a region may experience.

It is not possible to predict the changes that will occur, but managers can get an indication of the *range* of changes possible. By working with a range of possible changes rather than a single projection, managers can focus on developing the most appropriate responses based on that range rather than on a "most likely" outcome. To develop a set of scenarios—*e.g.*, internally consistent views of reasonably plausible futures in which decisions may be explored—quantitative or qualitative visions of the future are developed or described. These scenarios explore current assumptions and serve to expand viewpoints of the future. In the Climate Change impacts area, approaches for developing scenarios may range from using a number of different realizations from climate models representing a range of emissions growths, to analog scenarios, to informal synthetic scenario exercises that, for example, perturbate temperature and precipitation changes by percentage increments (*e.g.*, -5% change from baseline conditions, 0, +5%, +10%).

Model-based scenarios explore plausible future conditions through direct representations of complex patterns of change. These scenarios have the advantage of helping to further our understanding of potential system responses to a range of changes in drivers. When using spatially downscaled climate models and a large number of emissions scenarios and climate model combinations (as many as 30 or more), a subset of "highly likely" climate expectations may be identifiable for a subset of regions and ecosystems. More typically, results among models will disagree for many places, precluding any unambiguous conclusions. Where there is a high level of agreement, statements may be made such as, "for 80% of the different model runs, peak daily summer temperatures are expected to rise by at least x degrees." When downscaled and multiple runs are available, managers can use them to explore the consequences of different management options. For instance, Battin *et al*. (2007) were able to identify specific places where habitat restoration was likely to be effective in the face of Climate Change if the goal was recovery of salmon populations, and in specific places where restoration efforts would be fruitless given anticipated Climate Change.

Analog scenarios use historical data and previously observed sensitivity to weather and climate variability. When developing analog scenarios, if historical data are incomplete or non-existent for one location, observations from a different region may used. Synthetic scenarios specify changes in particular variables and apply those changes to an observed time series. For example, an historic time series of annual mean precipitation for the northeastern U.S. would be increased by 2% to create a synthetic scenario, but no other characteristics of precipitation would change. Developing a synthetic scenario might start by simply stating that in the future, it is possible that summers will be hotter and drier. That scenario would be used to alter the sets of historic time series, and decision makers would explore how management might respond.

Along with developing multiple scenarios using the methods described above, it may be helpful to do sensitivity analyses to discover a system's response to a range of possible changes in drivers. In such analyses, the key attributes of the system are examined to see how they respond to systematic changes in the climate drivers. This approach may allow managers to identify thresholds beyond which key management goals become unattainable.

All of these scenario-building approaches and sensitivity analyses provide the foundation for "if/then" planning, or "scenario planning". One of the most practical ways of dealing with uncertainty is scenario planning—that is, making plans for more than one potential future. Scenario planning is appropriate and prudent when there are large uncertainties that cannot be reduced in the near future, as is the case with climate change. The key to scenario planning is limiting the scenarios to a set of possibilities, typically anywhere from two to five. If sensitivity analyses are performed, those results can be used to select the most relevant scenarios that both address managers' needs and represent the widest possible, but still plausible, futures. The strategy is to then design a variety of management strategies that are robust across the whole range of scenarios and associated impacts. Ideally scenarios represent clusters of future projections that fit together as one bundled storyline that is easy to communicate to managers (*e.g.*, warmer and wetter, warmer and drier, or negligible change). When used deftly, scenario planning can alleviate decision-makers' and managers' frustration at facing so much uncertainty and allow them to proactively manage risks. For detailed guidance on using scenario data for climate impact assessments.

c. **Adaptive Management** (CCSP, 2008b, chapter 9)

Once adaptation approaches have been selected, after taking into account confidence levels, adaptive management is likely to be an effective method for implementing those approaches. It emphasizes managing based on observation and continuous learning and provides a means for effectively addressing varying degrees of uncertainty in our knowledge of current and future Climate Change impacts. Adaptive management is typically divided into two types: "passive" and "active". "Passive" adaptive management refers to using historical data to develop hypotheses about the best management action, followed by action and monitoring. Often models are used to guide the decisions and the monitoring can improve the models. "Active" adaptive management refers to actually conducting a management experiment, ideally with several different management actions implemented at once as a means of testing competing hypotheses.

Adaptive management to address Climate Change is an iterative process that involves the consideration of potential climate impacts, the design of management actions and experiments that take those impacts into account, monitoring of climate-sensitive species and processes to measure management effectiveness, and the redesign and implementation of improved (or new) management actions. To maximize the implementation of climate-sensitive adaptive management within federal systems, managers can focus on (1) previously established strategies that were designed for other management issues but have strong potential for application toward Climate Change impacts, and (2) new strategies that are not yet in place but appear to be feasible and within reasonable reach of current management structures. In other words, at a minimum, managers need to vigorously pursue changes that are relatively easily accomplished under existing programs and management cultures.

Recent examinations of the difficulty of actually using adaptive management have emphasized that the temporal and spatial scale, dimension of uncertainty, risks, and institutional support can create major difficulties with applying adaptive management. When one considers adaptive management (whether active or passive) in response to climate change, every one of these potential difficulties is at play. The critical challenge will be stating explicit scientific hypotheses, establishing monitoring programs with predefined triggers that initiate a re-examination of management approaches, and a flexible policy or institutional framework. These challenges do not mean adaptive management is impossible—only that attention to hypotheses, monitoring, periodic re-evaluations, and flexibility are necessary.

Another key element of adaptive management is monitoring of sensitive species and processes in order to measure the effectiveness of experimental management actions. In the case of adaptive management for climate change, this step is critical, not only for measuring the degree to which management actions result in positive outcomes on the ground, but also for supporting a better scientific understanding of how to characterize and measure ecological resilience. Most resource agencies already have monitoring programs and sets of indicators. As long as management goals are not changed, then these existing monitoring programs should reflect the outcomes of management actions on the ground. If management goals are altered because Climate Change is perceived to be so severe that historical goals are untenable, then entirely new indicators and monitoring programs may need to be designed. Whatever the case, monitoring is fundamental to supporting the reevaluation and refinement of management strategies as part of the adaptive process.

Re-Evaluate Priorities and Consider Triage

Climate Change not only requires consideration of how to adapt management approaches, it also requires reconsideration of management objectives. In a world with unlimited resources and staff time, climate adaptation would simply be a matter of management innovation, monitoring, and more accessible and useable science. In reality, priorities may need to be re-examined and reestablished to focus adaptation efforts appropriately and make the best use of limited resources. At the regional scale, one example of the type of change that may be needed is in selected estuaries where freshwater runoff is expected to increase and salt water is expected to penetrate further upstream. Given this scenario, combined with the goal of protecting anadromous fishes, models could be used to project shifts in critical propagation habitats and management efforts could be refocused to those sites. In Rocky Mountain National Park, because warmer winters are expected to result in greatly increased elk populations, a plan to reduce elk populations to appropriate numbers is being prepared with the goal of population control.

Prioritization requires information about the distribution of natural resources and conservation targets, the vulnerability of those targets to climate change, and costs of different management actions in different systems. Prioritization schemes may weight these three factors in different ways, depending on goals and needs. Knowing where resources and conservation targets are is relatively straightforward, although even baseline information on species distributions is often lacking. Prioritization schemes that weight rare species or systems heavily would likely target lands with more threatened and endangered species and unique ecosystems.

Because climate-driven changes in some ecological systems are likely to be extreme, priority setting may, in some instances, involve triage. Some goals may have to be abandoned and new goals established if Climate Change effects are severe enough. Even with substantially focused and creative management efforts, some systems may not be able to maintain the ecological properties and services that they provide in today's climate. In other systems, the cost of adaptation may far outweigh the ecological, social, or economic returns it would provide. In such cases, resources may be better invested in other systems. One simple example of triage would be the decision to abandon habitat management efforts for a population of an endangered species on land at the "trailing" edge of its shifting range. If the refuge that currently provides habitat for the species will be unsuitable for the species in the next 50 years, it might be best to actively manage for habitat elsewhere and, depending on the species and the circumstances, investigate the potential for relocation. Such decisions will have to be made with extreme care. In addition to evaluating projected trends in climate and habitat suitability, it will be necessary to monitor the species or habitats in question to determine whether the projected trends are being realized.

Manage at Appropriate Scales

Experience gained from natural resource management programs and other activities may offer insights into the application of integrated ecosystem management under changing climatic conditions. Integrated ecosystems management seeks to optimize the positive ecological and socioeconomic benefits of activities aimed at maintaining ecosystem services under a multitude of existing stressors. One lesson learned from this approach is that it may be necessary to define the management scale beyond the boundaries of a single habitat type, conservation area, or political or administrative unit to encompass an entire ecosystem or region. Currently, management plans for forests, rivers, marine protected areas, estuaries, national parks, and wildlife refuges are often developed for discrete geographies with specific attributes (species, ecosystems, commodities), without recognition that they may be nested within other systems. For example, marine protected areas are often within national estuaries; wild and scenic rivers are often within national parks. With few exceptions, plans are not developed with the ability to fully consider the matrix in which they are embedded and the extent to which those attributes may vary over time in response to drivers external to the management system. Climate Change adaptation opportunities may be missed if land and water resources are thought of as distinct, static, or out of context of a regional and even continental arena. A better approach would be to systematically broaden and integrate management plans, where possible. When spatial scales of consideration are larger, resource management agencies often have mutually reinforcing goals that may result in the enhancement of their ability to manage cooperatively across landscapes.

Manage for Change

Agencies have established best practices based on many years of past experience. Unfortunately, dramatic Climate Change may change the rules of the game, rendering yesterday's best practices tomorrow's bad practices. Experienced managers have begun to realize that they can anticipate changes in conditions, especially conditions that might alter the impacts of grazing, fire, logging, harvesting, park visitation, and so forth. Such anticipatory thinking will be critical, as Climate Change will likely exceed ecosystem thresholds over time such that strategies to increase ecosystem resilience will no longer be effective. At this point, major shifts in ecosystem processes, structures, and components will be unavoidable, and adaptation will require planning for management of major ecosystem shifts.

For example, some existing management plans identify a desired state (based on structural, ecosystem service, or ecosystem process attributes of the past) and then prescribe practices to achieve that state. While there is clarity and accountability in such fixed management objectives, these objectives may be unrealistic in light of dramatic environmental change. A desirable alternative management approach may be to "manage for change." For example, when revegetation and silviculture are used for post-disturbance rehabilitation, species properly suited to the expected future climate could be used. In Tahoe National Forest, white fir could be favored over red fir, pines could be preferentially harvested at high elevations over fir, and species could be shifted upslope within expanded seed transfer guides. It is also possible that, after accounting for change, restoration may cease to be an appropriate undertaking.

Scenario-based planning can be a useful approach in efforts to manage for change. This is a qualitative process that involves exploration of a broad set of scenarios, which are plausible—yet very uncertain—stories or narratives about what might happen in the future. Protected-area managers, along with subject matter experts, can engage in scenario planning related to Climate Change and resources of interest and put into place plans for both high-probability and low-probability, high-risk events. Development of realistic plans may require a philosophical shift concerning when restoration is an appropriate post-disturbance response. It is impractical to attempt to keep ecosystem boundaries static. Estuaries display this poignantly. After a flood, there is often intense pressure to restore to the pre-flooding state. To ensure sound management responses, guidelines for the scenarios under which restoration and rebuilding should occur could be established in advance of disturbances. In this sense, disturbances could become opportunities for managing toward a distribution of human population and infrastructure that is more realistic given changing climate.

7. Planning Process, Tools and Resources

a. Example of a Tribal Climate Change Adaptation Process

The previous chapters identified the impacts, vulnerabilities, and adaptation options related to Climate Change. The next step for a tribal nation is to develop and implement a process to determine the specific Climate Change vulnerabilities that will affect the tribe and it resources, and to identify and select the most promising adaptation options that will allow sustainable use of resources, and minimize adverse effects to tribal health and well-being. There are few examples in the literature or on the Internet of a Climate Change adaptation planning process conducted by a tribal nation. However, one of the most comprehensive tribal planning processes found on the Internet was conducted by the Center for Indigenous Environmental Resources (CIER) for the First Nations of Canada.

CIER used a variety of information sources to determine five priority climate change impacts for First Nations of Canada south of 60 degrees north latitude (CIER, 2008). This included literary research gathered throughout the project, the creation of an Advisory Committee, and a newly developed Adaptation Network. The feedback from these groups helped guide CIER's research on climate change impacts and also informed the selection of priority impacts. The Advisory

Committee was composed of Aboriginal people who were experienced with climate change impacts or adaptation in their respective region. CIER obtained feedback from this group through face-to-face meetings. CIER developed the adaptation network using two methods: a telephone survey and an on-line survey. The group contacted for a telephone survey was comprised of First Nations and non-First Nations people, some of whom are developing and actively implementing climate change work. The on-line survey was directed towards individuals from across Canada, the majority of who were members of First Nations. CIER identified additional climate change impacts from literary research and input provided by the Advisory Committee and Adaptation Network.

From the feedback received, CIER developed matrixes that containing existing or predicted climate change impacts in Canada as described in the literature, including the likely magnitude and duration of each impact. CIER then evaluated the affect of each impact on First Nations, and then selected five priority impacts. The final five priority impacts were selected because they are applicable in multiple eco-regions in Canada, affect all four pillars of sustainability (social, environment, culture, and economy) in First Nation communities, have a large magnitude, long duration, and will be difficult for First Nations to adjust to without active adaptation measures (CIER, 2008).

CIER recognized that all First Nations in Canada have unique social, economic and cultural characteristics. Given the diversity of ecosystems, vulnerabilities and characteristics of First Nations across Canada, the report emphasizes that it is important that each First Nation determine how they will be uniquely affected by Climate Change. The report also recommends that if First Nations are not aware of how their community may be affected, they can begin a dialogue using the selected five priority impacts (CIER, 2008).

CIER focused the adaptation strategies research on the five priority impacts. This resulted in a list containing almost 100 adaptation strategy options. Additionally, CIER included Adaptation Network responses provided in both the online and the telephone survey, given in a section on preferred or existing adaptation options. CIER shared this list of adaptation strategies with the advisory committee members in order to identify adaptation option priorities and to understand the reasoning behind these decisions.

CIER identified a number of potential initiatives for First Nations to adapt within each of the five priority impact areas. CIER developed these initiatives from literary research and feedback from the advisory network and adaptation committee, and the initiatives were based on adaptation strategies that individuals and communities were already implementing, or suggested ideas. CIER identified tools to assist the First Nations in evaluation Climate Change adaptation alternatives. These tools consisted of a database with relevant, accessible, and national information and two comprehensive lists of sustainable water use tools and resources available from various levels of government, communities, and businesses. The CIER report concluded that although some of these tools they identified are applicable to First Nations, there are some aspects of First Nations, especially in relation to culture, governance, decision-making, and Aboriginal and Treaty rights, which require additional considerations. Non-First Nation specific tools and resources can be transferable as long as users make appropriate and needed adjustments to suit their specific needs, Traditional Knowledge, and existing processes (CIER, 2008).

b. Tools and Resources

The following websites provide Climate Change planning tools and resources that may be useful for tribes developing adaptation strategies:

Institute for Tribal Environmental Professionals (ITEP)

On this website, ITEP offers information and resources tailored to tribes who seek a better understanding of climate change and its impacts to tribal communities. Through links from this website, tribes can find basic climate-change information, resources, contacts, and an open forum for expressing and discussing views on the matter. Also on this website, there are a series of tribal Climate Change profiles that help illuminate the impacts Native people face as well as solutions being developed to mitigate and adapt to ecosystem changes.
http://www4.nau.edu/tribalclimatechange/index.asp

Environmental Protection Agency (EPA) Climate Change Program

EPA's Climate Change Site offers comprehensive information on the issue of Climate Change in a way that is accessible and meaningful to all parts of society – communities, individuals, business, states and localities, and tribes. On this website you will find links to Climate Change Science, GHG emission inventories, health and environmental effects of Climate Change, EPA Climate Change initiatives, and U.S. Climate Change policy.
http://www.epa.gov/climatechange/

EPA Watershed Management Tools

One of the most useful tools for understanding Climate Change impacts on water resources, especially impaired waters, is the Climate Assessment Tool element of the BASINS water modeling program. BASINS is a multi-purpose environmental analysis system that integrates a geographical information system (GIS), national watershed data, and state-of-the-art environmental assessment and modeling tools into one convenient package. EPA intends to promote the use of this model and provide training to EPA, State and Tribal program staffs on how to use the model to support assessment of climate-related water resources impacts and program decisions.
http://www.epa.gov/waterscience/BASINS/

National Water Program Strategy: Response to Climate Change

This strategy, developed by the EPA Office of Water, provides an overview of the likely effects of climate change on water resources and the nation's clean water and safe drinking water programs. This strategy also describes over 40 specific actions the National Water Program intends to take to adapt program implementation in light of climate change.
http://www.epa.gov/water/climatechange/strategy.html

Intergovernmental Panel on Climate Change (IPCC)

The IPCC was established to provide the decision-makers and others interested in climate change with an objective source of information about climate change. The IPCC does not conduct any research nor does it monitor climate related data or parameters. Its role is to assess on a comprehensive, objective, open and transparent basis the latest scientific, technical and socio-economic literature produced worldwide relevant to the understanding of the risk of human-

induced climate change, its observed and projected impacts and options for adaptation and mitigation. The IPCC is a scientific body, the information it provides with its reports is based on scientific evidence and reflects existing viewpoints within the scientific community. The comprehensiveness of the scientific content is achieved through contributions from experts in all regions of the world and all relevant disciplines including, where appropriately documented, industry literature and traditional practices, and a two stage review process by experts and governments. On this website you will find links to IPCC meetings, documents, reports and presentations.
http://www.ipcc.ch/

US Climate Change Science Program (CCSP)
The CCSP integrates federal research on climate and global change, as sponsored by thirteen federal agencies and overseen by the Office of Science and Technology Policy, the Council on Environmental Quality, the National Economic Council and the Office of Management and Budget. On this website you will find links to CCSP research activities and reports published by CCSP.
http://www.climatescience.gov/

Western Climate Initiative (WCI)
The WCI, launched in February 2007, is a collaboration of seven U.S. governors and four Canadian Premiers. WCI was created to identify, evaluate, and implement collective and cooperative ways to reduce greenhouse gases in the region, focusing on a market-based cap-and-trade system. On this website you will find links to WCI reports, documents, economic analyses, and upcoming events.
http://www.westernclimateinitiative.org/

U.S. Forest Service Climate Change Resource Center (CCRC)
The CCRC is a reference website for resource managers and decision makers who need information and tools to address climate change in planning and project implementation on lands in the West. The CCRC addresses the manager's question "What can I do about climate change?" by providing information about basic climate sciences and compiling knowledge resources and support for adaptation and mitigation strategies. The site offers educational information, including basic science modules that explain climate and climate impacts, decision-support models, maps, simulations, case studies, and toolkits.
http://www.fs.fed.us/ccrc/

National Oceanic and Atmospheric Administration (NOAA)
NOAA is charged with helping society understand, plan for, and respond to climate variability and change. This is achieved through the development and delivery of climate information services, the implementation of a global observing system, and focused research and modeling to understand key climate processes. The NOAA climate mission is an end-to-end endeavor focused on providing a predictive understanding of the global climate system so the public can incorporate the information and products into their decisions. On this website you will find links to NOAA's research, monitoring, modeling and information services programs.
http://www.noaa.gov/climate.html/

Climate Impacts Group (GIG)

The CIG is an interdisciplinary research group studying the impacts of natural climate variability and global Climate Change on the U.S. Pacific Northwest. Through research and interaction with regional stakeholders, the CIG works to increase the resilience of the Pacific Northwest to fluctuations in climate. The CIG's research focuses on four key sectors of the PACIFIC NORTHWEST environment: water resources, aquatic ecosystems, forests, and coasts. The CIG is unique in its focus on the intersection of climate science and public policy. The Climate Impacts Group, based at the University of Washington, is one of eight regional climate impacts assessment groups in the nation funded by the National Oceanic and Atmospheric Administration (NOAA), and is part of the Center for Science in the Earth System at the Joint Institute for the Study of the Atmosphere and Ocean.
http://cses.washington.edu/cig/

National Tribal Environmental Council (NTEC)

The NTEC was formed in 1991 with seven tribes and input from several intertribal organizations, including the Council of Energy Resource Tribes and the Native American Rights Fund, as a membership organization dedicated to working with and assisting tribes in the protection and preservation of tribal environments. NTEC's mission is to ensure that Indian tribes and Alaska Native villages have the ability to protect, preserve and promote the wise management of air, land and water for the benefit of present and future generations. NTEC works to advance an understanding of the environment based on traditional tribal cultural and spiritual values, cultivate support for tribal control and management of tribal lands in accordance with each tribe's political and economic priorities, and encourage federal government agencies to adopt and implement policies that fulfill the trust responsibility to tribes.
http://www.ntec.org/

Tribes, Climate Change and Solutions

This website was designed and is maintained by National Wildlife Federation, Northern Rockies Office, in Missoula, MT. This website contains links to websites that provide Climate Change information at the international, national, regional and local levels. It also includes links to tribal Climate Change workshops, reports and presentations.
http://www.tribalclimate.org/solutions.htm

Affiliated Tribes of Northwest Indians (ANTI)

ATNI is a nonprofit organization representing 54 northwest tribal governments from Oregon, Idaho, Washington, southeast Alaska, Northern California and Western Montana. ATNI is an organization whose foundation is composed of Indian peoples. Representatives from the member tribes set the policy and direction through committees by way of resolutions during the three yearly meetings. ANTI periodically hosts conferences on climate change, with a specific focus on the Northwest and its potential implications for Tribal concerns.
http://www.atnitribes.org/#fallconf08

Center for Indigenous Environmental Resources (CIER)

CIER is a national, First Nation-directed environmental non-profit organization with charitable status and is based in Winnipeg, Manitoba, Canada. CIER was founded in 1994 by a small group

of First Nation leaders from across Canada who recognized the need for Aboriginal peoples to have the capacity to solve environmental problems affecting their lands and resources. We develop and implement sustainable solutions to proactively address environmental issues affecting First Nations lands and resources. We approach all of our efforts using an integrated approach that combines multiple perspectives and fosters collaborative relationships. The CIER website offers a variety of free publications and products for download and upon request. These publications are organized into the following categories: Taking Action on Climate Change, Building Sustainable Communities, Protecting Lands and Water, and Conserving Biodiversity.
http://www.cier.ca/information-and-resources/publications-and-products.aspx?id=190

Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments
This guidebook provides local government leaders with a new tool to help them plan for the impacts of climate change, such as an increased risk of drought and flooding, new diseases, and invasive species that are harmful to humans and the environment. The guidebook draws heavily on the Climate Impacts Group's experience in researching and communicating information on climate change impacts and planning to Pacific Northwest decision makers, and on King County's experience in developing and implementing its climate plan.
http://www.metrokc.gov/exec/news/2007/0912globalwarming.aspx

8. Conclusions

The IPCC has concluded unequivocally that the average temperature of the earth’s surface has significantly warmed since the mid-19th century, and that it is very likely that most of this global warming is due to increased concentrations of human generated greenhouse gases. Modeling based on various scenarios of increased GHG emissions shows that average surface temperatures will continue to increase until the atmospheric concentrations of GHGs are stabilized. By the mid-21st century, the choice of emission scenario becomes more important in terms of the magnitude of the projected warming, with model projections of increases in globally averaged temperature of approximately 2 to 3 °F for several of the IPCC scenarios. According to the IPCC, all of North America is very likely to warm during this century, and to warm more than the global average increase in most areas. The effects of global warming include changes in precipitation patterns, increased air temperatures, greater frequency of extreme weather events, earlier melting of snowpack, and rising sea levels.

Strategies for protecting climate-sensitive ecosystems, natural resources, and human health will be increasingly important for all people, but especially important to tribal nations because of their close association with the land, their relatively non-diverse economies, and their subsistence lifestyle. The scientific literature strongly supports the use of active (or proactive) adaptation methods to reduce risk of adverse effects of Climate Change on ecosystems through actions that increase the resilience of ecological systems to Climate Change stressors. Adaptive management is an iterative process that takes into consideration potential climate impacts, the design of management actions and experiments that take those impacts into account, monitoring of climate-sensitive species and processes to measure management effectiveness, and the redesign and implementation of improved management actions as needed.

Proactive adaptation requires the anticipation of stresses before they occur so that the response to these stresses is planned and strategic. Proactive adaptation measures can therefore decrease the magnitude of future stresses. Proactive adaptation measures can be less cost intensive over the long-term when compared to reactive measures. Incorporating proactive adaptation measures can reduce the amount or intensity of stress felt by the community when there are systems available to meet the challenges presented by climate change. Therefore, there are many social as well as economic benefits of planning for Climate Change and implementing proactive adaptation measures. Incorporating proactive adaptation measures is also a good option because they can help prevent or lessen the impacts of Climate Change on tribal nations by increasing resiliency and promoting sustainability.

In order to effectively respond to Climate Change, a tribal nation must develop a Climate Change adaption plan. The first step in developing a Climate Change adaptation plan is to establish a process to determine the specific Climate Change vulnerabilities that will affect the tribal nation, and then appropriate adaptation options in response to these vulnerabilities. This process, once implemented, will allow the tribal nation to select the adaptation options that are most beneficial to the tribe nation. According to the literature cited in the previous chapters, an effective Climate Change adaptation process consists of the following activities: (1) identify the types and magnitude of Climate Change impacts that are likely to occur in the region of concern; (2) determine the sensitivity and potential vulnerabilities of ecosystems, natural resources, human health and well-being to these impacts; (3) identify sustainable goals that into consideration the impacts of Climate Change; (4) assess the current status (baseline conditions) of ecosystems, natural resources, human health and communities with respect to these goals; (5) identify all feasible adaptation options that would meet the sustainable goals; (6) select the most effective approach (set of options) based on available resources and the projected effectiveness of the approach in meeting the sustainable goals; and (7) select measurable indicators of Climate Change and periodically monitor these indicators to decide if the selected adaptation approach is effective, or whether an alternative approach would be more beneficial.

The collaboration between the First Nations of Canada and the CIER cited in the previous chapter, to develop a comprehensive Climate Change adaptation strategy for the First Nations, and to identify five priority adaptation actions, is an example of how tribal nations can work together to meet their common goals of effectively responding to Climate Change. Such a collaborative process may also be appropriate for the tribal nations in the Pacific Northwest in developing a comprehensive Climate Change adaptation strategy.

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Appendix A

Current and Future Climate Change in the Pacific Northwest

This appendix is an excerpt from "State of Climate Modeling: Contribution to Region 10's Action Plan for Energy and Climate Change" by Robert Elleman, Gina Bonifacino, and Joanna Ekrem.

1.0 Current Climate Change

1.1 Current observations of climate warming

Surface observations show that the atmosphere has warmed in the past 50-150 years, especially since 1950. The global average surface temperature trend over the past 100 years (1906-2005) is 0.74 °C ± 0.18 °C (1.8 °F is 1 °C). The trend over the past 50 years, 0.13 °C per decade, is twice as much as the 100 year trend. Mid-latitude frost days have decreased, and heat waves have increased in duration. Average northern hemisphere temperatures are *very likely* (>90% confidence) the warmest 50 year period in the last 500 years and *likely* (>66% confidence) the warmest in the last 1300 years.

Changes in weather events are consistent with the atmospheric warming. The mid-latitude storm belts have strengthened and moved poleward in the past 30-40 years, as have westerly winds at the surface and throughout the lower atmosphere. Precipitation patterns at mid- and high-latitudes have shifted accordingly. Water vapor concentrations through the whole lower atmosphere around the globe are increasing with the higher global temperatures. Heavy precipitation events have increased in number, tropical Atlantic cyclones have increased in intensity, and droughts have increased in length and intensity.

Earth systems such as the cryosphere (ice and snow), oceans, and biosphere are responding to the warmer climate. For snow and ice, this includes less springtime snow cover, less mountain snowpack at lower elevations, fewer number of days lakes and rivers are frozen, less arctic summertime sea ice extent, smaller extent of permafrost and seasonally frozen ground, and lower glacier and ice cap mass. Warming is seen in large areas of the upper ocean, although decadal variability is responsible for cooling in the North Pacific and some other regions. Surface water is becoming less salty in high-latitude regions mostly from higher precipitation. Surface ocean pH has decreased on average by 0.1 units since 1750. Sea level rose between 1993 and 2003 at a rate of 3 mm/yr, roughly half of which was due to thermal expansion of a warming ocean and half due to melting glaciers, ice sheets, and ice caps. Northern Hemisphere ecological systems are experiencing earlier greening of vegetation in the spring, earlier spring migrations, longer growing seasons, and a poleward shift of algal, plankton, and fish concentrations in high-latitude seas. These changes are consistent with the atmospheric warming observed over the past 100 years.

It is likely that global warming would have been more pronounced over the past 50 years if not for the countering, cooling effect of atmospheric aerosols. The shorter atmospheric lifetime of aerosols than greenhouse gases is a challenge for addressing short-term climate change. If all emissions of greenhouse gases and aerosols were stopped today, the global mean temperature would initially increase more than if no emissions reductions were made. This is because the cooling aerosols will be removed from the atmosphere first, leaving only the warming effect from the longer-lived greenhouse gases. Already, environmental regulations in the past 20 years to reduce $PM_{2.5}$ will partially unveil the full warming potential of greenhouse gases over the next few decades. One scientific study estimated that if sulfate aerosols were instantaneously removed from the atmosphere, the global mean temperature would increase by about 0.8 ºC within 10-20 years, which is about the same as the total 20th Century warming. Since sulfate and other aerosols are emitted usually from the same sources as the greenhouse gases, any mitigation strategies to reduce emissions of greenhouse gas must also account for the reduction in the cooling aerosols.

Climate modelers have very high confidence (>90% probability) that human influences are responsible for the majority of global-scale climate change in the past 50 years. No sophisticated climate model can reproduce the observed mean and continental-scale warming trends without anthropogenic emissions (Figure 5; WG1TSp62). It is also *likely* (>66% probability) that anthropogenic forcing has contributed to a more extreme climate (e.g., both more frost days and more heat waves), more widespread warm ocean temperatures, and reduced arctic sea ice extent. Models have been unable to determine how much of the regional scale temperature is due to human influence.

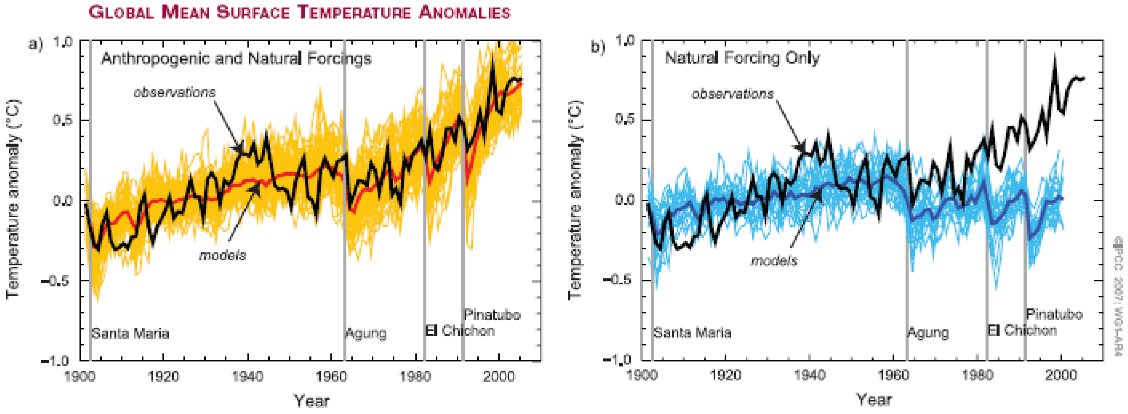


Figure 5. Climate models of the 20th Century in the 2007 IPCC AR4 (a) with and (b) without human influence on climate show that 20th Century warming is not due to natural forces alone.

The anthropogenic influence on sea level rise has been difficult to separate from the natural influence. Although it is *very likely* anthropogenic forcing has played a role in sea level rise since 1950, the observed sea level rise between 1961 and 2003 is 40% greater than what models can reproduce. In addition, there is considerable decadal variability in sea level – so much so that it is larger than the trend over the past 40 years. The decadal trend of sea level and the human role in sea level rise are major uncertainties in climate science.

1.2 Current Observations of Environmental Impacts in Region 10

The Region 10 states are already experiencing the regional effects of global warming. Effects are present in all four states but are more concentrated and pronounced in Alaska since Arctic temperatures over the past 100 years have increased at twice the rate of the global average.

1.2.1 Idaho, Oregon, and Washington

Scientific evidence for climate change in the Pacific Northwest is usually defined in terms of physical boundaries (e.g., Columbia River basin, western US, North America) rather than state boundaries. The Puget Sound region has warmed 1.5 ºC in the 20th Century, compared to 0.8 ºC in the Pacific Northwest and 0.6 ºC globally. Interannual climate variability from El Niño and the Pacific Decadal Oscillation accounts for perhaps one-third of the Pacific Northwest warming. The warming has been greatest in winter and at night, both of which likely decrease ecosystem exposure to extreme cold. The length of the growing season has increased by 2 days per decade on average since 1950, mostly due to earlier onset of springs. Forest growth is increasing in places where growth is limited by low temperatures, although this relationship in the Pacific Northwest is complicated by summertime water limitations.

Local sea level rise has differed substantially from the global average. Local differences arise from land subsidence and uplift, changes in ocean circulation, and local changes in water density. While global sea level rise has been 1.8 mm/yr over the past 40 years and 3.1 mm/yr between 1993 and 2003, land subsidence and uplift in the Puget Sound region has resulted in nearly no change in sea level at the entrance of the Strait of Juan de Fuca, an average sea level rise in the northern part of the Puget Sound, and a roughly double rise in the southern part of the Puget Sound.

Much of the evidence for climate change in the Pacific Northwest relates to water resources. April 1 snow water equivalent in the Cascades and Rockies (see Figure 6), especially at low elevations, decreased 15 and 30%, respectively, since 1950. Consistent with this, melt-season streamflow peaks 1 to 3 weeks earlier, and there are suggestions that spring soil moisture has increased. Total stream discharge in the Columbia River basin has decreased in the past 50 years. These changes in snowpack are attributed to a larger fraction of precipitation falling as rain than snow, rather than a reduction in overall frozen and liquid precipitation. North American precipitation has generally increased, but evapotranspiration (return of water from the earth surface to atmospheric water vapor) has also increased. The fraction of annual streamflow entering Puget Sound in the summer season has decreased from 25% to 21%. Salmon have declined due to warmer and drier summertime conditions.

Evidence of existing climate change impacts on ecosystems in the Pacific Northwest is not well-documented. One major reason is that it is hard to separate climate impacts from those related to land-use change, ecosystem destruction, and pollution. Pacific salmon are shifting northward and are now found in rivers feeding the Arctic Ocean. Warming in Oregon has led to reduced lake depth and susceptibility of toad eggs to a fungal parasite. An earlier spring stratification in Lake Washington has offset the peaks in phytoplankton and zooplankton.

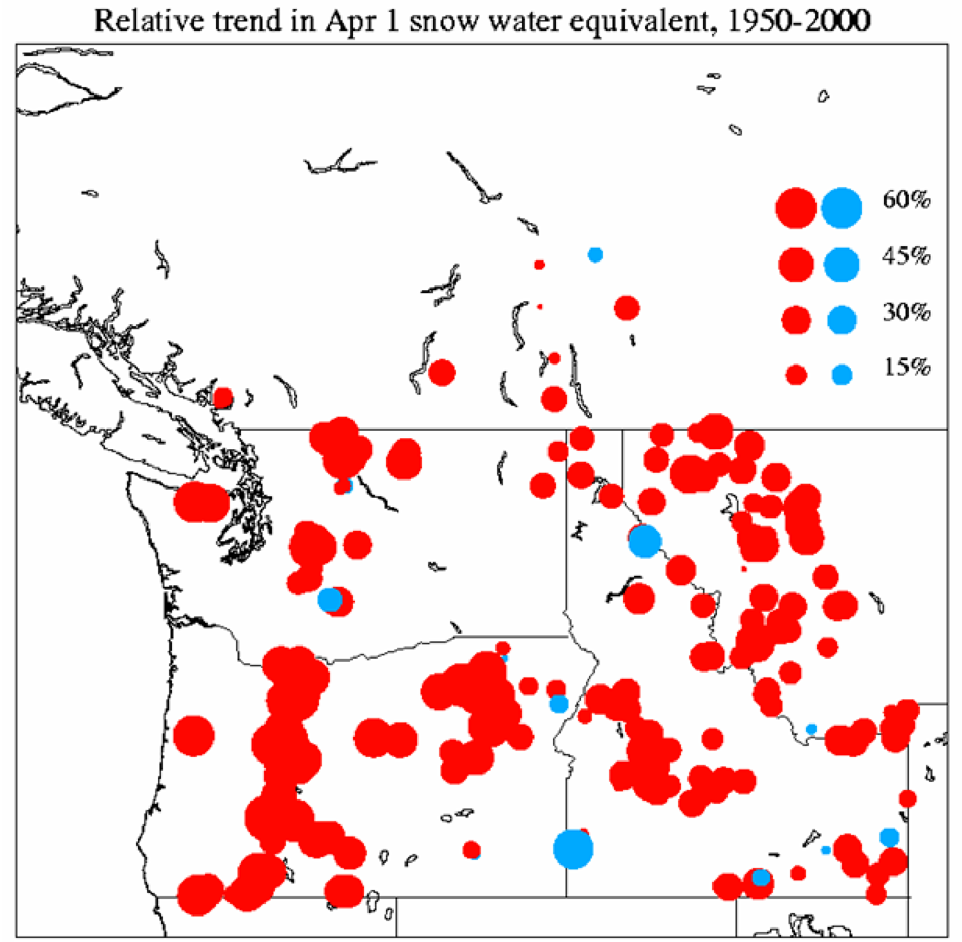


Figure 6. Evidence of climate change impact on Pacific Northwest hydrology. From Phil Mote's Climate Change 101 presentation, 17 Sept, 2007.

1.2.2 Alaska

The Arctic as a whole has warmed by 1-2 ºC since the 1970's. This is nearly 10 times the decadal average in the past 50 years for the entire globe. The warming has been even greater in northwestern North America (including Alaska), which has been one of the most rapidly warming regions of the world. Decadal trends are complex in the Arctic because of prominent climate variations on the same time scale. Regardless, the IPCC concludes "that the Arctic is in the early states of a manifestation of a human-induced greenhouse signature". With the warmer temperatures come reduced sea ice and glacier extent, shorter periods of river and lake ice in the sub-Arctic, a longer growing season, northward movement of shrubs into grasslands, an increase in photosynthetically active biomass, a substitution of Arctic birds and mammals with a more southern ecosystem dominated by pelagic birds, and evidence for permafrost degradation.

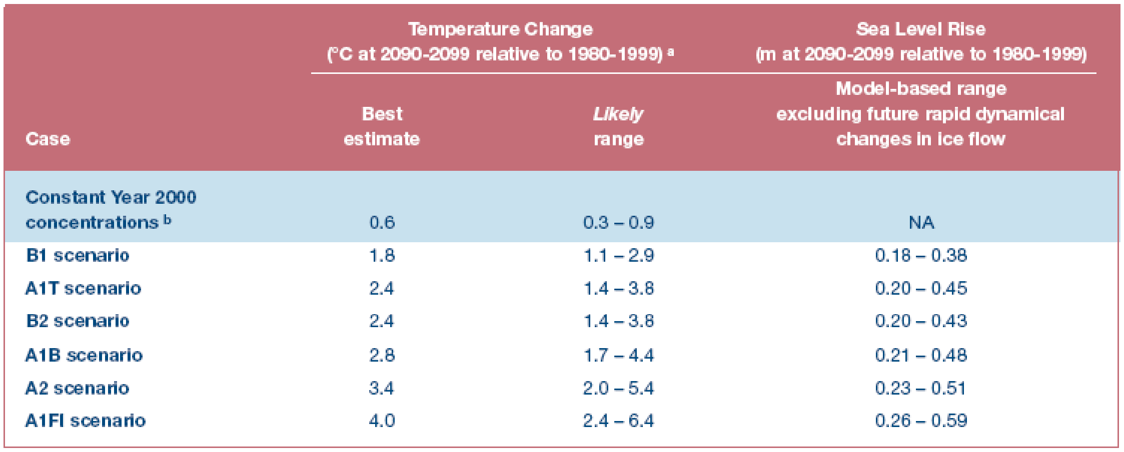
2.0 Future Climate Change

2.1 Predictions of Global Climate

Even if all anthropogenic emissions stopped today, inertia in the climate system would keep global mean temperatures rising for decades to come. Thus, we have already committed ourselves to a certain amount of climate change. In the IPCC AR4, the amount of committed climate change is defined by the warming if greenhouse gases are held constant at current values. This is less stringent than assuming all emissions stop immediately, but it nevertheless implies a drastic and unrealistic reduction in emissions. Even this unrealistically optimistic (and by now in 2007, impossible) scenario commits us to warming over the 21st Century equal what we experienced in the 20th Century.

Using this definition and greenhouse gas concentrations for the year 2000, we are committed to 0.1 ºC per decade warming for the next couple decades. Even if emissions increase as suggested by the SRES scenarios (e.g., A1B, A2, B1), about one quarter of the warming in 2050 relative to 1980-1990 comes from committed climate change. At least one quarter of the sea level rise is due to committed climate change.

Climate models predict that by the end of the 21st Century the mean surface temperature will increase by 1.8-4.0 ºC relative to 1980-1999. Emissions scenarios predict the same global warming through 2050 and then diverge afterwards. The spread represents the uncertainty in emissions patterns due to societal, technological, economic, and political changes. It is important to stress that none of the scenarios accounts for Kyoto or other greenhouse reduction agreements, though a couple of the scenarios include technological changes that could meet or exceed the reductions from current agreements. The scenario most climate researcher present as the most plausible, A1B, estimates a temperature increase of 2.8 ºC, or roughly 0.3 ºC per decade. This is about twice the warming rate of the past 50 years and four times the warming rate of the past 100 years. Each scenario in Table 1 has a *likely* range (> 66% confidence the result lies in this range) that reflects the variability of the different climate model results. Combining the SRES scenarios and the climate model spread, 21st Century warming is projected as 1.1-6.4 ºC. The low end of this range is still a warming rate similar to what we have experienced in the past 50 years, and that is an extraordinarily optimistic combination of scenarios and climate model configuration.



	Temperature Change (°C at 2090-2099 relative to 1980-1999) [a]		Sea Level Rise (m at 2090-2099 relative to 1980-1999)
Case	**Best estimate**	***Likely* range**	**Model-based range excluding future rapid dynamical changes in ice flow**
Constant Year 2000 concentrations [b]	0.6	0.3 – 0.9	NA
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

Table 1. Projected global temperature increase and sea level rise in 2095. From IPCC Working Group 1 Technical Summary, page 70.

The temperature change is projected to be positive everywhere on the planet, but it will be greatest over land, in drier areas, in winter and at high latitudes in the Northern Hemisphere. Heat waves are expected to be longer, more intense, and more frequent, while wintertime cold snaps are projected to decrease by 50 to 100% for most Northern Hemisphere locations. Snow cover will decrease and permafrost will thaw deeper each summer. The intensity of hurricanes and typhoons may increase, although the total number may decrease. The position of the mid-latitude jet stream and storm tracks are projected to move towards the poles. Correspondingly, precipitation will increase north of about 50º latitude and decrease in the subtropics (20-40º latitude). The effect on the Pacific Northwest is unclear since it lies in the fuzzy middle-ground between precipitation increases and decreases. There is high uncertainty about how climate patterns such as El Niño and the Pacific Decadal Oscillation will change due to global warming.

On a global average, precipitation will increase because a warmer atmosphere cycles more water and water vapor. However, the increase in precipitation varies regionally, and precipitation may even decrease in precipitation in some areas. The mid-latitude storm belt will intensify and move northward, leading to a northward expansion of the subtropics (e.g., Sahara and Southwest USA). World-wide, increased evaporation with higher temperatures will partially offset increases in precipitation and magnify decreases in precipitation.

Sea level will rise faster in the 21st Century than it did in the 20th Century, and oceans will have less ice and be more acidic. Scenario A1B projects a sea level rise roughly twice the rate of the 1961-2003 period. Only the most optimistic scenario, B1, has a range that does not exceed the observed rate in the past 40 years. Thermal expansion, as opposed to melting glaciers and ice sheets, represents 70 to 75% of the projected sea level rise. Actual sea level rise may be even higher since the results ignore the possibility of a catastrophic ice flow. In addition, local sea level rise depends on changes in ocean circulation and tectonic subsidence or lifting.

Ocean circulation, sea ice, and pH will be affected by climate change. The Gulf Stream, more accurately referred to as the Atlantic Meridional Overturning Circulation, will *very likely* (> 90% probability) slow down in the 21st Century, but it is *very unlikely* (< 10% probability) that it will abruptly slow like in the Hollywood movie “Day After Tomorrow”. The late summertime Arctic Ocean is projected is projected to be largely ice-free by 2100. The surface ocean pH will decrease by 0.14 to 0.35 units, compared to a decrease of 0.1 units from pre-industrial times to today. The acidification could affect marine organisms that use calcium carbonate to make exoskeletons.

Freshwater systems will also be affected. Glacier and snowmelt fed river basins such as in the lower Region 10 states will experience less storage capacity in snow and ice, a higher ratio of winter to summer flow, and possibly less flow during the low-flow season. Alaska is *very likely* (> 90% probability) to have higher runoff and water availability. Sea level rise will reduce the available freshwater through salinization of groundwater and estuaries. “Higher water temperatures, increased precipitation intensity and longer periods of low flows are likely to exacerbate many forms of water pollution”.

All these climate projections stop at 2100. To assess climate beyond 2100, models are reduced in complexity and ability to resolve finer scale details. If we continue on a likely emissions scenario and then stabilize at 2100, the global mean temperature would rise and the sea level would both continue, over time, to rise another 25% beyond the 21st Century warming and sea level rise. Additional sea level rise of up to 7 meters over the following thousands of years would come from the potentially irreversible melting of the Greenland Ice Sheet. These models suggest that we are committed to long-term climate change but also that current and future emissions still play a large role in our long-term climate change commitment.

2.2 Region 10 Specific Predictions and Impacts

2.2.1 Idaho, Oregon, and Washington

Temperature and Precipitation

The Pacific Northwest will experience warming consistent with the global average. The west coast of the United States is expected to warm by 2 to 3 ºC by 2100. As the warming will be higher in the middle of continents than over the oceans, continental climates in Idaho could warm 1 ºC more than the Pacific coasts of Washington and Oregon. The Climate Impacts Group at the University of Washington predicts that the Northwest, defined by the lower three states plus western Montana, will warm relative 1.1 ºC relative to 1970-2000 by the 2020s, 1.6 ºC by the 2040s, and by 3.1 ºC by the 2080s. The rate of warming, 0.3 ºC per decade is similar to the predicted global average warming rate and is three times the rate experienced in the 20th Century. By the 2040s, the change in mean temperature across the Northwest will exceed the year-to-year variability, which means that systems will be experiencing a climate beyond their natural range to cope.

Warming will occur in all seasons but will be greater in the summer. This result from climate modeling for the 2007 IPCC report is in contrast to traditionally held belief that wintertime temperatures will increase more in mid-latitude regions. Wintertime warming may be double the annual Northwest average of 3 ºC per century on the slopes of mountain ranges at elevations that are snow-covered at present but will be snow-free in the future. A similar pattern of exacerbated warming is likely to occur at the Cascade crest in springtime. Likely increased springtime cloudiness, the “Monterey-ization of the Northwest”, will decrease the diurnal temperature range. West of the Cascades, the lower daytime high temperature will be more significant than the higher nighttime low temperature and result in a cooler overall springtime. East of the Cascades, the effect is the opposite and this area will have warmer average springtime temperatures.

Precipitation is projected to increase slightly on an annual and Northwest average, but seasonal and smaller scale features are more important. As the mid-latitude storm belt strengthens and moves northward, wintertime precipitation in the Northwest increases, but the amount is likely less than 10% even by 2100 and is less than the current interannual variability. Summertime precipitation will decrease as dry summers like in the Southwest move northward, but this has a small effect since rainfall is already relatively low in summer. Wintertime flooding may become more frequent as more precipitation falls as rain rather than snow and heavy precipitation events become more common.

Precipitation changes in the Cascades depend on where the storms come from. If future storms come from the west, as suggested would become more frequent by Salathé et al., 2007, then the Cascades would experience a larger precipitation increase than the Northwest average and the lee of the Cascades as well as the British Columbia Coast Range would experience a smaller than average precipitation increase. If El Niño conditions become more frequent as is sometimes suggested, then the precipitation enhancements and moderations would be the opposite.

Circulation patterns such as El Niño and the Pacific Decadal Oscillation are important controls on future climate, especially along the west coast of North America. As the example of precipitation patterns west and east of the Cascades shows, interactions with local terrain can create complex interactions with climate change that exacerbate the sensitivity to interannual and decadal circulation patterns. Because climate models are not consistent about how these patterns will change in the future, there is still considerable uncertainty about certain aspects of regional climate change in the Northwest.

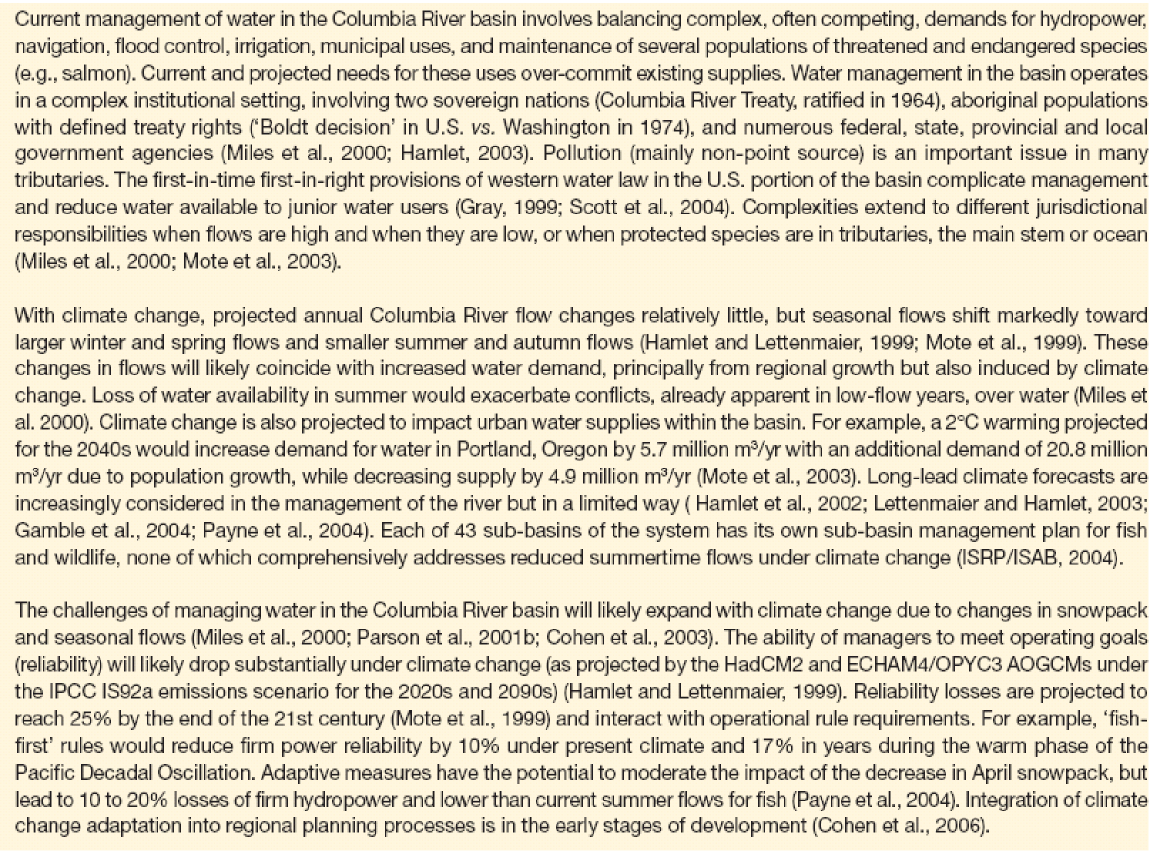
Sea Level

The sea level will rise at different rates along the coasts of the Pacific Northwest. The global sea level rise from a mid-range emission scenario (A1B) will be 2-5 mm/yr. Superimposed on this is land subsidence of 2 mm/yr in the southern part of the Puget Sound and uplift of a similar amount along the Olympic Peninsula coast with no land subsidence or uplift in the northern Puget Sound. Changes in ocean circulation, ocean density, and atmospheric pressure will add another 2 mm/yr. In total, by 2100 the sea level will be 1 to 3 feet higher in the Pacific Northwest and Puget Sound. As much as that sounds, we will feel the impact of this sea level rise through extreme events. With a 2 foot rise in sea level, a 100 year flood event becomes an annual event. The impact will be saltwater inundation of low-lying estuaries, saltwater intrusion into aquifers, and drainage of stormwater systems.

Hydrology and Water Quality

Much of the specific effects of climate change in the western United States, and the Pacific Northwest in particular, have focused on water resources. Most watersheds in the Pacific Northwest will see earlier snowmelt runoff peaks, increased winter and early spring flow, and substantially lower summertime flows. Hydrological modeling suggests that winter runoff in the Puget Sound basin will increase by 25% by 2040 and that summer runoff would decrease by 12% by 2040 and by 21% by 2075. Both the risk of wintertime flooding, and summertime extremely low flow rates, increase with climate change. The AR4 report highlights the Columbia River basin as particularly vulnerable to climate change because of its sensitivity to climate change and its interconnected demands for water resources (reproduced as Box 1). Higher summertime temperatures and higher evaporation rates from climate change would conflict with climate-induced weaker summertime flows. As an example, Portland, Oregon in the 2040's will likely demand 5.7 million m^3/yr more water because of a warmer climate while supply will decrease by 4.9 million m^3/yr. This is compared to an increased demand of 20.8 million m^3/yr from projected population increases. Seattle's 50-year low water year will occur every 10 years by the 2040s. Shifting streamflow towards the winter months will likely increase hydroelectric power supply in the winter, but it will decrease supply in the summer while at the same time rising temperatures will increase power and water demand, and warmer stream temperatures pressure salmon restoration efforts to increase flow.

Future water quality depends on many climate-sensitive parameters, such as annual and seasonal input from streams and rivers, ocean stratification, water temperature, salinity, dissolved oxygen, nutrients, and fecal coliform. There are not enough records of water quality long enough to discern a clear historical trend in most of these properties, and there have been no comprehensive studies of how water quality in the northwest might respond to climate change. There is some evidence for higher Puget Sound and Lake Washington temperatures in the past 40-50 years, decreased Puget Sound salinity, and greater summer stratification in Lake Washington. Higher air temperatures will lead to higher water temperatures, less dissolved oxygen at the surface, and increased water stratification, all of which promote worse water quality, although lower summer streamflow will decrease lake and Puget Sound stratification. Increased winter runoff will increase stratification, decrease salinity, and increase water exchange in lakes and the Puget Sound, but it may also overwhelm stormwater systems during heavy rains and deliver higher loadings of nutrients and pollution from septic systems, fields, and roads. Changes in wind speed and in ocean circulation would also affect water stratification and water exchange and thus nutrient loads, pollution loads, and dissolved oxygen levels.



Current management of water in the Columbia River basin involves balancing complex, often competing, demands for hydropower, navigation, flood control, irrigation, municipal uses, and maintenance of several populations of threatened and endangered species (e.g., salmon). Current and projected needs for these uses over-commit existing supplies. Water management in the basin operates in a complex institutional setting, involving two sovereign nations (Columbia River Treaty, ratified in 1964), aboriginal populations with defined treaty rights ('Boldt decision' in U.S. *vs.* Washington in 1974), and numerous federal, state, provincial and local government agencies (Miles et al., 2000; Hamlet, 2003). Pollution (mainly non-point source) is an important issue in many tributaries. The first-in-time first-in-right provisions of western water law in the U.S. portion of the basin complicate management and reduce water available to junior water users (Gray, 1999; Scott et al., 2004). Complexities extend to different jurisdictional responsibilities when flows are high and when they are low, or when protected species are in tributaries, the main stem or ocean (Miles et al., 2000; Mote et al., 2003).

With climate change, projected annual Columbia River flow changes relatively little, but seasonal flows shift markedly toward larger winter and spring flows and smaller summer and autumn flows (Hamlet and Lettenmaier, 1999; Mote et al., 1999). These changes in flows will likely coincide with increased water demand, principally from regional growth but also induced by climate change. Loss of water availability in summer would exacerbate conflicts, already apparent in low-flow years, over water (Miles et al. 2000). Climate change is also projected to impact urban water supplies within the basin. For example, a 2°C warming projected for the 2040s would increase demand for water in Portland, Oregon by 5.7 million m^3/yr with an additional demand of 20.8 million m^3/yr due to population growth, while decreasing supply by 4.9 million m^3/yr (Mote et al., 2003). Long-lead climate forecasts are increasingly considered in the management of the river but in a limited way (Hamlet et al., 2002; Lettenmaier and Hamlet, 2003; Gamble et al., 2004; Payne et al., 2004). Each of 43 sub-basins of the system has its own sub-basin management plan for fish and wildlife, none of which comprehensively addresses reduced summertime flows under climate change (ISRP/ISAB, 2004).

The challenges of managing water in the Columbia River basin will likely expand with climate change due to changes in snowpack and seasonal flows (Miles et al., 2000; Parson et al., 2001b; Cohen et al., 2003). The ability of managers to meet operating goals (reliability) will likely drop substantially under climate change (as projected by the HadCM2 and ECHAM4/OPYC3 AOGCMs under the IPCC IS92a emissions scenario for the 2020s and 2090s) (Hamlet and Lettenmaier, 1999). Reliability losses are projected to reach 25% by the end of the 21st century (Mote et al., 1999) and interact with operational rule requirements. For example, 'fish-first' rules would reduce firm power reliability by 10% under present climate and 17% in years during the warm phase of the Pacific Decadal Oscillation. Adaptive measures have the potential to moderate the impact of the decrease in April snowpack, but lead to 10 to 20% losses of firm hydropower and lower than current summer flows for fish (Payne et al., 2004). Integration of climate change adaptation into regional planning processes is in the early stages of development (Cohen et al., 2006).

Box 1. Summary of Columbia River climate change issues (WG2ch14p628).

Air Quality

Climate change can have important effects on air quality. Ozone events generally occur during episodes of stagnant, clear, warm summer conditions. Warm temperatures promote higher emissions and higher availability of ozone precursors, clear skies maximize UV light for photochemical reactions, and stagnant conditions allow pollution to concentrate near the surface over multiple days. Climate change can alter ozone concentrations through higher mean temperatures and through changes in weather patterns. Changes in weather patterns can be reflected in the duration of stagnant events, the amount of water vapor and cloud cover, ventilation and advection of pollution into or out of a region, and diluting or concentrating pollutants near the surface. By the 2050s, climate change alone – and neglecting changes in anthropogenic emissions – is projected to be responsible for an increase of 4.2 ppb in eastern US maximum 8-hour ozone concentrations and 7.6 ppb in the 4th highest 8-hour ozone concentrations using the relatively pessimistic A2 climate scenario. Another study using the A1B (balanced, middle of the road) scenario predicts a 0.9% increase in maximum 8-hour ozone in the western United States. The increase is due to a combination of factors including higher temperatures, fewer weather systems to increase ventilation, less intercontinental transport, more thunderstorms and production of NO_x from lightning, and fewer clouds on average. Over the western US, an increase in ozone from local production is offset by a decrease in intercontinental transport. The net effect in the Northwest remains unclear. It is important to stress that temperature-independent emissions (including land use) are held constant, and the change in intercontinental transport relates to the lifetime of ozone in a wetter climate rather than a change in wind speed or direction from Asia to North America.

For particulate matter, climate change interacts similarly as to ozone through impacts on emission rates, air chemistry, and dispersion away from a particular surface location. PM, like ozone, also accumulates under stagnant conditions but is more complicated. Under warmer conditions, individual chemicals in PM tend to be emitted at higher rates into the atmosphere and convert into chemicals that form PM, but also other chemical species tend to volatilize with higher temperature and are found in smaller concentrations in PM. Interactions with clouds and rain and the effect of changing precipitation and temperature on forest fires further complicate the situation. There is little research on how PM will change with a warmer climate. One study projects a 2% decrease in western US summertime PM from climate change alone in 2050 and projects a 3% increase on an annual basis. This study also states that climate change alone will increase the number of days major US cities violate the new 35 $\mu g/m^3$ 24-hour PM standard. There is little explanation for the PM changes under a warmer climate, although Leung and Gustafson (2005) suggest a warmer, drier, and more stagnant autumn by the 2050s is at least partly responsible.

2.2.2. Alaska

Temperature, Precipitation, and Oceans

High latitude environments, including much of Alaska, will experience changes in climate similar in scope but larger in magnitude as to what has been experience to date. By 2100, Arctic temperature will increase from 2000 by 2 to 9 ºC. The projected warming is double the global average, consistent with the doubly large warming seen in the Arctic relative to the globe in the past century. The warming will be more over the oceans than over the land in general, and more in autumn and winter than other seasons. A warmer atmosphere, especially in the winter, favors higher precipitation in the Arctic, as does the prediction of the mid-latitude storm belt strengthening and shifting northward and less frequent strong Arctic high pressure systems. Annual precipitation is modeled to increase by 10 to 28% under the modest A1B scenario. The winter time precipitation will increase in percentage more than the summertime (~30% versus ~20%). More precipitation will fall as rain rather than snow in areas that are closer to freezing, and there is a higher likelihood of rain on snow events and freeze-thaw events.

A wide range of emission scenarios predict that Arctic sea ice will decrease by 22-33% by the end of the 21st Century. The loss will be greater in the summer than the winter, and some areas may have more wintertime extent. Reduction or total loss in summertime ice will increase lead to increased human presence in the area through increased shipping, potential natural resource extraction, and tourism and travel. Less ice increases vulnerability to wave erosion and the associated increase in sediment and organic inputs to the marine environment. Sea level rise, thawing permafrost, and later ice freeze in the late winter when storms are stronger contribute to the greater wave erosion and water quality degradation. Marine ecosystems dependent on sea-ice edges (polar cod, ringed seals, etc.) will diminish, but ecosystems adapted to the open water, such as those comprising valuable Pollock fisheries, will take their place.

Hydrology and Water Quality

Higher temperatures will affect freshwater systems in Alaska. Models consistently predict higher river flows in the Arctic, especially in the cold season. Summertime flow may increase or decrease depending on the balance of higher precipitation and higher evaporation. Flooding may increase or decrease depending on the extent of warming and dynamics of each river basin towards ice flows and ice damming. Permafrost extents will likely decrease by 20-35% by 2050, mostly due to thawing along the southern edge of the sporadic and discontinuous permafrost zone. Initial permafrost melting will form new wetland ponds but extensive melting will drain wetlands. In some areas this will result in desertification. Snow cover extent will decrease 10-20% during the same period. Snow melt will occur earlier in the spring, and river and lake ice will form later in the autumn and break up earlier in the spring. Pulses of increased runoff, especially in the winter months, will very likely increase the loading of mercury and persistent organic pollutants to the land surface, increase sediment and carbon loadings of lakes and streams, microbial and trophic level productivity in nutrient-limited water systems, and sediment and organic transport to marine areas. Higher sediment loads will stress ecosystems by increasing biological oxygen demand and by falling to the bottom of the river or lake and covering habitat. Higher organic loading decreases UV light penetration and photochemical processing of organic material Permafrost, snow, and ice thawing will mobilize contaminants previously trapped in the soil and cryosphere.

Appendix B

Renewable Energy Technologies

Reference: U.S. Climate Change Technology Program – Strategic Plan, U.S. Department of Energy, DOE/PI-0005 (2006).

1. Overview of Renewable Technologies

Renewable sources of energy include the energy of the sun, the kinetic energy of wind, the thermal energy inside the Earth itself, the kinetic energy of flowing water, and the chemical energy of biomass and waste. These sources of energy, available in one or more forms across the globe, can be converted and/or delivered to end users as electricity, heat, fuels, hydrogen, and useful chemicals and materials. In the United States in 2003, of the 71.42 quads of net energy supply and disposition (98.22 quads total energy consumption), renewable resources contributed 5.89 quads (8 percent of supply, or 6 percent of the total). Of the renewable energy, 2.78 quads came from hydropower, 2.72 quads from burning biomass (wood and waste), 0.28 quads from geothermal energy, and 0.12 quads from solar and wind energy combined. An additional 0.24 quads of ethanol were produced from corn for transportation.

Hydropower is well established, but improvements in the technology could increase its efficiency and widen its applicability. Geothermal technologies are established in some areas and applications, but significant improvements are needed to tap broader resources. The installation of wind energy has been rapidly and steadily expanding during the past several years. In the past decade, the global wind energy capacity has increased tenfold—from 3.5 GW in 1994 to almost 59 GW by the end of 2006. Technology improvements will continue to lower the cost of land-based wind energy and will enable access to the immense wind resources in shallow and deep waters of U.S. coastal areas and the Great Lakes near large energy markets. The next generations of solar—with improved performance and lower cost—are in various stages of concept identification, laboratory research, engineering development, and process scale-up. Also, the development of integrated and advanced systems involving solar photovoltaics, concentrating solar power, and solar buildings are in early stages of development; but advances in these technologies are expected to make them competitive with conventional sources in the future.

The energy-production potential and siting of the various types of renewable energy facilities is dependent on availability of the applicable natural resources. Figures 1 shows U.S. solar resources, and Figure 2 shows wind capacity in the U.S. as estimated by the National Renewable Energy Laboratory (NREL) at the Renewable Resource Data Center (see http://nrel.gov/rredc).

2. Potential Role of Renewable Technologies

Renewable energy technologies are generally modular and can be used to help meet the energy needs of a stand-alone application or building, an industrial plant or community, or the larger needs of a national electrical grid or fuel network. Renewable energy technologies can also be used in various combinations—including hybrids with fossil-fuel-based energy sources and with advanced storage systems—to improve renewable resource availability. Because of this flexibility, technologies and standards to safely and reliably interconnect individual renewable electric technologies, individual loads or buildings, and the electric grid are very important. In addition, the diversity of renewable energy sources offers a broad array of technology choices that can reduce CO2 emissions. The generation of electricity from solar, wind, geothermal, or hydropower sources contributes no CO2 or other GHGs directly to the atmosphere. Increasing the contribution of renewables to the Nation's energy portfolio will directly lower GHG intensity (GHGs emitted per unit of economic activity) in proportion to the amount of carbon-emitting energy sources displaced.

Analogous to crude oil, biomass can be converted to heat, electrical power, fuels, hydrogen, chemicals, and intermediates. Biomass refers to both biomass residues (agricultural wastes such as corn stover and rice hulls, forest residues, pulp and paper wastes, animal wastes, etc.) and to fast-growing "energy crops," chosen specifically for their efficiency in being converted to electricity, fuels, etc. The CO2 consumed when the biomass is grown essentially offsets the CO2 released during combustion or processing. Biomass systems actually represent a net sink for GHG emissions when biomass residues are used, because this avoids methane emissions that result from landfilling unused biomass. Bio-refineries of the future could produce value-added chemicals and materials together with fuels and/or power from nonconventional, lower-cost feedstocks (such as agricultural and forest residues and specially grown crops) with no net CO2 emissions.

3. Renewable Technology Strategy

Transitioning from today's reliance on fossil fuels to a global energy portfolio that includes significant renewable energy sources will require continued improvements in cost and performance of renewable technologies. This transition would also require shifts in the energy infrastructure to allow a more diverse mix of technologies to be delivered efficiently to consumers in forms they can readily use. For example, changes to the electricity infrastructure are needed to accommodate greatly increased use of renewable electric generation. These changes include additional transmission lines to access those renewable resources that are located far from load centers; grid operating practices and storage to accommodate renewables that are intermittent, such as wind and solar; greater use of renewables in a distributed generation mode; and adapting current fossil generation for biomass co-firing. Fortunately, there already is substantial progress in adapting the electricity infrastructure to enable greater use of renewables generation, and additional changes that would be needed are relatively easy to make in a decade or so. In general, as performance continues to improve and costs continue to decline, improved new generations of technologies will replace today's renewable technologies. Combinations of renewable and conventional technologies and systems—and, therefore, integration and interconnection issues—will grow in importance.

The transition from today's energy mix to a state of GHG stabilization can be projected as an interweaving of individual renewable energy technologies with other energy technologies, as well as market developments through the upcoming decades. Today, grid-connected wind energy, geothermal, solar energy, and biopower systems are well established. Demand for these systems is growing in some parts of the world. Solar hot-water technologies are reasonably established, although improvements continue. Markets are growing for small, high-value or remote applications of solar photovoltaics; wind energy; biomass-based CHP; certain types of hydropower; and integrated systems that usually include natural gas or diesel generators. Other technologies and applications today are in various stages of research, development, and demonstration.

In the near term, as system costs continue to decrease, the penetration of off-grid systems could continue to increase rapidly, including integration of renewable systems such as photovoltaics into buildings. As interconnection issues are resolved, the number of grid-connected renewable systems could increase quite rapidly, meeting local energy needs such as uninterruptible power, community power, or peak shaving. Wind energy may expand most rapidly among grid-connected applications, with solar expanding as system costs are reduced. Environment friendly hydropower systems could be further developed. The use of utility-scale wind technology is likely to continue to expand onshore and is targeted to become competitive in select offshore locations between 5 and 50 nautical miles from shore and at water depths of 30 meters or less. Small wind turbines are on the verge of operating cost-effectively in most of the rural areas of the United States, and more than 15 million homes have the potential to generate electricity with small wind turbines. With a further maturing of the market, costs will be lowered to compete directly with retail rates for homeowners, farmers, small businesses, and community-based projects.

The biomass near-term outlook includes industry investment to make the production of corn-based ethanol (already produced at nearly 4 billion gallons) more efficient by increasing the quantity of ethanol through residual starch conversion, and conversion of fiber already collected and present at the operating facilities. The inclusion of biochemicals as byproducts will further help to improve the industry's profitability. The Biofuels Initiative launched in FY 2007 will accelerate demonstrations of biorefinery concepts, producing one or more products (bioethanol, bioproducts, electricity, CHP, etc.) from one plant using local waste and residues as the feedstock. Biodiesel use may continue to grow, replacing fossil-fuel-derived diesel fuel. The technology being developed to convert agricultural residues to ethanol is also partially applicable to the conversion of municipal solid waste to ethanol.

In the mid term, offshore wind energy could begin to expand significantly. Technology development may focus on turbine-support structures suitable for deeper water depths, and reducing turbine system and balance-of-plant costs to offset increased distance from shore, decreased accessibility, and more stringent environmental conditions. Land-based use of wind turbines is also likely to expand for large and small turbines as the costs for these systems continue to decrease. Small turbines may be used to harness wind to provide pumping for farm irrigation, help alleviate water-availability problems, and provide a viable source of clean and renewable hydrogen production.

Reductions in cost could encourage penetration by solar technologies into large-scale markets, first in distributed markets such as commercial buildings and communities, and later in utility-scale systems. Solar systems could also become cost-effective in new construction for commercial buildings and homes. The first geothermal plants using engineered geothermal systems technology could come online, greatly extending access to geothermal resources. Hydropower may benefit from full acceptance of new turbines and operational improvements that enhance environmental performance, lowering barriers to new development.

As a result of the Biofuels Initiative, biorefineries could begin using agricultural and forest residues, and eventually energy crops as primary feedstocks. Assuming success in reducing production costs and expanding the fuels distribution infrastructure, bioethanol and, to a lesser extent, biodiesel could achieve substantial market penetration in the 2030-2040 timeframe. This would be an important step in lowering U.S. dependence on imported petroleum.

In the long term, hydrogen from solar, wind, and possibly geothermal energy could be the backbone of the economy, powering vehicles and stationary fuel cells. Solar technologies could also be providing electricity and heat for residential and commercial buildings, industrial plants, and entire communities in major sections of the country. A major value for solar is that most residential and commercial buildings could generate their own energy on-site. Wind energy could be the lowest-cost option for electricity generation in favorable wind areas for grid power, and offshore systems could become prevalent in many countries by achieving a commercially viable cost by using floating platform technologies. Geothermal systems could be a major source of baseload electricity for large regions. Bio-refineries could be providing a wide range of cost-effective products as rural areas embrace the economic advantages of widespread demand for energy crops.

4. Status of Renewable Energy Technologies

Reference: U.S. Climate Change Technology Program – Technology Options for the Near and Long Term (August 2005)

Wind Turbines

Wind turbine technology converts the kinetic energy in wind to electricity. Grid-connected wind power reduces greenhouse gas emissions by displacing the need for natural gas and coal-fired generation. Village and off-grid applications are important for displacing diesel generation and for improving quality of life, especially in developing countries.

System Concepts

- Most modern wind turbines operate using aerodynamic lift generated by airfoil-type blades, yielding much higher efficiency than traditional windmills that relied on wind “pushing” the blades. Lifting forces spin the blades, driving a generator that produces electric power in proportion to wind speed. Turbines either rotate at constant speed and directly link to the grid, or at variable speed for better performance, using a power electronics system for grid connection. Utility-scale turbines for wind plants range in size up to several megawatts, and smaller turbines (under 100 kilowatts) serve a range of distributed, remote, and stand-alone power applications.

Representative Technologies

- The most common machine configuration is a three-bladed wind turbine, which operates “upwind” of the tower, with the blades facing into the wind. To improve the cost-effectiveness of wind turbines, technology advances are being made for rotors and controls, drive trains, towers, manufacturing methods, site-tailored designs, and offshore and onshore foundations.

Technology Status/Applications

- In the United States, the wind energy capacity tripled from 1,600 MW in 1994 to more than 6,700 MW by the end of 2004 – enough to serve more than 1.6 million households.

- Current performance is characterized by levelized costs of 4-6¢/kWh (depending on resource quality and financing terms), capacity factors of 30%-50%, availability of 95-98%, total installed costs of approximately $800-$1,100/kW, and efficiencies of 65%-75% of theoretical (Betz limit) maximum.

Solar Photovoltaic Systems

Solar photovoltaic (PV) arrays use semiconductor devices called solar cells to convert sunlight to electricity without moving parts and without producing fuel wastes, air pollution, or greenhouse gases. Using solar PV for electricity – and eventually using solar PV to produce hydrogen for fuel cells for electric vehicles or by producing hydrogen from water – will help reduce carbon dioxide emissions worldwide.

System Concepts

- Flat-plate PV arrays use global sunlight; concentrators use direct sunlight. Modules are mounted on a stationary array or on single- or dual-axis sun trackers. Arrays can be ground-mounted or on all types of buildings and structures (e.g., see semi-transparent solar canopy, right). The DC output from PV can be conditioned into grid-quality AC electricity, or DC can be used to charge batteries or to split water to produce hydrogen (electrolysis of water).

- PV systems are expected to be used in the United States for residential and commercial buildings, peak power shaving, and intermediate daytime load following. With energy storage, PV can provide dispatchable electricity and/or produce hydrogen.

- Almost all locations in the United States and worldwide have enough sunlight for cost-effective PV. For example, U.S. sunlight in the contiguous states varies by only about 25% from an average in Kansas. Land area is not a problem for PV. Not only can PV be more easily sited in a distributed fashion than almost all alternatives (for example, on roofs or above parking lots), a PV-generating station 140 km by 140 km sited at a high solar insolation location in the United States (such as the desert Southwest) could generate all of the electricity needed in the country (2.5×10^6 GWh/year, assuming a system efficiency of 10% and an area packing factor of 50% to avoid self-shading).

Representative Technologies and Status

- Wafers of single-crystal or polycrystalline silicon – best cells: 25% efficiency; commercial modules: 13%-17%. Silicon modules dominate the PV market and currently cost about $\$2/W_p$ to manufacture.

- Thin-film semiconductors (e.g., amorphous silicon, copper indium diselenide, cadmium telluride, and dye-sensitized cells) – best cells: 12%-19%; commercial modules: 6%-11%. A new generation of thin-film PV modules is going through the high-risk transition to first-time and large-scale manufacturing. If successful, market share could increase rapidly.

- High-efficiency, single-crystal silicon and multi-junction gallium-arsenide-alloy cells for concentrators – best cells: 25%-37% efficient; commercial modules: 15%-24%; prototype systems are being tested in high solar areas in the southwest United States.

- Grid-connected PV systems currently sell for about $\$6\text{-}\$7/W_p$ (17¢-22¢/kWh), including support structures, power conditioning, and land.

Solar Heating and Lighting

Solar heating and lighting technologies being developed for buildings applications include solar water heating and hybrid solar lighting.

System Concepts

- In solar heating systems, solar-thermal collectors convert solar energy into heat, usually for domestic hot water, pools, and space heating.

- In solar lighting systems, sunlight is transmitted into the interior of buildings using glazed apertures, light pipes, and/or optical fibers.

Representative Technologies

- Active solar heating systems use pumps and controls to circulate a heat-transfer fluid between the solar collector(s) and storage. System sizes can range from 1 to 100 kW.

- Passive solar heating systems do not use pumps and controls but rather rely on natural circulation to transfer heat into storage. System sizes can range from 1 to 10 kW.

- Transpired solar collectors heat ventilation air for industrial and commercial building applications. A transpired collector is a thin sheet of perforated metal that absorbs solar radiation and heats fresh air drawn through its perforations.

- Hybrid solar lighting systems focus concentrated sunlight on optical fibers and, with a controller, combine natural daylight with conventional illumination, depending on sunlight availability.

Technology Status/Applications

- Typical residential solar systems use glazed flat-plate collectors combined with storage tanks to provide 40%-70% of residential water heating requirements. Typical systems generate hot water equivalent to supplying 2,500 kWh/year at a cost of about 8¢/kWh.

- Typical solar pool heating systems use unglazed polymer collectors to provide 50%-100% of residential pool heating requirements. Typical systems generate 1,600 therms or 46,000 kWh/year and have 25% of the market.

Concentrating Solar Power Systems

Concentrating Solar Power (CSP) systems concentrate solar energy 50 to 5,000 times to produce high-temperature thermal energy, which is used to produce electricity for distributed or bulk generation process applications.

System Concepts

- In CSP systems, highly reflective sun-tracking mirrors produce temperatures of 400°C to 800°C in the working fluid of a receiver; this heat is used in conventional heat engines (steam or gas turbines or Stirling engines) to produce electricity at solar-to-electric efficiencies for the system of up to 30%.

- CSP technologies provide firm, nonintermittent electricity generation (peaking or intermediate load capacity) when coupled with storage.

- Because solar-thermal technologies can yield extremely high temperatures, the technologies could some day be used for direct conversion (rather than indirect conversion through electrochemical reactions) of natural gas or water into hydrogen for future hydrogen-based economies.

Representative Technologies

- A parabolic trough system focuses solar energy on a linear oil-filled receiver to collect heat to generate steam to power a steam turbine. When the sun is not shining, steam can be generated with a fossil fuel to meet utility needs. Plant sizes can range from 1.0 to 100 MW_e.

- A power tower system uses many large heliostats to focus the solar energy onto a tower-mounted central receiver filled with a molten-salt working fluid that produces steam. The hot salt can be stored extremely efficiently to allow power production to match utility demand, even when the sun is not shining. Plant size can range from 30 to 200 MW_e.

- A dish/engine system uses a dish-shaped reflector to power a small Stirling or Brayton engine/generator or a high-concentrator PV module mounted at the focus of the dish. Dishes are 2-25 kW in size and can be used individually or in small groups for distributed, remote, or village power; or in clusters (1-10 MW_e) for utility-scale applications, including end-of-line support. They are easily hybridized with fossil fuel.

Technology Status/Applications

- Nine parabolic trough plants, with a rated capacity of 354 MW_e, have been operating in California since the 1980s. Trough system electricity costs of about 12¢-14¢/kWh have been demonstrated commercially.

- Solar Two, a 10-MW_e pilot power tower with three hours of storage, provided all the information needed to scale up to a 30-100 MW commercial plant, the first of which is now being planned in Spain.

- A number of prototype dish/Stirling systems are currently operating in Nevada, Arizona, Colorado, and Spain. High levels of performance have been established; durability remains to be proven, although some systems have operated for more than 10,000 hours.

Biochemical Conversion of Biomass

Biomass resources are agricultural crops and residues, wood residues, grasses, and trees. Biomass absorbs CO_2 as it grows, offsetting the CO_2 emissions from harvesting and processing, and can be a substitute for fossil resources in the production of power, fuels, and chemicals. Biomass feedstocks currently supply about 3 quadrillion Btus (Quads) to the nation's energy supply, based primarily on the use of wood. The potential exists for increasing the total biomass contribution up to 10 Quads nationwide, which would have a positive impact on the farm economy. Cost, sustainable supply availability, biomass variability, and transportation systems are key challenges for biomass utilization. The use of biomass as an alternative to fossil resources reduces most emissions, including emissions of greenhouse gases (GHGs). Through the use of biomass materials that would otherwise go to waste, biomass systems can represent a net sink for GHG emissions because methane emissions that would result from landfilling the unused biomass would be avoided.

Sugars are important platform intermediates for producing fuels, products, and power from biomass. Technologies in manufacturing platforms – such as the sugars platform – can provide the basis for a biorefinery or be combined with those from other platforms. The sugars platform is used to break down biomass, cellulose, and hemicellulose polymers into their building blocks. The building blocks are sugars that can be converted to many products including liquid fuels (e.g., ethanol), monomeric components for the polymer market (e.g., lactic acid), and hydrogen. In addition to using sugar as a feedstock for fuel and chemical production, biomass rich in oils (such as soybean) can be converted to esters that are combusted like petroleum-based diesel. These oils have potential for the production of chemicals and other products, such as lubricants or polymers.

The biorefinery is analogous to an oil refinery. Multiple feedstocks are converted to a slate of products via multiple technology routes. Fuel production provides a large-volume product to achieve economies of scale, while lower-volume biobased coproducts and power can improve the economic competitiveness of biomass as a sustainable source of energy. Integrated biorefinery systems are being evaluated for their feasibility in producing fuels and products for potentially large commercial markets. A major challenge is to develop the ability to convert the fractionated biomass components into value-added products as efficiently as the current petrochemical business.

System Concepts

- The most common sugar-platform process consists of pretreating a biomass feedstock to release sugars from the fibrous cellulose and hemicellulose fractions. These sugars can be converted biologically into products such as ethanol or lactic acid, and can also be converted catalytically into products such as sorbitol. The products are then purified and sold as liquid fuels, sold into commodity chemical markets, or further converted and sold into other markets. The residue remaining from the sugar process can be burned to produce steam and electricity or further processed into other products such as animal feed.

- Oil technologies under development include conversion of glycerol to higher-value chemicals, including 1,3 propanediol.

Representative Technologies

- Sugar platform: hydrolysis of fibrous biomass that utilizes enzymes or acid catalysts, followed by microbial or catalytic conversion of the sugars to products.

- Glyceride platform: thermochemical transesterification of triglycerides.

- Fractionating biomass materials from grain and oil seeds, agricultural and forestry residues, or dedicated biomass feedstocks (such as grasses and woody crops) into component parts allows further development of value-added products such as chemical intermediates, wood products, biodiesel fuel, and composite materials.

Technology Status/Applications

- Enzymatic hydrolysis: A major barrier of this sugar-platform technology has been development of low-cost cellulase enzyme cocktails. DOE has recently completed cost-shared subcontracts with Genencor International and Novozyme Biotech to reduce the cost of enzymes to improve the economics of the process. Process options using those enzymes will lead to the first large-scale, sugar-platform biorefineries.
- R&D advances have been identified to lower the cost of sugars for products including biofuels. As production costs for biofuels are reduced commensurately, larger fuel markets will become accessible. The technical challenge is to advance biomass processing to a level of maturity comparable to that of the existing petroleum industry.
- Biobased products will be key elements in the development of integrated processes for producing fuels, chemicals, and power.

Thermochemical Conversion of Biomass

Biomass resources are agricultural crops and residues, wood residues, grasses, and trees. Biomass absorbs CO_2 as it grows, offsetting the CO_2 emissions from harvesting and processing, and can be a substitute for fossil resources in production of power, fuels, and chemicals. Biomass feedstocks currently supply about 3 quadrillion Btus (Quads) to the nation's energy supply based primarily on wood resources. The potential exists for increasing total biomass contribution to 10 Quads nationwide, which would create positive impacts on farming and forest products industries. Cost, sustainable supply availability, biomass variability, and delivery systems are key challenges for biomass utilization. Use of biomass resources as an alternative to fossil resources reduces most emissions, including emissions of greenhouse gases (GHGs). Through use of materials that would normally be waste, biomass systems bring about a net sink for GHG emissions, because methane emissions that would result from landfilling are avoided.

Thermal conversion of biomass is a manufacturing platform comprised of many technology routes and involves use of heat to break down biomass feed into an oil-rich vapor in pyrolysis and/or synthesis gas in gasification, which is used for generation of heat, power, liquid fuels, and chemicals. Technologies in this platform can provide the basis for a biorefinery, or be combined with other platform technologies. One advantage of thermal conversion processes is that they can convert nearly all biomass feedstocks into synthesis gas, including some feedstock components that are difficult to process by chemical or biological means.

The biorefinery is analogous to an oil refinery. Multiple feedstocks are thermally converted to a slate of products via multiple technology routes. Fuel production provides a large-volume product to achieve economies of scale, while lower volume biobased coproducts and power can improve the economic competitiveness of biomass as a sustainable source of energy. Integrated biorefinery systems are being evaluated for their feasibility in producing fuels and products for potentially large commercial markets. A major challenge is to develop the ability to convert the fractionated biomass components into value-added products as efficiently as the current petrochemical business of today.

Biomass combustion is a thermal process that converts biomass entirely to carbon dioxide and water vapor; and, thus, precludes conversion to intermediate fuels or chemicals. The existing biomass power industry primarily uses combustion to produce steam for heat and electricity generation. Co-combustion of biomass with coal, or "cofiring" has received recent interest as a way to reduce fossil carbon emissions from coal power plants. There are few significant technical barriers to increase use of these technologies.

System Concepts and Representative Technologies

Thermal conversion technology is important and has several key roles in an emerging bioeconomy:

- Most current biomass conversion is for heat and power generation and is based on direct combustion in small, biomass-only plants with relatively low electric efficiency of about 20%. Technology exists so that total system efficiencies can approach 90% if combined heat and power systems are applied. Most biomass direct combustion generation facilities use the basic Rankine steam cycle for electric power generation, which is made up of a steam boiler, an electric turbine, a condenser, and a pump. Evolution of combined cycles that integrate the use of gas and steam turbines can increase generation efficiency by up to two times.

Co-firing of biomass with coal also can increase overall biomass-to-electricity conversion efficiency.

- A source of syngas for catalytic production of fuels, chemicals, and hydrogen is important. Once a clean synthesis gas is obtained, it is possible to access and leverage mature process technologies developed in the petroleum and chemicals industry for the production of a wide range of liquid fuels and chemicals.

- A source of heat and power for biorefinery operation. Virtually all other conversion processes – whether physical or biological – produce residue that cannot be directly converted to the primary product(s). In order to mitigate waste streams and to maximize the efficiency of the biorefinery, these residues can and should be used for heat and power production. In existing biorefineries, residues are combusted in a steam boiler. There is a technological opportunity however, to use a gasifier coupled to a gas turbine combined cycle that can double conversion efficiency to electricity, while still producing steam from the gas turbine waste heat. Use of a biomass gasifier in a gasifier combined-cycle system can leverage on public and private investments in development of advanced- and next-generation gas turbine systems (more than $1 billion).

- Thermal conversion is a way to derive additional value from process residues. Within a biorefinery, thermal conversion and gasification can push many residues "up the value chain" through production of hydrogen or other higher-value products via thermal conversion to syngas followed by separation or synthesis steps.

- Gasification converts biomass to a syngas that can be substituted for natural gas in combustion turbines, shifted into hydrogen for fuel cell or other applications, or used in existing commercial catalytic processes for production of liquid fuels and chemicals. Several technologies exist in various stages of development for production of a suitable syngas, including indirect gasification, steam reforming of biomass, and gasification with oxygen or enriched air.

- Pyrolysis of biomass produces an oil-rich vapor that can be condensed for direct use as a fuel or as a hydrogen carrier, or refined for producing a variety of higher-value chemical products.

Technology Status/Applications

- The existing biopower sector, nearly 1,000 plants, is mainly comprised of direct combustion plants, with an additional small amount of cofiring (approximately 400 MWe). Plant size averages 20 MWe, and the biomass-to-electricity conversion efficiency is about 20%. Grid-connected electrical capacity was 9,700 MWe in 2001; more than 75% of this power is generated in the forest products industry’s combined heat and power applications for process heat. Combined utility and industrial generation in 2001 was more than 60 billion kilowatt-hours (about 75% of nonhydro renewable generation). Recent studies estimate that on a life-cycle basis, existing biopower plants represent a net carbon sink of 4 MMTC/yr. Biopower electricity prices generally range from 8¢−12¢/kWh.

- U.S. investment in equipment is $300-$500 M/year. At least six major engineering procurement and construction companies and several multinational boiler manufacturers are active.

- Biomass cofiring with coal ($50−$250/kW of biomass capacity) is the most near-term option for large-scale use of biomass for power-only electricity generation. Cofiring also reduces sulfur dioxide and nitrogen oxide emissions. In addition, when cofiring crop and forest product residues, GHG emissions are reduced by a greater percentage (e.g. 23% GHG emissions reduction with 15% cofiring).

- Small biopower and biodiesel systems have been used for many years in the developing world for electricity generation. OE is developing systems for village power applications for distributed generation that are more efficient, reliable, and clean for the developed world. These systems range in size from 3 kW to 5 MW, with field verification completed by the end of 2003.

Appendix C

State of Climate Modeling

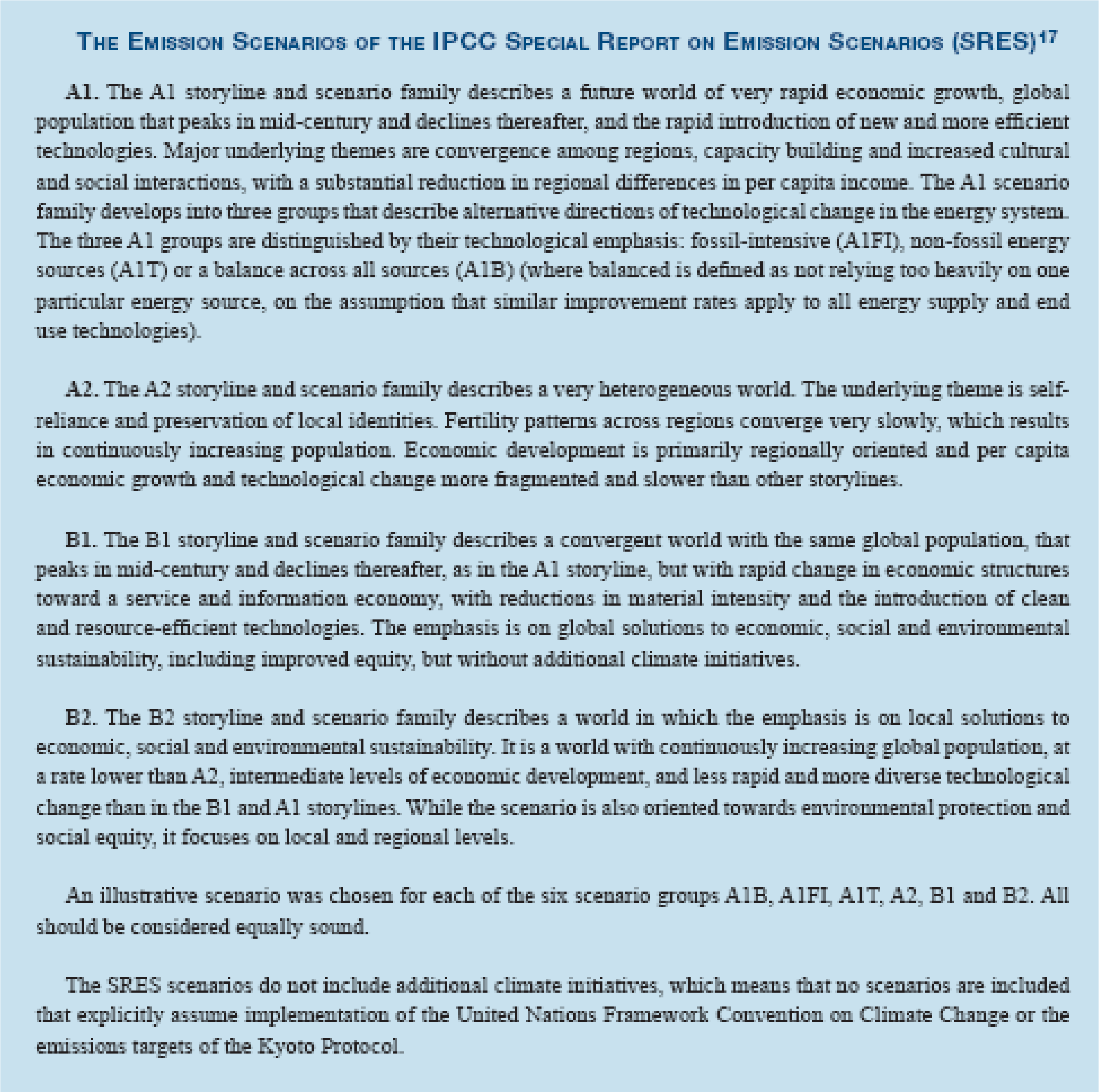
This appendix is an excerpt from "State of Climate Modeling: Contribution to Region 10's Action Plan for Energy and Climate Change" by Robert Elleman, Gina Bonifacino, and Joanna Ekrem.

1. Overview

Scientists use earth system or climate models to assess the human ("anthropogenic") influence on climate. Because the earth's climate undergoes natural variability, it is impossible to determine with observations alone what role humans have played in the 20th Century climate. Climate model results with and without anthropogenic perturbations are the primary tool to apportion natural and anthropogenic influence on the past and current climate. They are also the only tool for predicting future climate change.

Climate models are a computer representation of how scientists believe the earth system functions. They solve physical equations for the energy and motion of the atmosphere in three dimensions as a function of time. They include atmospheric processes such as winds, clouds, and storms; ocean dynamics related to currents and tides; ice and snow formation, movement, and melting; and land surface responses such as uptake/release of greenhouse gases and shifting vegetation zones. Up until recently, these models only treated the atmosphere, hence the term "climate model". Even though the atmospheric portion is still the most intricate part, these models now include other parts of the earth system. The term "climate model" remains common and is used in this report, but these models are also more appropriately called "earth system models" to emphasize their full scope.

Since there is no analogue in the past for the current human-induced changes, scientists rely on the global models to project future climate conditions. IPCC estimates of future emissions, called SRES scenarios, generally represent the "top-down" approach. They are global and macroscopic technological, societal, and economic forecasts developed by policy experts, economists, demographers, energy analysts, and environmental engineers. They represent the opposite approach to "bottom-up" emission inventories developed by U.S. states for the EPA National Emissions Inventory (NEI), which determine the current emissions from individual sources and aggregate to a coarser scale. The SRES scenarios represent uncertain estimates of various future worlds (Figures 1 and 2): a world of high economic growth, global trade, and innovation (A1), a heterogeneous and insolated world (A2), a world like A1 that focuses on global economic, social, and environmental sustainability (B1), and a world like A2 that focuses on environmental and societal sustainability (B2). A1 is further divided into a fossil fuel intensive (A1FI), non-fossil fuel intensive (A1T), and balanced (A1B) scenarios. None of the scenarios include Kyoto commitments or commitments from other, specific emissions reduction agreements. The A1FI and B1 scenarios are the most pessimistic and optimistic, respectively, while the A1B scenario is the one generally considered as the most likely path, although emissions growth since 2000 has exceeded the A1FI scenario.



THE EMISSION SCENARIOS OF THE IPCC SPECIAL REPORT ON EMISSION SCENARIOS (SRES)[17]

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI), non-fossil energy sources (A1T) or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

An illustrative scenario was chosen for each of the six scenario groups A1B, A1FI, A1T, A2, B1 and B2. All should be considered equally sound.

The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol.

Figure 1. Summary of SRES scenarios. From AR4 Working Group I Summary for Policymakers.

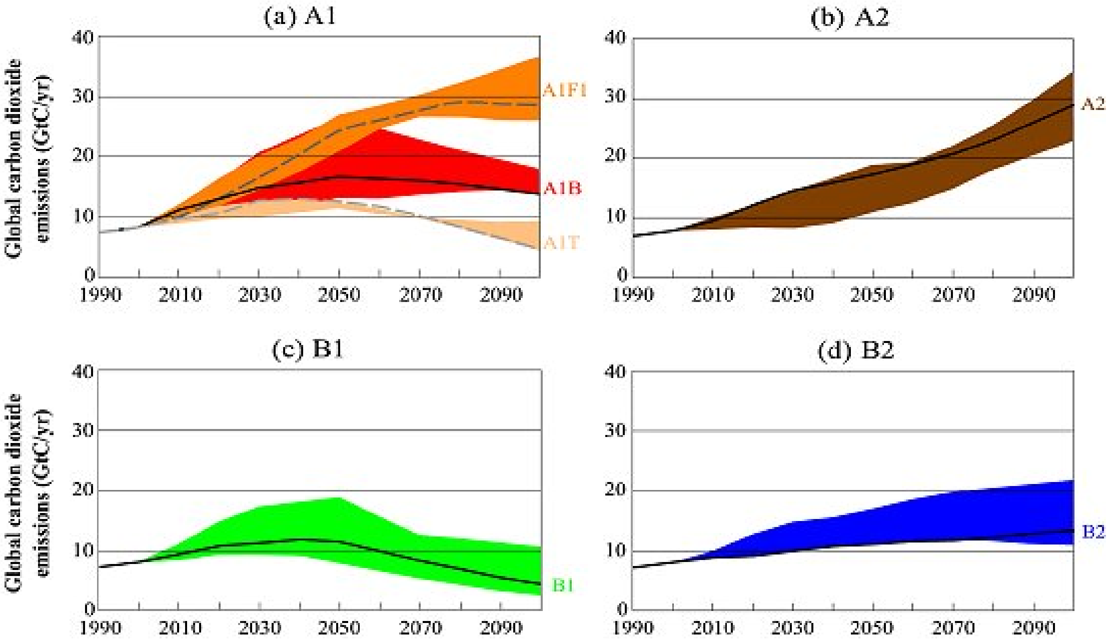


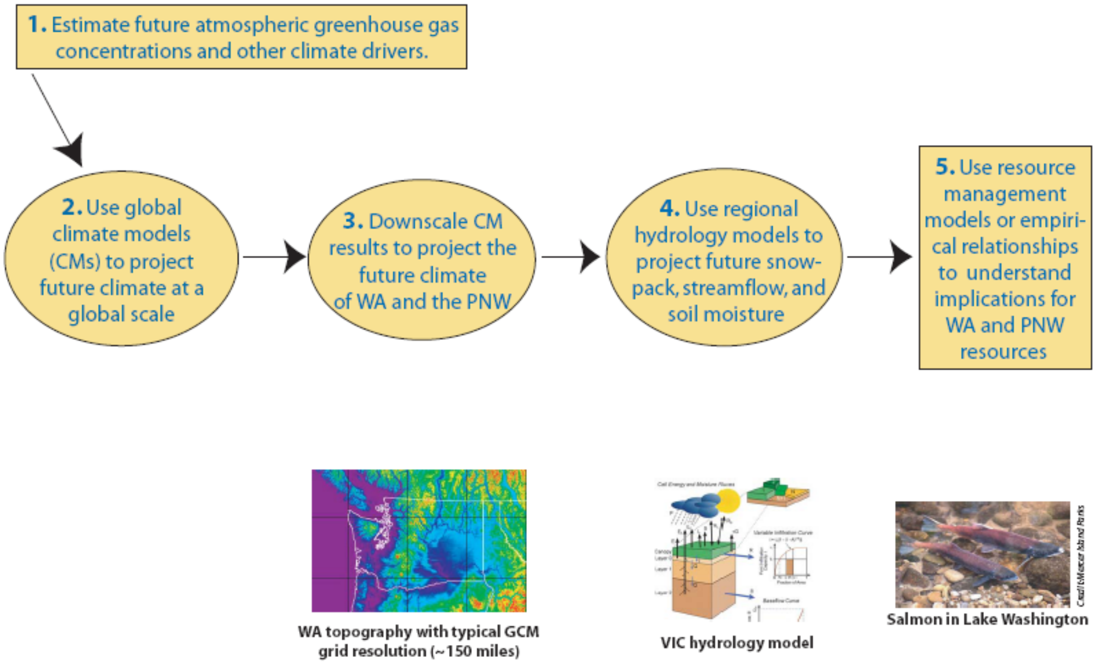
Figure 2. CO_2 Emissions from IPCC SRES scenarios (From Nakicenovic et al., 2000).

Although extraordinarily complex and detailed, even the fastest computers place a limit on the resolution of climate models and the models' ability to incorporate the most detailed knowledge. For example, the horizontal resolution of climate models is on the order of hundreds of kilometers. In most models at least the entire state of Washington is considered to have a uniform temperature, elevation, etc. Features such as the Cascades are barely represented.

Therefore, regional impacts on human systems and ecosystems are determined by statistical or dynamical downscaling of climate models. Statistical downscaling develops relationships between the climate at a particular location or region and a climate model's representation of the current climate. These relationships are then used in future climate scenarios to downscale the large-scale model results. The key assumption is that current relationships between the large and regional scale are appropriate for a future climate. Dynamical downscaling uses a nested regional model with much higher resolution than the parent global model. Its physics, dynamics, and scale are consistent with regional processes and it should provide a superior result to statistical downscaling. The drawback, however, is that the computational demand of regional models usually limits the ability to simulate long time periods and multiple scenarios.

Once downscaled to the regional level, earth system model output can be used as input to hydrological, air quality, water quality, sea level, ice flow, glacial, and ecosystem models to assess climate change impacts on the environment. For example, the Variable Infiltration Capacity (VIC) hydrological model can project streamflow in the Columbia River basin in the 2020s and 2040s using downscaled output from climate model scenarios. Another example is a currently-funded EPA STAR grant to John Rybczyk at Western Washington University to link sea-level rise estimates to regional hydrological, sediment, and wetland models to estimate the effect of climate change on juvenile salmon.

The process of using models to assess climate change and regional environmental issues is depicted as a cartoon in Figure 3. This is a sophisticated technique used by the Climate Impacts Group at the University of Washington and other institutions. Global climate models are scaled to the regional level to provide temperature, precipitation, cloudiness, and energy projections as input to a regional scale environmental model. The regional scale model then estimates the climate impact on some aspect of the local environment such as streamflow or air quality. The result of the regional scale model may provide the information necessary for decision making, or the output of the regional scale model is fed into a resource management model or an empirical relationship to determine how the environmental variable will impact the resource of interest. For the most part, however, regional impacts are determined in a more basic way. An association between current climate change and current resource changes is developed. Then, the association is used to estimate future resource impacts using model projections for future climate change. These simple associations are commonly used but are usually a poor substitute for a model that incorporates all known aspects of the system.



WA topography with typical GCM grid resolution (~150 miles)

VIC hydrology model

Salmon in Lake Washington

Figure 3. How to assess regional climate change impacts (Adapted from Kay et al., 2005).

Global climate models and regional climate impact models rely on observations of the earth system – atmosphere, ocean, vegetation, land surface, planetary energy balance, etc. – in the process of model development and model validation. Scientists come up with scientific theories by making measurements, developing explanations for phenomena, and formulating mathematical equations for a model. Targeted observations are used in the model development process to test individual parts of the model. Then when the whole model is in place, it is further tested on a suite of observations. One key test of a climate model is whether it can reproduce the spatial and temporal temperature and precipitation patterns in the 20th Century climate. Once the model has been "verified" against observations, it is set forward to make a prediction about the future based on assumptions scientists feed into it. The specific observations that are used in this process are too numerous to mention. Just about every sort of atmospheric, oceanic, or land surface measurement has been used along the way to develop and test models for predicting future climate impacts. However, probably the most used observation dataset is the global surface air temperature record since the mid 1800s.

2. Climate Impacts Models for the Pacific Northwest

Most hypothesized climate impacts come from examining analogous climate change in the past, or how current spatial variability in ecosystems can help diagnose potential climate impacts. In one example, Nakawatase and Peterson (2006) developed statistical relationships between climate variables and forest growth as a function of altitude in the Olympic Mountains. They then make conclusions of how forests there will be affected by climate change. More sophisticated techniques use hydrological, water quality, air quality, and ecosystem models with input from climate simulations of the future. In most cases, the future climate information is comprised of simple quantities such as change in mean temperature or stream flow. In limited cases such as for the EPA STAR air quality / climate projects, the full climate model output is downscaled to a regional weather model, whose full output is used to drive the air quality model. The following table identifies models that have been used to predict the impacts of Climate Change on temperature, precipitation, sea level, hydrology, water quality, air quality, and ecosystems in the Pacific Northwest.

Temperature and Precipitation

Model	Application	Contact
Statistical Downscaling	PNW temperature, precipitation, and snowpack	Mote, CIG
Statistical Downscaling	Fraser River precipitation and snowpack	Morrison, Vynx Design Inc.
MT_CLIM	physical model to downscale for mountain topography	
MM5	mesoscale climate change in PNW	Leung, DoE Richland
MM5	mesoscale climate change in PNW	Salathe, CIG

Sea Level

Model	Application	Contact
GCM plus subsidence	Puget Sound	Canning, CIG

Hydrology

Model	Application	Contact
DHSVM	Snohomish River flow	Battin, NOAA-Northwest Fisheries
DHSVM	Western US river flooding	Hamlet, CIG
VIC	Western US snow water equivalent	Mote, CIG
VIC	Columbia River basin waterflow	Snover, CIG
VIC	Columbia River basin waterflow	Mote, CIG
UBC watershed model	Fraser River Valley	Morrison, Vynx Design Inc.
GLACPRED	Glacier extent in Glacier NP	Hall, SUNY-Syracuse
Storage and Transmission Model (STM)	Portland City Water Supply	Palmer, CIG
ColSim	salmon in Columbia River	Mote, CIG

Water Quality

Model	Application	Contact
QUAL2Kw	Wenatchee River temperature	Cristea, UW
Chapra methodology	Snohomish River temperature	Battin, NOAA-Northwest Fisheries

Air Quality

Model	Application	Contact
CMAQ	ozone nation-wide with PNW focus	Lamb, WSU
CMAQ	Ozone and PM nation-wide, examined by region	Manomaiphiboon, Georgia Tech
CMAQ	Ozone and PM nation-wide, examined by region	Tagaris, Georgia Tech
CMAQ	ozone nation-wide	Nolte, EPA ORD
Fire Scenario Builder + CALPUFF	northwestern national parks	McKenzie, USFS Wildland Fire Sciences
SAQM	ozone nation-wide	Tao, Illinois State Water Survey

Ecosystems

Model	Application	Contact
Shiraz population model	Snohomish River salmon	Battin, NOAA-Northwest Fisheries
generalized linear models	wildfires in western United States	McKenzie, USFS Wildland Fire Sciences
wetland and salmon model	Padilla Bay and Skagit Bay	Rybczyk, WWU