CLIMATE CHANGE AND WATER RESOURCES: POTENTIAL IMPACTS AND IMPLICATIONS

by

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Introduction

The recurring drought and heat observed over large portions of the western U.S. have generated adverse and costly effects, including lost agricultural productivity in rainfed regions of the mid-west and Great Plains, record wildfires in Oregon, Colorado and California, and large fish kills in California's Klamath River triggered by warm water temperatures. Drought has persisted for nearly a decade in some regions of the western U.S., leading to severe stress on water resources. The intensity and frequency of recent droughts, coupled with increased frequency of other extreme weather events such as hurricanes, and rising temperatures observed globally over the past decade has raised concerns that fundamental climate shifts may be occurring in North America and elsewhere.

This paper reviews the current understanding of possible impacts of global climate change on water resources, with emphasis on the frequency and intensity of drought. The focus on drought, rather than long-term climate change more generally, is intended to provide managerial and policy relevance to what otherwise is an overwhelmingly complex topic. The paper reviews the physical and economic consequences of drought, as well as the potential to mitigate the adverse consequences of these events through changes in water resource management, such as using long-term forecasts and other meteorological information. Examples from empirical research that address water-related problems in upland settings of North America are also provided.

Background

A range of potential effects of global climate change on water resources and agriculture has been suggested (see recent reports from the Intergovernmental Panel on Climate Change, IPCC). These include increased surface temperatures and evaporation rates, increased global precipitation, increased proportions of precipitation received as rain, rather than snow, earlier and shorter runoff seasons, increased water temperatures, and decreased water quality. Variability in precipitation patterns is also expected to increase, resulting in more frequent droughts in the western U.S. and elsewhere (see Adams et al. 1999, for a detailed review of the effects of climate change on agriculture and agricultural resources).

The economic consequences of drought are well documented. On average, annual costs in the United States due to drought are estimated at $6 to 8 billion (Knutson, 2001). Flooding and hurricanes, though more publicized than drought, are reported in the same publication to be responsible for only $3.6 to 7.2 billion in annual damages combined, although this estimate will likely be higher when damages from the 2005 hurricane season (i.e. Katrina) are included. Some of the economic costs of drought arise from direct physical impacts, such as crop failure, municipal water shortages, wildfires, and fish and wildlife mortality. However, indirect effects are also important. For example, water deficits reduce hydroelectric power generation, and increase electricity prices. The National Oceanographic and Atmospheric Administration (2002) and Claussen (2001) offer comprehensive discussions of the physical and socioeconomic impacts of drought in the United States.

Water resource managers, agricultural producers, timber managers and policy makers can reduce the negative effects of drought through a number of strategies. These include revising water storage and release programs for reservoirs, adopting drought tolerant cropping practices, adjusting crop insurance programs, pre-positioning fire suppression equipment, and supporting water transfer opportunities. The ability to anticipate and efficiently prepare for future drought conditions is currently limited, however, by imprecise long-term weather forecasts and climate models. Improvements in some forms of climate forecasts, such as those associated with the El

Niño-Southern Oscillation phenomenon (ENSO), offer potential for reducing the impacts of both drought and flooding. However, economic costs associated with drought could be further reduced if drought forecast improvements increased the ability to detect drought farther in advance, enhanced forecast accuracy, and improved the geographical detail of forecasts to pinpoint drought location, intensity, and duration.

Global climate change, water resources and drought

The ability of the earth's atmosphere to trap solar radiation and increase global temperature (the so-called "greenhouse effect") has been recognized for at least 150 years. More recently, global climate change has been a topic of intense scientific and political debate. Certain evidence is unequivocal; carbon dioxide concentrations (the most abundant greenhouse gas in the earth's atmosphere) have been increasing steadily for over a century. Specifically, CO2 levels have increased 30% since the late 1800s, and are higher now than they have been in the last 400,000 years (National Assessment Synthesis Team or NAST, 2000). The decade of the 1990s was also the warmest (on a global scale) in over a century. Average annual temperature of the United States has risen almost 0.6° C (1.0° F) over the 20th century (NAST, 2000). The role that humans have played in recent global warming, and whether it is possible to offset that effect in any meaningful time scale, is still debated. The belief that global warming will continue, however, is becoming more widely accepted in the science and policy community. Thus, it is prudent to consider both the impacts of such warming as well as mechanisms to adjust to those effects.

Several general circulation models (GCMs) have predicted U.S. average annual temperatures to rise 3 to 5° C (5 to 9° F) over the next 100 years (NAST, 2000). Atmospheric scientists anticipate numerous climatic effects to arise from these increasing temperatures. For example, precipitation, which has increased in the U.S. by 5 to 10% over the 20th century (IPCC, 2001a), is predicted to continue to increase in many regions, particularly those at higher latitudes (Frederick and Gleick, 1999; Gleick, 2000). Two GCMs, the Canadian Climate Centre, and the Hadley Centre in the United Kingdom, have projected specific precipitation changes across the U.S. These include 25% precipitation increases in the Northeast, 10 to 30% increases in the Midwest, 20% increases in the Pacific Northwest, 10% precipitation decreases in the southern coast of Alaska, and up to 25% declines in the Oklahoma panhandle, north Texas, eastern Colorado and western Kansas (NAST, 2000). Caution should be exercised in using any of these as predictions, given the coarseness of geographical scale in existing GCMs.

Water quantity, timing, and quality

Increases in precipitation, given warmer atmospheric conditions, will not necessarily mean more available water at the state or regional level. The higher evaporation rates that accompany rising temperatures are expected to result in less water available in many regions (Frederick and Gleick, 1999). For example, GCMs project global average evaporation to increase 3 to 15% with doubled CO_2 levels (Gleick, 2000). Simulation studies suggest that precipitation must increase by at least 10% to balance evaporative losses resulting from a 4° C temperature increase (Gleick, 2000). Projections of rising evaporation rates indicate they will outpace precipitation increases, on a seasonal basis, in many regions (IPCC, 1998; Gleick, 2000). The greatest deficits are expected to occur in the summer, leading to decreased soil moisture levels and more frequent and severe agricultural drought (IPCC, 1998; Gleick, 2000).

Shifts in the form and timing of precipitation and runoff, specifically in snow-fed basins, are also likely to cause more frequent summer droughts. More precisely, rising temperatures are expected to increase the proportion of winter precipitation received as rain, with a declining proportion arriving in the form of snow (IPCC, 2001b; Frederick and Gleick, 1999). It is expected that snow pack levels will form much later in the winter, accumulate in much smaller quantities, and melt earlier in the season (IPCC, 2001b).

These changes in snow pack and runoff are of particular concern to hydropower generation, irrigated agriculture and to commercial and recreational fisheries. For example, if the runoff season occurs primarily in winter and early spring, rather than late spring and summer, water availability for summer-irrigated crops will decline during crucial spring and summer months, causing water shortages to occur earlier in the growing season. Timing of runoff will affect the value of hydropower potential in some basins if peak water run-off occurs during non-peak electricity demand. Shifts in runoff, precipitation, and evaporation patterns may also intensify interstate and international water allocation conflicts, as water managers struggle to meet obligations of compacts and court decrees given more variable water availability and timing in headwater areas.

A shift in stream hydrographs to more winter flow may also disrupt the life cycle of anadromous species, such as salmon, which depend on late spring flows to “flush” young salmon to the ocean. Unless reservoir systems are in place to capture and store winter runoff for late spring or summer use, reduction in summer flows is expected to lead to higher water temperatures. Summer temperatures already exceed the lethal levels for salmonids and other coldwater fish species in some streams in the U.S. and Canada; further warming could lead to more frequent fish kills, such as those observed recently in the Klamath River of northern California.

Water quality impairment is also predicted to increase under climate change (IPCC, 2001b; NAST, 2000; Gleick, 2000). Specifically, precipitation is expected to occur more frequently through high-intensity rainfall events, causing increased runoff and erosion. Sediments and pollutants, such as fertilizer, will be transported into streams and groundwater systems, decreasing water quality (Gleick, 2000). Water quality will also be impaired in areas receiving less precipitation, as nutrients and contaminants become more concentrated (IPCC, 2001b).

Rising air and water temperatures will also impact water quality by increasing primary production, organic matter decomposition, and nutrient cycling rates in lakes and streams, resulting in lower dissolved oxygen levels (IPCC, 2001b). Increased evaporation rates from open water-bodies threaten to increase the salinity of surface water. Lakes and wetlands associated with return flows from irrigated agriculture are of particular concern (IPCC, 2001b). Water quality impairment is thus a threat to agricultural water supplies, as well as to fish and wildlife (Adams et al, 1988).

Coastal areas are additionally at risk of water quality impairment due to saltwater intrusion (Frederick and Gleick, 1999). As global temperatures increase, seawater warms, causing ocean density to decrease and sea levels to rise (Solow, 1993). Sea levels are also rising in response to the melting of land ice, which includes glaciers, and the Greenland and Antarctica ice sheets (Solow, 1993). Global sea levels rose 10 to 20 cm during the 20th century (NAST, 2000). The Intergovernmental Panel on Climate Change projects a sea-level rise over the next century of 38 to 66 cm (Claussen, 2001). Rising sea levels may also affect water availability indirectly by causing water tables to rise. Higher water tables cause surface runoff to increase at the expense of aquifer recharge. Groundwater quality and recharge are impaired by rising sea levels and saltwater intrusion. Radical changes to the freshwater hydrology of coastal areas, caused by saltwater intrusion, threaten many coastal regions' freshwater supplies.

El Niño-Southern Oscillation and seasonal to interannual climate variability

The possible long-term effects of global climate change on drought and other extreme weather phenomenon are based on climate models that are associated with high levels of uncertainty, particularly at the regional or state level. A more immediate and predictable effect of climate change is the anticipated increase in the frequency of ENSO events and intensity of ENSO-related droughts and floods (IPCC, 2001a; Gleick, 2000).

The El Niño-Southern Oscillation (ENSO) is a natural weather phenomenon resulting from interactions between the atmosphere and ocean in the tropical Pacific Ocean (Trenberth, 1996). Concurrent weakening and strengthening of ocean and air currents causes warm and cold ocean currents to mix, with one covering the other (warm water over cold during an El Niño; cold water over warm during a La Niña) (IPCC, 2001a). Changes in the thermal profile of ocean currents alter wind, sea surface temperature, and precipitation patterns in the tropical Pacific, and drive climatic effects throughout much of the world (IPCC, 2001a).

El Niño and La Niña events are associated with both droughts and floods in many regions of the world. For example, El Niño events cause drier winters in the northwestern U.S., the Great Lakes region, southwestern Mexico, and parts of South America, but cause increased precipitation in southern California (IPCC, 1998). The effects of global warming on the behavior of ENSO events are uncertain. However, more frequent ENSO events, as suggested by Timmermann et al. (in Gleick, 2000), would increase the variability of precipitation and streamflow in many ENSO-sensitive regions of North and South America (IPCC, 1998), leading to greater risk of droughts and floods (IPCC, 2001a).

The negative economic consequences of ENSO events in North America have been estimated in several studies (e.g. Adams et al., 1995, and Chen et al., 2001, for the U.S.; Adams et al., 2004, for Mexico). ENSO-related droughts have historically generated billions of dollars in damage annually in the United States, as have ENSO-related floods. Increased drought frequency and intensity under global warming scenarios threatens to increase these damages, unless adaptive measures are taken.

Examples of Water Resource Challenges in the Uplands

Upland areas in much of North America are largely in agriculture or forest uses. In addition to timber, forested areas produce a range of marketed and non-marketed ecosystem services, such as recreational activities, habitat for fish and wildlife, and the sequestration of carbon. In regions where agriculture is the dominant land use, agriculture not only provides food and fiber, but also positive and negative externalities, ranging from open space and carbon sequestration potential, to air and water pollution. Earlier discussions in the paper highlighted some possible effects of climate change, primarily drought, on these activities. This section provides a more detailed examination of means of mitigating a few of these effects; specifically, the effect of prolonged droughts on irrigated and rainfed agriculture in Oregon and southwestern Mexico, and the impacts of rising water temperatures on salmonid production in the Pacific Northwest.

Agriculture and Climate Change

Numerous studies have estimated the effects of climate change on agriculture and agricultural resources (See Adams, Hurd and Reilly for a review of these studies). Most of the early studies focused on changes in "average" climate over relatively large regions. More recently, attention has been on changes in climatic variability that may arise from the general warming of the earth's atmosphere. As noted earlier, this variability is expected to manifest itself as more extreme weather events, such as droughts or floods, or more systematic climate anomalies, such as the El Niño-Southern Oscillation phenomena.

Two recent studies address the consequences and mitigation possibilities for agriculturalists in dealing with two aspects of changes in weather variability. The first (Peck and Adams, 2006 estimates the effects of more frequent and severe drought on irrigated agriculture in the Pacific Northwest. The other (Adams et al, 2004) assesses the impacts and adjustment possibilities for rain-fed agriculture in southwestern Mexico. Each is described briefly below.

In the first study, Peck and Adams develop a six-year farm model within a dynamic and stochastic decision environment to examine the effects of increased drought frequency and intensity on irrigated agriculture. The model is parameterized for a representative mixed-crop farm in eastern Oregon. The farm receives water from the irrigation district's reservoirs, which store spring snowmelt from the mountains. The water allotment for the upcoming growing season is uncertain (known only in probability) at the time a producer makes fall decisions. Producers therefore choose fall activities that maximize expected profit over the planning horizon. The water supply is revealed in early spring, after which spring decisions are made. Fall decisions constrain spring decisions, which creates intra-year dynamics. The farm system also includes agronomic constraints that generate inter-year dynamics. The model is solved for the following four climate scenarios: base case, increased drought frequency (case 1), increased drought intensity (case 2), and increased drought frequency and intensity (case 3). The three climate change scenarios' relative impact on expected farm profit and cropping patterns, as compared to the base case, is discussed below.

The following table summarizes the impact of the climate change scenarios, when responded to optimally, on expected profit for the 6-year period, standard deviation of profit, minimum profit (when 6 years of drought are experienced), and maximum profit (when 0 years of drought are experienced). Note that the probability of a six-year drought increases from 0.4% to 1.6% when the frequency of drought increases from 4 to 5 out of 10 years.

Case	**Drought frequency** (x of 10 yrs)	**Droughtintensity** (water supply in ac-inch/ac)	**E(profit)** (US$1,000) [% change]	**Std Dev** (US$1,000) [% change]	**Min profit** (US$1,000) [% change]	**Max profit** (US$1,000) [% change]
Base	4	24	1,328	19	1,297	1,349
1	5	24	1,324 [-0.3]	14 [-25]	1,303 [+0.5]	1,345 [-0.3]
2	4	18	1,257 [-5.4]	77 [+310]	1,126 [-13.2]	1,331 [-1.3]
3	5	18	1,248 [-6.0]	15 [-21]	1,224 [-5.6]	1,272 [-5.7]

The impact of increased drought intensity (case 2) on expected profit, standard deviation, and minimum and maximum profit is more severe than that of increased drought frequency (case 1). Producers adapt to increased drought frequency by reducing the concentration of high-value, fall-prepared crops in any particular year of the planning horizon, which reduces the risk of crop failure in the event of a dry year. Producers adapt to increased drought intensity by decreasing the acres of low-value, fall-planted crops, and the acres of crops with low profit per acre-inch of water. These adaptations provide more flexibility in the spring plan, after the water allotment is revealed, and save more water for high-value crops in the event of a dry year. In both cases, producers also shift irrigation technology for some crops from furrow to furrow with tail-water reuse. When both drought frequency and intensity increases (case 3), expected profit is only slightly less than when drought intensity alone increases. Standard deviation and minimum profit are actually better for case 3 than case 2, although maximum profit is not. Producers adapt to case 3 using a combination of the adaptations seen for cases 1 and 2. Producers, in summary, are better able to mitigate for more frequent moderate drought than for less frequent but more intense drought. The implication of climate change for agriculture clearly varies depending on the distributional characteristics of the affected water supply.

In the second study, Adams et al develop a profit maximizing mathematical model of crop production in five southwestern states of Mexico to assess the economic consequences of ENSO events and to identify possible actions by which negative impacts can be minimized. The model encompasses the large number of crops found in the region and is representative of current cultural and agronomic practices in the area. The effects of weather associated with three ENSO states (El Niño, La Niña, and Normal) on crop yields are modeled with plant biophysical simulation models. The main behavioral response of producers is to change crop mixes in anticipation of various ENSO states. The advantage of such behavior is reflected in the difference in profits between decisions based on events' historical probability of occurrence and those based on a long-range forecast of such an event, as is now commonly available from NOAA and Mexican climate agencies.

The results indicate that the three ENSO events affect agriculture in different ways. Specifically, an El Niño results in economic losses across the region amounting to almost $ 1 billion pesos, whereas a La Niña slightly increases total production and profits. Thus, if El Niño events become more common as a result of climate change, the expectation is for increased economic losses in this region. The results also reveal that a strategy of using pre-season ENSO forecasts in planting decisions can offset some of the expected losses of an El Niño and increase some of the benefits that may follow from a La Niña event. In the case of an El Niño, use of forecasts to make crop mix decisions can offset 15 to 20 per cent of the losses associated with the use of traditional crop mixes. These estimates assume that forecast accuracy is approximately 70% (Prob. 0.7); lower or higher levels of accuracy will affect the gains from using forecasts.

The implication is that use of forecast information, coupled with flexibility in planting and other cultural decisions, will be increasingly important in dealing with a more variable climate.

Water Quality and Fisheries

The streams that drain upland areas in the PNW, western Canada, and Alaska provide critical breeding and rearing habitat for salmonids and other cold-water fish species. Salmon play an important commercial, recreational and cultural role in this region, and have been a religious icon for native peoples for thousands of years. Salmon populations are depressed in many parts of the region due to a number of factors, including over-harvesting, dams, logging, and water diversions. Some populations within the U.S. are sufficiently depressed to be listed as "endangered' or "threatened" under provisions of the Endangered Species Act. Warming water temperature in streams has recently been recognized as another threat to salmonids. Causes of this warming include mis-management of riparian zones in the uplands, water diversions, and general atmospheric warming.

Continued climatic warming is expected to exacerbate rising water temperatures. In anticipation of this effect, Oregon and other states have enacted temperature standards for the protection of salmonids under the Total Maximum Daily Load provisions of the Clean Water Act (as amended). Although the temperature standard may vary by location and season, the standard is approximately 17 degrees Celsius. The challenge to managers for achieving this standard is that most streams currently exceed it during at least part of the year. In some cases, temperatures exceeding lethal levels (24-25 degrees Celsius) are observed during critical summer and fall periods.

Several studies have examined least cost ways to meet the TMDL standard for temperature. One study (Watanabe, Adams and Wu, 2006, Watanabe et al, 2005) focuses on a higher-elevation, mid-size stream in eastern Oregon (the Grande Ronde River), while the other (Seedang, Adams and Landers) addresses temperature issues in a larger stream in western Oregon (the Willamette River). Both streams are home to several salmonid species and both contain stocks of these species that are listed as endangered or threatened. Although the studies' stream location and geomorphology differ, the studies are similar in that they combine input and models from hydrology, forestry, geomorphology and economics to develop cost-effective management regimes that achieve the temperature standard.

Several findings are common to both studies. First, in some regions of each watershed, it is not possible to meet the standard under any management regime. This calls into question the nature of the standard, given that future climate warming will increase the areas in violation. Failure to meet the standard, however, does not mean that some cooling will not be beneficial. Second, in areas that can reach compliance, a range of management actions are required to achieve the standard in a cost effective manner, including riparian restoration, stream flow augmentation, and river channel restoration to increase hyporheic cooling. Third, the results suggest that targeting of key reaches or areas of the watershed is needed to achieve the standard cost-effectively. This implies that location matters in stream management, and that a "one size fits all" regulatory regime is not likely to be successful or cost-effective today nor in a warming world with increased climate variability.

Coping with drought and other events: the case for climate forecasts

One step towards preparing for potential increased frequency and intensity of drought, ENSO, or other climate events is an improved understanding of potential regional precipitation and evaporation shifts under a changed climate. The accuracy, precision, and timing of seasonal or longer-term forecasts are likely to affect their adoption by farmers and other resource managers. Providing reliable year-to-year forecasts of precipitation is difficult; decadal forecasts as provided by GCMs are even more problematic. However, as noted in the previous sections, some types of forecasts, such as those associated with ENSO events, are becoming more reliable (NAST, 2000; Trenberth, 1996). Adaptation strategies to ENSO events, such as changing crop mixes, are currently being practiced in many parts of the western hemisphere.

More accurate, precise and timely forecasts can reduce the risk for decision makers and decrease economic losses due to drought (see NOAA, 2002). Current drought management tools can also be reassessed and revised in light of the more reliable information provided. For example, drought insurance programs may need to revise coverage conditions and premiums in order to provide efficient coverage in the changed climate. Increased crop diversity on individual farms or in economic regions could also reduce losses during extreme weather events (IPCC, 2001b). Reservoir capacity, timing of water releases, and safety will need to be reconsidered and updated as well. Voluntary water transfers, with or without climate change, will become an increasingly important tool to mitigate water distribution problems. Municipalities are currently considering the vulnerability of their fresh surface and groundwater supplies to drought, pollution and saltwater intrusion, and may need to consider new protection programs and supplemental water sources. Improved confidence in regional forecasts of climate change impacts is, however, of primary importance in helping regional managers understand risk levels, identify management priorities, and define realistic adaptations.

Summary

Global climate change is likely to increase the frequency and intensity of drought for many regions of the world. Although subject to substantial uncertainty, regional forecasts of long term climatic change from GCM’s do offer a glimpse into possible future climatic conditions. Predicted impacts vary by region, but include increased temperatures and evaporation rates; increased, but more variable precipitation; higher proportions of winter precipitation arriving as rain, not snow; earlier and more severe summer drought, and decreased water quality.

Drought currently results in substantial economic losses in the United States annually. These losses, which occur across a range of sectors, from agriculture and energy to recreation, have profound effects on local communities. More frequent or intense drought imply increased costs to society, unless agricultural producers, water users and others are able to adapt. Improved forecasts concerning future drought conditions, particularly at the regional scale, are necessary for managers and policy makers to identify efficient adaptive strategies, and reduce the economic costs of drought.

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