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Economic Damages from Climate Change: An Assessment of Market Impacts

by

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Economic Damages from Climate Change: An Assessment of Market Impacts

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1. Introduction and Overview

A recent assessment of the market consequences of global climate change in the US by Jorgenson et al. (2004) concludes that “projected climate change has the potential to impose considerable costs or produce temporary benefits for the US economy over the 21st century, depending on the extent to which pessimistic or optimistic outcome (scenarios) prevail.” However, the report warns that: “due to threshold effects in certain key sectors, the economic benefits simulated under optimistic assumptions are not sustainable and economic damages are inevitable. …. most, if not all, potentially positive impacts of climate change under optimistic assumptions are likely to be transient and unsustainable over the long run in the face of steadily rising temperatures.”

In this paper we review these conclusions in the light of some research that we have recently conducted with colleagues that focuses on market impacts from climate change on US agriculture and on agriculture, water, forestry, and sea level in California. Our focus here is both empirical and methodological. With regard to empirical findings, our analysis casts some doubt on the optimistic scenarios employed by Jorgenson et al. (2004). We also present some specific examples of threshold effects in the California context that reinforce the warning by Jorgenson et al. that economic damages become more pronounced with rising temperatures. The main methodological implication of our California findings is that excessive averaging of changes in climate variables – whether the averaging is temporal, spatial, or sectoral – tends to understate the damages from global warming. We also develop some additional methodological implications regarding the analysis of climate change impacts on water supply and sea level rise and the costs of adjustment to climate change impacts.

The California findings are taken from a major scenarios study project conducted for the State of California’s Climate Action Team in which we participated and which one of us helped to direct. The scenario project was requested by Governor Schwarzenegger in June 2005, when he announced his climate change policy for California: he called for a reduction of greenhouse gas (GHG) emissions in California to the level they had been in 2000 by the year 2010, and to their level in 1900 (i.e., the Kyoto target) by 2020. In addition, he set a longer run goal of reducing GHG emissions 80% below their 1990 level by 2050. In support of these goals, he directed the state agencies, organized in what became known as the Climate Action Team, to produce a report to the State Legislature by January 2006 on the impacts of climate change on California. The scenarios project draws heavily on research under way at the California Climate Change Center, a virtual center with locations at UC Berkeley and the at Scripps Institution of Oceanography at UC San Diego, which was initiated in 2003 and was intended to be completed by 2008. Since the research is still under way, the findings of the Scenarios Project are necessarily preliminary and incomplete. The economic analysis in particular is still incomplete; some preliminary results are available for water supply, agriculture, and fire, but not yet for forestry, sea level rise, energy, or other impacts.[3]

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[3] An overall summary of the Scenarios Project can be found in Cayan et al. (2006). There are 20 separate technical reports which can be accessed at http://www.climatechange.ca.gov/climate_action_team/reports/index.html . Other reports resulting from

2. Beware of Averages

A general observation about the impact methodology is that, while climate change is a global phenomenon, the impacts of climate change are likely to be *local*. That is, the impacts when measured along any particular dimension are likely to vary spatially depending on geography, topography, and other local factors. By way of example, consider temperature. Much of the literature tends to focus on the change in global average temperature as a summary statistic for alternative scenarios of climate change scenario but temperature varies spatially, and the change in temperature at a given point in time under a given scenario at any one locale may be quite different from that at another. This is illustrated in Table 1 and Figure 1 which present some data on the change in temperature in California and the change in global temperature for the same two IPCC global emission scenarios. The global climate model from which these projections are derived is HadCM3, and the two emission scenarios are A1fi, which is version of a global "business as usual" scenario, and B1, which is a scenario designed to decarbonize the global economy and stabilize the global atmospheric concentration of CO_2. Under the B1 scenario, the global CO_2 concentration is stabilized at about 550 ppm (a doubling relative to the level at the beginning of the nineteenth century) by 2100; under the A1fi scenario, the global CO_2 concentration rises to 970 ppm by 2100, and continues rising thereafter.

The average change in *global* average annual temperature over the period 2070-2099 compared to the reference period 1961-1990, as projected by HadCM3 model, is 2.0 ˚C under the B1 scenario and 4.1 ˚C under the A1fi scenario.[4] For the state of California, however, and for individual regions in California, the changes in temperature are rather different. The HadCM3 projections were translated to a finer spatial scale in California using a statistical downscaling procedure with a 1/8˚ square grid (each grid cell is about 150 km^2).[5] The first thing to note from Table 1 is that the increases in average annual temperature projected for California are substantially larger than the projected increases in the global average annual temperature – an increase of 2.0˚C globally versus 3.3˚C for California under the BI scenario, and an increase of 4.1˚C globally versus 5.8˚C for California under the A1fi. In part this reflects the fact that increases in temperature are generally larger on land masses than over the ocean, and further away from the equator, so that the average temperature increase for North America generally is larger than the global average temperature increase. Even within California, there is some spatial variation in the rate of temperature increase. As Figure 1 shows, there is less warming along the coast and in the south, and more warming inland and to the north.

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climate change research conducted at the UC Berkeley Climate Change Center can be found http://calclimate.berkeley.edu .

[4] These data are taken from Hayhoe et al. (2004), Table 1. HadC3 is a medium-sensitivity GCM. The Hayhoe et al. also presents results from the PCM model, which a low-sensitivity GCM. The GCM results were released in 2003 for use in the coming IPCC assessment.

[5] HadCM3 employs a grid size of 3.75˚ by 2.5˚ The downscaling technique uses a regression model that maps the probability density functions for the monthly HadCM3 projections of precipitation and temperature over the reference period onto those of the historically observed data for the micro scale grid for the same period, so that the mean and variance of the of the historical data are reproduced in the HadCM3 projections. The regression model is then applied to the HadCM3 monthly projections of precipitation and temperature running from 2000 through 2099.

In addition to spatial variation in temperature increase, there is also a significant seasonal variation. This is actually a new finding from the current versions of the GCM models; it differs from projections in the versions of the models that were used in previous IPCC assessments. The degree of winter warming (December, January, February) in the new model results is similar to what previous versions of the model had projected. But, whereas the earlier GCMs projected about the same warming in summer (June, July, August) as in winter, the new GCM results project a significantly greater warming in the summer than in the winter. Thus, whereas the global average annual temperature increases by 2.0˚ or 4.1˚C depending on the emission scenario, the statewide average summer temperature increases by 4.6˚ or 8.3˚C, respectively. Moreover, in some parts of California – for example, the Central Valley – the increase in summer time temperature approaches 10˚C under the higher emission scenario. The change in global average annual temperature is thus a very bad proxy for the change in summer time temperature in the major farming areas of California.

If the effects of climate change were linear in the degree of warming, the temporal and spatial variation would be less important. However, as shown below, some of the impacts are likely to be nonlinear and convex functions of the degree of warming: there are thresholds, and the damages increase disproportionately as a threshold is passed. Thus, the impact on plant growth in the San Joaquin Valley of a 10˚C temperature increase is likely to be significantly more than two and a half times the impact of a 4.1˚C temperature increase there.

Damages are therefore likely to be understated if the assessment ignores the temporal and spatial variation, and simply uses the overall average temperature change.[6] For this reason, we feel that climate change impact assessments need to be more careful about using averages than has generally been the custom in the past.

3. Impacts on Water

In addition to spatial and temporal averaging, there is also sectoral averaging, namely treating the economic units within a given sector as homogenous and representing the sector by a single “representative firm.” This, too, can produce misleading results because of non-linearities in the damage function.

We start with a simple example involving water supply that can be viewed as both spatial and sectoral averaging. The example comes from a recent study focused not on climate change but rather on the potential economic costs of a severe earthquake in the San Francisco area. The study considered a hypothetical seismic event that damaged the levees protecting some of the islands in western part of the San Francisco Bay Delta, leading to flooding of these islands and an intrusion of saltwater into what is now a freshwater system. About two thirds of California’s population receives at least some of

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[6] This follows, in effect, from Fenchel’s inequality for convex functions: the overall average change in the value of the function is larger than when the function is evaluated at the overall mean.

its water supply from freshwater passing through the Delta, and the protection of the Delta is a matter of the highest importance for the California Department of Water Resources (DWR). The two largest urban water utilities in the San Francisco area – the City of San Francisco and the east Bay MUD systems -- do not depend on the Delta for their water supply and would not be affected by the seismic event in the DWR scenario; they obtain their water from rivers on the east side of the Central valley and their aqueducts by-pass the western edge of the Delta. However the two major government water projects in California – the federal Central Valley Project (CVP) and the State Water Project (SWP) -- both divert water to central and southern California along the western side of the Delta and, in the DWR earthquake scenario, they would be forced to stop water diversions for a period of up to 30 months before the flows of freshwater could be restored. Four urban water agencies in the eastern and southern portion of the San Francisco Bay area would be affected: three smaller utilities rely heavily on the State Water Project and would lose about three quarters of their water supply; another, larger utility would lose about a third of its water supply if the SWP shut down. Under the DWR earthquake scenario, these utilities would have to impose very severe rationing on water use, leading so substantial economic losses for residential and industrial water users. However, for the Bay area as a whole, the reduction in the regional water supply resulting from the seismic event is very small – about 5% of the overall regional supply. If one conducted a regional analysis and treated the entire region as a single, integrated, urban water using unit, there would be no significant economic loss from a reduction of that order of magnitude. But, because the region does not have an integrated, inter-connected water supply system, there will be very large economic losses in the four affected utilities but zero losses for the other utilities in the region.

If a seismic event like the one hypothesized DWR did occur, there would of course be a very strong incentives to construct pipeline or aqueducts connecting the affected utilities with others whose water supply is unaffected by the earthquake. This would spread the burden more widely and greatly reduce the economic loss from water shortages. But two points should be noted. First, the construction of connections takes some time and, in the immediate aftermath of the earthquake, there could be some significant rationing by the affected water agencies, generating initial economic losses. Second, the construction of connections is costly, and this cost is part of the economic cost resulting from the seismic event. It would not be adequately recognized if one simply calculated the cost based on the percentage reduction in overall regional water supply, which is what most existing climate impact analyses tend to do.

This is a specific example, but the larger point is that, for water to be economically valuable, it has to be available at the right place and at the right time (and with the right quality) for it to be put to use. While this is true of many inputs to production, it holds with special force for water because water is bulky and costly to transport.[7] Consequently, shocks that disrupt the timing and/or location of water supply

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[7] In this regard, water differs significantly from, say, electricity. Whereas electricity is hard to store but relatively easy to transmit over long distances, water is relatively easy to store but expensive to transmit over any distance.

can impose significant economic costs that are hard to pick up in a highly aggregated analysis.

For California and other parts of the west and southwest, the timing and location of precipitation are crucial elements in figuring the potential economic costs of climate change on water supply. In these arid, though now highly populated regions, a key fact of life is the mismatch where and when precipitation occurs and where and when it is used. Focusing on California in particular, two thirds of all the precipitation falling on California occurs north of Sacramento, while about two thirds of all the water use in California occurs south of Sacramento. Moreover, 80% of the precipitation in California occurs between October and March, while we estimate that 75% of all the water used in California is used between April and September -- this is when most of the agriculture water use occurs and urban water use, too, is larger during this period because of the significant usage for outdoor irrigation.

To overcome the mismatch in the timing and location of precipitation, California has constructed an extensive system of dams, reservoirs and aqueducts to capture the winter precipitation and hold it for use in the late spring and summer, and to move this water to the areas where it is used. The man-made storage is supplemented to an important degree by the snow pack in the Sierra Nevada, which provides a natural form of water storage. Typically the snow starts to melt in March and the runoff of snowmelt continues through August or September: it provides the streamflow in the rivers that line the east side of the Central Valley. In a typical year, the snow pack in the Sierras on April 1st holds an amount of water equivalent to about one third of the state's major surface water storage; the other two thirds is held in the state's major man-made reservoirs.

It follows that there are two "varieties" of surface water supply used in California: streamflow diverted by water users from rivers in California, and water stored by the CVP or SWP which is sold under contract to specific water users. Both derive from winter precipitation, and both will be seriously affected by global warming, though the effects will play out somewhat differently. In both cases, the key driver is the projected increase in winter temperatures, as a result of which more precipitation falls as rain instead of snow, and the snow that does fall melts earlier in the spring. Consequently, the amount of water stored in the snow pack on April 1st is greatly reduced. By the end of the century (see Figure 2), using the downscaled HadCM3 projections, the amount of water stored in the Sierra snow pack on April 1 falls on average by 63% under the B1 scenario and by 89% under the A1fi scenario.[8]

With regard to surface water diverted by water users from streamflow in rivers, the reduction in snowpack at the start of April means reduced streamflow during the irrigation season. In 2070-2099 under the HadCM3 B1 emission scenario, spring and summer streamflow falls by about 40% compared to the 1961-1990, while under the A1fi

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[8] Under the A1Fi scenario, there is no snow in the Sierras by the end of the century except in the southern Sierras and at the highest elevations. This essentially wipes out the California ski industry. It should be noted that a similar warming and a similar reduction in the snow pack occur in the Pacific Northwest, thus eliminating many of the immediate substitutes for California ski sites.

scenario it falls by about 55%. With regard to water surface water supply by the major water projects, total annual streamflow into the major reservoirs is projected to decrease by about 25% under the HadCM3 B1 scenario and 30% under the HadCM3 A1fi scenario. However, the actual reduction in water supply deliveries from these reservoirs is likely to be larger than these figures indicate because, with winter warming, the inflow now occurs over a compressed time period – more occurs in January and February, less in March and April – and during this period reservoir operators will still need to leave provide some empty reservoir space in order to avoid potential flooding from winter storms. Consequently, reservoir operators are likely to be able to store a somewhat smaller fraction of winter streamflow for use as water supply in the late spring and summer. Moreover, with increased warming, there is a greater likelihood of drought, and hence an enhanced need to sometimes hold back on water deliveries at the end of summer and instead reserve some water for carry-over storage to the coming year against the contingency of a dry winter next year.

One way to characterize the change in inflow is by reference to the Sacramento Four River Index, which is used to classify the type of water year into five categories: wet, above normal, below normal, dry, and critical.[9] Over the historical period 1922–1974 in California, 48% of the years were wet or above normal, and 40% were dry or critical. With Had CM3 A1fi scenario, by 2070–2099, however, only 22% of the years are wet or above normal, while 70% are dry or critical. Moreover, the increase in incidence of dry/critical years is also accompanied by longer and more severe spells of drought.

At this point, it is useful to pause in order to comment on the significance of projected changes in precipitation for our analysis of climate change impacts on California water. The change in precipitation has been the central focus of many previous studies of climate change impacts on water supply, including the US National Assessment in 2002. For California and the West, we believe this is a mistake.

First, we should acknowledge that the projections of a decrease in precipitation, which translate into the decreases in total annual streamflow into the major reservoirs mentioned above, are different from the predictions generated by previous versions of the Hadley model. The previous versions projected a substantial increase in precipitation. The more important point, however, is that precipitation projections are *not* the major driver of the water supply impacts of climate change in California: it is the projections of temperature that are the major factor.

The study by Jorgenson et al. (2004) asserts that "For the economy, wetter is better" because of the implied benefit for agriculture. We believe that this assertion is

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[9] The index is a weighted average of April–July unimpaired runoff (40%), October–March unimpaired runoff (30%), and the previous year's index (30%). Unimpaired runoff is calculated as the sum of Sacramento River flow, Feather River flow, Yuba River flow, and American River flow. A water year with an index equal to or greater than 9.2 million acre-feet (MAF) is classified as *wet;* a year with an index equal to or less than 5.4 MAF is classified as *critical.*

incorrect when it comes to economic impacts in California and the West because it overlooks the *timing* and, in many cases, the location of precipitation in those areas.

As noted above, the key fact in these areas is the mismatch between the time of the year when the precipitation occurs and the time when the bulk of the water use occurs, and also the mismatch between the locations where precipitation occurs and the locations where water use occurs. As a result, in these areas precipitation falling on a field is *not* the direct source of supply for the water used on the field – unlike the Mid-West or the East Coast, where it *is* the direct source of water supply. As John Wesley Powell famously pointed out, west of the 100th meridian, the precipitation that occurs during the growing season is inadequate for plants' needs, and there has to be a supplemental supply either from local groundwater or from surface water imported from elsewhere. By way of illustration, compare corn in Iowa and cotton in the San Joaquin Valley of California. Corn is the major crop grown in Iowa, and it has a water (ET) requirement of about 22 inches. All of this is supplied by local precipitation during the growing season plus the soil moisture in the ground from precipitation just prior to planting. Cotton in the San Joaquin Valley has an ET of about 31.5 inches, and the combined soil moisture at planting plus precipitation during the growing season amounts to less than 2 inches, leaving about 30 inches (95%) to be supplied by supplemental irrigation. Much of this does come from precipitation, but it comes from precipitation during the winter and, in many cases, from winter precipitation much further north.

Because of the timing, we would argue that raw precipitation is typically *not* a valuable resource for the California economy. In the winter in California, there typically is more water than can immediately be used or stored, and the excess flow runs off to "waste" in the ocean. If the precipitation in January or February doubled overnight, say, that would not lead to any noticeable increase in the effective water supply for California. To convert the additional precipitation into useful water supply requires some form of storage. And storage is costly. In short, in California, wetter means more winter precipitation, but more winter precipitation by itself means nothing from an economic perspective.

A corollary is that, in California, water markets by themselves are not a particularly helpful solution to the problems created by climate change. Water markets can play a valuable role in re-allocating water from one set of users to another, which is certainly important because of urban growth and the increasing urban demand for water. But, with regard to climate change, the central fact is that, even with no change in precipitation, the winter warming reduces California's effective supply of water for the reasons described above. It is the change in temperature, not precipitation, that is economically significant for California.

The summer warming also enters the picture, but in a separate role. Whereas the winter warming reduces the effective water supply, the summer warming increases the demand for water both in California agriculture and in outdoor urban uses. By the end of the century, the warmer temperatures associated with the A1fi scenario are expected to increase the crop demand by about 13% (Baldocchi et al, 2006). There would probably be a similar effect on urban demand for outdoor lawn watering.

For the purpose of summarizing how changes in water supply and demand translate into economic impacts, we now focus on a variant of the climate change scenario described thus far. Instead of the Hadley model, we now use the GFDL global climate model, and, instead of the A1fi scenario, we use a variant business as usual scenario, the A2 emissions scenario.[10] [11]

There is a complex pattern to the change in water deliveries under the A2 scenario over the period 2070-2099 compared to the historical reference period that depends both on the type of water user and the year being considered. The type of user makes a difference because of the variation in the source of water (some have access to groundwater, others do not), the type surface water right (some users receive water through contracts with the CVP or SWP, others have their own water right to divert streamflow; the diversion rights vary by seniority) the amount of water to which they have access, and the cost of this water (for example, groundwater pumping depths vary considerably around the Central Valley). There is also significant hydrologic variation from one year to another which complicates the characterization of the change in water supply. This is illustrated in Figure 3, which shows the frequency distributions of deliveries to CVP (agricultural) contractors in the San Joaquin Valley both in the reference (base) period, 1961-1990, and at the end of the century, in 2070-2099. If one focuses on the median water deliveries – the amounts in the historical base and the GFDL A2 climate change scenario that are delivered 50% of the time – the climate change leads to a 31% reduction in the delivery to agricultural contractors in the San Joaquin Valley. If one focuses on a measure of more reliable supply, such as the amount that can be counted on for delivery 75% of the time, climate change reduces this by about 32% relative to the historical base. But, if one looks at the amount that can be counted on for delivery 90% of the time, climate change reduces this by about 20% relative to the base.

The data presented in Figure 3 refer to just one group of water users in the San Joaquin Valley. Other users have different sources of supply and are affected differently by climate change; for example, those with private rights to divert surface water fare somewhat better than CVP and SWP contractors,[12] and those who use groundwater are affected least of all. For agricultural users in the San Joaquin Valley taken as a whole, about half the time in the period 2070-2099 there is only a 10% reduction in water availability compared to the historical base period. In the next third of years, there is an

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[10] Under the A2 scenario, the global CO_2 concentration rises to about 800 ppm by 2100.

[11] This is the model and the emission scenario that were used in the recent Scenario Project for the Climate Action Team in California. The economic analysis presented below is taken from Hanemann et al. (2006). Our purpose in presenting these results is not to emphasize the specific dollar figures, which are still tentative and subject to revision and amplification. Rather, the intent is to illuminate the methodological issues that arise when conducting a bottom up analysis of the economic cost of climate change impacts on water in the West, and that are generally overlooked in most of the existing literature.

[12] Our analysis here is optimistic and disregards the fact that existing water rights are tied to a particular time pattern of water diversions and will have to be modified when the timing of the snowmelt changes. Modifying water rights may turn out to be a lengthy and costly exercise, but our analysis ignores this.

on average 48% reduction in water availability. And in the worst 1/6 of years, there is on average a 68% reduction in water availability. Since the economic costs vary non-linearly with the magnitude of the reduction in water availability, as shown below, this is another instance where using a simple average produces a significant underestimate of the overall expected economic impact.

The economic consequences of this reduction in surface water availability are calculated assuming that, to the extent economically feasible, reductions in surface water availability are offset by increased groundwater pumping and that the marginal land and the least economically profitable crops are abandoned, while more productive land and more valuable crops remain in production.[13] Given these assumptions, we conduct two sets of analyses. One is for an average year over the whole period 2070–2099; the other is for an average year among the lowest 1/6 of years when surface water availability is most heavily restricted.[14] We find that in an average year over 2070–2099, the climate change scenario leads to an annual loss of $278.5 million in net revenue (9%) compared to the net revenue in average year in the base period. The loss of net revenue consists of two elements: there is a loss of net revenue on land that is now fallowed, and there is also a loss of net revenue on land that is still farmed but with more expensive groundwater. In the lowest 1/6 of years, the situation is more complicated. Because these are relatively water-short years, even in the base period some land is fallowed in the worst 1/6 of years and some net revenue is lost. With climate change, in the worst 1/6 of years in 2070-2099 there is an average loss of $803 million (26%) compared to the average net revenue in the worst 1/6 of years in the base period.[15] Thus, with climate change, economically bad years for California agriculture occur more frequently, and there are worse losses in the bad years.[16]

A similar pattern occurs for urban water users. We find that supply shortages for urban water users in Southern California in 2070-2099 occur about twice as frequently under the GFDL A2 scenario as with the historical (i.e., non-climate change) hydrology – 34% of the time versus 18% in the base period – and are far more severe in terms of economic loss. The analysis uses the historical hydrology of the period 1961-1990 combined with the predicted population of urban Southern California in 2070-2099. In this analysis a shortage situation is defined as arising whenever urban demand exceeds urban supply by more than 5% -- it is assumed that shortages smaller than this threshold

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[13] This, too, is somewhat optimistic because it ignores the existing pattern of ownership of water rights, and assumes that ownership can and will be transferred costlessly and efficiently.

[14] A different economic assumption is used in each case. In the average year analysis, it is assumed that farmers can respond to variation in water availability by changing crops or irrigation technology as well as water source. By contrast, the lowest 1/6 of the years are considered akin to a short-run drought emergency situation in which farmers have a given irrigation technology that cannot be modified in the short-run, so their only options are to pump more groundwater or modify their cropping pattern. In these circumstances, farmers are likely to give up their relatively less profitable crops and husband limited or expensive water for their more valuable crops (which are most likely to be tree crops).

[15] Because of the reduced water supply and the increased cost of groundwater pumping, the climate change scenario leads to higher prices for agricultural commodities produced in the Central Valley. This generates a loss of consumer’s surplus for the consumers of these commodities which we have not yet calculated.

[16] The details of this analysis of economic costs of climate change to agricultural water users – and of the analysis of impacts on urban users that follows below – are provided in Hanemann et al. (2006).

can be met by stretching existing supplies with no need for rationing and no loss to urban water users. When a shortage exceeds this threshold, it is assumed that the urban water agency preferentially favors industrial and commercial users by imposing a less stringent rationing on them than on residential users. At this time we quantify only the loss to the residential users, which we measure as the loss of their consumer's surplus using a linear demand function with a short-run price elasticity of -0.05.[17] Under the climate change scenario, the loss to residential users in Southern California averages about $5 billion in a shortage year in 2070-2099, compared to an average loss of $1.7 billion in a shortage year with the same 2070-2090 population but the historical 1961-1990 hydrology. Thus, shortage years occur about twice as frequently with climate change and become about three times as costly. The extra loss for residential consumers due to climate change when a shortage year does occur averages about $3.2 billion per occasion.

Besides the loss associated with rationing in shortage years, there is an additional component to the economic cost of climate change for urban water users which has been overlooked in the existing literature. This arises from the fact that, because of the greater economic value associated with the continuous and uninterrupted provision of water to urban users, urban water agencies are generally willing to invest in measures to assure a much higher degree of supply reliability than is provided to agricultural water users.[18] Urban water managers are very highly motivated to minimize the chance of facing shortages and having to impose rationing. It is extremely likely, therefore, that, when faced with the increased likelihood of shortages due to the effects of climate change on surface water supply in California, urban water managers will take additional measures to protect their supply reliability. These measures probably include both the construction of additional local storage, thus raising the reserve margin of water stored as a percent of annual total delivery, and also the development of some new sources of supply that are less vulnerable to the effects of climate change. Examples of the latter include water saved through improved water conservation, the reuse of (tertiary) treated wastewater effluent, and water from desalination. Certainly the last two items, if not the first, are more expensive than conventional surface water supplies, but they provide a higher degree of reliability in the face of drought. The salient point is that the "drought-proof" supplies entail a cost that the urban water agency has to pay every year, not just in shortage years; in effect, they are an insurance policy against future supply uncertainty. The amount of this insurance purchased depends, in part, on the level of risk aversion exhibited by water managers. In our analysis, estimated the additional annual cost of improved supply reliability required in Southern California for offsetting climate change by 2070-2099 at around $300 million per year, but this is probably too conservative an estimate.

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[17] The use of a threshold below which shortages cause no economic loss, the assumption that industrial and commercial users are shielded more from rationing in smaller than larger shortages when the threshold is exceeded, and the consumer's surplus formula for estimating the loss to residential consumers all introduce elements of convexity into the urban loss function.

[18] This is why we were able to assume that urban water agencies can finesse a shortage of up to 5% with no loss at all to water users.

In addition to the water supply impacts discussed so far, there are three other pathways by which climate change will create economic costs for water users in California. One type of impact is due to the effects on watershed lands of an increase in the frequency of forest fires due to the increased summer warming in California. In the aftermath of a fire in a watershed, there is typically increased soil erosion leading to the sedimentation of reservoirs. This can be quite costly to repair, but at present we have no specific scenario or cost data relating to this water supply impact.

The other two impacts on water supply in California are associated with sea level rise and are discussed in the following section.

4. Sea Level Rise

The driving cause behind the rise in sea level is the increase in global temperature, but the causal pathway and the time path over which sea level rise will impact the California economy are different from those described above with regard to the water supply impacts. The sea level is rising due to two factors, both of which are affected by increases in global temperature: thermal expansion of sea water, and the melting of continental ice sheets and glaciers which deposits freshwater in the ocean. The resulting rise in the sea level has so far been gradual, and is likely to continue to be gradual unless there is dramatic change in the Greenland or Antarctic ice sheets. Over the past century, the sea level off the coast of California has risen by about 20 cm (8 inches). With just the continuing thermal expansion of the ocean, but no dramatic change in the ice sheets, the sea level off California is expected to rise an additional 22-35 inches by 2100 (Cayan et al. 2006b)

The rise in sea level has several adverse consequences. As the level of the sea rises, low lying coastal lands become inundated. Lands that were wet only at high tide become wet most of the time. Coastal structures that are built above the water, like docks, piers and levees, become too close to the water level to function effectively or are submerged. There is increased erosion of coastal bluffs. There is flooding of beaches. And, there is increased saltwater intrusion into both freshwater estuaries and coastal aquifers.

The main focus of the existing economic literature on sea level rise has been the inundation of low lying coastal land, and the economic costs associated with either the loss of land or the cost of constructing sea wall barriers to protect against inundation. This is a rather narrow focus, and it omits several of the adverse impacts listed above.

Two of the omitted impacts have harmful implications for California’s water supply – the increased saltwater intrusion into coastal aquifers and freshwater estuaries. Sea water intrusion into coastal aquifers that renders the groundwater unfit for water supply has long been a significant concern in Southern California and in the Monterey Bay area. Southern California has invested substantial sums in seawater repulsion by way of the injection of treated wastewater effluent into coastal aquifers. While this seawater intrusion will certainly worsen as the level of the sea rises, at this point we have not factored it into our analysis of the water supply impacts of climate change in California.

The intrusion of seawater into the freshwater San Francisco Bay Delta Estuary has begun to receive considerable attention in California, partly as result of Hurricane Katrina and also because of the recent seismic study by DWR mentioned above. As noted there, the Delta is the crucial hub for the transmission of water by the two largest water projects in California, the CVP and the SWP. The key to the functioning of this hub is the network of Delta islands which are protected by levees build mainly between 1880 and 1940 when much of the Delta was converted from a freshwater tidal marsh to its present form. The Delta consists mainly of organic peat soils which oxidize and shrink when they are dewatered and exposed to oxygen. Over time, the levees protecting the islands have subsided, and the interior of the islands, which has been farmed intensively, has subsided even more dramatically, turning the islands into "bathtubs" rather than conventional islands (see Figure 4). In several cases the interior Delta land is now up to 20 feet lower than the water level outside.

If ever the levees are breached, the islands flood. And because the interior of the islands is increasingly below sea level, pumping the water out and reclaiming the flooded island is becoming increasingly difficulty. The recent DWR study focused on the effects of a 6.5 magnitude earthquake in the Delta region[19] and determined that it would be likely to cause 30 levee breaches and lead to the flooding of 16 Delta islands, many of which it would be permanently impossible to restore. The immediate inflow of salt water would render the Delta useless as a water supply source for as much as 30 months. Moreover, when water deliveries did resume, they would be smaller in quantity and much lower in quality than before (Snow, 2006).

Although most of the analysis of the Delta's vulnerability to date has focused on the seismic risks, there is also a significant risk from climate change in the form of sea level rise. However, an important factor that needs to be added to the analysis of these and other aspects of sea level rise in California is the effect of *storminess*. Even if the mean sea level is still below the level of the adjacent land, the combination of high tides and storms can produce waves that cause inundation. The more the sea level rises, the more likely it is that storm induced inundation will occur.

This is the focus of considerable research at the Scripps Institution of Oceanography.[20] Storms temporarily raise local sea level due to the combination of low barometric pressure and high wind associated with storms. When storms occur in combination with high tides and El Nino/Southern Oscillation (ENSO) events they can generate quite massive waves along the California coast. Storm surge along the California coast, excluding the effect of waves, rarely exceeds 1 ft in amplitude; but wave-induced surge on a beach can reach 5 or 6 feet during large wave events (Flick 2006). Such extreme wave events were experienced along the California coast during the

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[19] This magnitude earthquake was considered to have about the same occurrence probability as a hurricane like Katrina.

[20] Bromirsky et al. (2004); Cayan et al. (2006b)

severe ENSO winters of 1982-1983 and 1997-1998. During the latter, abnormally high tides in the first week of February, 1998 produced the worst flooding in the San Francisco Bay area in more than 40 years.[21]

Cayan et al. (2006b) present an analysis of how the incidence of extremely high wave events along the California coast could increase as the mean sea level rises. They focus on hourly sea levels, and define an extreme event as one where the hourly sea level height lies above the historical 99.99% level for the period 1960-1978 (i.e., hourly sea levels *lower* than this were experienced 99.99% of the time). Such extreme events tend to occur when heavy winter storms coincide with high tides, as happened in 1982-83 and 1997-98. The frequency of such events escalates sharply as the sea level rises. By the end of the century (2070-2099), if the mean sea level at San Francisco does *not* rise above its level in 2000, Cayan et al. project that an extreme hourly sea level event would occur about 15-20 times (hours) per year in San Francisco. If the mean sea level at San Francisco in 2070-2099 is 20 cm higher than its level in 2000, they project that an extreme hourly event would occur about 150-200 times per year in San Francisco . If the mean sea level at San Francisco is 40 cm higher than its level in 2000, they project that an extreme hourly event would occur about 1,500 times per year. If the mean sea level is 60 cm higher than its level in 2000, they project that an extreme hourly event would occur about 7,000 times per year. And, if the mean sea level is 80 cm higher, they project that an extreme hourly event would occur about 20,000 times per year.

When they occur, extreme wave events can not only cause flood damage along the California coast; they could also affect the Delta and cause breaches in the levees and flooding of delta islands – this happened in both of the previous ENSO events.[22] It seems possible, therefore, that, by 2100, even without a major seismic event in the Delta, the increased incidence of extreme wave events associated with sea level rise could itself lead to irreversible flooding of Delta and a permanent disruption of the California water supply system.

Besides damage along the coast and in the Delta, storminess has significant implications for another component of the economic damage from sea level rise, namely the cost of sea wall construction. The timing of the sea wall construction is an important variable determining its cost because the analysis typically uses a discount rate and calculates the present discounted value of the costs of protection against sea level rise. Thus, the date when the sea wall is constructed makes a difference – the discounted present value is lower if the sea wall is constructed in 2085, say, than in 2060. The literature tends to assume what is known as efficient adaptation: the sea wall is

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[21] During this event, "the Pacific Ocean surged over parking lots and the coastal highway at San Francisco's Ocean beach, and whitecaps up to 6 feet splashed over the city's waterfront Embarcadero for the first time in recent memory. Elsewhere, U.S. Highway 1010 north of the Golden Gate Bridge was flooded by as much as 4 feet of water from San Francisco Bay, and other low-lying areas around the bay were also swamped, forcing hundreds of people to flee their homes." The winter storms of 1997-1998 resulted in "hundreds of millions of dollars in flood and storm damage in the San Francisco Bay region." (Ryan, 2000).

[22] This threat is particularly significant because the force exerted on levees by the surrounding water is proportional to the square of the rise in water level.

constructed only if the market economic benefits exceed the cost and only when it is needed, not before (Yohe et al., 1999). The latter is typically defined as when the projected level of the sea rises above the level of the adjacent coastal land. Storminess is significant in this context because it can lead to an earlier timing of sea wall construction. With a storm, there can be flooding before the mean sea level has reached up to the level of the coastal land, and this flooding can generate a political demand to take protective action without waiting for further floods to occur. With an earlier timing of sea wall construction, there is a higher discounted present value of the cost of protection.[23] In effect, this is another instance where averages can be misleading: the analysis is based on the average sea level, but the economic damage is triggered by the maximum wave level.

So far, our discussion of sea level rise has focused on the sea as a source of damage. But the sea is also a source of benefit resulting from beach recreation. In some areas this is an important component of the regional economy, Southern California and Florida being examples. In California, according to the National Survey on Recreation and the Environment, more than 151 million visits were made to California beaches in 2000. Of these as many as 146 million visits were made to the beaches in Southern California. In another study, using data taken directly from lifeguard records, it was estimated that total beach attendance in Los Angeles and Orange Counties alone exceeded 79 million visits in 2000. In addition to contributing greatly to the quality of life in Southern California, beach recreation is an important part of the economy. The total California tourism industry generates more than $75 billion in travel spending annually, and supports more than 1 million jobs, making it the third largest employer and the fifth largest contributor to the state's economy. Much of this tourism activity is associated with Southern California and its beaches.

Sea level rise and storminess are very damaging to beaches. Storms erode beaches. A rising sea level means more erosion. The standard response to beach erosion is beach nourishment, or replenishment of sand resources, which can be very expensive (Davison et al., 1992). California already spends millions a year beach on beach nourishment programs. Sea level rise will intensify these problems. Building hard structures to protect the coast limits the ability of beaches to migrate inland as sea level rises, leading to the narrowing and, ultimately, elimination of the beach. This creates an additional category of economic costs from sea level rise, namely the increased cost of beach nourishment and the loss of consumer's surplus due to the reduced opportunity for beach recreation when beaches erode, shrink, or are eliminated. These costs have not been factored into existing estimates of the economic costs of sea level rise in the US, but we are currently working to measure them for California.

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[23] Building sea walls is an expensive proposition. In California, the cost now averages about $6,000 per linear foot (Flick, personal communication).In Southern California alone, it is estimated that about 120 miles of coastline will need armoring during the course of this century. The total cost of the protection needed there alone amounts to about $3.8 billion in today's prices. In addition, there are maintenance costs which can be about 4 -10% per year.

5. Temperature-Related Extreme Events: Floods and Fire

Since Hurricane Katrina last year, there has been an increased focus on the economic costs associated with hurricanes in particular, and extreme natural events in general, that may occur with increased frequency or increased intensity as a result of global warming. This also applies in California. While California does not face any threat of hurricanes, it does face threats of flooding and fire which are related directly to global warming.

The flooding referred to here is different from the coastal flooding and the flooding of Delta islands mentioned above in connection with sea level rise: instead, it is inland flooding associated with winter warming and the shift of precipitation from snow to rain. The shift of precipitation to rain implies an increase in immediate winter runoff, which has the potential to cause flooding damage downstream in the Sacramento and San Joaquin River systems.[24]

Chung et al. (2005) provide an illustration of this potential for increased winter flooding using a simple hydrologic model of the Feather River watershed and simulating the peak runoff in a winter storm as the snow level elevation rises from 4,500 feet (1,400 meters, m) to successively higher levels with increasing winter temperature. As the snow-level elevation rises to 5,000, 6,000, or 7,000 feet (1,500, 1,800, 2,100 m), the peak runoff from a winter storm increases by 23%, 83%, and 131%, respectively; with each increase, there is a higher probability of flooding in the Sacramento Valley. They also point out that the 100-year, 3-day peak flows on the American, Tuolumne, and Eel Rivers have more than doubled between the first half of the twentieth century and the second; more generally, the annual peak 3-day mean discharges are becoming more variable and larger for most sites in California. These changes closely track the increase in winter warming that has been detected throughout California and the West since about 1950.[25] The trend for bigger floods in the Central Valley over the past fifty years compared to the first half of the last century is especially noticeable on the American River in connection with Folsom Dam. Folsom was designed to reduce flows in the American River to a level that could be safely handled by downstream levees. The dam was designed based on historic flow records with the design criterion of storing the excess flow from a 500-year flood. However, since construction started in 1950, there have been 5 floods on the American River larger than the pre-1950 recorded maximum flood, and the design flood is now viewed as a 50-year flood rather than a 500-year flood. Consequently, the flood control space in Folsom that was once thought adequate to protect downstream areas is no longer adequate.

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[24] Such flooding happened on a quite large scale in the massive ENSO winters of 1982-83 and 1997-98. It almost happened this spring, following an exceptionally wet March and April.

[25] Mote et al. (2005) show that, since about 1950, snow accumulation across the western coterminous United States has shown losses on the order of 10% in April 1 snow water equivalent. Over this period, the onset of the snowmelt spring pulse has shifted forward in time by 10–30 days throughout the western United States, with the largest shifts seen in the Pacific Northwest and the Sierra Nevada (Stewart et al. 2005).

There are two additional factors that are likely to exacerbate the economic damages from flooding in the Central Valley which is expected to result from climate-induced increases in winter runoff. One factor is the high natural flood risk in the Sacramento Valley due to the deleterious sedimentation of the Sacramento River by hydraulic mining in the 1860s and 1870s. A little known fact is that the existing flood risk of the city of Sacramento is the greatest of any major city in the US. Sacramento is currently considered to be protected against only a 77-year flood. By contrast, New Orleans was considered (at least until now) to be protected against roughly a 250-year flood. With climate change, what is currently considered a 77-year flood will certainly become far more likely as the century progresses.

The second factor is that, while the Sacramento and San Joaquin Rivers are protected by 1,600 miles of levees, these levees are generally in poor condition. Most of them were built more than a century ago on foundations that are subject to seepage and movement. Over time, the levee system has significantly deteriorated, partly due to deficiencies in the original design and partly due to inadequate maintenance.[26] During the 1997-98 ENSO winter, there were 30 breaks in these levees. The resulting flooding forced more than 120,000 people from their homes; more than 55,000 were housed in 107 shelters, the largest sheltering operation in California’s history, and an estimated 30,000 residential and 2,000 business properties were damaged or destroyed (DWR 2005).

The flood risks in the Central Valley associated with the global warming scenarios over the period through 2100 are still be evaluated. However, some preliminary results are available with respect to the effect of warming of wildfire. Under the GFDL A2 emission scenario, the risk of large wildfires in California is projected to increase by 55%, almost twice the increase projected for the B1 scenario (Westerling 2006). Because wildfire risk is determined by a combination of factors including precipitation (which can promote the growth of the vegetation that later becomes fuel for fire) and wind, as well as temperature, future wildfire risks will not be uniform across the state. In many regions, wildfire projections depend critically on future precipitation patterns. For example, if precipitation increases as temperature rises, wildfires in the grasslands and chaparral ecosystems of Southern California are expected to increase by approximately 30% towards the end of the century. In contrast, a hotter, drier climate could promote up to 90% more fires in Northern California by the end of the century by drying out and increasing the flammability of forest vegetation (Luers et al. 2006)

When they occur, extreme events are likely to generate at least three kinds of market damages. One form of market damage is the loss of output, whether caused by direct destruction of output (e.g., crops standing in the field are flooded) or by disruption in the supply of an input or (e.g., electricity is shut off, workers are rendered homeless and leave town) or in the production process itself (e.g., the factory is flooded). The second form of market damage is destruction of physical capital. This not only affects the production process in the current period, but it also requires a diversion of productive

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[26] These are to be distinguished from the 1,000 miles of levees in the Delta. There are several interesting parallels between the Sacramento River/ San Joaquin River Flood Control System and the New Orleans Flood System.

resources in future years to replace the capital that was lost, thereby lowering consumption in the future years. The third form of market damage is morbidity or mortality suffered by human casualties of the extreme event, which disrupts the flow of labor services and reduces the size of the labor force. With a few notable exceptions, most of the existing literature on the costs of climate change has focused largely on the first type of damage.[27] It is likely that all three types of damage exhibit some degree of convexity. We conjecture that the convexity may be pronounced for the second and third types of damage because physical thresholds may be more have a more prominent role in determining the magnitude of these damages.

6. Impacts on Agriculture

In this section we switch from presenting the results of recent work on climate change impacts in California to presenting two sets of recent work by our colleagues that deal with the impacts of climate change on US agriculture.

The first set of papers, by Schlenker, Hanemann and Fisher (2005, 2006) refutes some empirical findings by Mendelsohn, Nordhaus and Shaw (MNS) (1994) about how US agriculture is likely to be affected by climate change. MNS had emphasized the contrast between their work and the previous literature on the topic. The previous literature had adopted a largely agronomic approach, based either on individual crop production functions or on the use mathematical programming to select an optimal cropping pattern. By contrast, MNS adopted what they called a Ricardian approach that involves the regression of a hedonic equation for farmland value as a function of climate and other variables. The previous approaches did not allow for the effect of substitution among alternative land uses, especially non-agricultural uses, on the economic impact of climate change on land profitability and value. The Ricardian approach does allow for substitution in the uses of land. If, when climate changes, a piece of land becomes unsuited for typical agricultural uses but still is suited for other, valuable, non-agricultural uses, this will be reflected in the price of the land and it should be picked up in the hedonic regression. In this case, an agronomically-focused analysis that looked narrowly at agricultural uses would overstate the loss of value induced by the climate change, whereas the Ricardian approach would correctly identify that the substitution of appropriate non-agricultural uses reduced the loss of value.

This theoretical argument is certainly persuasive. What made it even more powerful was that, when MNS conducted their empirical analysis, they found a much smaller economic loss in US agriculture from climate change than had previously been found. They viewed this as substantiation of their argument regarding the ameliorating effect of substitution in land use – or, the ameliorating effect of what came to be called more generally adaptation by economic agents.

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[27] Hallegatte and Hourcade (2006) have made an important contribution in analyzing the second type of damage. Jorgenson (2004) is a perhaps the first study to incorporate the third type of damage.

Since then, adaptation has become something of a mantra for climate change economists, boosted by further replications of the MNS results by Mendelsohn and other colleagues. To most observers, the logic seemed unassailable. The Ricardian approach makes full allowance for adaptation, while the other approaches do not. We know theoretically that adaptation lowers damages. The Ricardian approach finds lower damages to US agriculture than the other approaches. This is empirical proof of the potency of adaptation.

Besides of the potency of adaptation, another possible reason for the empirical results obtained by MNS is that there might have been some problem with the data they used. After all, the empirical strategy used by MNS implies that precipitation in a given county measures the water supply in that county and is the pathway by which climate change in the county is transmitted to agriculture in the county. However, as we noted above, much of the agriculture to the west of the 100th meridian is irrigated, and irrigation breaks the link between local precipitation and water supply. Moreover, some of the individual regression coefficient estimates obtained by MNS seemed odd, notably the coefficients associated with July precipitation. These coefficients implied that an increase in July precipitation lowers farmland value. However, July is the heart of the growing season for crops, and it is hard to believe that crops do not benefit from access to water then. One wonders whether the result is an artifact of the data. For example, the most valuable farmland in the US is in California and parts of Arizona, yet these areas are some of the driest and hottest parts of the US in July. The farmland there is valuable not because of the dryness but in spite of it – farming is viable in these areas only because of the availability of irrigation. The MNS regression analysis does not control for irrigation, and one wonders whether this drives their results.

The issue of irrigation was raised by Darwin (1999); Mendelsohn and Nordhaus (1999) responded by attempting to control for irrigation; they found that this made absolutely no difference to their results. However, Schlenker, Hanemann and Fisher (2005) subsequently found that they had not controlled adequately for irrigation: they had allowed for irrigation to shift the intercept in the hedonic regression equation, but they had not allowed for it to affect any of the slope coefficients measuring the marginal impacts of precipitation and temperature in January, April, July, or October on farmland value. We found that all of those coefficients are affected by the presence of irrigation, both individually and collectively. We further argued that irrigated regions needed to be treated separately because in those areas local precipitation is not an adequate measure of water supply: the effects of precipitation are transmitted through a surface water storage and transmission supply, and the water supply needs to be measured directly for each water supply system. Since these measurements are not readily available, we recommended a case study approach for dealing with the affects of climate change on agriculture in irrigated areas, whereby measures of water availability and reliability would be developed for individual systems. However, in dry land (rainfed) farming areas – east of the 100th meridian – local precipitation is the major component of water supply for agriculture, and we felt that the Ricardian approach could appropriately be applied.

In Schlenker, Hanemann and Fisher (2006) we proceeded to apply the Ricardian approach to US counties east of the 100th meridian. Using the results of the HadCM3 A1fi and B1 emissions scenarios downscaled to the US county level, we found that there are sharp regional differences in the impacts of climate change: northern counties generally benefit, while southern counties generally suffer. The overall result is that there would be decrease in aggregate farmland value east of the 100th meridian of 27% by 2070-2099 under the B1 scenario, and 69% under the A1Fi scenario. This is quite different from the relatively optimistic results obtained by MNS.

Our finding that, when properly applied to the non-irrigated farming areas in the US, the Ricardian approach shows large damages from the climate change scenarios should *not* be taken as an indication that adaptation is unimportant and cannot significantly soften the damages from climate change. Adaptation is clearly important. But, adaptation is generally neither perfect nor costless – as is shown by our California case study summarized in the preceding sections.

Another aspect of climate change impacts on agricultural production is considered by Schlenker and Roberts (2006) who conduct a fine grained analysis of the relationships between weather and corn, soybean and cotton yields in the US. They use a unique data set providing daily weather records covering cropland areas within each county of the entire country for the period 1950-2004. They employ a sophisticated non-parametric estimation procedure that imposes no a priori restriction on the shape of the relationship between temperature and yields. They find a very robust and highly significant relationship between temperature and yields that is non-linear, but in a strikingly different way from the type of nonlinearity generally assumed in the economic literature on climate change. The convention in the climate change literature is to represent yield as a quadratic function of temperature: starting from a low temperature level, increases in temperature at first improve crop yield but later harm it. There is nothing wrong with this general notion per se, but the se of a quadratic functional form makes the relationship *symmetric*: because of the symmetry, while an x° degree increase in temperature in a hot area produces damage to crops, the same x° degree warming in a cool area can produce benefits that exactly offset the damage in the hot area. However, Schlenker and Roberts (2006) find that the relationship is not at all symmetric. As shown in Figure 5, the relationship is actually bimodal but fairly flat up to a temperature of about 29° C for corn and soybeans, and 33° C in the case of cotton, and then sharply downward sloping for temperatures above those thresholds. Consequently, the damage from an x° degree warming beyond those thresholds greatly offsets the benefits from x° degree warming occurring below them.

8. Concluding Observations

Our primary goal in this paper has been to focus on some of the methodological issues that arise in measuring the market impacts from climate change. We have intended the California case study to serve as an illustration of these points, and we want to emphasize the qualitative results rather than specific numerical results since these are still be revised. We feel that the case study has been useful because it has allowed us to develop a detailed, bottom-up approach to the assessment of economic impacts. We believe this highlights some important issues that tend to be obscured in a more aggregative, top-down approach to impact analysis.

Our key message is that, because of convexities in the cost functions, averaging the impacts can produce misleading underestimates of the market costs of climate change. One needs to beware of averages – whether spatial, temporal, or sectoral averages. The global average change in temperature may be a misleading indicator for the change in temperature in California. The change in annual average temperature may be a misleading indicator for the change in temperature during the growing season. The impact on water supply in average year provide a misleading indication of the impact in the most water-short years. The reduction in the larger region's overall water supply may be a misleading indication of the consequences associated with a much larger reduction in a very small portion of the region. The rise in mean sea level may be a misleading indication of the rise in maximum storm surge. And, a flood control system that is OK on average is not much use as a protection against flooding if its weakest link is pretty bad.

8. References [TO BE COMPLETED]

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TABLE 1 CHANGES IN TEMPERATURE GLOBALLY AND IN CALIFORNIA, 2070-2099*

	EMISSION SCENARIO**	
	A1fi	B1
Change in global average annual temperature	4.1	2
Change in statewide average annual temperature in California	5.8	3.3
Change in statewide average summer temperature in California	8.3	4.6
Change in statewide average winter temperature in California	4	2.3

*Change relative to 1990-1999. Units are ˚C
** Projections from HadCM3

Source: Hayhoe et al. (2004)

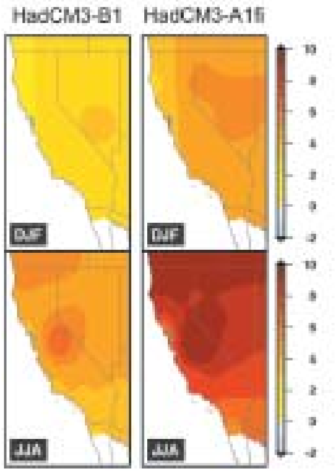


Figure 1: Projected Increase in Summer Temperatures in California Under Alternative Emission Scenarios, 2070-2099 Relative to 1961-1990.

Source is Figure 1 in Hayhoe et al. (2004).

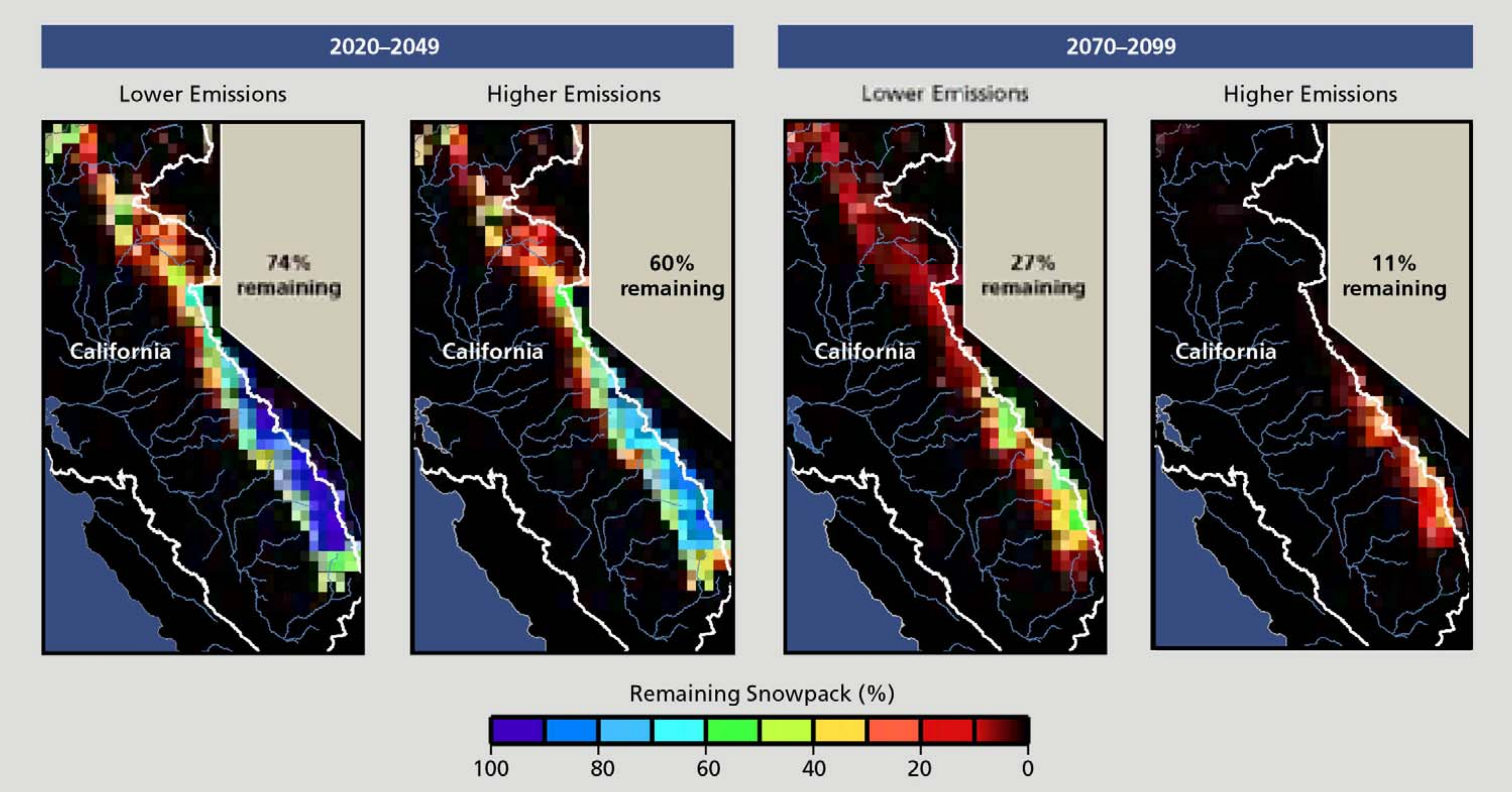
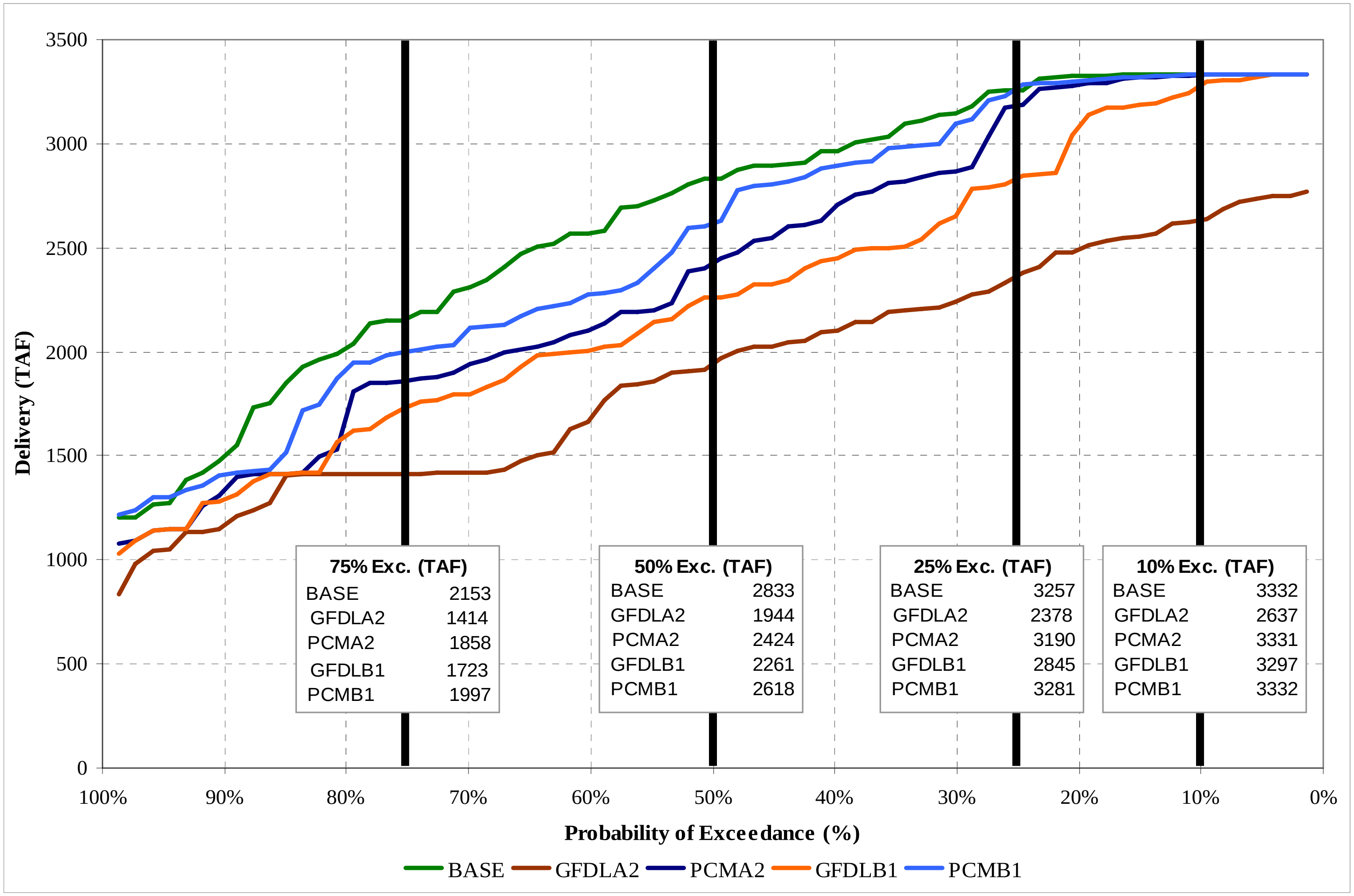


Figure 2: Projected Decrease in Water Equivalent of Sierra Snowpack Under Alternative Emission Scenarios, Relative to 1961-1990. Source is Hayhoe et al. (2004).



75% Exc. (TAF)	
BASE	2153
GFDLA2	1414
PCMA2	1858
GFDLB1	1723
PCMB1	1997

50% Exc. (TAF)	
BASE	2833
GFDLA2	1944
PCMA2	2424
GFDLB1	2261
PCMB1	2618

25% Exc. (TAF)	
BASE	3257
GFDLA2	2378
PCMA2	3190
GFDLB1	2845
PCMB1	3281

10% Exc. (TAF)	
BASE	3332
GFDLA2	2637
PCMA2	3331
GFDLB1	3297
PCMB1	3332

Figure 3: Projected Deliveries to CVP Contractors in the San Joaquin Valley Under Alternative Climate Change Scenarios, 1961-1990 and 2070-2099.

Source is Vicuna (2006)

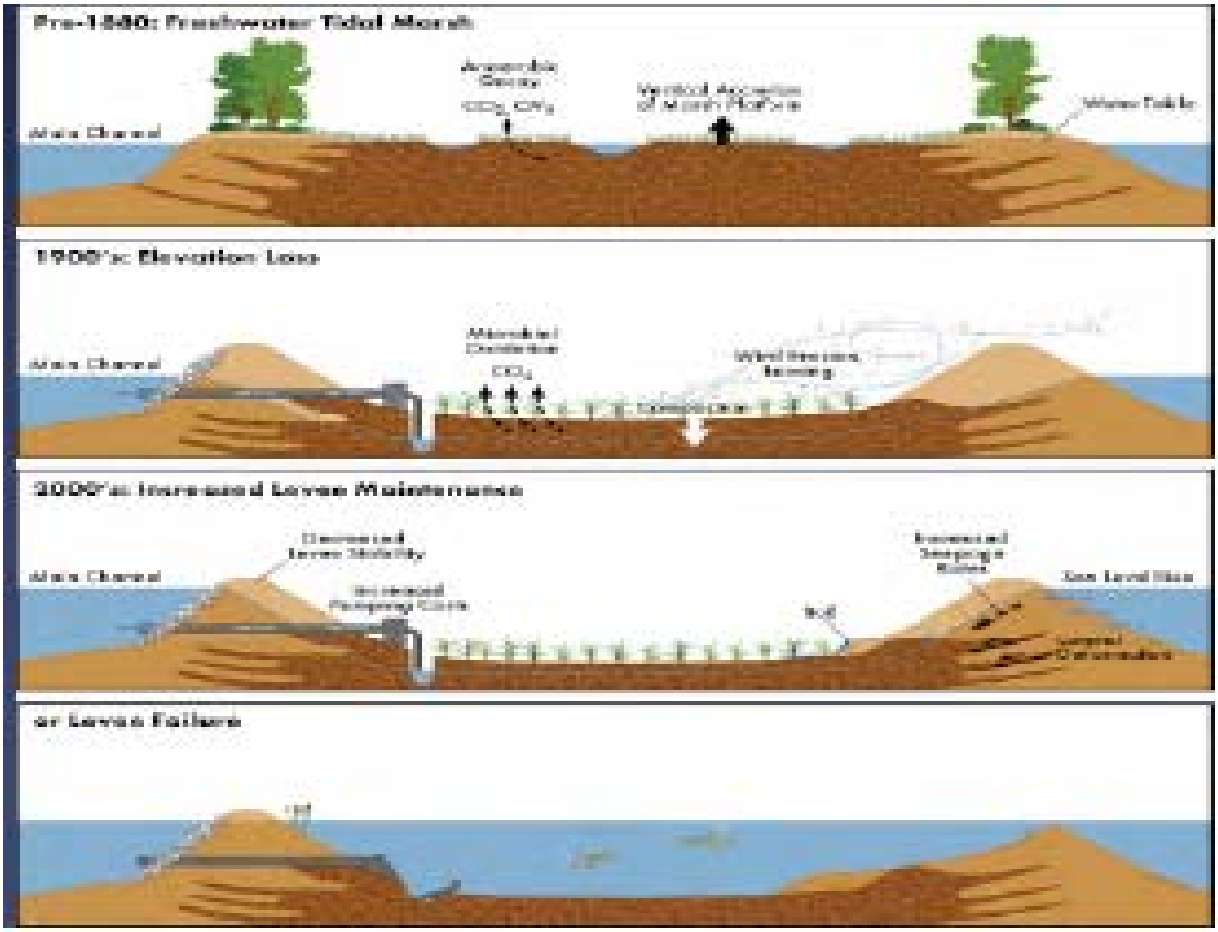


Figure 4: How the Delta Islands Became Bathtubs

Source: DWR (2006)

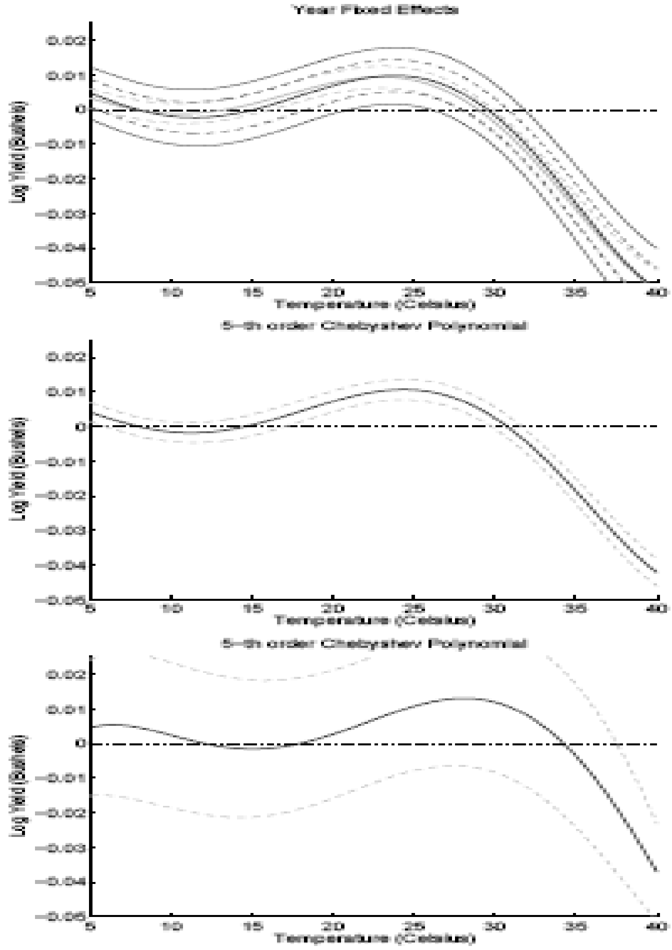


Figure 5: Nonlinear Relationship Between Temperature and Corn, Soybean and Cotton Yields.

The upper panel is corn; the middle panel is soybean; and the lower panel is cotton. The panels display the impact of a given temperature for one day of the growing season on yearly log yield. The curves are relative to a temperature of 8 C in the case of corn and soybean, and 12 C for cotton.

Source: Schlenker and Roberts (2006, Figure 7).