Statement of

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Introduction

Madam Chair and members of the committee: thank you for inviting me here to testify today. My name is Philip Duffy; I am a physicist at the Lawrence Livermore National Laboratory, an Adjunct associate Professor at the University of California, Merced, and Director of the University of California's Institute for Research on Climate Change and its Societal Impacts. I have worked for nearly 20 years on understanding climate change, and recently have focused on its "societal impacts:" effects on water, agriculture, human health, and so on.

My purpose in testifying today is to discuss the likely impacts of climate change on California's water system, including water supply reliability, water demand, flood risk, and levee stability. I will discuss both what we think we know and what we think we do not know about these important issues. Although I will focus on California, many of the issues I will discuss are pertinent to much of the Western U.S.

California's water supply is highly vulnerable to climate change. Parts of our State are very wet, but the parts with highest population densities are semi-arid or dry; on average, precipitation provides barely enough water to meet our needs. Unusually large year-to-year variability in precipitation means that we experience periodic water scarcity. Although my discussion will focus on climate change, since that is my area of expertise, other factors, notably demographic changes and the need to maintain healthy ecosystems, also threaten our future water supply. Our major challenge is to understand how to cope with these several simultaneous threats, each of which is highly complex and involves significant uncertainty. The task is urgent, for I and others believe that California will experience a water crisis, unless we act to stop it.

Historical Climate Change

Let me start by reviewing what has been learned from climate observations made since the start of the 20th century. I will then discuss what we expect to happen in the future, and make recommendations for future research that will help reduce key scientific uncertainties.

Like most of the world, California has become warmer since 1900. Recent research suggest that some temperature increases in California have been too rapid to be due entirely to natural factors; this implies that humans have caused at least some of this warming. (As you know, this conclusion was reached some time ago for global-scale warming by the UN's Intergovernmental Panel on Climate Change.)

Other observations confirm measured temperature increases. The seasonal timing of river flows has changed, with more flow in winter and less in the late Spring and Summer. This is a consequence of warming, which causes more precipitation to come in the form of rain (rather than snow), and snow to melt earlier in the Spring. This trend towards earlier-in-the-year river flows has been shown to be too rapid to be entirely natural, implying that humans are at least partly responsible for it. This trend is of great concern, because our water storage infrastructure generally lacks the capacity to store additional wintertime river flow; thus this shift in the timing of river flows results in a significant loss of useable water.

Consistent with this picture, the water content of spring snow—which constitutes a major part of our water supply—has decreased in most of the West, including most of California, since 1950. A recent study estimates that half of the snow reductions seen since 1950 have been caused by humans.

Climate variability causes floods, threatens water supply reliability, and complicates the lives of water managers. As noted above, year-to-year variability in precipitation in California is unusually large. A range of geological data indicate that California experienced prolonged droughts during the Middle Ages that were much more severe than any in the industrial period. The cause of these severe droughts is not well understood, and we cannot rule out the possibility of similar events in the future.

Sea levels along the California coast have risen since the start of the 20th century. Recent satellite measurements suggest that the rate of sea-level rise is increasing, although this may be a short-term surge of unknown cause, or an artifact of changing measurement techniques. The primary cause of recent sea level rise is believed to be thermal expansion of seawater; as discussed below, this may change in the future as land ice sheets begin to melt. Melting of sea ice does not contribute to sea level rise.

In summary, observations in California (and much of the Western U.S.) show trends that are not only consistent with "global warming," but *in*consistent with natural climate variability. Furthermore, these trends, if continued, will reduce the reliability of California's water supply, and will likely have other important impacts.

<u>Future climate and water resource impacts</u>

(a) Warming and water supply consequences

Turning now to future climate change and its impacts, there is no doubt that temperatures will continue to increase in California and elsewhere. The exact rate of warming cannot be accurately predicted, in part because of imperfect understanding of the relevant science, and in part because the major driver of climate change—the rate of future greenhouse gas buildup in the atmosphere—is unknowable, since it depends on decisions to be made in the future by individuals, corporations, and governments. Even at the low end of the range of projections used by the UN's Intergovernmental Panel on Climate Change (IPCC), however, projected warming for the 21st century far exceeds that observed during the 20th century. At the high end of the range, projected warming of nearly 10 degrees Fahrenheit is projected for California by 2100; I believe that this would have far-reaching and devastating impacts for water resources and many other aspects of life in our State.

Continued warming will result in difficulty meeting water deliveries. The fundamental reason is reductions in snow, which we depend upon to keep man-made reservoirs full in late Spring and Summer, after the snow melts. Although reductions in snow will be accompanied by *increased* flows into our reservoirs in winter, those reservoirs generally lack the capacity to capture additional wintertime flow, and thus this water will be lost. Because the prediction of continued warming is extremely robust, the trend towards reduced snow that is already under way seems virtually certain to continue. Projections of future snow show a range of results, but losses of 30% to 90% by 2100 are typical. The rate of snow loss is sensitive to the projected rate of future greenhouse gas emissions, so reducing emissions should significantly mitigate this problem.

(b) Future Precipitation

Future changes in precipitation in California cannot be predicted with any accuracy at this time. We cannot even say with certainty if overall precipitation will increase or decrease in our State, although a decrease is perhaps more likely. This uncertainty results from the complexity of processes governing precipitation, as well as an accident of geography, in which California lies partly within a broad region in which precipitation is predicted to increase, and partly within another region in which precipitation is predicted to decrease. The exact location of the boundary between these regions is unknown, hence we cannot say if precipitation in increase or decrease in California as a whole. Despite these uncertainties, I wish to emphasize that any increases in precipitation, although helpful, are unlikely to be enough to compensate for reductions in water supply caused by warming. Hence increased water scarcity is likely, even though precipitation may increase.

It is also worth noting that when we consider a larger region in the Southwest U.S. that includes most of California, there is a strong consensus among climate models for a much drier future: the median model predicts a 25% decrease in precipitation minus evaporation—the net natural supply of water—by 2100 (Seager et al, 2007).

As noted above, California experiences great year-to-year variability in precipitation, which often results in water shortages and associated problems. Unfortunately, today's science does not allow us to predict if this variability is likely to increase or decrease as climate change progresses. This is a critical issue that should be investigated further.

(c) Flood risk

The subject of climate change impacts on flood risk has been investigated much less than impacts on water supply. Nonetheless, there is reason to believe that climate change will increase flood risk. The fundamental reason is that a warmer atmosphere holds more moisture, hence the potential for intense precipitation is increased; this is the reason for intense tropical precipitation. Climate models predict increases in extreme precipitation events; these models do not simulate floods, but the implication of increased flood risk is inescapable. Furthermore, actions taken to minimize flood risk reduce the water supply:

the primary response is to require that reservoirs be kept less full, so that a surge in river flow could be absorbed. Thus a perception of increased flood risk will compound future water-supply problems. Because of the potential seriousness of this problem, one of the recommendations I will make below is further research into effects of climate change on flood risk.

(d) Water demand

As short-term warm spells demonstrate, increasing temperatures tend to result in increased urban water demand. Hence temperature increases associated with climate change will also tend to increase urban water demand, although presumably long-term water scarcity would result in some conservation measures becoming institutionalized.

The situation for agricultural water demand is more complex. All things being equal, higher temperatures result in increased loss of moisture by plants and soils to the atmosphere, and hence increased need for irrigation. Studies of climate change and agricultural water demand have shown that this effect can be very significant. However, increased atmospheric CO_2 itself tends to *reduce* plant water demand, at least in laboratory tests, through a "CO_2-fertilization" effect. It is not known how strong this effect will be under real-world conditions; hence the net effect of climate change on crop water demand is uncertain. Several studies have predicted a relatively small increase.

(e) Soil moisture

Reduced spring and summer river flows, as well as reduced snow cover and earlier snow melt, all noted above, tend to reduce soil moisture. Warmer temperatures also contribute to this through increased evaporation. It seems likely that all these trends will continue. In addition to increasing irrigation demands in agricultural regions, reduced soil moisture will likely contribute to wildfire frequency and severity and ecosystem vulnerability. Moreover, drier soils may lead to increases in windblown and disturbance-related dust emissions and associated air quality impacts.

(f) Sea level rise

Besides the obvious risk of coastal inundation, sea level rise threatens our water supply, through three means. First, water levels in the Sacramento/San Joaquin Delta (particularly in the western Delta) are influenced by sea level. Even very modest rates of continued sea level rise will result in greatly increased frequencies of extreme high water levels. This poses a significant risk to Delta levees, and hence to the large part of our water supply that percolates through the Delta. Second, a higher sea level will tend to increase salinities in the Delta. To maintain acceptable water quality, more water will have to be released through the Delta; this water cannot then be used to meet urban or agricultural demand. Finally, at least in principle, a rising sea level will result in increased salt concentrations in some groundwater reservoirs; this could affect the suitability of this water for most uses. Seawater intrusion into coastal groundwater aquifers has been well documented in California; however, the predominant cause is probably groundwater pumping. In practice, increased salinity in groundwater due to sea level rise is difficult to distinguish from increased salinity due to pumping of groundwater.

Future sea level rise is highly uncertain. The most important—and worrisome—source of uncertainty is the possibility of significant loss of the Greenland ice sheet. Until recently, this was thought to be unlikely to occur any time soon. New observational evidence, however, shows that the Greenland ice sheet is starting to shrink. This raises the possibility of much more rapid sea level rise than was previously thought possible. A number of recent reports have cited 140 cm (55") as the highest of several estimates for possible sea level rise by 2100. As the author of one of those reports, I must tell you that sea level could rise at that rate *without* significant melting of Greenland. Thus, although I feel that it is not possible at present to give a meaningful "high end" estimate of sea level rise by 2100, such an estimate would certainly be greater than 55".

Summary and recommendations

In closing, I see a number of likely and worrisome consequences of climate change for California's water resources. First, as noted above, temperature increases in California are virtually certain to accelerate, and consequences of this warming—particularly reductions in snow—will reduce our water supply in late Spring and Summer. I and others attach high confidence to this prediction because (1) warming alone is sufficient to cause the problem, and future warming is virtually certain, and (2) the climate trends that will cause these problems are already under way. At the same time, wintertime flood risk will likely increase; thus we face the prospect of both increased flood risk and increased water scarcity. As noted above, measures taken to minimize flood risk tend to further reduce the water supply, so these issues are intrinsically linked. These threats to our surface water supply suggest the need for increased use of groundwater, yet sea level rise and unsustainable use practices threaten to make that more difficult to do. On the demand side, urban water demand will certainly tend to increase with warming; population increases will compound this increase. Agricultural demand also will likely tend to increase, although this is less certain. As has been widely discussed, a number of factors, including sea level rise, threaten levees in the Sacramento/San Joaquin Delta that serve a number of important functions, including protecting much of our water supply from excessive salinity.

In my opinion, efforts to understand this complex situation, although admirable and certainly useful, have been inadequate. First, specific issues, for example flood risk, urgently need further investigation; below I list other such topics. More importantly, as the above discussion indicates, all the issues discussed here—flood risk, water supply, sea level rise, and ecosystem management—are inherently linked. Despite this, they have been studied largely in isolation (although there are notable exceptions to this). This is probably appropriate as an initial step, and certainly much useful knowledge has been gained this way.

Nonetheless, I feel that a concerted effort is needed that will *simultaneously* consider all the factors influencing California's water resources: climate change, demographic changes, and the needs to maintain healthy ecosystems and a strong economy. This effort should consider various scenarios for climate change, population growth, land use change, etc., and examine how under each scenario we can balance the needs for water supply, flood control, ecosystem health, and economic vitality using all the means at our disposal: new infrastructure, better operations practices, use of groundwater, conservation, etc. This sort of investigation will illustrate the choices we will face in balancing competing societal priorities as face the challenges of the future.

<u>Appendix: Research Recommendations</u>

At this point we can be confident that we understand the general outline of the effects of climate change on water resources, but many specifics need to be understood better.

• Increased flood risk is a potentially serious problem *per se*, and, as noted above, has implications for water supply reliability. Despite this, relatively little research has been done on this topic. Until we know how serious the flood risk problem is, we *cannot* know the severity of our future water supply problem. Thus, additional research on flood risk—and its implications for water supply—should be a high priority.

• Second, as noted above, future changes in precipitation are highly uncertain. Although it is unlikely that any increases in precipitation will be enough to offset increased water scarcity caused by warming, additional precipitation would certainly help. Thus, narrowing the uncertainty in future precipitation should be a high research priority.

• Droughts result from temporary reductions in precipitation. It is therefore just as important to understand how climate change will affect *variations* in precipitation as it is to understand how it will affect average precipitation. This should also be a high priority for research.

• More broadly, we need improved predictions of climate at the regional scale that is relevant to water resource and other societal impacts problems. Some progress could be made through systematic application of existing capabilities, but improved physical understanding and models are also needed.

• Third, it is important to understand the effects of climate change, including the CO_2-fertilization effect, on agricultural water demand.

• As noted above, future sea level rise is highly uncertain because of difficulty in predicting how rapidly land ice sheets, particularly in Greenland, will melt. This problem of course affects many nations, and could be addressed at a national or international level.

• We need improved monitoring of climate change, in California and elsewhere. This should include measurements of temperature, precipitation, snow cover, snow depth, river flow, soil moisture, and other quantities. To be useful, these measurements need to be made in many locations, and, most importantly, need to be sustained over decades. This monitoring is unglamorous and is unlikely to yield important results quickly, but it is essential to understanding climate change and how to cope with it.

• As noted above, climate change is only one of several factors that will stress our water system in coming decades. Others stressors are population growth, land use changes, increases in energy costs, etc. At the same time, improvements in technology will presumably make *more* water available, through conservation, improved purification methods, and so on. It is essential that we look at the combined effects of all of these factors on our water system. Initial efforts to do this have been very useful, and should be expanded. Because factors such as climate change involve significant uncertainty, we will have to consider many combinations of scenarios for climate change, population growth, new infrastructure, etc. Much of the value of this exercise, in my opinion, will be that it will illustrate the choices that our society will face as water scarcity increases.