CLIMATE CHANGE BUILDING BLOCKS
OCTOBER 2, 2006

1928	**1979**	**2003**
South Cascade Glacier, Washington	South Cascade Glacier, Washington	South Cascade Glacier, Washington

Presented by:

Climate Change Technical Subcommittee
Regional Water Supply Planning Process

Acknowledgements

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This document would not have been possible without the revisions and comments from member of the Climate Change Technical Subcommittee, which include the following individuals:

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Building Blocks for Climate Change
October 2, 2006

As evidenced by the large number of newspaper and magazine articles, peer-reviewed papers, and popular books, the subject of climate change is viewed as an extremely important topic. Because of the volume of information that has been generated, it is very useful to identify some of the more salient conclusions that have been drawn over the past two decades of research. Summaries of studies on the causes and impacts for climate change have appeared often in the peer-reviewed literature, the most significant being the three, multi-volume reports produced by the Intergovernmental Panel on Climate Change (IPCC), which was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environmental Programme (UNEP) to assess scientific, technical and socio-economic information relevant for the understanding of climate change, its potential impacts and options for adaptation and mitigation. These IPCC reports, known as Assessment Reports[1], have been published in 1990, 1995, and 2001 (with the next to be published in 2007) and contain the most extensively peer reviewed critiques available. Another resource outlining the potential regional effects of climate change in the Pacific Northwest is the Climate Impacts Group's (Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle) reports for the Puget Sound Action Team. Both the Overview Report and the Foundations Document outline many of the scenarios which could impact the Puget Sound region[2].

Climate Variability and Climate Change
For the purposes of this document, climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. The *United Nations Framework Convention on Climate Change* (UNFCCC), in its Article 1, defines "climate change" as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". The UNFCCC thus makes a distinction between "climate change" attributable to human activities altering the atmospheric composition, and "climate variability" attributable to natural causes.

The IPCC defines climate change somewhat differently from the UNFCCC in that non-anthropogenic change is included as part of IPCC's definition. The IPCC defines climate variability as variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability). The IPCC defines climate change as any change in climate over time, whether due to natural variability or as a result of human activity. Because the IPCC reports are used as a primary data source, the authors of this document use the IPCC definition of climate change as to avoid assignment of causality of this change. The primary purpose of this

[1] The IPCC Assessment Reports and other information are available online at http://www.ipcc.ch/
[2] For more information, see http://www.cses.washington.edu/cig/outreach/files/psat1005.shtml

document is to identify the changes that are occurring and as a preliminary step in estimating their potential impacts.

In the following pages, a number of the more important conclusions from the past IPCC reports, along with results from other studies are presented in an attempt to provide a series of "building blocks" to serve as a foundation on which to base what is known about climate change and its likely impacts. The building blocks presented here are associated both with the global trends and forecasts, along with information associated specifically with the Pacific Northwest.

The building blocks presented below are summarized in 13 areas, including the impacts of climate change on temperature, precipitation, snowpack and glaciers, streamflows, and sea level rise and on salmonid habitat and populations.

It is important to note that there is a solid scientific consensus that the earth has warmed during the 20^{th} century and it is forecasted to continue to do so throughout the 21^{st} century. A recent National Resource Council study (NRC 2006) confirms this warming and concludes that the global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries. The essential building blocks are summarized in Table 1 and listed in detail in the following pages.

Uncertainties remain in our understanding of future climate. The IPCC suggests that:

> "Uncertainties will remain inherent in predicting future climate change, even though some uncertainties are likely to be narrowed with time. Consequently, a range of climate scenarios should usually be considered in conducting impact assessment.
>
> There is a cascade of uncertainties in future climate predictions which includes unknown future emissions of greenhouse gases and aerosols, the conversion of emissions to atmospheric concentrations and to radiative forcing of the climate, modeling the response of the climate system to forcing, and methods for regionalizing GCM results." (IPCC Climate Change 2001: The Scientific Basis (2001), page 741)

Other uncertainties include impacts on hydrologic, ecosystem responses, and human systems.

This document uses the term "forecast climate" to mean a climate prediction that is the result of an attempt to produce a most likely description or estimate of the actual evolution of the climate in the future (e.g., at seasonal, interannual, or long-term time scales) (IPCC, 2001)

This document uses the term "projection" to mean a projection of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from *climate predictions(or forecasts)* in order to emphasize that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions, concerning, for example, future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty.

These definitions are meant to directly reflect those used by the IPCC.

Impacts of Climate Change on Temperature

Building Block 1 – The global average temperature has increased during the 20th century and is forecasted to increase in the 21st century.

Building Block 2 – Warming in the Puget Sound Region has increased at a faster rate during the 20th century than the global average and increases in temperature are forecasted to continue.

Building Block 3 – Increased surface temperatures in the Pacific Northwest will increase the rates of evaporation and transpiration (evapotranspiration).

Impacts of Climate Change on Precipitation

Building Block 4 – Global precipitation is projected to increase in the future, although there is less certainty in predicting changes in precipitation than in temperature.

Building Block 5 – The occurrence of heavy precipitation events has increased over the U.S. during the 20th century. This trend is projected to continue during the 21st century.

Impacts of Climate Change on Snowpack and Glaciers

Building Block 6 – The loss of snowpack and glaciers in the Pacific Northwest mountains has been due to increased temperatures in the 20th century.

Building Block 7 – Forecasted increases in temperatures associated with climate change will further reduce snowpack and glaciers in the Pacific Northwest mountains.

Impacts of Climate Change on Streamflows

Building Block 8 – Climate change is projected to increase winter flows and decrease summer flows in snowmelt influenced river systems of the Pacific Northwest, particularly transient watersheds.

Building Block 9 – Climate change is projected to increase the frequency of flood events in most western Washington river basins.

Building Block 10 – Climate change is projected to increase the frequency of drought events in the Pacific Northwest.

Impacts of Climate Change on Sea Level Rise

Building Block 11 – Climate change is forecasted to raise global mean sea level in the 21st century.

Impacts of Climate Change on Salmonid Habitat

Building Block 12 – Climate change is forecasted to increase temperatures of rivers, streams, lakes, and river mouth estuaries in the Puget Sound region.

Building Block 13 –Climate change, as described in Building Blocks 1-12, is forecasted to contribute toward stream flow and temperature conditions that have been shown to negatively impact freshwater and estuarine habitat of most species of salmonids in the Puget Sound watersheds.

Impacts of Climate Change on Temperature

Building Block 1 – The global average temperature has increased during the 20th century and is forecasted to increase in the 21st century.

a) "It can be said with a high level of confidence that global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries. This statement is justified by the consistency of the evidence from a wide variety of geographically diverse proxies."

National Academy of Sciences, "Surface Temperature Reconstructions for the Last 2,000 Years," Climate Research Committee, Committee on Surface Temperature Reconstructions for the Last 2,000 Years, Board of Atmospheric Sciences and Climate, Division on Earth and Life Studies, National Research Council, 2006, page 3.

b) "[T]he globally averaged surface temperatures have increased by 0.6 ± 0.2°C over the 20th century"

IPCC, 2001: "Summary for Policymakers". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken, and K. S. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 3]

c) "[T]he globally averaged surface air temperature is projected by models to warm by 1.4 to 5.8°C by 2100 relative to 1990"

IPCC, 2001: "Summary for Policymakers". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken, and K. S. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 3]

d) "Climate change simulations are assessed for the period 1990 to 2100 and are based on a range of scenarios for projected changes in greenhouse gas concentrations and sulfate aerosol loadings"

IPCC, 2001: "Projections of Future Climate Change". Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken, and K. S. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 527]

e) "[Climate] projections are made after considering a range of possible future human development scenarios and resultant greenhouse gas concentrations, and feeding those greenhouse gas concentrations into global climate models. Climate models apply the laws of physics to the atmosphere, ocean, and land surface. They have been demonstrated to simulate 20th century climate quite well, including the observed trends in temperature."

Snover, A. K., P. W. Mote, L. Whitely Binder, A.F. Hamlet, and N. J. Mantua. 2005. "Uncertain Future: Climate Change and its Effects on Puget Sound. A report for the Puget Sound Action Team by the Climate Impacts Group," (Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle). [Reference found on page 34]

NOTE: The projected temperature increases cited in bullet (b) result from a range of projected emission rates some of which include the estimated effects of all greenhouse gases, not CO_2 alone [data are available at https://esg.llnl.gov:8443/index.jsp].

Building Block 2 – Warming in the Puget Sound has increased at a faster rate during the 20th century than the global average and increases in temperatures are forecasted to continue.

a) "As for the whole Pacific Northwest, warming [in the Puget Sound-Georgia Basin region] has been greatest for JFM and least for OND. For all seasons, the greatest warming has occurred in the last 30 years. For the annual average, the 20th century warming was 1.5°C, substantially greater than the warming over the whole Northwest (0.8°C) and the whole globe (0.6°C)." The Pacific Northwest region is defined by Mote et al. 2003.

Mote, P.W., 2003. "Twentieth-century fluctuations and trends in temperature, precipitation, and mountain snowpack in the Puget Sound/Georgia Basin region." *Canadian Water Resources Journal,* 28, 567–586.

Supporting Citation:
Mote, P. W., E. A. Parson, A. F. Hamlet, K. N. Ideker, W. S. Keeton, D. P. Lettenmaier, N. J. Mantua, E. L. Miles, D. W. Peterson, D. L. Peterson, R. Slaughter, and A. K. Snover, 2003. "Preparing for climatic change: The water, salmon, and forests of the Pacific Northwest." *Climatic Change,* 61, 45-88.

b) "Climate models project a warming rate in the Pacific Northwest of roughly 0.2-1.0°F (0.1-0.6°C) per decade at least to 2050, with average warming of 1.8°F (1.0°C) by the 2020s and 3.0°F (1.7°C) by the 2040s (Figure 3), relative to 1970-1999 average temperature. Even the lowest estimated warming would change the Northwest's climate significantly more than the warming of the 20th century."

Snover, A. K., P. W. Mote, L. Whitely Binder, A. F. Hamlet, and N. J. Mantua. 2005. "Uncertain Future: Climate Change and its Effects on Puget Sound. A report for the Puget Sound Action Team by the Climate Impacts Group," (Center for Science in the

Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle). [References found on page 14]

c) "Global surface temperatures have increased between 0.4 and 0.8°C since the late 19th century, but most of this increase has occurred in two distinct periods, 1910 to 1945 and since 1976. The rate of temperature increase since 1976 has been over 0.15°C/decade. Our confidence in the rate of warming has increased since the SAR due to new analyses including: model simulations using observed SSTs with and without corrections for time-dependent biases, new studies of the effect of urbanization on global land temperature trends, new evidence for mass ablation of glaciers, continued reductions in snow-cover extent, and a significant reduction in Arctic sea-ice extent in spring and summer, and in thickness. However, there is some disagreement between warming rates in the various land and ocean-based data sets in the 1990s, though all agree on appreciable warming."

IPCC, 2001: "Observed Climate Variability and Change". Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J. T.,Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp. [Reference found on page 129]

Building Block 3 – Increased surface temperatures in the Pacific Northwest will increase the rates of evaporation and transpiration (evapotranspiration).

a) "Streamflow during seasonal low flow periods would decrease in many areas due to greater evaporation; changes in precipitation may exacerbate or offset the effects of increased evaporation."

IPCC, 2001: "Summary for Policymakers". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken, and K. S. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 9]

b) "Demand for water is generally increasing due to population growth and economic development, but is falling in some countries because of increased efficiency of use. Climate change is unlikely to have a big effect on municipal and industrial water demands in general, but may substantially affect irrigation withdrawals, which depend on how increases in evaporation are offset or exaggerated by changes in precipitation. Higher temperatures, hence higher crop evaporative demand, mean that the general tendency would be towards an increase in irrigation demands."

IPCC, 2001: "Summary for Policymakers". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken, and K. S. White (eds.)].

Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 9]

c) "Gregory et al. (1997), for example, show with the HadCM2 climate model that a rise in greenhouse gas (GHG) concentrations is associated with reduced soil moisture in Northern Hemisphere mid-latitude summers. This was the result of higher winter and spring evaporation, caused by higher temperatures and reduced snow cover, and lower rainfall inputs during summer."

IPCC, 2001: "Hydrology and Water Resources". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on pages 199]

Supporting Citation:
Gregory, J. M., J. F. B. Mitchell, and A. J. Brady, 1997. "Summer drought in northern midlatitudes in a time-dependent CO_2 climate experiment." *Journal of Climate*, 10, 662–686.*

d) "Increasing temperature generally results in an increase in potential evaporation, largely because the water-holding capacity of air is increased. Changes in other meteorological controls may exaggerate or offset the rise in temperature, and it is possible that increased water vapor content and lower net radiation could lead to lower evaporative demands."

IPCC, 2001: "Hydrology and Water Resources". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on pages 198]

e) "The effects on simulated [evapotranspiration] ET due to rising temperatures are somewhat counter intuitive. While higher temperatures tend to increase the potential ET, the availability of soil moisture at different times of the year and the resulting effects to vegetation may ultimately limit the actual ET. Therefore, depending on season, reductions in average ET, as compared to the base case, can occur despite higher temperatures."

Hamlet, A.F., and Lettenmaier, D.P., 1999. "Effects of Climate Change on Hydrology and Water Resources in the Columbia River Basin." *Journal of the American Water Resources Association,* 35(6) 1597-1623

f) Mostly driven by temperature changes, [potential evapotranspiration] PET changes were positive for every scenario at every site. The largest average annual increases for the transient scenarios were 27 and 24 percent for the Columbia (GFTR) and Missouri (HCTR) River basins, respectively, in Decade 5. The smallest Decade 5 increase was 6 percent, for Savannah (MPTR). The 2_CO2 scenarios had slightly higher PET than the highest Decade 5 scenario for every site. In general, changes in PET were consistent with temperature changes in direction, timing (i.e., relative interdecadal changes, such as the majority of the warming for HCTR occurring by Decade 2) and magnitude. Precipitation changes also appeared to moderate PET changes, however. Exceptions to the general relationship between temperature and PET also resulted from variations in the seasonal distribution of temperature changes among the climate change scenarios (increased temperatures in the summer months contribute disproportionately to annual changes in PET); hence comparison of annual temperature changes with annual PET could be misleading. For example, although the temperature changes for the MPTR scenarios in the Boston study were little over half those of the HCTR scenarios, the PET increases for the two sets of scenarios were very similar.

Lettenmaier, D.P., Wood, A.W, Palmer, R.N., Wood, E.F. and Stakhiv, E.Z. 1999. "Water resources implications of global warming: a U.S. regional perspective." *Climatic Change,* 43(3), 537-79.

Impacts of Climate Change on Precipitation

Building Block 4 – Global precipitation is projected to increase in the future, although there is less certainty in predicting changes in precipitation than in temperature.

a) "Based on global model simulations and for a wide range of scenarios, global average water vapour concentration and precipitation are projected to increase during the 21st century."

IPCC, 2001: "Summary for Policymakers". Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 882 pp. [Reference found on page 13.]

b) "Climate model predictions of precipitation remain highly uncertain. Many models suggest higher rainfall over North America accompanying warming in simulations of the IS92a emission scenario. While some models suggest widespread and substantial increases in rainfall over most of North America, other models suggest a weaker increase in rainfall."

IPCC, 2001: "North America". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 744]

Supporting Citation:
IPCC, 1995: Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J. T., L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 65–131.

c) "Current climate models simulate a climate change-induced increase in annual precipitation in high and mid-latitudes and most equatorial regions but a general decrease in the subtropics, although across large parts of the world the changes associated with global warming are small compared to those resulting from natural multi-decadal variability, even by the 2080s."

IPCC, 2001: "Hydrology and Water Resources". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on pages 197]

Supporting Citation:
Carter, T. R., M. Hulme, J. F. Crossley, S. Malyshev, M. G. New, M. E. Schlesinger, and H. Tuomenvirta, 2000. "Climate Change in the 21st Century - Interim Characterizations based on the New IPCC Emissions Scenarios." *The Finnish Environment,* 433, Finnish Environment Institute, Helsinki, 148 pp.

d) "Most models suggest modest (0-10 percent) increases in winter precipitation and in annual precipitation by mid-21st century; these changes are less certain than warming and will still largely fall within the range of variability observed in the 20th century."

Snover, A. K., P. W. Mote, L. Whitely Binder, A.F. Hamlet, and N. J. Mantua. 2005. "Uncertain Future: Climate Change and its Effects on Puget Sound. A report for the Puget Sound Action Team by the Climate Impacts Group," (Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle). [References found on page 14]

e) "This difference in the magnitude of trend (compared with variability) has two implications. First, human influence on precipitation will take longer to emerge from natural variability than human influence on temperature; future precipitation trends are inherently harder to predict because of this variability. Globally, human influence on precipitation has not yet been detected and probably will not be for at least a decade, whereas human influence on temperature was detected a decade ago."

P. W. Mote, Snover, A. K., L. Whitely Binder, A.F. Hamlet, and N. J. Mantua. 2005. "Uncertain Future: Climate Change and its Effects on Puget Sound-Foundation Document. A report for the Puget Sound Action Team by the Climate Impacts Group," (Center for Science in the Earth System, Joint Institute for the Study of the

Atmosphere and Oceans, University of Washington, Seattle). [Reference found on page 7]

Building Block 5 – The occurrence of heavy precipitation events has increased over the U.S. during the 20th century. This trend is projected to continue during the 21st century.

a) "There is evidence that the frequency of extreme rainfall has increased in the United States and in the United Kingdom; in both countries, a greater proportion of precipitation is falling in large events than in earlier decades."

IPCC, 2001: "Hydrology and Water Resources". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 197]

Supporting Citations:
Karl, T. R. and R. W. Knight, 1998. "Secular trends of precipitation amount, frequency, and intensity in the United States." *Bulletin of the American Meteorological Society,* 79(2), 231-241.

Osborn, T. J., M. Hulme, P. D. Jones, and T. A. Basnet, 2000. "Observed trends in the daily intensity of United Kingdom precipitation." *International Journal of Climatology*, 20, 347–364.

b) "[T]here are indications that the frequency of heavy rainfall events generally is likely to increase with global warming."

IPCC, 2001: "Hydrology and Water Resources". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 197]

Supporting Citations:
Hennessy, R. J., J. M. Gregory, and J. F. B. Mitchell, 1997. "Changes in daily precipitation under enhanced greenhouse conditions." *Climate Dynamics*, 13, 667–680.

McGuffie, K., A. Henderson-Sellers, N. Holbrook, Z. Kothavala, O. Balachova, and J. Hoekstra, 1999. "Assessing simulations of daily temperature and precipitation variability with global climate models for present and enhanced greenhouse climates." *International Journal of Climatology***,** 19, 1–26.

c) "Intensification of the rainfall amounts, as measured by 5 day precip, precip intensity, and precip >95th, produces positive changes over all the land masses. These changes are deemed significant by a majority of models across the mid- to high latitudes of the northern hemisphere and the tropical regions of South America and Africa. Reasons for this pattern are likely related to two factors: 1) proportionately more precipitation and precipitation intensity in areas of existing storm tracks and associated dynamical moisture convergence resulting simply from the greater moisture holding capacity of the warmer air, and 2) a slight poleward shift of the midlatitude storm tracks (e.g. Meehl et al., 2005a; Yin, 2005).

Tebaldi et al., 2005. "Going to the extremes." *Climatic Change*, forthcoming

Supporting Citations:
G.A. Meehl, J.M. Arblaster and C. Tebaldi, (2005). "Understanding future patterns of increased precipitation intensity in climate models." *Geophys. Res. Letters*, v.32.

Yin, J. 2005. "A consistent poleward shift of the storm tracks in simulations of 21st Century climate." *Geophys. Res. Lett.* 32, Art. No. L18701.

d) "Though almost all areas [globally] show increases in precip intensity (positive differences) for this multi-model mean [precip intensity differences between 2080-2099 minus 1980-1999], there is a distinct pattern to the changes. Increases of precipitation intensity are greatest in the tropics, as well as over northern Europe, northern Asia, the east coast of Asia, northwestern and northeastern North America, southwestern Australia, and parts of south-central South America."

Meehl, G., Arblaster, J., and Tebaldi, C., 2005. "Understanding future patterns of increased precipitation intensity in climate model simulations." *Geophysical Research Letters*, 32.

e) "In the midlatitudes there is a widespread increase in the frequency of very heavy precipitation during the past 50 to 100 yr."

Groisman et al., 2005. "Trends in Intense Precipitation in the Climate Record." *Journal of Climate*, 18, 1326-1350.

f) "Three model projections of a greenhouse-enriched atmosphere and the empirical evidence from the period of instrumental observations indicate an increasing probability of heavy precipitation events for many extratropical regions including the United States."

Groisman et al., 2005. "Trends in Intense Precipitation in the Climate Record." *Journal of Climate*, 18, 1326-1350.

g) "Climate change has the potential to create local and regional conditions that involve water deficits and surpluses, sometimes seasonally in the same geographic locations. The most widespread serious potential impacts are flooding, landslides, mudslides, and avalanches driven by projected increases in rainfall intensity and sea-level rise."

IPCC, 2001: "Technical Summary". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 38]

h) "Analysis of and confidence in extreme events simulated within climate models are still emerging, particularly for storm tracks and storm frequency. In general, the analysis of extreme events in both observations and global climate models is underdeveloped."

IPCC, 2001: "Technical Summary of the Working Group I report". Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 882 pp. [Reference found on page 54.]

Impacts of Climate Change on Snowpack and Glaciers

Building Block 6 – The loss of snowpack and glaciers in the Pacific Northwest mountains has been due to increased temperatures in the 20th century.

a) "The declines in Northwest spring snowpack presented here provide further evidence of regional increases in temperature and are qualitatively consistent with observed trends in temperature and precipitation at nearby stations. Both the dependence on elevation and the regression analysis confirm the role of temperature in reducing snowpack since the mid-20th century. Relative declines are most pronounced in the Cascades, where warming, moderate elevation, and declines in precipitation have all contributed to declines in SWE."

Mote, P. W. 2003. "Trends in snow water equivalent in the Pacific Northwest and their climatic causes." *Geophysical Research Letters,* 30(12), 1601, doi: 10.1029/2003GL017258

b) "The dates of peak snow accumulation and 90% (of peak) melt have generally been occurring earlier in the year, and these trends are clearly sensitive to winter temperature regimes, with the greatest changes apparent in areas with warmer winter temperatures (e.g., near-coastal mountains in the PNW and CA). These effects are consistent with the observed trends toward earlier peak snowmelt runoff. The sensitivity analysis shows that the changes in the timing of peak accumulation and 90% melt are primarily a temperature related effect. The date of 10% (of peak) accumulation has also trended earlier in the year but is shown to be related primarily to trends in fall precipitation rather than to trends in temperature."

Hamlet, A. F., P. W. Mote, M. Clark, and D. P. Lettenmaier. 2005. "Effects of temperature and precipitation variability on snowpack trends in the western U.S." *Journal of Climate,* 18(21), 4545–4561.

c) "In much of the West, hydrologic changes have been observed in the past 50 years that are consistent with atmospheric warming, especially in winter and spring snowmelt-dominated river basins. These changes include: reductions in spring snowpack, earlier spring snowmelt runoff, increases in winter flow, [and] decreases in summer flow. Most of these changes have been quantitatively linked to rising temperatures."

Mote, P. W., A. K. Snover, L. Whitely Binder, A. F. Hamlet, and N. J. Mantua, 2005. "Uncertain Future: Climate change and its effects on Puget Sound - Foundation Document." Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington. 37 pp. [Reference found on page 9]

d) "In the Puget Sound area, Mote (2003) examined 20th century fluctuations and trends in snow water equivalent (SWE) which has been monitored at several sites ("snow courses") since the 1940s. All 20 of the locations in Washington that represent Puget Sound drainages showed declines in April 1 SWE since 1950, most (especially those at lower elevations) in excess of 25%. The [magnitude of these] declines depended on elevation."

Mote, P. W., A. K. Snover, L. Whitely Binder, A. F. Hamlet, and N. J. Mantua, 2005. "Uncertain Future: Climate change and its effects on Puget Sound - Foundation Document." Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington. 37 pp. [Reference found on page 9]

Supporting Citations:
Mote, P. W. 2003. "Twentieth-century fluctuations and trends in temperature, precipitation, and mountain snowpack in the Puget Sound/Georgia Basin region." *Canadian Water Resources Journal,* 28, 567–586.

Melack, J. M., J. Dozier, C. R. Goldman, D. Greenland, A. M. Milner, and R. J. Naiman, 1997. "Effects of climate change on inland waters of the Pacific coastal mountains and western Great basin of North America." *Hydrological Processes*, 11, 971–992.

Cooley, K. R., 1990. "Effects of CO2-induced climatic changes on snowpack and streamflow." *Hydrological Sciences Journal*, 35(5), 511–522.

Duell, L. F. W. Jr., 1992. "Use of regression models to estimate effects of climate change on seasonal streamflow in the American and Carson River Basins, California-Nevada. In: Managing Water Resources during Global Change," American Water Resources Association 28th Annual Conference Proceedings, Reno, NV, USA, 1-5 November 1991 [Herrmann, R. (ed.)]. American Water Resources Association, Bethesda, MD, USA, pp. 731–740.

Fyfe, J. C. and G. M. Flato, 1999. "Enhanced climate change and its detection over the Rocky Mountains." *Journal of Climate*, 12(1), 230–243.

Rango, A., 1995. "Effects of climate change on water supplies in mountainous snowmelt regions." *World Resources Review*, 7(3), 315–325.

Rango, A. and V. Van Katwijk, 1990. "Water supply implications of climate change in western North American basins." In: *International and Transboundary Water Resources Issues*, American Water Resources Association 27th Annual Conference Proceedings, Toronto, ON, 1-4 April 1990 [Fitzgibbon, J.E. (ed.)]. American Water Resources Association, Bethesda, MD, USA, pp. 577–586.

Wilby, R. L., L. E. Hay, and G. H. Leavesley, 1999. "A comparison of downscaled and raw GCM output: implications for climate change scenarios in the San Juan River basin, Colorado." *Journal of Hydrology*, 225(1–2), 67–91.

Lettenmaier, D. P. and T. Y. Gan, 1990. "Hydrologic sensitivities of the Sacramento-San Joaquin River Basin, California, to global warming." *Water Resources Research*, 26(1), 69–86.

Lettenmaier, D. P., K. L. Brettmann, L. W. Vail, S. B. Yabusaki, and M. J. Scott, 1992. "Sensitivity of Pacific Northwest water resources to global warming." *The Northwest Environmental Journal*, 8, 265–283.

Lettenmaier, D. P., D. Ford, S. M. Fisher, J. P. Hughes, and B. Nijssen, 1996. *Water Management Implications of Global Warming, 4: The Columbia River Basin.* Report to Interstate Commission on the Potomac River Basin and Institute for Water Resources, U.S. Army Corps of Engineers, University of Washington, Seattle, WA, USA.

Building Block 7 – Forecasted increases in temperatures associated with climate change will further reduce snowpack and glaciers in the Pacific Northwest mountains.

a) "Even a conservative estimate (0.3°C/decade) of the likely warming rate for western mountains in winter would, by 2100, move the 0º isotherm [to] where the 3ºC isotherm now lies: most of the westernmost mountains would be in the transient snow zone, in which snow accumulates and melts repeatedly during the snow season."

   Mote, P. W. (In press). "Climate-driven variability and trends in mountain snowpack in western North America." To appear in *Journal of Climate*.

b) "The results from the mass balance modeling based on the climate model scenarios are unambiguous: due to a strong temperature increase in each of these regions, the mass balances of all of the considered glaciers will become strongly negative and all glaciers will start to retreat considerably in the near future. Glaciers in more maritime climatic conditions generally will experience a more pronounced change (e.g. South Cascade Glacier, Engabreen) than glaciers in continental conditions (e.g. Glacier No. 1, Gulkana Glacier, Storglacia¨ren). This signal is not clearly visible and it may be hidden in other signals of processes which determine the sensitivity of glaciers. Of course, if the elevation range of the mean equilibrium line comes close to the elevation range of the surrounding topography, a large portion of the ice surface becomes ablation zone and the glacier will disappear.

Dyurgerov, M. 2003. "Mountain and subpolar glaciers show an increase in sensitivity to climate warming and intensification of the water cycle." *Journal of Hydrology* 282:164-176.

c) "Northern Hemisphere snow cover and sea-ice extent are projected to decrease further."

IPCC, 2001: "Summary for Policymakers". Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 882 pp. [Reference found on page 16]

d) "Glaciers and ice caps are projected to continue their widespread retreat during the 21st century."

IPCC, 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 882 pp. [Reference found on pages 16]

Impacts of Climate Change on Streamflows

Building Block 8 – Climate change is projected to increase winter flows and decrease summer flows in snowmelt influenced river systems of the Pacific Northwest, particularly transient watersheds.

a) "Many studies of snowmelt-dominated systems show similar seasonal shifts to greater winter runoff and reduced summer flow"

IPCC, 2001: "North America". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 745]

b) "Available evidence suggests that global warming may lead to substantial changes in mean annual streamflows, seasonal distributions of flows, and the probabilities of extreme high or low-flow conditions."

IPCC, 2001: "North America". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N.

Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 745]
Lettenmaier, D. P. and T. Y. Gan, 1990. "Hydrologic sensitivities of the Sacramento-San Joaquin River Basin, California, to global warming." *Water Resources Research*, 26(1), 69–86.

Supporting Citations:
Loukas, A. and M. C. Quick, 1996. "Effect of climate change on hydrologic regime of two climatically different watersheds." *Journal of Hydrologic Engineering*, 1(2), 77–87.

Hughes , J. P., D. P. Lettenmaier, and E. F. Wood, 1993. "An approach for assessing the sensitivity of floods to regional climate change." In: The World at Risk: Natural Hazards and Climate Change, American Institute of Physics Conference Proceedings 277, Cambridge, MA, USA, 14-16 January 1992 [Bras, R. (ed.)]. American Institute of Physics, New York, NY, USA, pp. 112–124.

c) "A major proportion of annual streamflow is formed by snow melting in spring. These areas include large parts of North America, Northern and Eastern Europe, most of Russia, Northern China, and much of Central Asia. The most important climate change effect in these regions is a change in the timing of streamflow through the year. A smaller proportion of precipitation during winter falls as snow, so there is proportionately more runoff in winter and, as there is less snow to melt, less runoff during spring. Increased temperatures, in effect, reduce the size of the natural reservoir storing water during winter."

IPCC, 2001: "Hydrology and Water Resources". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 203]

d) "The patterns of change [in total annual runoff] are broadly similar to the change in annual precipitation—increases in high latitudes and many equatorial regions but decreases in mid-latitudes and some subtropical regions – but the general increase in evaporation means that some areas that see an increase in evaporation means that some areas that see an increase in precipitation will experience a reduction in runoff."

IPCC, 2001: "Hydrology and Water Resources". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 203]

Supporting Citations:
Alcamo, J., P. Döll, F. Kaspar, and S. Siebert, 1997. "Global Change and Global Scenarios of Water Use and Availability: An Application of Water GAP 1.0." University of Kassel, Kassel, Germany, 47 pp. (plus appendices).

e) "What emerges is a picture of coherent year-to-year fluctuations in the timing of spring throughout the region, reflected in both vegetation and hydrology, and clearly associated with regional temperature anomalies. Furthermore, there is evidence for a substantial trend toward earlier springs during the operation of the two networks, amounting to onsets of spring one to two weeks earlier in recent decades than in previous decades."

Cayan, D. R., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson, 2001. "Changes in the onset of spring in the western United States." *Bulletin of the American Meteorological Society,* 82, 399-415.

f) "Analyses of streamflow, snow mass, temperature, and precipitation in snowmelt-dominated river basins in the western United States indicate an advance in the timing of peak spring season flows over the past 50 years."

Regonda, S. K., B. Rajagopalan, M. Clark, and J. Pitlick, 2005. "Seasonal cycle shifts in hydroclimatology over the western United States." *Journal of Climate,* 18, 372-384.

g) "Streamflow timing has shifted toward occurring earlier in the water year at most snowmelt dominated gauges across an area much larger than previously recognized, while mean annual flows have remained constant or marginally increased. Evidence for the shift includes earlier snowmelt onsets and advances in the center of mass of the annual hydrograph, which is called center timing (CT). Consistent with these advances are decreased spring and early summer (AMJJ) fractional flows and increasing fractions of annual flow occurring earlier in the water year."

Stewart, I. T., D. R. Cayan, and M. D. Dettinger. 2005. "Changes toward earlier streamflow timing across western North America." *Journal of Climate,* 18, 1136-1155.

Building Block 9 – Climate change is projected to increase the frequency of flood events in most western Washington river basins.

a) "Higher winter temperatures are likely to increase the chance of flooding in Puget Sound as more winter precipitation falls as rain rather than snow in moderate elevation mountain areas, such as the Cascades. If winter precipitation increases, as some models suggest, the risk of flooding would be compounded. Flooding increases in free-flowing rivers are a concern because management of high flows is not an option. In managed systems high stream flows can be controlled to a certain extent. Most urban areas located on river mouths are partially protected by upstream flood-control reservoirs or were developed sufficiently far above the waterline to protect against flooding. Agricultural districts in river deltas (such as the Skagit) are partly protected by dikes. However, increases in natural flows could still cause increased flooding in managed systems when these protective measures are overwhelmed."

Snover, A. K., P. W. Mote, L. Whitely Binder, A.F. Hamlet, and N. J. Mantua. 2005. "Uncertain Future: Climate Change and its Effects on Puget Sound. A report for the Puget Sound Action Team by the Climate Impacts Group," (Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle). [Reference found on page 18]

Supporting Citations:
Mote, P. W., M. Holmberg, N. J. Mantua, and Climate Impacts Group. 1999. "Impacts of Climate Variability and Change, Pacific Northwest." National Atmospheric and Oceanic Administration, Office of Global Programs, and JISAO/SMA Climate Impacts Group, Seattle, Washington. 110 pp.

b) "[changing flood risk can be] categorized by mid-winter temperature regimes. Relatively cold basins where snow processes dominate the annual hydrologic cycle (< -6° C in mid winter) typically show reductions in flood risks due to overall reductions in spring snowpack during the 20th century. Relatively warm rain dominant basins (> 5° C in mid winter) show little systematic change. Intermediate or transient basins show a very wide range of effects depending on competing factors associated with the relative role of antecedent snow and contributing basin area during storms that cause flooding in the simulations."

Hamlet and Lettenmaier 2006. "Effects of 20th century warming and climate variability on flood risk in the western United States." *Journal of Climate*, submitted.

c) "The climate change signals in daily precipitation and runoff characteristics suggest that the climate change induced by increased atmospheric CO2 is likely to increase extreme hydrologic events in the Western United States, especially in the mountainous regions along the Pacific Ocean. The projected signals in precipitation characteristics suggest that both the number of wet days and the mean intensity of each event will increase, causing precipitation-intensity frequency distributions to shift toward higher values."

Kim, J., 2005. "A projection of the effects of the climate change induced by increased CO2 on extreme hydrologic events in the western U.S." *Climatic Change*, 68, 153-168

d) "There is some evidence that the intensity of rainfall events may increase under global warming, as a result of increases in the precipitable water content of the atmosphere. This may increase flooding risks in some watersheds."

IPCC, 2001: "North America". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 745]

Supporting Citations:
Trenberth, K. E. and D. J. Shea, 1997. "Atmospheric circulation changes and links to changes in rainfall and drought." In: Conference Preprints, AMS Thirteenth Conference on Hydrology, 2–7 February, 1997, Long Beach, CA. American Meteorological Society, Boston, MA, USA, pp. J14–J17

e) "Possible changes in runoff patterns, coupled with apparent recent trends in societal vulnerability to floods in parts of North America, suggest that flood risks may increase as a result of anthropogenic climate change (see Section 15.2.5). Changes in snowpack accumulation and the timing of melt-off are likely to affect the seasonal distribution and characteristics of flood events in some areas. For example, in mountainous western watersheds, winter and early spring flood events may become more frequent."

IPCC, 2001: "North America". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 750]

Supporting Citations:
Melack, J. M., J. Dozier, C. R. Goldman, D. Greenland, A. M. Milner, and R. J. Naiman, 1997. "Effects of climate change on inland waters of the Pacific coastal mountains and western Great basin of North America." *Hydrological Processes*, 11, 971–992.

Lettenmaier, D. P., A. W. Wood, R. N. Palmer, E. F. Wood, and E. Z. Stakhiv, 1999. "Water resources implications of global warming: a U.S. regional perspective." *Climatic Change*, 43(3), 537–579.

f) "Available evidence suggests that global warming may lead to substantial changes in mean annual streamflows, seasonal distributions of flows, and the probabilities of extreme high- or low-flow conditions. Runoff characteristics may change appreciably over the next several decades, but in the near term, the hydrological effects of global warming are likely to be masked by ongoing year-to-year climatic variability."

IPCC, 2001: "North America". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 745]

Supporting Citations:
Cubasch, U., G. Waszkewitz, G. Hegerl, and J. Perlwitz, 1995. "Regional climate changes as simulated in time-slice experiments." *Climatic Change*, 31(2–4), 273–304.

Leavesley, G. H., 1994. "Modeling the effects of climate change on water resources: a review." *Climatic Change*, 28, 159–177.

Matalas, N. C., 1998. "Note on the assumption of hydrologic stationarity." *Water Resources Update*, 112, 64–72.

Mearns, L. O., F. Giorgi, L. McDaniel, and C. Shields, 1995. "Analysis of daily variability of precipitation in a nested regional climate model: comparison with observations and doubled CO_2 results." *Global and Planetary Change*, 10, 55–78.

Miller, K. A., 1997. "Climate Variability, Climate Change and Western Water." Western Water Policy Review Advisory Commission, National Technical Information Service, Springfield, VA, USA, 54 pp.

Rogers, P., 1994. "Assessing the socioeconomic consequences of climate change on water resources." *Climatic Change*, 28, 179–208.

Trenberth, K. E. and D. J. Shea, 1997. "Atmospheric circulation changes and links to changes in rainfall and drought." In: Conference Preprints, AMS Thirteenth Conference on Hydrology, 2–7 February, 1997, Long Beach, CA. American Meteorological Society, Boston, MA, USA, pp. J14–J17

Building Block 10 – Climate change is projected to increase the frequency of drought events in the Pacific Northwest.

a) "From the perspective of water resource operations, the projected hydrologic changes would have the greatest effect from spring to autumn, when the reservoir system refills and is intended to maintain storage until the winter reservoir drawdown for flood control and hydropower production. Increasing winter inflows associated with seasonality shifts would necessitate the continuation of present flood control policies despite the decreased ability of the system to replenish current evacuations in the spring. Lower summer streamflows would exacerbate the reduced reservoir refill by increasing drafts for instream flow targets. The lower resulting storage at the end of summer would reduce the ability of the system to meet present firm power production (hydropower "safe yield") targets during the winter, before reservoir storage begins to be restored by winter precipitation. Hydropower revenues were predicted to be relatively unaffected, however, because annual streamflow volume changes were generally small, and fall and early winter generation reductions would be compensated by increases in late winter and spring.

   The starkest result of this study is an evolving tradeoff between reservoir releases to maintain instream flows for fish, and hydropower production. In order to maintain performance of the reservoir system with respect to instream flow targets developed under the NMFS Biological Opinion associated with ESA listing of Columbia River salmonids, substantial (10-20 percent, depending on the future time period) reductions in firm hydropower would be required. Even with these reductions in firm power, late summer minimum flows would still be lower than at present."

Payne, J.T., Wood, A.W., Hamlet, A.F., Palmer, R.N. and Lettenmaier, D.P. (2004). "Mitigating the effects of climate change on the water resources of the Columbia River basin." Climatic Change, 62(1-3), 233-256.

b) "In the PNW river basins we have examined, the largest impacts stem not from the changes in total annual flow (which, for the 2020s, range from –6% to +22%) but from changes in flow during certain seasons. Unregulated smaller, rainfed and mixed rain/snow streams west of the Cascades are already susceptible to winter flooding, especially in the wetter winters of La Niña years (Mote et al., 1999, Table 4). Projected warmer, wetter winters suggest further increases in the risk of winter flooding in these basins, and continuing growth in population and infrastructure near rivers may also increase the property vulnerable to such flooding. Detailed assessments of this risk, and its potential consequences for property damage and human health, have not yet been conducted but should be a high priority. As mentioned earlier, large reductions in summer flow are likely in smaller river basins with a relatively large portion of their catchments near the current mid winter snow line, even if their total annual flow increases. Water supply systems with higher storage to flow ratios may be relatively robust to such changes in streamflow (since winter runoff can be captured), whereas systems with limited storage are potentially more vulnerable.

In large, snowmelt-dominated systems like the Columbia, simulations suggest that there is little increased risk of flooding because spring peak flows are not expected to increase much (Figure 8) and because the management system is adequate to respond to floods. The Columbia's water resources are believed to be much more strongly influenced by changes in low flows both because of limited reservoir storage and institutional considerations (Callahan et al., 1999; Miles et al., 2000). Reduced summer flows are likely to reduce both summer hydropower resources and irrigation water supplies by mid-century, exacerbating already-sharp allocation conflicts between consumptive use for irrigation, increasing priority for maintaining instream flow for fish habitat, and (west of the Cascades) population growth with its increased demand for energy and water for municipal and industrial use.

Increasing supply-side stresses on the water resources systems on the west side of the Cascades are likely to coincide with increased water demand stemming from population growth but also induced by climatic change itself; lawns and irrigated crops use more water in a warmer summer. For example, an analysis of the impacts of climate change on Portland's municipal water supply for the 2040s (Palmer and Hahn, 2002) projected that a warming of about 2.0 C would decrease annual minimum storage (a measure of water supply system performance) by about 1.3 billion gallons, and would increase demand by 1.5 billion gallons. Population growth is currently estimated to increase demand in the 2040s by 5.5 billion gallons (ibid.), only moderately larger than the combination of changes in supply and demand resulting from climatic change."

Mote, P.W., E.A. Parson, A.F. Hamlet, W.S. Keeton, D.P.,Lettenmaier, N.J. Mantua, E.L. Miles, D.W. Peterson, D.L. Peterson, R., Slaughter, and A.K. Snover, 2003, "Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest." *Climatic Change* 61: pp 45-88.

Supporting Citations:
Mote, P. W. and 18 co-authors: 1999. "Impacts of Climate Variability and Change: Pacific Northwest, A report of the Pacific Northwest Regional Assessment Group for the U.S. Global Change Research Program." JISAO/SMA Climate Impacts Group, University of Washington, Seattle.

Callahan, B., Miles, E., and Fluharty, D. 1999. "Policy Implications of Climate Forecasts for Water Resources Management in the Pacific Northwest", *Policy Sciences* 32, 269.

Miles, E. L., Snover, A. K., Hamlet, A. F., Callahan, B., and Fluharty, D. 2000. "Pacific Northwest Regional Assessment: The Impacts of Climate Variability and Climate Change on the Water Resources of the Columbia River Basin." *J. Amer. Water Res. Assoc*. 36, 399.

Palmer, R. N. and Hahn, M. 2002. "The Impacts of Climate Change on Portland's Water Supply: An Investigation of Potential Hydrologic and Management Impacts on the Bull Run System, A Report for the Portland Water Bureau", Dept of Civil and Environmental Engineering, University of Washington.

Hamlet, A.F., Lettenmaier, D.P., 2000. "Long-range climate forecasting and its use for water management in the Pacific Northwest region of North America." *J. Hydroinformatics*, Volume 02.3, pp 163-182.

c) "The frequency of summer drought will increase in many interior continental locations, and it is likely that droughts as well as floods, associated with El Niño events will intensify."

IPCC, 2001: "Developing and Applying Scenarios". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 148]

d) "There is a general drying of the mid-continental areas during summer in terms of decreases in soil moisture, and this is ascribed to a combination of increased temperature and potential evaporation not being balanced by precipitation."

IPCC, 2001: "Projections of Future Climate Change". Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 576]

e) "A change in mean flow or in variability could cause the physical infrastructure to be inadequate for the intended purposes or increase the risk of failure of the water resource system under extremes of drought or flood. In large water systems, such risks are buffered by robustness and resilience in the design of the system; smaller systems may be more vulnerable under climate scenarios beyond those considered in their design."

   IPCC, 2001: "North America". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on pages 742-743]

f) "Quantitative definitions of drought rarely remain stationary for long periods of time due to their dependence on changing water management practices and physical characteristics. However, as a benchmark, the low streamflow in water year 1992 may be taken as a current drought threshold in the Columbia basin. This adverse period produced a net loss of approximately $237 million for Bonneville Power Administration and created serious water shortages in several other water resources systems in the PNW including Yakima River basin. Taking this adverse streamflow sequence on the Columbia as a current drought threshold, then, allows a quantitative comparison of drought frequency for the base case and future scenarios."

   "For the [Max Planck Institue] MPI simulations, the frequency of droughts of this severity more than quadruples by 2045, while for the [Hadley Centre] HC simulation, it nearly doubles by 2045."

   Hamlet, A.F., and Lettenmaier, D.P., 1999. "Effects of Climate Change on Hydrology and Water Resources in the Columbia River Basin." *Journal of the American Water Resources Association,* 35(6), 1597-1623.

g) "Future changes of worst 3-day heat waves defined in this way in the model are not uniformly distributed in space but instead show a distinct geographical pattern. Though differences are positive in all areas, indicative of the general increase of nighttime minima, heat wave severity increases more in the western and southern United States and in the Mediterranean region, with heat wave severity showing positive anomalies greater than 3°C in those regions. Thus, many of the areas most susceptible to heat waves in the present climate (greatest heat wave severity) experience the greatest increase in heat wave severity in the future. But other areas not currently as susceptible, such as northwest North America, France, Germany, and the Balkans, also experience increased heat wave severity in the 21st century in the model."

   Meehl, G., and Tebaldi, C., 2004. "More Intense, More Frequent, and Longer Lasting Heat Waves in the 21st Century." *Nature*, 305, 994-997.

Impacts on Sea Level Rise

Building Block 11 – Climate change is forecasted to raise global mean sea level in the 21st century.

a) "The potential impacts of sea-level rise on coastal systems have been emphasized in recent years. Much less attention has been given to the effects of increases in air and sea-surface temperatures; and changes in wave climate, storminess, and tidal regimes. There are at least two reasons for this lack of attention. First, low-lying coastal areas such as deltas, coastal plains, and atoll islands are regarded as particularly vulnerable to small shifts in sea level. Second, global sea-level rise is regarded as one of the more certain outcomes of global warming and already is taking place. Over the past 100 years, global sea level has risen by an average of 1-2 mm yr^{-1}, and scientists anticipate that this rate will accelerate during the next few decades and into the 22nd century."

IPCC, 2001: "Coastal Zones and Marine Ecosystems". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 348]

b) "Global mean sea-level has risen by about 0.1-0.2 mm yr^{-1} over the past 3,000 years and by 1-2 mm yr^{-1} since 1900, with a central value of 1.5 mm yr^{-1}. [The Third Assessment Report] TAR [Working Group I] WGI Chapter 11 projects that for the full range of the six illustrative scenarios in the IPCC's Special Report on Emissions Scenarios, sea level will rise by 0.09-0.88 m between 1990 and 2100. This range is similar to the total range of projections given in the SAR of 0.13-0.94 m. Higher mean sea level will increase the frequency of existing extreme levels associated with storm waves and surges."

IPCC, 2001: "Coastal Zones and Marine Ecosystems". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 348]

c) "A number of these are particularly relevant for water utilities located in coastal areas, including: 1) lowland inundation and wetland displacement; 2) altered tidal range in rivers and bays; 3) changes in sedimentation patterns; 4) severe storm-surge flooding; 5) saltwater intrusion into estuaries and freshwater aquifers[.]"

Miller, K., D. Yates, C. Roesch and D. J. Stewart, 2005. "Climate Change and Water Resources: A Primer for Municipal Water Providers." National Center for Atmospheric Research, Boulder, CO, 83 pp. [Reference found on page 45]

d) "Specific changes predicted to occur in North American wetlands are wide ranging. Sea-level rise will result in loss of coastal wetlands in many areas, with potentially important effects on ocean fisheries."

IPCC, 2001: "North America". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 753]

Supporting Citations:
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Turner, R.E., 1997. "Wetland loss in the northern Gulf of Mexico: multiple working hypotheses." *Estuaries*, 20, 1–13.

e) "Climate change can have significant impacts on wetland structure and function, primarily through alterations in hydrology, especially water-table level. Wetland flora and fauna respond very dynamically to small changes in water-table levels."

IPCC, 2001: "North America". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 753]

Supporting Citations:
Clair, T. A. and J. M. Ehrman, 1998. "Using neural networks to assess the influence of changing seasonal climates in modifying discharge, dissolved organic carbon, and nitrogen export in eastern Canadian rivers." *Water Resources Research*, 34(3), 447–455.

Clair, T. A., J. Ehrman, and K. Higuchi, 1998. "Changes to the runoff of Canadian ecozones under a doubled CO_2 atmosphere." *Canadian Journal of Fisheries and Aquatic Science*, 55, 2464–2477.

Poiani, K. A., W. C. Johnson, and T. G. Kittle, 1995. "Sensitivity of a prairie wetland to increased temperature and seasonal precipitation changes." *Water Resources Bulletin*, 31(2), 283–294.

Impacts on Salmonid Habitat

Building Block 12 – Climate change is forecasted to increase temperatures of rivers, streams, lakes, and river mouth estuaries in the Puget Sound region.

a) "River water temperature depends not only on atmospheric temperature but also on wind and solar radiation (Orlob et al., 1996). River water temperature will increase by a slightly lesser amount than air temperature (Pilgrim et al., 1998), with the smallest increases in catchments with large contributions from groundwater. Biological and chemical processes in river water are dependent on water temperature: Higher temperatures alone would lead to increases in concentrations of some chemical species but decreases in others. Dissolved oxygen concentrations are lower in warmer water, and higher temperatures also would encourage the growth of algal blooms, which consume oxygen on decomposition."

IPCC, 2001: "Hydrology and Water Resources". Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. [Reference found on page 207]

Supporting Citations:
Orlob, G.T., G.K. Meyer, L. Somlyody, D. Jurak, and K. Szesztay, 1996. "Impact of climate change on water quality." In: Water Resources Management in the Face of Climatic/Hydrologic Uncertainties [Kaczmarek, Z., K. Strzepek, and L. Somlyody (eds.)]. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 70–105.*

Pilgrim, J.M., X. Fang, and H.G. Stefan, 1998. "Stream temperature correlations with air temperatures in Minnesota: implications for climate warming." *Journal of the American Water Resources Association*, 34, 1109–1121.*

b) "Many factors contribute to increased water temperature in freshwater and marine systems. Climate plays a role in determining water temperature via its influence on air temperature, the temperature of stream and river inflows, and the degree of stratification in marine systems. Information on trends in water temperature for freshwater and marine systems in the Puget Sound basin is limited, but there is evidence of warming during the 20th century. Looking toward the future, global warming is almost certain to lead to additional [warming] of the surface waters of Puget Sound and its tributary rivers as a result of the projected increases in regional temperatures and decreases in summer stream flow."

Snover, A. K., P. W. Mote, L. Whitely Binder, A.F. Hamlet, and N. J. Mantua. 2005. "Uncertain Future: Climate Change and its Effects on Puget Sound. A report for the Puget Sound Action Team by the Climate Impacts Group," (Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle). [Reference found on page 22, 23]

c) "To model the nonseasonal variations in stream water temperatures, also called residuals (i.e., the difference between actual measured temperature and the annual component represented by the Fourier series), Kothandaraman found a significant relationship between air and water temperature residuals. In a regression analysis, it was determined that air temperature residuals (difference between measured air temperature and air temperature calculated by a Fourier series) of the day and the preceding 2 days explained the water temperature residuals of the present day well. Similarily, Kothandaraman (1972) found good relationships between air and water temperature residuals."

Caissie, D., M.El-Jabi, and A. St.-Hilair; 1998. "Stochastic modeling of water temperature in a small stream using air to water relations." *Canadian Journal of Civil Engineering*; 25:250-260.

d) "The results in these two tables indicate that an increase of water temperature is inevitable if the 2 X CO_2 climate scenario materializes, even if streamflow rates and shading remain unchanged."

"Changes in stream water temperature due to climate change were calculated with simultaneous changes in air temperature, solar radiation, relative humidity and wind speed as input. The relative contributions of each of these weather parameters were not studied separately. A sensitivity analysis of the model (Sinokrot and Stefan, 1992) indicated, however, that the model is most sensitive to air temperature and solar radiation. The outputs from the general circulation models show that the major change in weather is in the air temperature. Therefore, one can conclude that the change in water temperature is primarily due to the change in air temperature and, to a minor degree, to the change in solar radiation."

Sinokrot, B.A. and Stefan, H.G. 1993. "Projected Global Climate Change Impact on Water Temperatures in Five North Central U.S. Streams." *Climatic Change* 24: 353-381, 1993.

Supporting Citations:
Sinokrot, B.A. and Stefan, H.G. 1992. *Deterministic Modeling of Stream Water Temperatures: Development and Applications to Climate Change Effects on Fish Habitat,* University of Minnesota, St. Anthony Falls Hydraulic Laboratory Report No. 337, Minneapolis, MN.

e) "In studies of the impact of potential climate changes on stream ecosystems, especially fishes, stream temperature plays a crucial role. As there is a strong correlation between stream temperatures and air temperatures above 0°C, researchers have often used linear regression models to determine stream temperatures (Johnson, 1971; Crisp and Howson, 1982; Webb, 1987; Stefan and Preud'homme, 1993; Pilgrim et al., 1998; Erickson and Stefan, 1996)."

Mohseni O. and Stefan, H. G., 1999. "Stream Temperature/Air Temperature Relationship: A Physical Interpretation." *Journal of Hydrology*; 218(3-4):128-141.

Supporting Citations:
Johnson, F.A. 1971. "Stream temperatures in an Alpine area." *Journal of Hydrology;* 14:322-336

Crisp, D.T., Howson, G., 1982. "Effect of air temperature upon mean water temperature in streams in the north Pennines and English Lake District." *Freshwater Biology,* 12: 359-367

Pilgram, J.M., Fang, X., Stefan, H.G., 1998. "Stream temperature correlations with air temperatures in Minnesota: implications for climate warming." *JAWRA* 34(5) 1109-1121

Erickson, T.R., Stefan, H.G., 1996. "Correlation of Oklahoma stream temperatures with air temperatures." University of Minnesota, St. Anthony Falls Laboratory, Project Report No. 398, Minneapolis, MN.

Stefan, H.G., Preud'homme, E.B., 1993. "Stream temperature estimation from air temperature." *Water Resources Research* 29(1), 27-45

Webb, B.W., 1987. "The relationship between air and water temperatures for a Devon River." Rep. Trans. Devon Ass. Advnt. Sci. 119, 197-222

Building Block 13 – Climate change, as described in Building Blocks 1-12, is forecasted to contribute toward stream flow and temperature conditions that have been shown to negatively impact freshwater and estuarine habitat of most species of salmonids in the Puget Sound watersheds.

a) "Fish and other animals will be affected by climate change in many ways - directly via changes in habitat and indirectly via changes in the availability of food."

Snover, A. K., P. W. Mote, L. Whitely Binder, A. F. Hamlet, and N. J. Mantua. 2005. "Uncertain Future: Climate Change and its Effects on Puget Sound. A report for the Puget Sound Action Team by the Climate Impacts Group," (Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle). [Reference found on pages 30]

Supporting Citations:
Pulwarty, R. S. and K. T. Redmond, 1997. "Climate and Salmon Restoration in the Columbia River Basin: The Role and Usability of Seasonal Forecasts." *Bulletin of the American Meteorological Society,* 78(3), 381-397

Winder, M. and Schindler, D. E, 2004. "Climate Change Uncouples Trophic Interactions In An Aquatic Ecosystem. Ecology." 85(8), 2004, pp. 2100–2106

b) "Lower summer flows and warming waters may negatively affect salmon that depend on rivers during the summer months."

Snover, A. K., P. W. Mote, L. Whitely Binder, A.F. Hamlet, and N. J. Mantua. 2005. "Uncertain Future: Climate Change and its Effects on Puget Sound. A report for the Puget Sound Action Team by the Climate Impacts Group," (Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle). [Reference found on page 7]

Supporting Citations:
Boesch, D. F., J. C. Field, and D. Scavia (eds.). 2000. "The Potential Consequences of Climate Variability and Change on Coastal Areas and Marine Resources: Report of the Coastal Areas and Marine Resources Sector Team," U.S. National Assessment of the Potential Consequences of Climate Variability and Change, U.S. Global Change Research Program. NOAA Coastal Ocean Program Decision Analysis Series No. 21. NOAA Coastal Ocean Program, Silver Spring, Maryland. 163 pp.

Crozier, L. G. and R.W. Zabel. 2006. "Climate Impacts at multiple scales: evidence for differential population responses in juvenile Chinook." *Journal of Animal Ecology.* Vol 75, 5 pg 1100-1109

Groot, C., Margolis, L., and W.C. Clarke. 1995. "Stress and Tolerance," Chapter 8 *in Physiological Ecology of Pacific Salmon*. UBC Press, Vancouver.

McElhaney, P. et al. 2000. Viable Salmonid Populations and the Recovery of Evolutionarily Significant Units. NOAA Fisheries, NWFSC, Seattle.

S. P. Cox and S. G. Hinch, 1997. "Changes in size at maturity of Fraser River sockeye salmon (Oncorhynchus nerka) (1952-1993) and associations with temperature." *Canadian Journal of Fisheries and Aquatic Sciences*, 54, 1159-1165.

c) "Increased winter flooding in certain streams, reduced summer and fall flows, and warmer stream and estuary temperatures are all likely and are all harmful for salmon. If outward migration patterns for wild juveniles change, whether because warmer streams make them mature earlier or because freshets occur earlier, then the ocean and estuary conditions they find upon arrival might not match those they have evolved to exploit."

"Climate models presently lack the detail to project changes in many specific environmental factors that are most important for salmon, such as the timing of seasonal coastal upwelling, variations in coastal currents, and vertical stability of the water column. But where climate models are informative, their projections for PNW salmon are largely unfavorable. Increased winter flooding in certain streams, reduced summer and fall flows, and warmer stream and estuary temperatures are all likely and are all harmful for salmon. If outward migration patterns of wild juveniles change, whether because warmer streams make them mature earlier or because freshets occur earlier, then the ocean and estuary conditions they find upon arrival might not match those they have evolved to exploit. The strength and seasonality of upwelling appears unlikely to change in a warming climate (Mote and Mantua, 2002)."

Mote, P. W., E. A. Parson, A. F. Hamlet, K. N. Ideker, W. S. Keeton, D. P. Lettenmaier, N. J. Mantua, E. L. Miles, D. W. Peterson, D. L. Peterson, R. Slaughter, and A. K. Snover, 2003. "Preparing for climatic change: The water, salmon, and forests of the Pacific Northwest." *Climatic Change* 61, 45-88.

Supporting Citations:
Mote, P. W. and Mantua, N. J. 2002. "Coastal Upwelling in a Warmer Future." *Geophys. Res. Letts*, DOI 10.1029/2002GL016086.

T. Beechie, E. Buhle, M. Ruckelshaus, A. Fullerton and L. Holsinger, 2006. “Hydrologic regime and the conservation of salmon life history diversity.” *Biological Conservation*, 130(4), 560-572.

Nakano, S., F. Kitano and K. Maekawa, 1996. “Potential fragmentation and loss of thermal habitats for charrs in the Japanese archipelago due to climatic warming.” *Freshwater Biology,* 36(3), 711-722.

Rieman, B. E., D. C. Lee, and R. F. Thurow, 1997. “Distribution, status, and likely future trends of bull trout within the Columbia River and Klamath River Basins.” *North American Journal of Fisheries Management*, 17, 1111-1125.

Beamish, R. J., and D. R. Bouillon, 1993. “Pacific salmon production trends in relation to climate.” *Canadian Journal of Fisheries and Aquatic Sciences,* 50, 1002-1016.

Chatters, J. C., D. A. Neitzel, M. J. Scott, S. A. Shankle, 1991. “Potential impacts of global climate change on Pacific Northwest spring chinook salmon (*Oncorhynchus tshawytscha*): An exploratory case study.” *Northwest Environmental Journal*, 7(1), 71-92.

Neitzel, D. A., M. J. Scott, S. A. Shankle and J. C. Chatters, 1991. “The effect of climate change on stream environments: the salmonid resource of the Columbia River Basin.” *Northwest Environmental Journal*, 7(2), 271-293.

d) “Data examined in this study suggest that, just as in marine environments, interannual environmental variations can affect freshwater production of Oregon Coastal Native coho on a regional scale. Cooler temperatures, later fall transitions, intermediate second winter flows, and higher second spring flows all correlated with higher natural smolt production on the Oregon Coast. There was no evidence of a correlation with first winter flows or summer flows.”

Lawson, P.W., E.A. Logerwell, N.J. Mantua, R.C. Francis, and V.N. Agostini, 2004. “Environmental factors influencing freshwater survival and smolt production in Pacific Northwest coho salmon (*Oncorhynchus kisutch*).” *Canadian Journal of Fisheries and Aquatic Sciences*, 61, 360-373.

e) “Studies on the relation of temperature to tolerance, preference, metabolic rate, performance, circulation, and growth of sockeye salmon all point to a physiological optimum in the region of 15°C. Natural occurrence is limited in time and space at temperatures above 18°C despite being able to tolerate 24°C. Forms of physiological inadequacy can be demonstrated which account for such restrictions in distribution. Predictive power for locating and accounting for concentrations of young fish in thermally stratified lakes appeared to provide "proof" for the controlling influence of the physiological optimum temperature. Early literature on the ecology of sockeye supported this view.”

Brett, J.R. 1971. "Energetic response of salmon to temperature: a study of some thermal relations in the physiology and freshwater ecology of sockeye salmon." *American Zoologist* 11: 99-113.

Supporting Citations:
Beacham, T.D. and C.B. Murray, 1990. "Temperature, egg size, and development of embryos and alevins of five species of Pacific salmon: a comparative analysis." *Trans. Amer. Fish. Soc.* 119: 927-945.

Burger, C.V. et al. 1985. "Comparison of spawning areas and times for two runs of Chinook salmon in the Kenai River, Alaska." *Canadian Journal of Fisheries and Aquatic Sciences*. 42: 693-700.

Hoar, W.S. 1988. The physiology of smolting salmonids. Pages 275-343 in W.S. Hoar and D.J. Randall, eds. Fish physiology, Vol XI. Academic Press, New York.

Ratliff, D.E. 1992. "Bull trout investigations in the Metolius River-Lake Billy Chinook system." Pages 37-44 in P.J. Howell and D.V. Buchanan, eds. Proceedings of the Gearhart Mountain bull trout workshop. American Fisheries Society, Oregon Chapter, Corvallis.

Spence, B.C. et al. 1996. "An Ecosystem Approach to Salmonid Conservation." TR 4501-96-6057. ManTech Environmental Research Services, Corp. Corvallis, Or.

f) "Although the consequences of prolonged migration delays for Okanagan sockeye are not well known, various studies suggest that delays associated with temperatures >17°C may be accompanied by increased susceptibility to disease, impaired maturation processes, increases to stress parameters, reduced swimming performance, reduced efficiency of energy use during migration or spawning and reduced viability of gametes (references in review by MacDonald et al., 2000). Moreover, exposure to temperatures >20–21°C for more than a few days may trigger complex physiological and biochemical changes associated with poor spawning success, poor egg quality and senescent death prior to spawning as observed for some populations of Somass River (K. Hyatt, unpublished data) and Fraser River sockeye (MacDonald et al., 2000) during high temperature and low discharge years in 1992 and 1998."

"Impact and adaptation responses of Okanagan sockeye to stressful thermal regimes during migration provide at least circumstantial evidence for specific mechanisms operating on adult sockeye to support such an outcome. Thus, although the cumulative impacts of dams, water regulation, over fishing, irrigation and intensive land use have undoubtedly driven salmon stock declines, salmon responses to cyclic CVC [climate variation and change] events likely also play an important role. Indeed, some authors have concluded that strong interactions between cyclic natural and cumulative anthropogenic variations combine to induce a pattern of 'ratchet–like' declines in salmon stocks. Thus a given stock will exhibit increases and decreases with the periodicity of the natural cycles but over a number of cycles will exhibit a time–weighted trend to decline (Lawson, 1993). These observations are consistent with long–term patterns of abundance observed for both ESA listed Redfish Lake (Gustafson et al., 1997) and unlisted Okanagan sockeye salmon (Hyatt and Rankin, 1999)."

Kim D. Hyatt, Margot M. Stockwell and D. Paul Rankin, 2003. "Impact and Adaptation Responses of Okanagan River Sockeye Salmon (*Oncorhynchus nerka*) to Climate Variation and Change Effects during Freshwater Migration: Stock Restoration and Fisheries Management Implications." *Canadian Water Resources Journal* 689 Vol. 28, No. 4.

Supporting Citations:
Lawson, P.W. 1993. "Cycles in Ocean Productivity, Trends in Habitat Quality, and the Restoration of Salmon Runs in Oregon." *Fisheries*, 18(8): 6–10.

Gustafson, R., T.C. Wainwright, G.A. Winans, F.W. Waknitz, L.T. Parker and R.S. Waples. 1997. "Status Review of Sockeye Salmon from Washington and Oregon." National Oceanic and Atmospheric Administration Technical Memo. NMFS–NWFSC– 33. National Marine Fisheries Service–Northwest Fisheries Center, Seattle WA.

Hyatt, K.D. and D.P. Rankin. 1999. "A Habitat Based Evaluation of Okanagan Sockeye Salmon Escapement Objectives." Canadian Stock Assessment Secretariat Research Document, 99/191. 59 p. Available from http://www.dfo–mpo.gc.ca/csas/CSAS/English/Research_Years/1999/a99_191e.htm.

MacDonald, S., M. Foreman, T. Farrell, I. Williams, J. Grout, A. Cass, J. Woodey, H. Enzenhoffer, C. Clarke, R. Houtman, E. Donaldson and D. Barnes. 2000. "The Influence of Extreme Water Temperatures on Migrating Fraser River Sockeye Salmon (Oncorhynchus nerka) During the 1998 Spawning Season." Canadian Technical Report of Fisheries and Aquatic Science, 2326.

g) "Stream temperature directly influences the metabolic rates, physiology, and life-history traits of aquatic species and helps to determine rates of important community processes such as nutrient cycling and productivity (Allen 1995). Fluctuations in water temperature induce behavioral and physiological responses in aquatic organisms and permanent shifts in stream temperature regimes can render formerly suitable habitat unusable for native species (Holtby 1988, Quigley and Arbelbide 1997, Wissmar and others 1994b). Because of the ecological importance of stream temperature, preventing or mitigating anthropogenic thermal degradation is a common concern for resource managers (Coutant 1999)."

Poole, G.C., and C.H. Berman. 2001. "An ecological perspective on instream temperature: natural heat dynamics and mechanisms of human-caused degradation." *Environmental Management*; 27 (6): 787-802.

Supporting Citations:
Allen, J. D., 1995. Stream Ecology: Structure and function of running water. Chapman & Hall, New York, 388 pp.

Holtby, L. B., 1988. "Effects of logging on stream temperatures in Carnation Creek, British Columbia, and associated impacts on the coho salmon (*Oncorhynchus kisutch*)." *Canadian Journals of Fisheries and Aquatic Sciences 45*:502-515

Quigley, T. M., and S. J. Arbelilbide. 1997. An assessment of ecosystem components in the interior Columbia basin and portions of the Klamath and Great basins. USDA Forest Service Pacific Northwest Research Station General Technical Report PNW-GTR-405, Vol. 3.

Wissmar, R. C., J. E. Smith, B. E. McIntosh, H. W. Li, G. H. Reeves, and J. R. Sedel. 1994b. Ecological health of river basins in forested regions of eastern Washington and Oregon. USDA Forest Service Pacific Northwest Research Station General Technical Report PNW-GTR-326.

Coutant, C. C. 1999. Perspectives on temperature in the Pacific Northwest's fresh waters. Oak Ridge Natioal Laboratory Environmental Sciences Division Publication 4849 (ORNL/TM-1999/44).

h) "A nearly 50% reduction in thermal habitat is projected for cold and cool water species, but only a 14.2% decrease is estimated for warm water fish. Sic Rainbow trout and white sucker fish distribution will be least affected in higher latitude or elevation locations. Suitable habitat will be eliminated by climate warming throughout the range of a species – north as well as south."

"Although our analysis of climate change effects has many uncertainties, several well-founded conclusions are possible. Major reductions in stream habitat for cold and cool water species would result from climate warming, but these effects would likely be reduced for fish living in lakes, especially larger, deeper lakes that stratify in summer, providing thermal refuges for inhabitants (e.g. Magnuson et al. 1990; Stefan et al. 1995). Although effects will be greater in some areas than others because of warming hot spots or regional hydrology, the effects will be broad on species that are widely distributed; habitat will be reduced for warm water fish in the south and increased in the north; habitat will be reduced more uniformly for cool and cold water species across their entire ranges. The primary beneficiaries of climate change will be species that are currently widely distributed in the U.S. Those species with smaller ranges will suffer the greatest initial losses."

Eaton, J. G., Scheller, R. M., 1996. "Effects of climate warming on fish thermal habitat in streams of the United States." *Limnol. Oceanogr*, 41(5) 1109-1115

Supporting Citations:
Magnuson, J. J., J. D. Meisner, and D. K. Hill. 1990. "Potential changes in thermal habitat of Great Lakes fish after global climate warming." *Trans. Am. Fish. Soc.* 119(2):254–264.

Stefan, H. G., M. Hondzo, J. G. Eaton, and J. H. McCormick. 1995. "Predicted effects of global climate change on fishes in Minnesota lakes." Pg. 57–72 in Climate

Change and Northern Fish Populations, R. J. Beamisk, ed. *Can. Spec. Publ. Fish. Aquat. Sci*. 121. Ottawa: National Research Council Canada.

i) "Increased water temperatures, decreased spawning flows, and, most importantly, increased magnitude of winter peak flows and consequent bed-scour, are all likely to increase salmon mortality in the Snohomish River Basin and in other watersheds in the region. The resulting downward pressure on salmon populations is liable to make the attainment of recovery targets more difficult. Even if climate change conforms to the relatively benign projections of the HadCM3 climate model, salmon population model results suggest that, in the absence of habitat restoration, by 2050 Snohomish Chinook salmon populations would decline by 20%. Climate effects on fish abundance are likely to be greatest in high elevation areas, mirroring the spatial distribution of changes in stream flow. Projected temperature effects show less spatial pattern, but temperatures only reached levels detrimental to salmon in the lower watershed."

Battin J., Wiley, M.W., Ruckelshaus, R.H., Palmer, R.N., Korb, E., Bartz, K.K., Imaki, H., (2006). "Projected impacts of climate change on salmon habitat restoration." Proceedings of the National Academy of Science, (in review).

(*) = Referenced in IPCC, 2001.

Table 1

Impact of Climate Change on	Building Block
Temperature	**1 – The global average temperature has increased during the 20th century and is forecasted to increase in the 21st century.**
	2 - Warming in the Puget Sound Region has increased at a faster rate during the 20th century than the global average and increases in temperature are forecasted to continue.
	3 - Increased surface temperatures in the Pacific Northwest will increase the rates of evaporation and transpiration (evapotranspiration).
Precipitation	**4 – Global precipitation is projected to increase in the future, although there is less certainty in predicting changes in precipitation than in temperature.**
	5 – The occurrence of heavy precipitation events has increased over the U.S. during the 20th century. This trend is projected to continue during the 21st century.
Snowpack and Glaciers	**6 - The loss of snowpack and glaciers in the Pacific Northwest mountains has been due to increased temperatures in the 20th century.**
	7 - Forecasted increases in temperatures associated with climate change will further reduce snowpack and glaciers in the Pacific Northwest mountains.
Streamflows	**8 – Climate change is projected to increase winter flows and decrease summer flows in snowmelt influenced river systems of the Pacific Northwest, particularly transient watersheds.**
	9 – Climate change is projected to increase the frequency of flood events in most western Washington river basins.
	10 - Climate change is projected to increase the frequency of drought events in the Pacific Northwest.
Sea Level Rise	**11 – Climate change is forecasted to raise global mean sea level in the 21st century.**
Salmonid Habitat	**12 – Climate change is forecasted to increase temperatures of rivers, streams, lakes, and river mouth estuaries in the Puget Sound region.**
	13 – Climate change, as described in Building Blocks 1-12, is forecasted to contribute toward stream flow and temperature conditions that have been shown to negatively impact freshwater and estuarine habitat of most species of salmonids in the Puget Sound watersheds.