3. Climate Change Scenarios

Abstract

Physically based scenarios of future climate are essential in assessing the potential impacts of climate change and supporting related long-term planning activities and policy decisions. To project future climate, global climate models (GCMs) and regional climate models (RCMs) are used. In studies assessing climate impacts, the outputs from GCMs or RCMs are used as inputs to hydrologic models. However, the outputs from GCMs or RCMs are at a relatively coarse spatial and temporal resolution. These coarse spatial and temporal scales are not matched to the hydrologic models, which are typically implemented at much finer resolution. Thus, post-processing of the GCM data, or "downscaling", is commonly used to obtain data at a finer resolution. Climate change is projected to have a significant effect on meteorological and hydrological variables such as temperature, precipitation, and sea-level over the Pacific Northwest (PNW) and for the Skagit River. Temperature is projected to increase for both the PNW and the Skagit River basin, though a smaller increase in temperature is expected for the Skagit River basin in comparison with the PNW as a whole. Average temperatures for the Skagit basin by the 2080s are projected to be 5.8 ^{o}F (A1B scenario) and 4.0 ^{o}F (B1 scenario) warmer than the 20th century baseline. Although changes in annual mean precipitation are small in future projections, substantial seasonal changes in precipitation are projected for both the PNW and the Skagit River basin, with increasing precipitation projected in winter, spring, and fall and decreasing precipitation projected in summer. Average changes in precipitation for the Skagit River basin by the 2080s (for A1B) are projected to be 9.8 %, 8.0 % and 19.2 % increase in winter, spring, and fall precipitation, respectively, with a 27.6 % decrease in summer precipitation. Global sea level has risen through the 20th century and is currently rising at an increasing rate. Sea levels are projected to increase substantially over the 21st century in the PNW. Very conservative estimates based on projections from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report suggest moderate expected increases in mean

sea level of at least 13 inches in Puget Sound, with a high extreme (low likelihood) estimate of about 50 inches. The science behind sea level rise projections is progressing rapidly and more recent global studies suggest much higher rates of global sea level rise. Short-term changes in sea level at local to regional scales can differ substantially (even in sign) from global changes, but are related to short-term fluctuations in climate rather than long-term trends.

3.1 Global Climate Models

Global Climate Models (GCMs) are physically based numerical models simulating key elements of the climate system. GCMs simulate a number of meteorological variables by calculating energy and moisture fluxes between the sun, atmosphere, land, ocean, and ice. GCMs are used to estimate future climate conditions associated with increasing greenhouse gas concentrations and related internal feedback mechanisms such as increases in water vapor in the atmosphere which increase the greenhouse effect, or losses of sea ice which decrease the reflectivity (albedo) of ice covered areas. The GCMs used in the 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) have been developed by a number of independent research groups. The model outputs simulated by 21 GCMs are available to other researches through the IPCC Data Distribution Center.

Future greenhouse gas emissions scenarios are one of the key forcing factors that determine future climate change. Over 40 emissions scenarios have been produced by the IPCC Special Report on Emissions Scenarios (IPCC, 2000). The emissions scenarios are based on a range of assumptions about future technological change and energy use as well as future trajectories for the global economy and population (NHC, 2008). Table 3.1 shows the most commonly used emissions scenarios for GCMs runs. Even under the lowest emissions scenario, B1, the projected global concentration of carbon dioxide (CO_2) by 2100 is higher by a factor of 1.6 (at 600 ppm) than baseline conditions in 2005 (about 380 ppm) (Table 3.1; NHC, 2008). Under the “business as usual” scenario, A2, the global CO_2 concentration is projected to increase to 1200 ppm by

2100. For purposes of comparison, B1 and A2 can be selected as a low emissions scenario and higher emissions scenario, respectively. However, the A1B emissions scenario, which projects higher emissions at the beginning of the century than A2 and lower emissions at the end of the century (a plausible response to increasing impacts over time), is often selected as an alternate emissions scenario (Mote and Salathé, 2010). If analysis is focused on the mid-21st century climate change, the A1B greenhouse gas emissions scenario represents potentially greater warming than the A2 scenario. Also, a larger number of GCMs were run with the A1B greenhouse gas emissions scenario than with the A2 scenario; they provide more information regarding the range of plausible effects. To analyze the impacts of rapid and essentially uncontrolled greenhouse gas accumulations by 2100, the A1FI emissions scenario might be the most appropriate choice, although the number of GCM simulations of this emissions scenario is limited. It is worth noting that actual greenhouse emissions have in recent years exceeded the average of the A1FI scenario family, although they have not exceeded the single representative scenario used in the IPCC GCM simulations (URL 1).

Table 3.1 A brief summary of the main features of selected IPCC emissions scenarios (Source: NHC, 2008).

Scenario	2100 CO_2 Conc.(ppm)	Economy and Population	Energy Sources
B1	600	Sustainable economy with emphasis on equity, reduced consumption, environment. Global economic convergence. 2100 population 7 Billion.	Largely non-fossil
A1B	850	Rapid growth, materialistic, market-oriented, high consumption economy. Global economic convergence. 2100 population 7 Billion.	Balanced fossil/ non-fossil
A2	1200	Moderate, uneven economic growth, regionally varied, function of culture. No global economic convergence. 2100 population 15 Billion.	Regionally mixed depending on availability
A1FI	1550	Rapid growth, materialistic, market-oriented, high consumption economy. Global economic convergence. 2100 population 7 Billion.	Fossil-intensive

Table 3.2 Summary of ten global climate models selected for Columbia Basin Climate Change Scenarios Project (Source: Randall et al., 2007).

Model ID, Vintage	Source	Atmosphere Top Resolution
UKMO-HadCM3, 1997	Hadley Centre for Climate Prediction and Research/Met Office, UK	$2.5^{o} \times 3.75^{o}$
CNRM-CM3, 2004	Météo-France/Centre National de Recherches Météorologiques, France	~ $1.9^{o} \times 1.9^{o}$
ECHAM5/MPI-OM, 2005	Max Planck Institute for Meteorology, Germany	~ $1.9^{o} \times 1.9^{o}$
ECHO-G,1999	Meteorological Institute of the University of Bonn, Meteorological Research Institute of the Korea Meteorological Administration (KMA), and Model and Data Group, Germany/Korea	~ $3.9^{o} \times 3.9^{o}$
PCM, 1998	National Center for Atmospheric Research, USA	~ $2.8^{o} \times 2.8^{o}$
CGCM3.1(T47), 2005	Canadian Centre for Climate Modeling and Analysis, Canada	~ $2.8^{o} \times 2.8^{o}$
CCSM3, 2005	National Center for Atmospheric Research, USA	$1.4^{o} \times 1.4^{o}$
IPSL-CM4, 2005	Institute Pierre Simon Laplace, France	$2.5^{o} \times 3.75^{o}$
MIROC3.2(medres), 2004	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	~ $2.8^{o} \times 2.8^{o}$
UKMO-HadGEM1,2004	Hadley Centre for Climate Prediction and Research/Met Office, UK	~$1.3^{o} \times 1.9^{o}$

The uncertainty in future climate change impacts is often estimated from an ensemble (group) of GCMs simulations which provide a range of results. To reduce computational requirements, some models which perform less well in reproducing important features of the observed regional climate are often excluded from the analysis. A common method for evaluating a model's performance is to compare the model's simulation of 20th century climate with observed regional temperature and precipitation (Mote and Salathé, 2010) or other important aspects of historical variability. The Climate Impacts Group, for example, selected the top 10 GCMs whose 20th century simulations showed the smallest bias in temperature and precipitation and the best reproduction of North Pacific climate variability for a recent climate change study on the Pacific Northwest Columbia River Basin (Hamlet et al., 2010). Brief information on the 10 GCMs is shown in Table 3.2 (detailed information and references of all 21 models are described in Table 8.1 of Randall et al. (2007)). Among the 10 GCMs selected, UKMO-HadGEM 1 or CCSM3 tend to be the warmest in each scenario and each decade, and IPSL_CMS is the wettest. Evaluation metrics and additional details are discussed by Mote and Salathé (2010).

3.2 Dynamical Downscaling Using Regional Scale Climate Models (RCMs)

Although GCMs provide a great deal of meaningful information at the regional scale, they have many limitations, particularly for watersheds like the Skagit whose hydrologic behavior is informed by topographic variations at sub-regional scales. For example, GCMs do not explicitly resolve the topography of the North Cascades and the Skagit River basin. Regional Scale Climate Models (RCMs) provide greatly improved representation of mountain topography and important feedback mechanisms such as the snow albedo feedback, which results in more rapid warming in areas with loss of snowpack (Salathé et al., 2010). RCMs also provide explicit and more realistic simulations of storms, providing improved tools for the assessment of hydrologic extremes such as flooding at daily or even hourly timescales. RCMs are usually not run over the entire globe, but instead are typically "nested" within a GCM domain. Use of nested RCMs for climate impacts assessment is commonly referred to as "dynamic downscaling". A good description of the details of dynamic downscaling and a comparison with GCM simulations can be found in Salathé et al. (2010).

While providing many potential advantages over GCMs for regional scale assessment, RCMs are very computationally intensive to run, which frequently limits the length and number of future climate change scenarios available. Comprehensive assessment of uncertainties deriving from the different GCM simulations that could potentially provide input data to the RCMs at the outer boundaries (*large scale forcing*) is therefore generally not possible at the current time due to the computational expense associated with such efforts.

3.3 Statistical Downscaling Approaches

As noted in the previous section, some important regional topographic features such as the Cascade Mountains are not represented by GCMs, making metrological data from GCMs unsuitable as input data for hydrologic models in their raw form. In studies assessing climate impacts, a downscaling process is often applied to relate monthly time scale simulation of temperature (T) and precipitation (P) data at around 200 km resolution produced by a GCM to daily time scale data required for a hydrologic model at finer (e.g. at 6 km) resolution (Hamlet et al., 2010). Statistical downscaling methods such as Delta Method and Transient Bias Correction and Statistical Downscaling (BCSD), as well as the Hybrid Delta method (which combines the strengths of the previous two methods) are described in detail by Hamlet et al. (2010). Here we give a brief overview of three statistical downscaling approaches.

3.3.1 Delta Method

One of the simplest statistical downscaling methods is the Delta method, which applies monthly changes in large scale temperature and precipitation from a GCM to historical temperature and precipitation observations at more local scales. The advantage of the Delta method is that it preserves the observed sequence of temporal and spatial variability from gridded observations, which makes for easy interpretation and straight-forward comparison with historical observations. For example, a particular drought or flood year in the historical record can be directly compared in future projections. The other advantage of the Delta method is that bias from GCMs is automatically removed and the spatial resolution of each GCM is not very important when changes are calculated at the regional scale.

One significant weakness of the Delta method is that information about potential changes in the probability distributions of temperature and precipitation simulated by the GCMs, such as changes in the variance or extremes, is ignored. For example, increased precipitation from the GCM simulation is captured by simply multiplying the changes (or delta) of precipitation on days with precipitation in the historic record but the actual number of days with precipitation simulated from GCMs are not transformed. These simplifications are intentional, and were originally intended to avoid the profound limitations of early GCMs in simulating regional climate, but as GCMs have steadily improved, a desire to incorporate more information from them has resulted.

3.3.2 Transient Bias Corrected and Statistical Downscaling (BCSD) Method

More sophisticated statistical downscaling method is the Bias Corrected Statistical Downscaling (BCSD) (Wood et al., 2002). In comparison with the Delta method, the Transient BCSD approach extracts more information from the large scale GCM simulations. The trend in the monthly GCM simulations of temperature and precipitation is preserved in the Transient runs, making the BCSD approach an appropriate tool for assessing rates of change. The spatial variability and realizations of interannual and interdecadal variability in the GCMs are also preserved. These preserved climate trends and variability are useful for applications such as modeling ecological systems but can make the interpretation of the results more difficult for other applications such as water resources planning. The quality of BCSD results are heavily dependent on the quality of the GCM simulations from which they derive, so caution should be exercised in interpreting these results (Mote and Salathé, 2010; Hamlet et al., 2010).

3.3.3 Hybrid Delta Downscaling Method

This downscaling method combines the strengths of the two methods described above, by combining the more detailed spatial and probabilistic information extracted from GCM simulations using the BCSD method with the historically accurate time series behavior of the traditional delta method (Hamlet et al., 2010). Most of the specific results that we discuss for the Skagit River basin in subsequent sections are based on this downscaling method.

3.4 Climate Change Impacts on Meteorological Conditions and Sea Level Rise

In this section, projected climate change impacts on PNW (regional) and Skagit basin (local) temperature and precipitation are presented, and projected impacts to global and regional sea level are discussed.

3.4.1 Changes in Temperature

PNW temperatures have warmed by about 0.8 °C (1.5 ^{o}F) since 1920 (Mote et al., 2003) and are predicted to increase over the 21st century with higher certainty than the other variables (Christensen and Hewitson, 2007; Mote and Salathé, 2010). Figure 3.1 shows a summary of temperature simulations from ~20 GCMs averaged over the PNW for two emissions scenarios: the A1B (medium emissions) and B1 (a low emissions) greenhouse gas scenarios (Mote and Salathé, 2010). As shown in Figure 3.1, the changes in projected temperature by the end of the 21st century are strongly dependent on the emissions scenario: by the 2080s, the temperature increase relative to 1970-99 is almost 7.0 ^{o}F for A1B and 4.7 ^{o}F for B1. This finding shows that a reduction in the concentration of greenhouse gases will be an important factor in mitigating regional warming on long time scales.

The signal to noise ratio for temperature is very high, meaning that the magnitude of warming is very large in comparison with the observed normal variability. For example, by the 2050s the new 5th percentile value for the B1 scenario (which is the lowest value in the yellow band) is close to the 95th percentile shown for end of the 20th century (the upper range of the grey band). This result supports the argument that statistically significant increases in temperatures will be readily apparent in future observations.

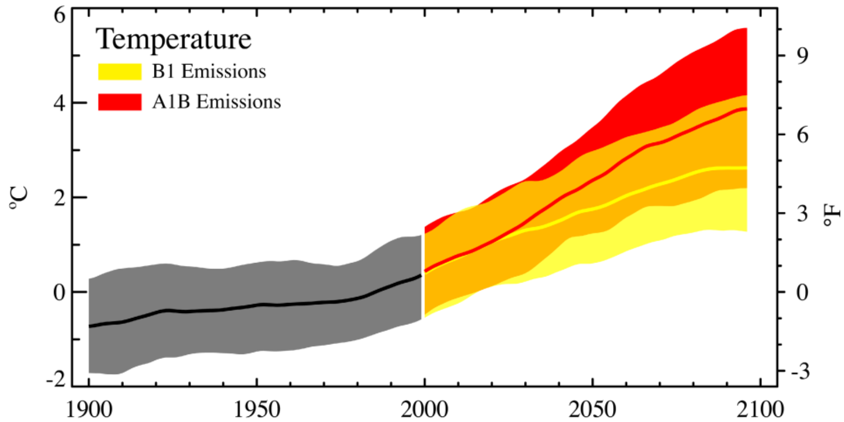

Figure 3.1 Summary of the 20th and 21st century annual average temperature simulations from 20 GCMs over the PNW, relative to the 1970-99 mean, for two greenhouse gas emissions scenarios. Solid lines show the mean. The grey bands show the range (5th to 95th percentile) for the historical simulations, the colored bands show the range of future projections for each emissions scenario (Source: Mote and Salathé, 2010).

Figure 3.2 and Table 3.3 show a summary of the 20th and 21st century monthly mean temperature simulations from ~10 GCMs averaged for the Skagit River basin near Mount Vernon for the A1B and B1 emissions scenarios. By the end of the 21st Century, the temperature increase is about 5.8 °F for A1B and 4.0 °F for B1 in comparison to historical average temperature (water years 1916-2006) (see Table 3.1), which is a somewhat smaller change compared to the PNW as a whole. This is explained primarily because the Skagit basin is relatively close to the coast, which warms more slowly than the interior due to proximity to the ocean. The projected monthly mean temperature also shows a seasonal pattern; the changes in projected temperature are largest in summer with largest increase in August. This seasonal pattern essentially increases in strength as projections move toward the end of the 21st century (Mote and Salathé, 2010).

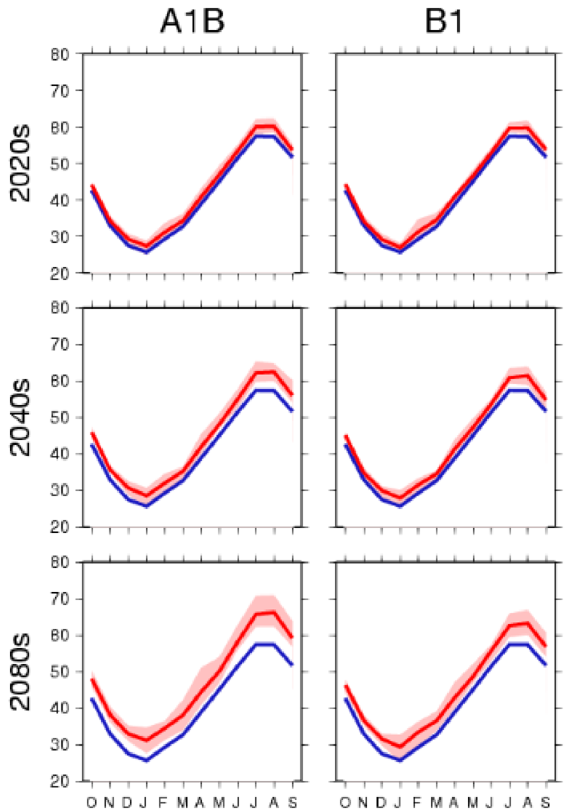

Figure 3.2 Summaries of the 20th and 21st century monthly mean temperatures (in ^oF) for A1B (left) and B1 (right) scenarios for the Skagit River basin upstream of Mount Vernon. The blue line represents historical monthly mean temperature (water years 1916-2006), while the red line represents projected monthly mean temperature across ~ 10 Hybrid Delta simulations for the A1B and B1 scenarios. The red band represents the range of individual scenario (Source: URL 2).

Table 3.3 Summaries of the 20th and 21st century annual and seasonal mean temperatures (in ^oF) for the A1B and B1 scenarios for the entire Skagit River basin upstream of Mount Vernon. (DJF=winter, MAM=spring, JJA=summer, and SON=fall).

Scenarios	Annual	DJF	MAM	JJA	SON
Historical	40.8	28.3	38.4	54.6	41.9
2020 A1B	42.6	29.9	40.0	57.0	43.4
2020 B1	42.5	29.8	40.0	56.6	43.4
2040 A1B	44.1	31.0	41.0	59.1	45.2
2040 B1	43.2	30.5	40.4	57.8	44.2
2080 A1B	46.6	32.9	43.4	62.3	47.7
2080 B1	44.8	31.7	41.9	59.6	45.8

3.4.2 Changes in Precipitation

In contrast to temperature, the signal to noise ratio for annual precipitation is very low, meaning that changes in mean precipitation from GCM simulations are not statistically significant (see Figure 3.3). Although systematic changes in annual precipitation are small, substantial seasonal changes in precipitation are projected for the 21st century as shown in Figure 3.4. The ensemble means show the precipitation increasing in winter, autumn and spring, and decreasing in summer in comparison with the 1970-99 average climate. These patterns of seasonal change increase in intensity as the projections move toward the end of the 21st century.

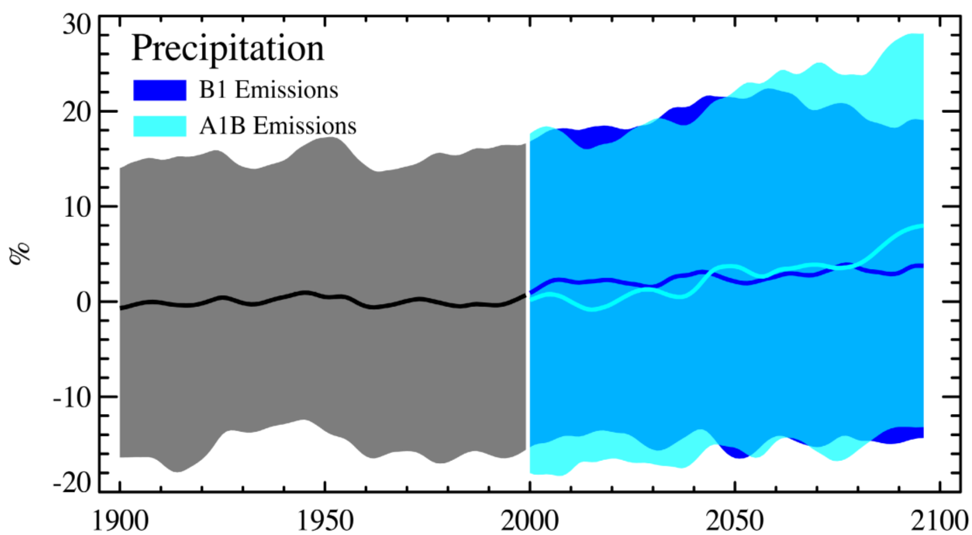

Figure 3.3 Summary of 20th and 21st century annual precipitation simulations from 20 GCMs over the PNW, relative to the 1970-99 mean, for two greenhouse gas emissions scenarios. Solid lines show the mean. The grey bands show the range (5th to 95th percentile) for the historical simulations and the colored bands show the range of future projections for each emissions scenario (Source: Mote and Salathé, 2010).

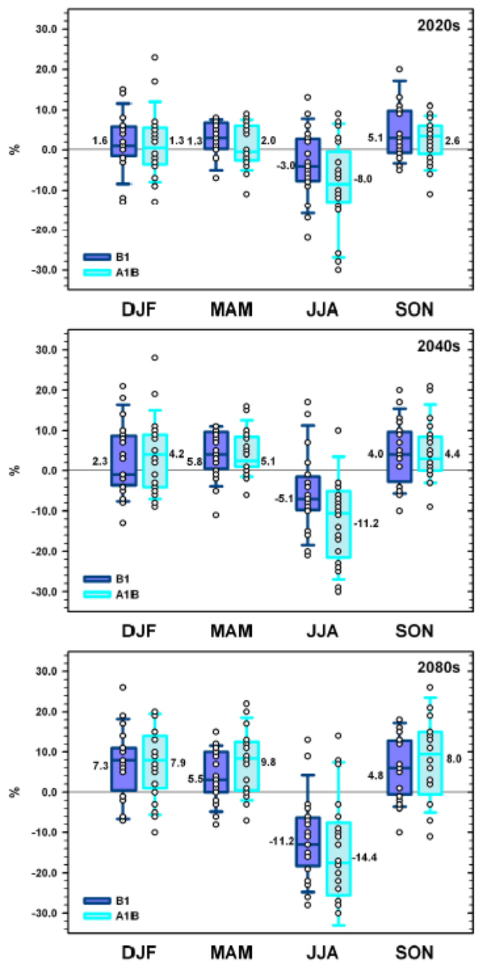

Figure 3.4 Range of projected changes in precipitation for each season (DJF=winter, MAM=spring, JJA=summer, and SON=fall), relative to the 1970-99 mean. Circles are individual model values. Box-and-whiskers plots indicate 10th and 90th percentiles (whiskers), 25th and 75th percentiles (box ends), and median (solid middle bar) for each season and scenario (Source: Mote and Salathé, 2010).

Similar patterns are observed for the precipitation projections for the Skagit River basin (see Figure 3.5 and Table 3.4). Average changes in precipitation for the Skagit River basin by the 2080s (for A1B) are projected to increase by 9.8 % in winter, 8.0 % in spring and 19.2 % in fall but to decrease 27.6 % in summer. Because GCM precipitation projections for the 21st century are much more uncertain than temperature projections, greater caution is required when using changes in precipitation in planning and policy decisions.

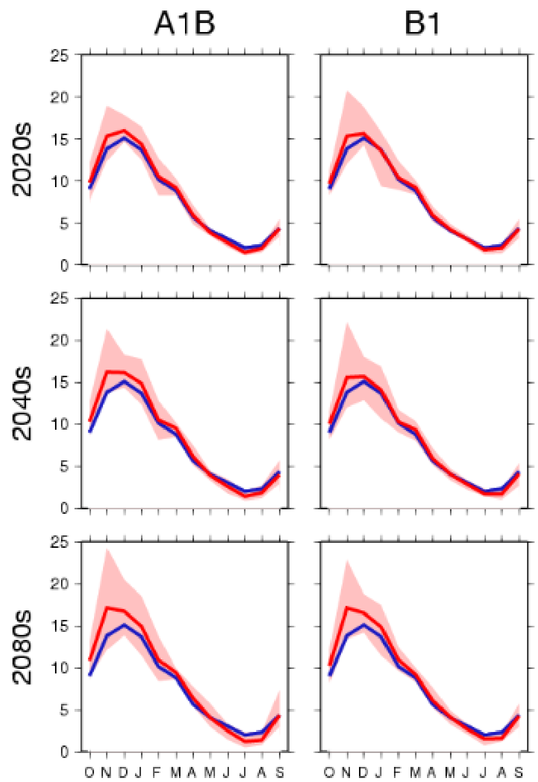

Figure 3.5 Summaries of 20th and 21st century monthly mean precipitations (in inches) for A1B (left) and B1 (right) scenarios for the Skagit River basin upstream of Mount Vernon. The blue line represents historical monthly mean precipitation (water years 1916-2006), while the red line represents projected monthly mean precipitation across ~10 Hybrid Delta simulations for A1B and B1 scenarios. The red band represents the range of individual scenario (Source: URL 2).

Table 3.4 Summaries of 20th and 21st century annual and seasonal mean precipitation (in inches) for A1B and B1 scenarios for the entire Skagit River basin upstream of Mount Vernon. (DJF=winter, MAM=spring, JJA=summer, and SON=fall).

Scenarios	Annual	DJF	MAM	JJA	SON
Historical	91.8	38.9	18.5	7.3	27.2
2020 A1B	95.2	40.9	18.9	6.0	29.4
2020 B1	94.8	39.6	19.3	6.8	29.2
2040 A1B	97.4	41.5	19.6	5.8	30.5
2040 B1	95.3	40.0	19.3	6.2	29.7
2080 A1B	100.3	42.7	19.9	5.3	32.4
2080 B1	99.0	42.2	19.4	5.8	31.6

3.4.3 Changes in Sea Level

Global sea level has risen through the 20th century and is currently rising at an increased rate (Nicholles et al., 2010; IPCC, 2007). For example, the mean rate of global sea level rise (SLR) from 1993 to 2009 was about 3 mm/year, which is significantly higher than the average during the previous half century (Figure 3.7) (Nicholles et al., 2010; IPCC, 2007). However, sea-level is not rising uniformly around the world as shown in Figure 3.6 (IPCC, 2007; Nicholles et al., 2010). In some regions such as the western Pacific and eastern Indian Oceans, sea level has risen up to five times faster than the global mean rise, while in other regions such as the eastern Pacific (i.e. the west coast of the United States) and the Western Indian Oceans, sea level has been falling (Figure 3.6) (IPCC, 2007; Nicholles et al., 2010). Spatial variability of the rates of sea level rise, however, likely reflects decadal fluctuations rather than long-term trends (IPCC, 2007; Nicholles et al., 2010).

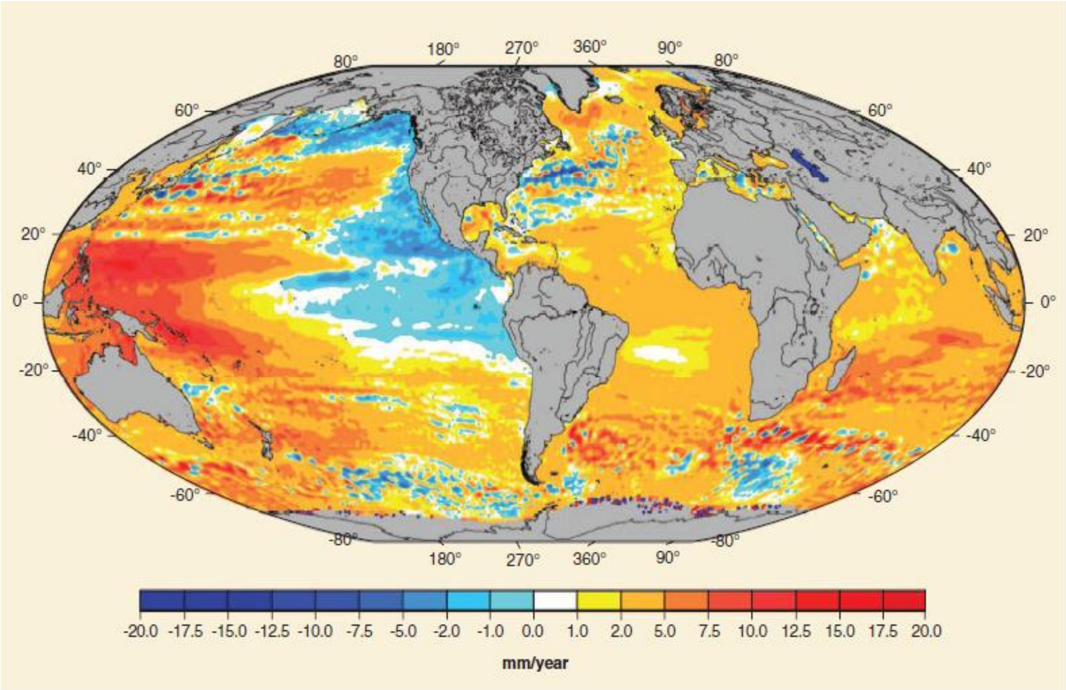

Figure 3.6 Regional sea-level trends from satellite altimetry from 1993 to 2009 (Source: Nicholles et al., 2010).

The IPCC's Fourth Assessment Report (AR4) projected that global sea level rise will be between 18 and 38 cm (7.1 and 15.0 in) for the lowest emissions scenario, and between 26 to 59 cm (10.2 and 23.2 in) for the highest emissions scenario (IPCC, 2007). These estimates of sea level dynamics were based on published studies of glacial dynamics available at the time the IPCC report was being prepared. More recent monitoring and modeling studies, which were not included in the IPCC process, have shown much more rapid loss of ice mass. When rapid glacial dynamics are included, projected SLR will be much higher than the IPCC AR4 projection (Rahmstorf, 2007; Horton et al., 2008; Pfeffer et al., 2008; Vermeer and Rahmstorf, 2009; Grinsted et al., 2010; Nicholls and Cazenave, 2010). For example, semi-empirical approaches linking SLR to temperature change showed that the range of global sea level projection will be 0.34 to 1.79 m (1.12 to 5.87 ft) by 2100 (Rahmstorf, 2007; Horton et al., 2008; Vermeer and Rahmstorf, 2009; Grinsted et al., 2010). Global sea level projections also vary considerably depending on the assumptions used in these empirical relationships--such as which IPCC projection (IPCC TAR or AR4), which emissions scenarios, or which GCMs are used. Figure 3.7 shows the IPCC AR4 SLR projections as well as three more recent semi-empirical SLR projections. Rahmstorf (2007) assumed a linear relationship between the rate of SLR and temperature, reporting 0.5-1.4 m (1.64 – 4.59 ft) of SLR by 2100 for A1FI scenarios of the IPCC Third Assessment Report. For the IPCC AR4 A1FI scenario, Vermeer and Rahmstorf (2009) and Grinsted et al. (2010) reported 1.13-1.79 m (3.71 – 5.87 ft) and 0.34 – 1.6 m (1.12-5.25 ft) of SLR for the 21st century, respectively. Vermeer and Rahmstorf (2009) and Grinsted et al. (2010) modified the linear relationship by considering more rapid response.

Projected 21st century local SLR in the PNW was estimated by Mote et al. (2008) by combining the estimates of global SLR from the 2007 IPCC report and local factors such as atmospheric circulation and vertical land movement due to tectonic movement (e.g. isostatic rebound). The very low, medium, and very high SLR projections for Puget Sound for 2050 and 2100 are shown in Table 3.5. The end-of-century very low estimates for global SLR are based on the IPCC's B1 emissions scenario. For the medium global SLR estimate, an average of six emissions scenarios is used. The very high estimate of global SLR includes the IPCC's A1FI emissions scenario and a rough estimate of the upper limit of ice sheet contributions of 34 cm (13.4 in) for 2100.

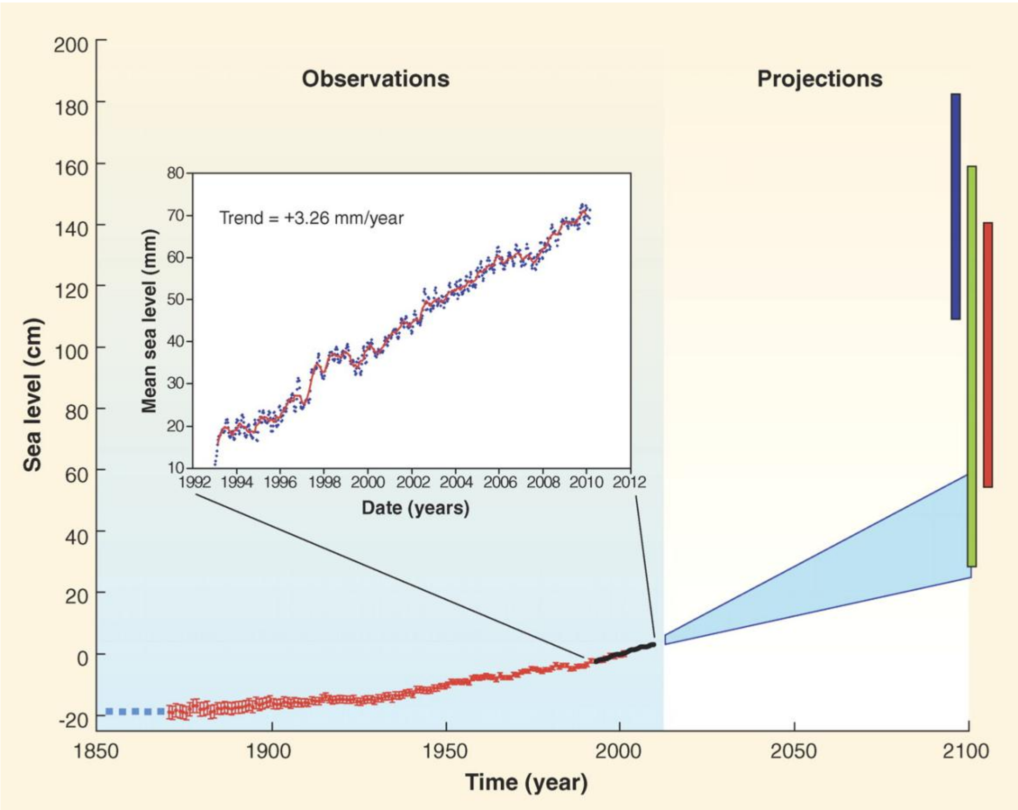

Figure 3.7 Global mean sea level evolution over the 20th and 21st centuries. The red curve is based on tide gauge measurements. The black curve is the altimetry record (zoomed over the 1993–2009 time span). Projections for the 21st century are also shown. The shaded light blue zone represents IPCC AR4 projections for the A1FI greenhouse gas emissions scenario. Bars are semi-empirical projections [red bar: (Rahmstorf, 2007); dark blue bar: (Vermeer and Rahmstorf, 2009); green bar: (Grinsted et al., 2010)] (Source: Nicholls and Cazenave, 2010).

Averaged sea level rise projection over 18 models for the moderate IPCC A1B emissions scenarios suggests that sea level along the coast of western North America is likely to be about 2-3 cm below the global average possibly due to northward wind (Mote el al., 2008; IPCC, 2007; Nicholles et al., 2010). The local atmospheric circulation impacts on SLR are estimated in the very low SLR scenarios by subtracting 1 cm (0.4 in) by 2050 and 2 cm (0.8 in) by 2100 from the very low SLR estimates and are assumed to be negligible for the medium scenarios (Table 3.5).

However, several models project increases in wintertime southerly (i.e. from the south) winds. The very high SLR scenarios consider this component by adding 7 cm (2.8 in) by 2050 and 15 cm (5.9 in) by 2100 into the very high SLR estimates, respectively (Table 3.5).

Table 3.5 Calculation of very low, medium and very high estimates of sea level changes in Puget Sound for 2050 and 2100 relative to 1980-1990 (Adapted from Mote et al., 2008).

SLR Estimate	Components	2050	2100
Very Low	Global SLR (Thermal Expansion and Melting of Global Ice)	9 cm (3.5 in)	18 cm (7.1 in)
	Local Atm. Dynamics	-1 cm (-0.4 in)	-2 cm (-0.8 in)
	Local Vertical Land Movement	0 cm (0.0 in)	0 cm (0.0 in)
	Total	8 cm (3.1 in)	16 cm (6.3 in)
Medium	Global SLR (Thermal Expansion and Melting of Global Ice)	15 cm (5.9 in)	34 cm (13.4 in)
	Local Atm. Dynamics	0 cm (0.0 in)	0 cm (0.0 in)
	Local Vertical Land Movement	0 cm (0.0 in)	0 cm (0.0 in)
	Total	15 cm (5.9 in)	34 cm (13.4 in)
Very High	Global SLR (Thermal Expansion and Melting of Global Ice)	38 cm (15.0 in)	93 cm (36.6 in)
	Local Atm. Dynamics	7 cm (2.8 in)	15 cm (5.9 in)
	Local Vertical Land Movement	10 cm (3.9 in)	20 cm (7.9in)
	Total	55 cm (21.7 in)	128 cm (50.4 in)

An earlier study of vertical land movement (VLM) in the PNW suggested that south Puget Sound was subsiding at a rate of about 2 mm/yr (Holdahl et al., 1989; Mote et al., 2008; Schweiger, 2007). Recent studies found that little or some small uplifts occurred in southern Puget Sound and VLM in further north Puget Sound was less than 2 mm/yr (Verdonck, 2006; Schweiger, 2007; Mote et al., 2008). Because estimates of VLM in Puget Sound are not consistent among studies, VLM in Puget Sound was assumed to be negligible for very low and medium SLR estimates (Mote et al., 2008). Subsidence of 10 cm (3.9 in) by 2050 and 20 cm (7.9 in) by 2100 is assumed for the very high SLR estimate in Puget Sound (Table 3.5) (Mote et al., 2008). For the Skagit River basin, Schweiger (2007) used VLM of -7 cm (-2.4 in) by 2050 and -9 cm (-3.5 in) by 2100. Mote et al. (2008) estimated that the very high SLR in Puget Sound by 2100 would be 128 cm (50.4 in). It is noted that Mote et al. (2008) used IPCC's SLR projection for A1FI, which is 59 cm (23.2 in). Even though Mote et al. (2008) considered future contributions to SLR from the melting glaciers of Greenland and Antarctica (34 cm), their highest global SLR estimate of 93 cm (36.6 in) is much lower than the 179 cm (70.5 in) reported by Vermeer and Rahmstorf (2009). When considering a global SLR estimate of 179 cm (70.5 in), the approach taken in Mote et al. (2008) would suggest that PNW sea-level could increase as much as 214 cm (84.3 in) by the end of the 21st century.

3.5 Summary and Conclusions

Future climate is projected using physically based models such as global climate models (GCMs) and regional climate models (RCMs). These projections are used to assess the potential impacts of climate change and to support related long-term planning activities and policy decisions. Projected future climate and other key findings include the following:

- Different GCMs show different future climate projections depending on greenhouse gas emissions scenarios and their unique sensitivity to these forcings. Among the top 10 GCMs, which are selected based on each GCM's performance, UKMO-HadGEM 1 or CCSM3 tend to be the warmest in each scenario and each decade, and IPSL_CMS is the wettest.
- In comparison with GCMs, RCMs provide greatly improved representation of regional topographic features such as the Cascade Mountains and consequently simulate more realistic storms at daily or even hourly timescales. Because they are very computationally

intensive to run, the length and number of future climate change scenarios are limited in RCMs.

- To assess hydrologic impacts, the outputs from GCMs or RCMs are used as inputs to hydrologic models but spatial and temporal resolution of the outputs from GCMs are not matched to those required for hydrologic models. Thus, downscaling is commonly used to transform monthly time scale data at a coarse special resolution reproduced by GCMs to daily time scale data at finer special scales required for hydrologic model simulation.
- Projected changes in temperature for the Skagit River basin are broadly consistent with the PNW temperature projections, though the changes in temperature are somewhat smaller for the Skagit River basin relative to those over the PNW as a whole. For both the PNW and the Skagit River basin, temperature projections are higher for higher emissions scenarios (A1B) than for low emissions scenarios (B1), showing that regional warming on long time scales could be mitigated by reducing the concentration of greenhouse gases. The amount of warming over the next several decades is insensitive to the emissions scenario, supporting the argument that adaptation may be the only viable approach to avoiding impacts in the near term.
- Precipitation projections both for the PNW and for the Skagit River basin show wetter winters and drier summers relative to historical climate, though the changes in annual mean precipitation are not statistically significant. Greater caution is required when precipitation projections are used in planning and policy decisions, because precipitation projections are much more uncertain than temperature projections.
- Global sea level has risen through the 20th century and is currently rising at an increased rate, though there is spatial variability of the rates of sea level rise: sea level in some regions has been rising several times faster than the global mean rise, while sea level in other regions has been falling.
- Without the efforts of reducing the concentration of greenhouse gases, SLR in the PNW is estimated to increase dramatically. For highest emissions scenarios (A1FI), SLR of 128 - 219 cm (50.4 – 86.2 in) is estimated for Puget Sound by 2100. For the low

emissions scenarios (B1) only 16 cm (6.3 in) of SLR is projected for the same time period. Vertical land motion is also believed to be a significant factor contributing to relative sea level rise in the near coastal environment of Puget Sound, but more detailed monitoring is needed to more accurately estimate the importance of these changes. No detailed estimates of relative SLR for the Skagit River basin lowlands are currently available, for example.

URL 1: http://www.realclimate.org/index.php/archives/2010/06/recent-trends-in-co2-emissions/
URL 2: http://www.hydro.washington.edu/2860/products/sites/?site=6021

3.6 References

Christensen, J.H., and Hewitson, B., 2007. Chapter 11. Regional Climate Projections. In: Climate change 2007: The Physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change, Solomon, S, et al., (eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Grinsted, A., Moore, J. C., and Jevrejeva, S., 2009. Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. *Clim. Dyn.* 34, 461-472.

Hamlet, A.F., Salathé, E.P., and Carrasco, P., 2010. Statistical downscaling techniques for global climate model simulations of temperature and precipitation with application to water resources planning studies. A report prepared by the Climate Impact Group for Columbia Basin Climate Change Scenario Project, University of Washington, Seattle, WA. http://www.hydro.washington.edu/2860/products/sites/r7climate/study_report/CBCCSP_chap4_gcm_draft_20100111.pdf

Holdahl, S.R., Faucher, F., and Dragert, H., 1989. Contemporary vertical crustal motion in the Pacific Northwest, in:Choen and Vanicek (eds), Slow deformation and transmission of stress in the earth. American Geophysical Union, Geophysical Monograph.

Horton, R., Herweijer, C., Rosenzweig, C., Liu, J., Gornitz, V., Ruane, A.C., 2008. Sea level rise projections for current generation CGCMs based on the semi-empirical method. *Geophysical Research Letters*, 35:L02715, doi:10.1029/2007GL032486.

The Intergovernmental Panel on Climate Change (IPCC), 2000. Emissions Scenarios. A special report of working group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA http://www.ipcc.ch/ipccreports/sres/emission/index.htm

Intergovernmental Panel on Climate Change (IPCC), 2007. Climate Change 2007. The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds.: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M.C., Averyt, K., Tignor, M., and Miller, H.L.). Intergovernmental Panel on Climate Change, Cambridge and New York.

Maurer, E. P. and Hidalgo, H. G., 2008, Utility of daily vs. monthly large-scale climate data: an intercomparison of two statistical downscaling methods, *Hydrol. Earth Syst. Sci*., 12, 551-563, doi:10.5194/hess-12-551-2008.

Mote, P.W., Parson, E.A , Hamlet, A.F., Keeton, W.S., Lettenmaier, D. P., Mantua, N.J., Miles, E.L., Peterson, D.W., Peterson, D.L., Slaughter, R., and Snover, A.K., 2003. Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest. *Climatic Change*, 61 (1-2), 45-88.

Mote, P.W., Petersen, A., Reeder, S., Shipman, H., and Binder, L.W., 2008. Sea level rise in the coastal waters of Washington State. A report prepared by the Climate Impact Group, Center for Science in the Earth System, University of Washington, Seattle, and the Washington State Department of Ecology.

Mote, P.W. and Salathé, E.P., 2010. Future climate in the Pacific Northwest. *Climatic Change*, doi: 10.1007/s10584-010-9848-z.

Nicholls, R. J. and Cazenave, A., 2010. Sea-Level Rise and Its Impact on Coastal Zones. *Science*, 328, 1517-1520

Northwest Hydraulic Consultants (NHC), 2008. Overview of climate change impacts and vulnerability of Snohomish County for selected water-related infrastructure, services, and environmental values. NHC project #21613.

Pfeffer, W. T., Harper, J. T., and O'Neel, S., 2008. Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise. *Science*, 321, 1340-1343.

Rahmstorf, S., 2007. A semi-empirical approach to projecting future sea-level rise. *Science*, 315, 368-370.

Randall, D.A., Wood, R.A., Bony, S., Colman. R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R.J., Sumi, A., and Taylor, K.E., 2007. Chapter 8 Climate models and their evaluation. In: Climate change 2007: The Physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change, Solomon, S, et al., (eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Salathé, E.P., 2005. Downscaling simulations of future global climate with application to hydrologic modeling. *International Journal of Climatology*, 25:419-436.

Salathé, E.P., Leung, L.R., Qian, Y., and Zhang, Y., 2010. Regional climate model projections for the State of Washington. *Climatic Change*, doi: 10.1007/s10584-010-9849-y.

Schweiger, L.J., 2007. Sea-level rise and coastal habitats in the Pacific Northwest: An analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon. National Wildlife Federation, Washington.

Verdonck, D., 2006. Contemporary vertical crustal deformation in Cascadia. *Technophysics*, 417, 221-230.

Vermeer, M. and Rahmstorf, S., 2009. Global sea level linked to global temperature. *Proc. Natl. Acad. Sci. U.S.A.* 106, 21527-21532.

Wood, A.W., Maurer, E.P., Kumar, A., and Lettenmaier, D.P., 2002. Long-range experimental hydrologic forecasting for the eastern United States. *J Geophys Res-Atmos*, 107, 4429-4443.