Endangered Species Act Section 7(a)(2) Supplemental Biological Opinion

Consultation on Remand for Operation of the Federal Columbia River Power System

Action Agencies:	U.S. Army Corps of Engineers (Corps) Bonneville Power Administration (BPA) U.S. Bureau of Reclamation (Reclamation)
Consultation Conducted by:	NOAA's National Marine Fisheries Service (NOAA Fisheries) Northwest Region
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Issued by:	for Will Stelle Regional Administrator

Climate Sections of the 2014 FCRPS Supplemental Biological Opinion

This document excerpts the main sections of the 2014 FCRPS Supplemental Biological Opinion that address climate and climate change:

Section 2.1.4.1 (BiOp pages 152-167) examines recent climate patterns, with an emphasis on those relied upon in the 2008 Biological Opinion analysis, and compares the observations with the 2008 Biological Opinion's analytical assumptions.

Section 2.1.4.2 (BiOp pages 168-182) reviews new information on climate change and its effects on salmon and steelhead, updating reviews in the 2008 and 2010 Biological Opinions.

Section 3.9 (BiOp pages 435-442) reviews reasonable and prudent alternative (RPA) actions that help to implement recommendations of the ISAB (2007) to reduce the impact of climate change on listed species.

Literature Cited (BiOp pages 565-610) has citations for the previous sections.

Appendix D is a collection of Lisa Crozier's literature reviews for impacts of climate change on Columbia River salmon. D1 is a review of 2012 literature (beginning on p. D-3), D2 reviews 2010 literature (beginning on p. D-51), and D3 reviews 2011 literature (beginning on p. D-109).

The full biological opinion is available at: http://www.westcoast.fisheries.noaa.gov/fish_passage/fcrps_opinion/federal_columbia_river_power_system.html

2.1.4 Recent Climate Observations and New Climate Change Information

Qualitative considerations of weather and climate, as they affect salmon and steelhead survival, were described in Section 5.7 of the 2008 BiOp, and quantitative aspects were described in Section 7.1.1. Several indices of climate, such as the Pacific Decadal Oscillation (PDO), the El Niño-Southern Oscillation (ENSO), and freshwater flows (caused by precipitation and runoff patterns) are correlated with survival of listed salmon and steelhead (e.g., Logerwell et al. 2003; Scheuerell and Williams 2005; Petrosky and Schaller 2010; Haeseker et al. 2012; Peterson et al. 2012; Burke et al. 2013) and therefore affect the rangewide status of the species.

The 2008 BiOp applied three future climate scenarios to prospective quantitative estimates of interior Columbia basin salmon and steelhead extinction risk and productivity to capture a reasonable range of future ocean survivals based on recommendations of the Interior Columbia River Technical Recovery Team (ICTRT and Zabel 2007). Future climate scenarios explicitly incorporated the climate indicators described further in this section. The three climate scenarios were:

§ 1980 through 2001 (*Recent* Climate, with mostly warm years and mostly poor survival);

§ 1977 through 1997 (*Warm PDO* Climate, with almost exclusively warm years and poor survival); and

§ 1946 through 2001 (*Historical* Climate, with a mixture of cool years with good survival and warm years with poor survival).

The 2008 BiOp gave the greatest weight to projections based on the Recent climate scenario.

To apply these scenarios to projections of future survival (e.g., to evaluate prospective actions in the 2008 BiOp), ICTRT and Zabel (2007) expressed combined estuary and ocean survival as functions of climate indices, such as upwelling and the PDO, because of significant correlations of these factors with survival. Each future climate scenario was therefore defined by specific climate variables, such as upwelling and the PDO, and the historical occurrence of those variables over the three periods described above.

The 2008 BiOp also included Comprehensive Fish Passage (COMPASS) model estimates of juvenile survival during mainstem migration. Survival projections using the COMPASS model were based in part on Snake and Columbia River flow rates over a wide range of conditions.

In Section 2.1.4.1, NOAA Fisheries examines recent climate patterns, with an emphasis on those relied upon in the 2008 BiOp analysis, and compares the observations with the 2008 BiOp's analytical assumptions. Additionally, in Section 2.1.4.2, we review new information on climate change and its effects on salmon and steelhead, updating reviews in the 2008 and 2010 BiOps.

New information regarding our understanding of physical and biological processes in the Columbia River estuary and plume are reviewed separately in Section 2.2.3.1. Although most of the new information does not directly address climate and climate change, the new information regarding plume dynamics, fish behavior, and habitat use indicate the importance to plume dynamics of climate factors reviewed in this section, such as Columbia River outflow and wind-generated nearshore processes, including coastal upwelling.

Eulachon survival is associated with many of the same climate factors as salmon and steelhead (Gustafson et al. 2010). Although the discussion of climate in this section focuses on impacts to salmon and steelhead, we also consider it relevant to eulachon survival and productivity.

2.1.4.1 Recent Climate Observations

In this section, we highlight climate variables that have been discussed in previous FCRPS BiOps, especially those variables and indices that were used to calculate the three ocean climate scenarios that were incorporated into the 2008/2010 BiOps' analyses for interior Columbia basin salmonids (ICTRT and Zabel 2007; see discussion above). The primary purpose of this review is to determine if recent climate conditions have been within the range of climate conditions relied upon in the 2008/2010 BiOps' analyses.

2.1.4.1.1 Pacific Decadal Oscillation

The PDO is a measure of north Pacific sea-surface temperature variability, but the index is correlated with both terrestrial and oceanic climate effects (Mantua et al. 1997). Pacific Northwest salmon and steelhead survival is generally high when ocean temperatures are cooler (negative PDO) and survival is generally low when ocean temperatures are warm (positive PDO), although this pattern is reversed for Alaskan stocks (e.g., Hare et al. 1999; Peterson et al. 2012). While this pattern reflects a general correspondence, the PDO is not always a good indicator of salmon survival, as demonstrated by lower returns in 2013 than were predicted based on the PDO and other ocean indicators (see Section 2.1.1.6.3 *NWFSC Ocean Indicators and the AMIP Projection Model for Future Years*).

The 2008 BiOp included a general discussion of the PDO in Section 5.7.2 and Figure 5.7.1-2 displayed a time series of estimates through Jan 2008. The PDO during spring months of ocean entry relevant to salmon and steelhead ocean survival was one of the factors used to model the future climate scenarios in the 2008 BiOp, as described above. The 2010 Supplemental BiOp updated the PDO index through September 2009 and Figure 2.2.1.3.1.6 demonstrated that there had been a higher proportion of negative PDO years (cool, with presumably higher survival) since 2001 than would be predicted by the Recent climate scenario.

The 2008 BiOp Section 5.7.2 described a pattern of PDO cycles over the last century, with cool (negative: "good" Pacific Northwest salmon survival) PDO regimes prevailing in 1890–1924 and again in 1947–1976 and warm (positive: "poor" Pacific Northwest salmon survival) regimes from 1925–1946 and from 1977 through at least the late 1990s (Mantua and Hare 2002).

It is now possible to further update the PDO observations and compare them with the 2008 BiOp's assumptions (Figures 2.1-33 and 2.1-34). Recently, the sign of the PDO has changed more frequently than in the past, with shifts since the late 1990s occurring on approximately 2- to 6-year intervals rather than on decadal or multi-decadal intervals. From 2002 to 2013, 6 years had a positive mean spring PDO (warm, lower survival), with 2003 through 2006 being the years with the highest values. Six years had a negative mean spring PDO (cold, higher survival). The distribution of 2002 through 2012 PDO observations is more similar to the Historical climate scenario, which resulted in a mixture of good and poor years for salmon survival, than to either the Recent or Warm PDO climate assumptions in the 2008 BiOp, which were both dominated by poor survival years. The overall mean spring PDO for the entire 2002 through 2013 time period is lower (i.e., cooler) when compared to multi-year means for the Recent ($P = 0.02$) climate scenario and Warm PDO ($P < 0.01$) climate scenario described in the 2008 BiOp (Figure 2.1-33), but does not differ from the Historical climate scenario ($P = 0.88$).

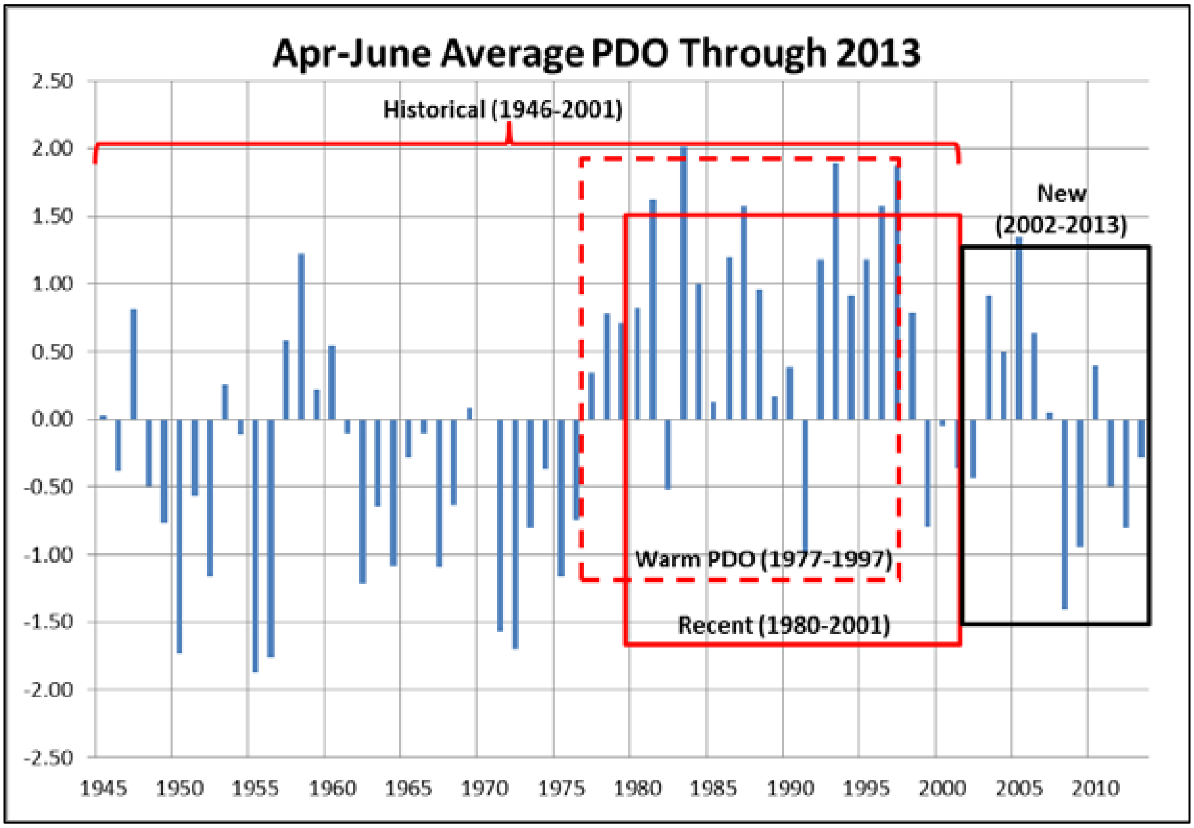
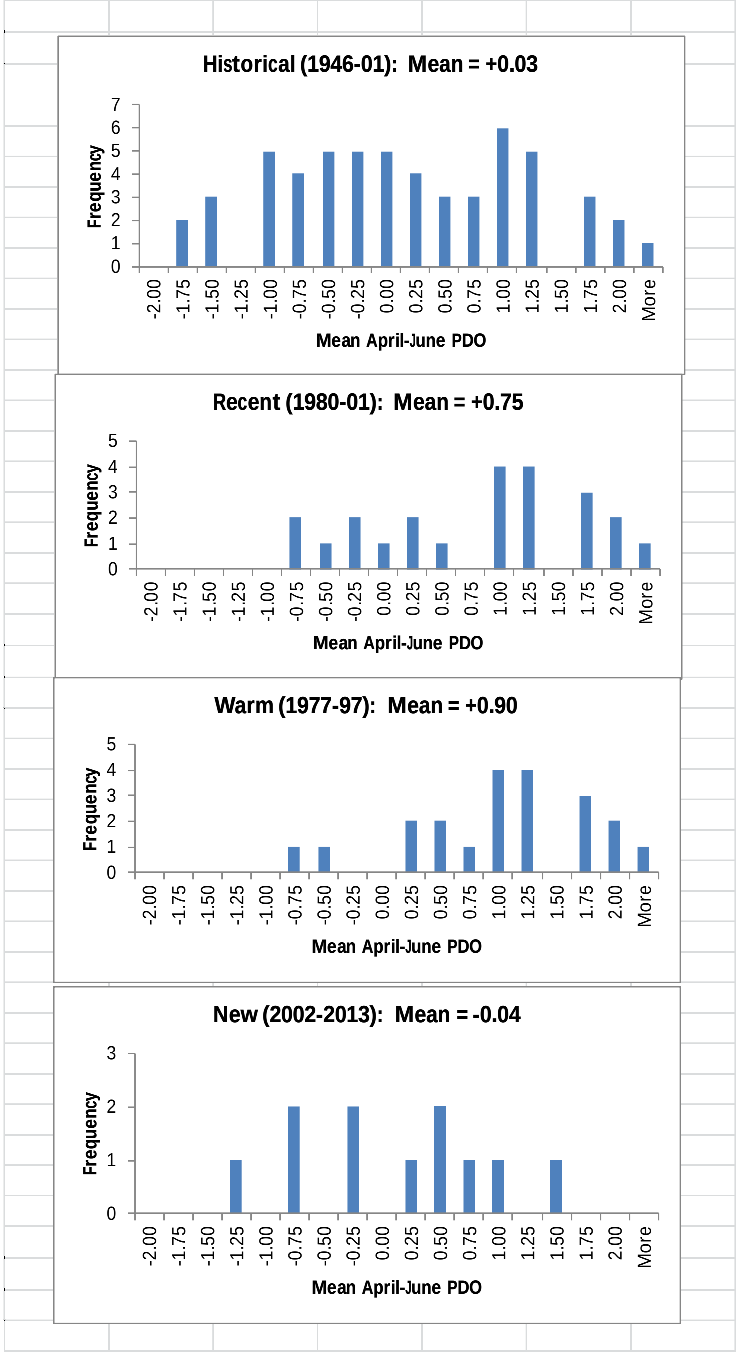


Figure 2.1-33. Pacific decadal oscillation (PDO) index 1946–2012. Positive values are warmer than average and are associated with poor survival of Pacific Northwest salmon and steelhead. Negative values are cooler than average and are associated with higher survival of salmon and steelhead (Source: University of Washington PDO web page: http://jisao.washington.edu/pdo/ downloaded August 20, 2013.) Time periods corresponding to ocean climate scenarios in the 2008 BiOp are displayed.



Historical (1946-01): Mean = +0.03

Recent (1980-01): Mean = +0.75

Warm (1977-97): Mean = +0.90

New (2002-2013): Mean = -0.04

Figure 2.1-34. Histograms showing the frequency of mean spring (April through June) PDO indices. The distribution and mean of new observations since the 2008 BiOp (2002–2013) can be compared with PDO distributions and means represented by three sets of future climate assumptions considered in the 2008 BiOp. Positive values are warmer than average and are associated with poor survival of salmon and steelhead. Negative values are cooler than average and are associated with higher survival of salmon and steelhead (Source of data: University of Washington PDO web page: http://jisao.washington.edu/pdo/ accessed on August 20,2013).

2.1.4.1.2 El Niño Southern Oscillation

Coastal waters off the Pacific Northwest are influenced by atmospheric and ocean conditions not only in the north Pacific Ocean (as indexed by the PDO), but also in equatorial waters, especially during El Niño events. Strong El Niño events result in the transport of warm equatorial waters northward along the coasts of Central America, Mexico, and California and into the coastal waters off Oregon and Washington. El Niño events are of shorter duration than PDO phases, generally lasting 6 to 18 months. El Niño conditions are generally associated with poor survival of salmon and steelhead (e.g., Scheuerell and Williams 2005; Peterson et al. 2012) due to lower productivity and changes in the distribution of predator and prey species. Unusually cool water (La Niña) conditions are generally beneficial to salmon and steelhead. El Niño and La Niña conditions also affect terrestrial climate and hydrology (e.g., Barlow et al. 2001).

The 2008 BiOp Section 5.7.1 described the ENSO in more detail and presented a time series of estimates through November 2007. The ENSO was not included as a predictor variable in modeling the three future climate scenarios in the 2008 BiOp; however, El Niño conditions are likely to have influenced salmonid marine survival during the climate scenario time periods. The 2010 Supplemental BiOp, Section 2.2.1.3.1.6, extended the time series through April 2010 and compared conditions in the last decade with those during the time periods associated with the three climate scenarios considered in the 2008 BiOp. It concluded that El Niño conditions in the past decade had not been as strong as those predicted by either the Recent climate scenario or the Warm PDO climate scenario evaluated in the 2008 BiOp.

It is now possible to further update the ENSO observations and compare them with the 2008 BiOp's assumptions (Figure 2.1-35). During the time periods encompassed by the Recent and Warm PDO climate scenarios, the pattern is described by Peterson et al. (2012) as consisting of two "very large" El Niño events (1983–1984 and 1997–1998), two smaller events (1986 and 1987), and a prolonged event from 1990 to 1995. Since 2001, El Niño events of the same or lower magnitude as the 1986 and 1987 events occurred in 2002 through 2005 and from spring 2009 through May 2010. La Niña conditions occurred in many of the other years.

We used the National Weather Service Climate Prediction Center's definition of warm events[39] to objectively determine if the frequency of warm El Niño events has changed compared to the time periods represented by the 2008 BiOp's three climate assumptions. The frequency of warm event months, defined in this manner, was nearly identical for the time periods represented by the three climate scenarios (25% to 28%) and the period from 2002–2012 (24%). We also compared means of the Oceanic Niño Index (ONI) for all months encompassed by warm events in each of the four BiOp climate periods. We found that the average magnitude of warm events was lowest for the 2002–2012 period, the averages varied by only 0.3°C from the lowest (2002–

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[39] Warm and cold episodes are based on a threshold of ± 0.5°C for the ONI (3 month running mean of ERSST.v3b SST anomalies in the Niño 3.4 region [5°N-5°S, 120°-170°W]), based on centered 30-year Base Periods updated every 5 years. For historical purposes cold and warm episodes are defined when the threshold is met for a minimum of 5 consecutive over-lapping seasons. http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml

2012; 0.9°C) to the highest (Recent; 1.2°C) climate periods. In summary, in years since those that make up the climate scenarios relied upon in the 2008 BiOp, El Niño conditions have not been stronger or more frequent than those implicitly captured in the 2008 BiOp's assumptions.

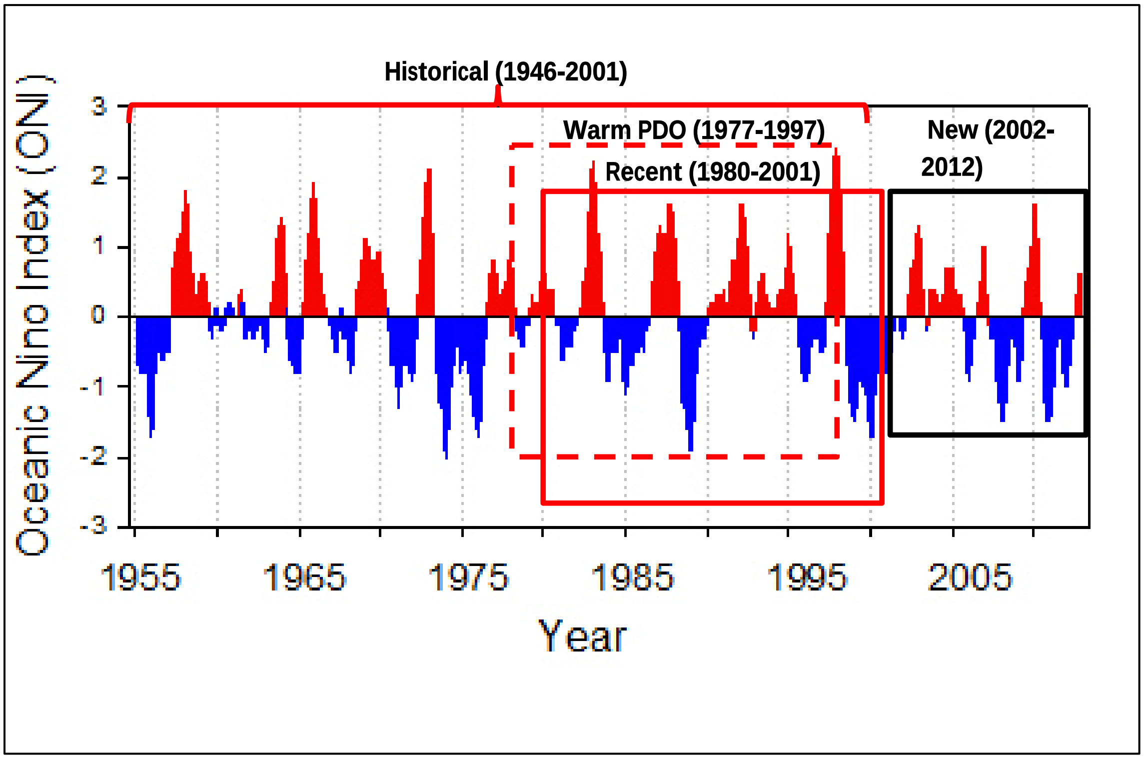

Figure 2.1-35. Values of the Oceanic Niño Index (ONI), 1955 through 2012. Red (positive) values indicate warm conditions in the equatorial Pacific; blue (negative) values indicate cool conditions in equatorial waters. Large and prolonged El Niño events are indicated by large, positive values of the index: note the ONI greater than +2 associated with the 1972, 1983, and 1998 events. Note cool anomalies (La Niña) during 1999–2002 and 2007–spring 2009. A La Niña event developed in equatorial waters from mid-2010 to June 2011, but transitioned to positive values in 2012. Figure and caption are reproduced from Peterson et al. (2012). Time periods corresponding to ocean climate scenarios in the 2008 BiOp have been added.

2.1.4.1.3 Upwelling Index

Upwelling is a wind-driven process that brings nutrients up from depth into the photic zone, increasing ocean productivity and the availability of food for juvenile salmon (Peterson et al. 2012). The 2008 BiOp included a general discussion of upwelling in Section 5.7.2. Salmon survival is generally higher when upwelling is more intense during months corresponding to early ocean growth of juvenile salmon (e.g., Scheuerell and Williams 2005; Petrosky and Schaller 2010), although Peterson et al. (2012) cautions that knowledge of upwelling intensity alone does not always provide good predictions of salmon survival. Factors such as the source of bottom water that is upwelled, and whether El Niño conditions are occurring, can influence the expected upwelling signal as well. Peterson et al. (2012) hypothesize that although upwelling is necessary to stimulate plankton production, its impact is greatest during negative phases of the

PDO. The onset and duration of the upwelling season are also important factors that influence salmon survival (Peterson et al. 2012).

Spring and summer upwelling (exact months dependent upon species) were among the factors used to model the 2008 BiOp's future climate scenarios. Spring (April–May) upwelling intensity was lower than the long-term average in most of the new years subsequent to those represented in the 2008 BiOp's future climate scenarios (Figure 2.1-36). Exceptions were 2007 through 2009, which were greater than the long-term average. The average intensity of spring upwelling in 2002 through 2012 (11.7 m^3/s/100 km) did not differ significantly ($P > 0.24$) from mean estimates associated with the 2008 BiOp's Recent and Warm PDO climate scenarios (11.9 and 10.9 m^3/s/100 km, respectively) but was lower than the Historical average (17.2 m^3/s/100 km, $P = 0.05$).

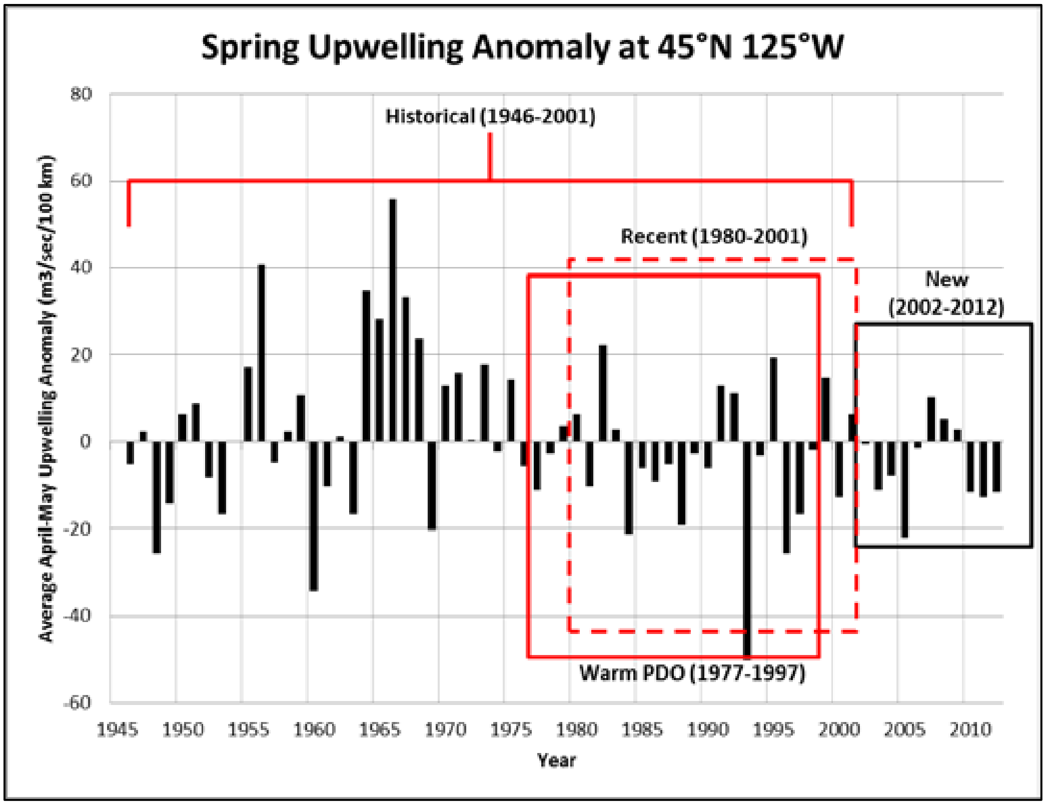

Figure 2.1-36 Anomalies (differences between the 1946–2012 mean and individual yearly values) of the average April and May coastal Upwelling Index, 1946–2012. Positive values represent above-average upwelling and negative values represent below-average upwelling. Units are m^3/s/100 km coastline. Data from NOAA Pacific Fisheries Environmental Laboratory http://www.pfeg.noaa.gov/products/pfel/modeled/indices/upwelling/upwelling.html. Time periods corresponding to ocean climate scenarios in the 2008 BiOp are displayed.

2.1.4.1.4 Ocean Ecosystem Indicators and Overall Pattern of Ocean Conditions

Peterson et al. (2012)—using data collected along the Newport Hydrographic Line and from other Oregon sites and broad areas affecting the Pacific northwest—developed a set of 18 marine indices that represent climatic and biological factors influencing survival of juvenile salmon and steelhead during their first year in the ocean. These indicators include large-scale climate factors described above (PDO, upwelling, and ONI); more local measures of temperature and salinity of coastal waters; and biological drivers such as the copepod community structure, and direct salmon measurements, which were the catches of juvenile Chinook and coho salmon in surveys conducted during their first summer at sea. The indicators are combined into a qualitative assessment of whether the ocean entry conditions in a given year are representative of "good" or "poor" survival of juvenile salmon and steelhead (Table 2.1-20).

Table 2.1-20. Ocean ecosystem indicators, 1998–2012, and rank scores (among the 15 years) upon which color-coding of ocean ecosystem indicators is based. Lower numbers indicate better ocean ecosystem conditions, or "green lights" for salmon growth and survival, with ranks 1–5 green/medium gray, 6–10 yellow/light gray, and 11–15 red/dark gray. To arrive at these rank scores, 15 years of sampling data were compared across years (within each row), and each year received a rank between 1 and 15 (Reproduced from Peterson et al. 2012).

Ecosystem Indicators	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
PDO (December-March)	14	6	3	10	7	15	9	13	11	8	5	1	12	4	2
PDO (May-September)	9	4	6	5	10	14	13	15	11	12	2	8	7	3	1
ONI Jan-June	15	1	1	6	11	12	10	13	7	9	3	8	14	4	5
46050 SST (May-Sept)	13	8	3	4	1	7	15	12	5	14	2	9	6	10	11
NH 05 Upper 20 m T winter prior (Nov-Mar)	15	9	6	8	5	12	13	10	11	4	1	7	14	3	2
NH 05 Upper 20 m T (May-Sept)	13	10	12	4	1	3	15	14	7	8	2	5	11	9	6
NH 05 Deep Temperature	15	4	8	3	1	11	12	13	14	5	2	10	9	6	7
NH 05 Deep Salinity	15	3	6	2	5	13	14	9	7	1	4	11	12	8	10
Copepod Richness Anomaly	15	2	1	6	5	11	10	14	12	9	7	8	13	3	4
N. Copepod Biomass Anomaly	14	10	6	7	4	13	12	15	11	9	3	8	5	1	2
S. Copepod Biomass Anomaly	15	3	5	4	2	10	12	14	11	9	1	7	13	8	6
Biological Transition	14	10	6	5	7	13	9	15	12	2	1	4	11	3	8
Winter Ichthyoplankton	15	7	2	4	5	14	13	9	12	11	1	8	3	10	6
Chinook Juv Catches (June)	14	3	4	12	8	10	13	15	9	7	1	5	6	11	2
Coho Juv Catches (Sept)	11	2	1	4	3	6	12	14	8	9	7	15	13	5	10
Mean of Ranks	13.8	5.5	4.7	5.6	5.0	10.9	12.1	13.0	9.9	7.8	2.8	7.6	9.9	5.9	5.5
RANK of the Mean Rank	15	4	2	6	3	12	13	14	10	9	1	8	11	7	4
Principle Component Scores (PC1)	6.56	-2.22	-2.95	-1.60	-2.12	2.08	3.12	4.21	1.10	-0.30	-4.39	-0.91	1.13	-1.76	-1.96
Principle Component Scores (PC2)	-0.51	0.04	-0.24	-0.76	-1.96	-1.53	2.55	-0.43	-0.66	1.07	-0.50	0.96	-0.74	1.36	1.35
Ecosystem Indicators not included in the mean of ranks or statistical analyses															
Physical Spring Trans (UI Based)	3	6	14	12	4	9	11	15	9	1	5	2	7	8	13
Upwelling Anomaly (Apr-May)	7	1	13	3	6	10	9	15	7	2	4	5	11	13	11
Length of Upwelling Season (UI Based)	6	2	14	9	1	10	8	15	5	3	7	3	11	13	11
NH 05 SST (May-Sept)	10	6	5	4	1	3	15	13	8	12	2	14	9	7	11
Copepod Community Structure	15	3	5	7	2	12	11	14	13	8	1	6	10	9	4

Based on the suite of ocean ecosystem indicators, 1998, 2003 through 2005, and 2010 were years in which ocean entry conditions were generally unfavorable for salmon survival. Favorable years were 1999 through 2000, 2002, 2008, and 2012. It is difficult to compare these qualitative assessments to those predicted by the 2008 BiOp's three future climate scenarios because the rankings are based on a 15-year period that is largely subsequent to the years represented by the scenarios.

This assessment, or a more quantitative model based on 32 indicators (Burke et al. 2013), has been used to predict adult returns 1 to 2 years in the future. The 2010 Supplemental BiOp discussed this index in Section 2.2.1.3.2.7 and predicted relatively high Chinook returns in 2010 and intermediate returns in 2011, based on the 2008 and 2009 ocean ecosystem indicators. As described in Section 2.1.1.5.3 (*Overview of Patterns of Abundance and Productivity*) and in Figure 2.1-22, Chinook returns were above average in these years, as predicted. Future predictions of the ocean ecosystem indicators are considered in Section 2.1.1.6 (*Other Information on the Abundance of Interior Columbia Basin Salmon and Steelhead*), including the need to investigate possible inclusion of additional factors to explain lower than predicted returns in 2013.

2.1.4.1.5 Freshwater Stream Flow

Tributary stream flow is relevant to survival of listed salmon and steelhead during the first 1 to 2 years of life when juvenile salmon and steelhead are rearing in freshwater and when mainstem flows are relevant to smolt survival during seaward migration and following ocean entry. We discuss each in more detail below and compare new observations with those considered directly or indirectly in the 2008 BiOp.

Tributary Stream Flow (Salmon River)

For interior Columbia basin salmon and steelhead that generally rear in snowmelt-fed streams, the lowest flow levels generally occur in late summer or early fall. The level of flow can affect available habitat area; the distribution and availability of prey; refuges from predators; water temperature; and other factors (e.g., Arthaud et al. 2010; Poff and Zimmerman 2010; Nislow and Armstrong 2012; Roni et al. 2013a). This can potentially affect growth and survival of juvenile salmonids. Consistent with these expectations, mean fall (September and October) flow levels in Salmon River tributaries correlate positively with parr-to-smolt survival of juvenile spring/summer Chinook salmon (Crozier and Zabel 2006; Crozier et al. 2008; Crozier and Zabel 2013). Tributary stream flow was not a factor in the ocean climate scenarios evaluated in the 2008 BiOp, and previous FCRPS biological opinions have not presented empirical tributary flow observations.

We present streamflow from the Salmon River in Idaho (Figure 2.1-37) because that is the site used by Crozier and Zabel (2006, 2013) and Crozier et al. (2008) after they determined that it correlated strongly with stream flow within various tributaries of the Salmon River. This site also has a long historical flow record with few data gaps. Figure 2.1-38 indicates that the approximately 1980 through 2001 Base Period included a range of mean fall flows that were nearly equally distributed above and below the 1946 to 2012 long-term average. In contrast, most of the recent observations have been lower than the long-term average, with the mean fall flow level for the recent years (1,020 cfs) lower than the Base Period mean (1,158 cfs). This suggests that streamflow conditions have been less favorable to parr-to-smolt survival since the 2008 BiOp's Base Period, at least for interior Columbia basin spring/summer Chinook. Because of similarities in juvenile rearing requirements, this is likely true for juvenile steelhead in the interior Columbia basin as well.

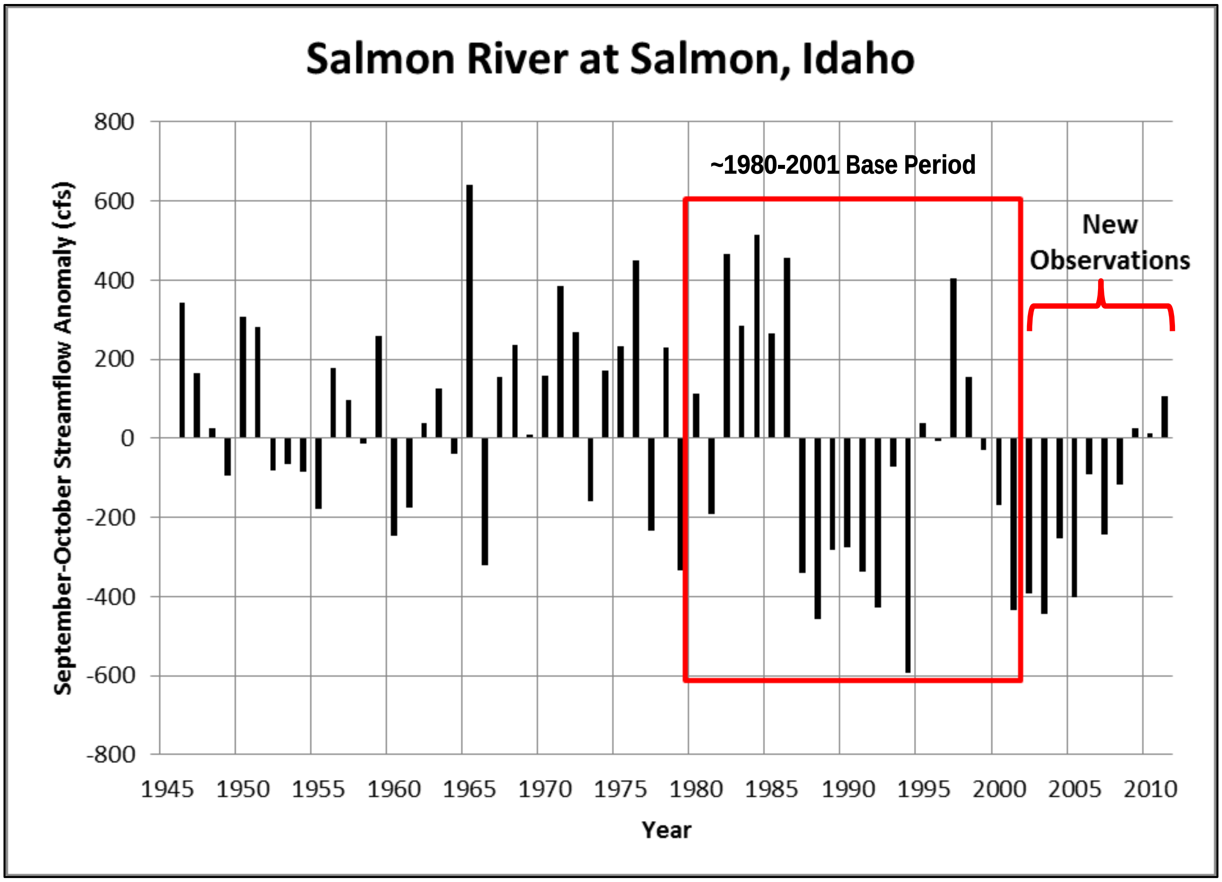

Figure 2.1-37. Anomalies (differences between the 1946–2011 mean and individual yearly values) of the average September and October streamflow in the Salmon River at Salmon, Idaho, 1946–2012. Positive values represent above-average flows and negative values represent below-average flows. Units are cubic feet per second (cfs). The 2008 BiOp's Base Period of approximately 1980–2000 is indicated by the red box, followed by new observations. Data are from U.S. Geological Survey Station 13302500, available from: http://waterdata.usgs.gov/id/nwis/uv/?site_no=13302500&PARAmeter_cd=00065,00060,00010

Mainstem Snake/Columbia Stream Flow

Section 5.1.3 of the 2008 BiOp describes several effects of mainstem Snake and Columbia River flow on survival of smolts during seaward migration. Increased flow generally increases migration speed, which decreases exposure to factors such as predation and temperature stress in reservoirs (e.g., Ferguson 1995), and it affects ocean entry timing and early ocean survival (Scheurell et al. 2009). Juvenile survival through the hydropower system is correlated with water travel time (Haeseker et al. 2012), which is in part a function of flow. Water travel time, derived from mean springtime Columbia River flow at Bonneville Dam, was included as a factor in determining the three future ocean climate conditions in the 2008 BiOp (ICTRT and Zabel 2007).

Consistent with ICTRT and Zabel (2007), we compared mean springtime flow at Bonneville Dam after 2001 with Columbia River flows during the 2008 BiOp's Base Period (Recent climate scenario) and the periods represented by the Historical and Warm PDO climate scenarios (Figure

2.1-35). Columbia River spring flows during the years since the 2008 BiOp (2002–2011) averaged 263 thousand cubic feet per second (kcfs), which was nearly identical to the mean flow of 262 kcfs during the 1980–2001 Base Period (and Recent climate scenario). Lowest Columbia River flows during the new years were in 2005 and 2010 (affecting smolt migration of the 2003 and 2008 brood years of spring Chinook and steelhead), while the highest flows were in 2006 and 2011 (2004 and 2009 brood years). Mean flows during the years corresponding to the Warm PDO climate scenario were lower (256 kcfs) than the more recent means; and the mean for the Historical climate scenario was higher (289 kcfs) than the more recent means.

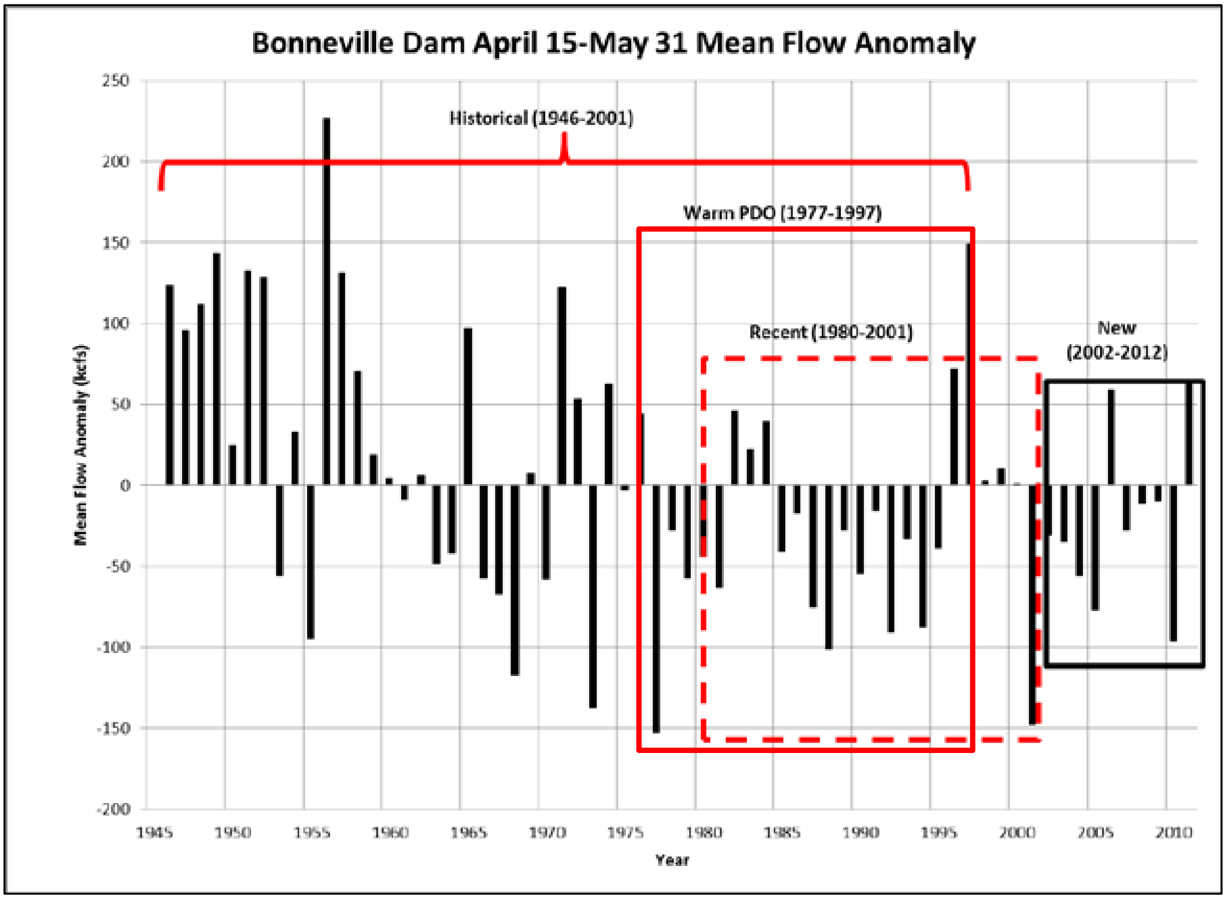

Figure 2.1-38. Anomalies (differences between the 1946–2011 mean and individual yearly values) of the average April 15 through May 31 Columbia River flow at Bonneville Dam in thousand cubic feet per second (kcfs). Periods corresponding to ocean climate scenarios in the 2008 BiOp are indicated. Raw data from the Corps, summarized by the Fish Passage Center (spreadsheet: WTT calcs 29-11 from cp w UC.xls).

2.1.4.1.6 Freshwater Temperatures

Tributary Stream Temperatures

Stream temperature can affect growth and survival of juvenile salmon and steelhead rearing in interior Columbia basin streams. The ISAB (2007b) reviewed temperature effects on juvenile salmon including:

- Excluding fish from reaches with temperatures at or near their thermal tolerance
- Increasing metabolism at higher temperatures, thereby either increasing or decreasing fish growth rate, depending upon the availability of food
- Increasing the metabolism of predators at higher temperatures, thereby increasing predation rates on salmonids
- Affecting susceptibility to pathogens and parasites, which increases when fish become thermally stressed
- Affecting migration timing
- Affecting survival in subsequent life stages based on the fish size and migration timing determined in part by temperature during juvenile rearing

Consistent with these expectations, mean summer (May through August) temperatures in Salmon River tributaries negatively correlate with parr-to-smolt survival of some populations of juvenile spring/summer Chinook salmon, while having a neutral or positive effect on other populations (Crozier et al. 2010; Crozier and Zabel 2013). Tributary temperature was not a factor in defining the ocean climate scenarios evaluated in the 2008 BiOp. Previous FCRPS biological opinions have not presented tributary temperature data.

Crozier et al. (2010) found that cumulative growing degree-days[40] measured in various streams in the Salmon River basin correlate strongly with mean May–August air temperature, which was also a strong predictor of fish length. An advantage of using air temperature, rather than stream temperature, is that most of the stream temperature data sets in the interior Columbia basin are of relatively short duration or of irregular length. We therefore present mean monthly air temperature in the Salmon River basin, as used by Crozier et al. (2010) and Crozier and Zabel (2013) in Figure 2.1-39.

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[40] "Growing degree-days" are defined as the sum of daily mean temperatures in Celsius during the period of salmon growth.

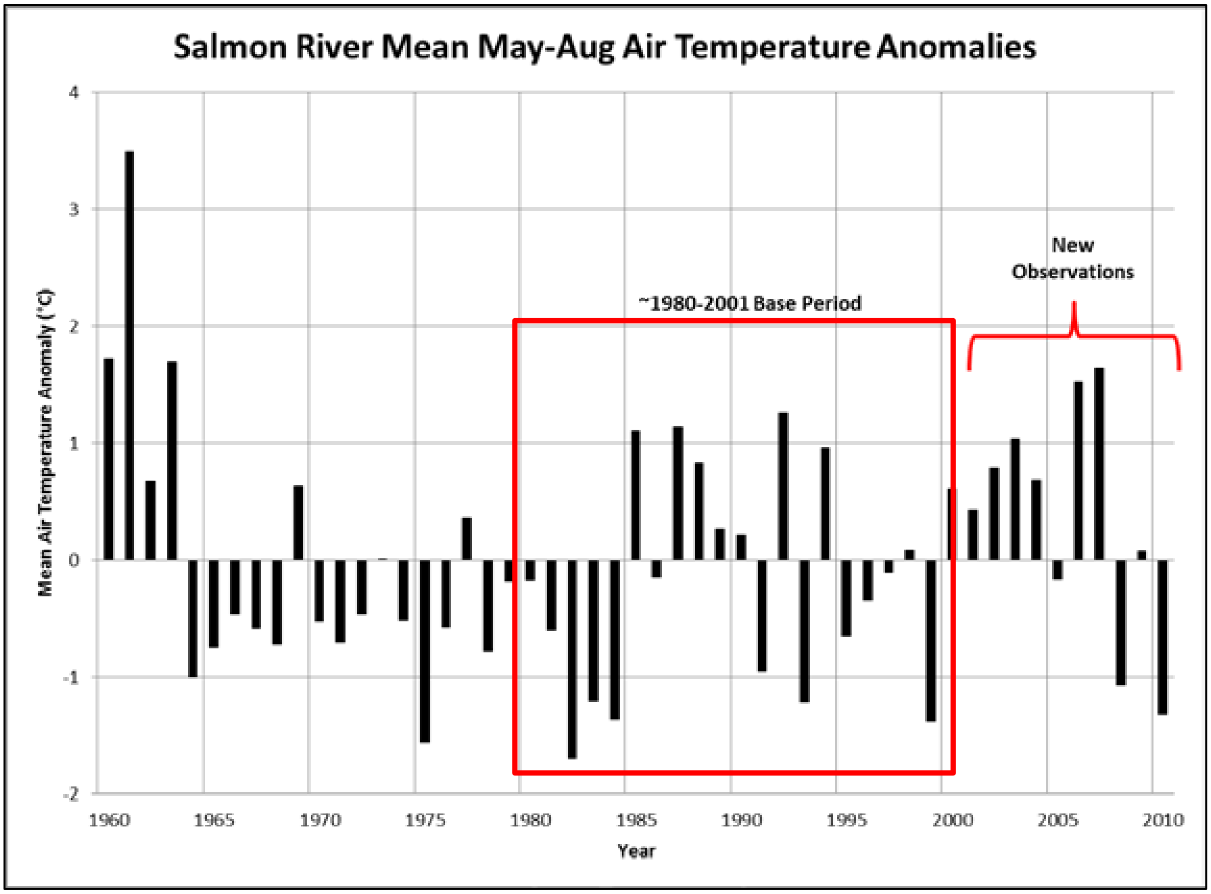

Figure 2.1-39. Anomalies (differences between the 1960–2010 mean and individual yearly values) of the average May through August air temperatures from meteorological stations in the Salmon River basin. As described in the text, air temperatures correlate strongly with stream temperatures and fish growth. Time periods corresponding to the 2008 BiOp's Base Period and more recent observations are indicated. Raw data provided by the NOAA Western Regional Climate Center (http://www.wrcc.dri.edu/climsum.html) and basin averages provided by L. Crozier, NOAA Fisheries.

Figure 2.1-39 indicates that new observations since the 2008 BiOp include a higher percentage of years with above-average mean temperatures than the percentage of above-average years in the 2008 BiOp's approximate Base Period. The mean temperature of all years in the new period was higher than that of the Base Period (12.1°C versus 11.7°C). Based on Crozier and Zabel (2013), these higher temperatures in recent years could be associated with lower parr-to-smolt survival for some Salmon River spring/summer Chinook populations. However, it could also have resulted in higher growth rates and larger smolt sizes—which would lead to higher survival rates in other life stages that could compensate for reduced survival at the parr-to-smolt life stage.

Mainstem Columbia River Temperatures

Mainstem Columbia River temperature can affect timing and survival of adult and juvenile salmon and steelhead migrating through the mainstem Snake and Columbia rivers (e.g., Crozier et al. 2011). The ISAB (2007b) noted that higher temperatures during adult migration may lead to increased mortality or reduced spawning success as a result of lethal temperatures, delay, increased fallback at dams, or increased susceptibility to disease and pathogens. Crozier et al. (2011) showed a rise of 2.6°C in mean July water temperature in the lower Columbia River at Bonneville Dam between 1949 and 2010.

Effects of increasing water temperatures on adult passage were particularly apparent in 2013. As described in Section 3.3, high temperature in the adult fish ladder at Lower Granite Dam in July resulted in failure of adult SR sockeye salmon, summer-run SR spring/summer Chinook, and SR steelhead to pass the dam for approximately one week. A second high-temperature event in September 2013 resulted in failure of adult SR fall Chinook and SR steelhead to pass the dam for about a week. Remedies to reduce the likelihood of similar occurrences in the future are discussed in Section 3.3.

We used the same Bonneville Dam temperature data as Crozier et al. (2011)[41], which was obtained from DART[42] (2013) to more specifically evaluate the pattern of mainstem temperatures during the Base Period and extended Base Periods (Figures 2.1-40 and 2.1-41).

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[41] December 2, 2013, email from L. Crozier to C. Toole, "temp data." Includes spreadsheets "Dam conditions 2008 2013.xlsx", "Bonntemps3nospikes.csv", and "Plastic.raw19392010.csv."

[42] Columbia River Data Access in Real Time (DART) at http://www.cbr.washington.edu/dart/dart.html. Accessed November 2013.

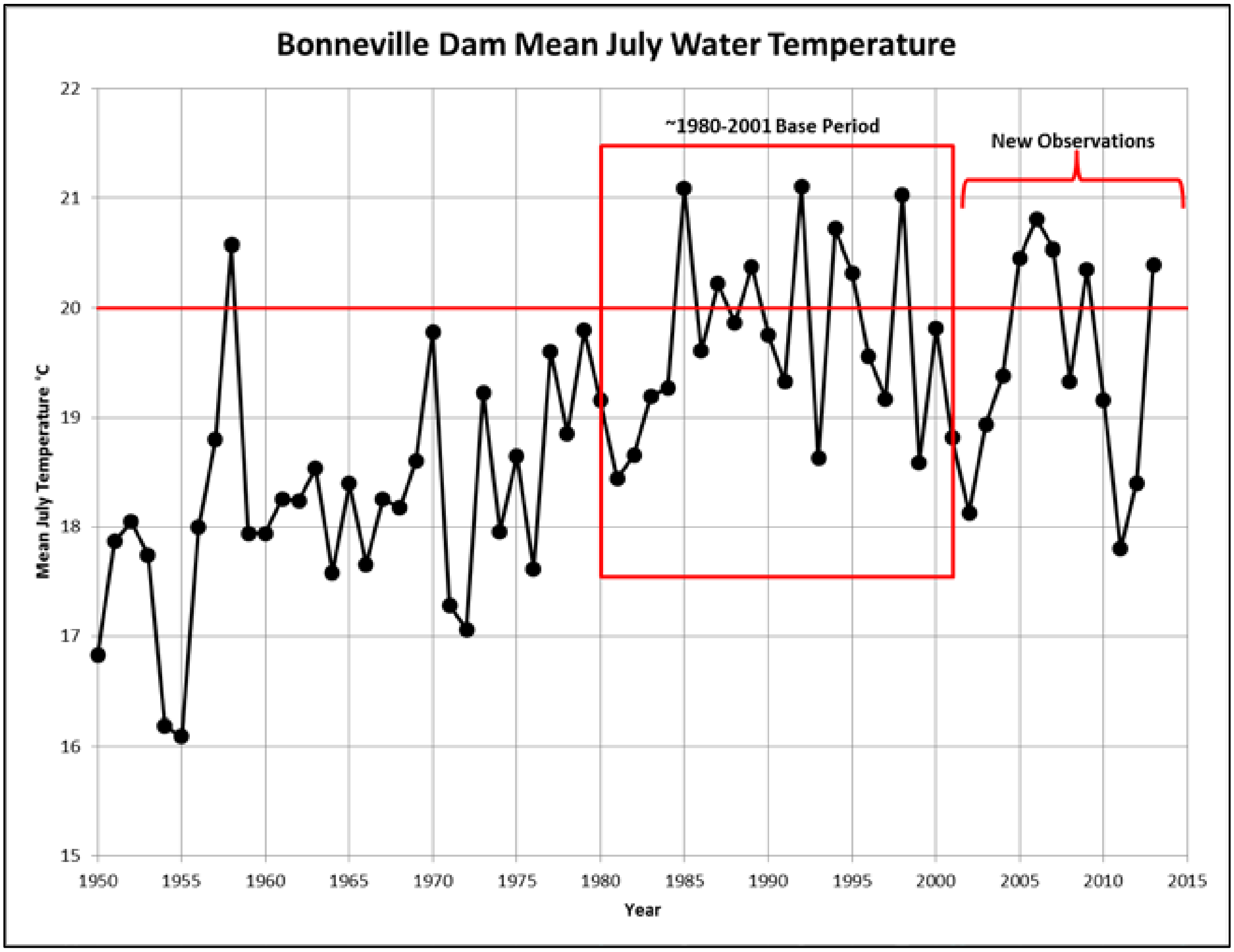

Figure 2.1-40. Mean July water temperature at Bonneville Dam, 1950 through 2013. The Washington State Water Quality Standard of 20°C is displayed. Time periods corresponding to the 2008 BiOp's Base Period and more recent observations are indicated. Data obtained from Columbia River Data Access in Real Time (DART; http://www.cbr.washington.edu/dart/dart.html). Accessed November 2013.

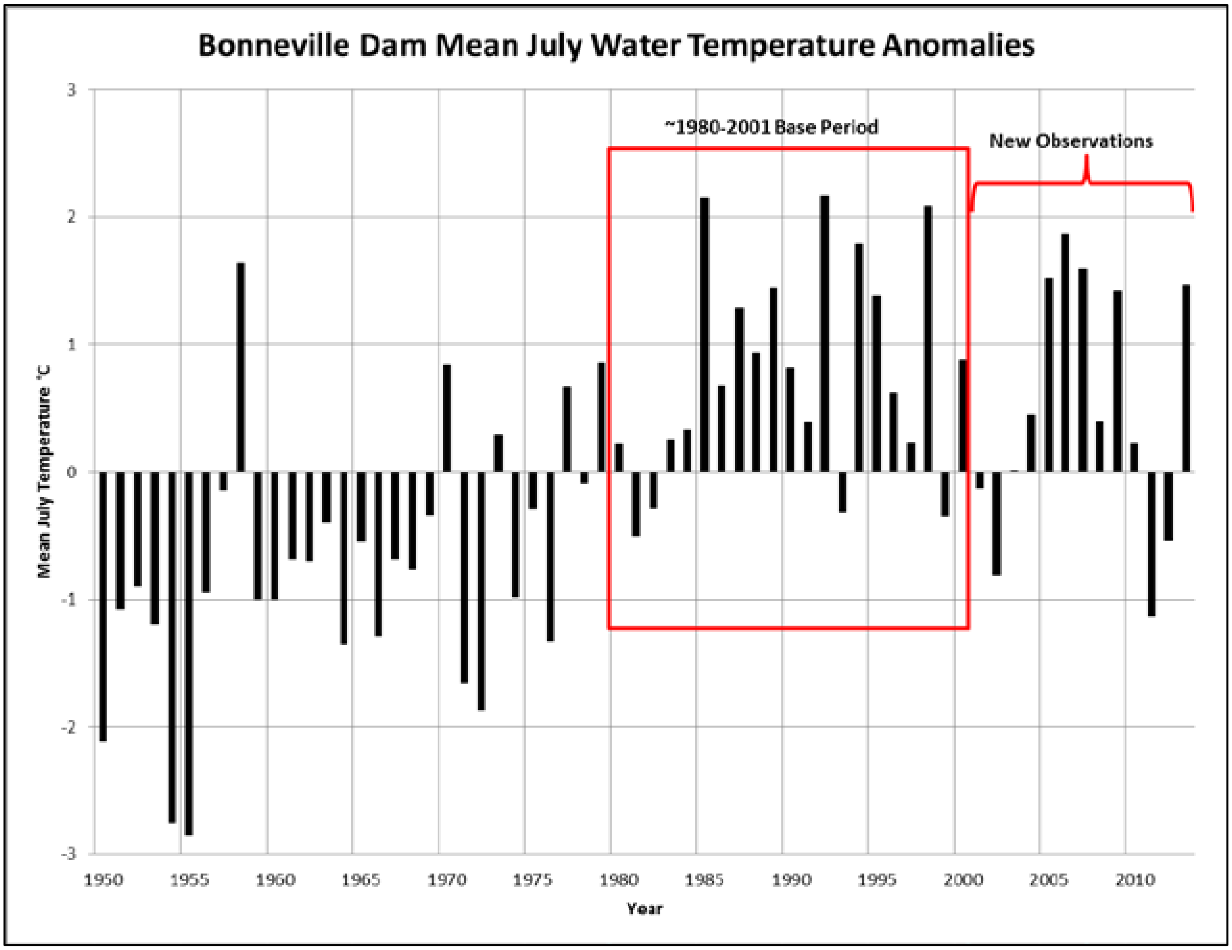

Figure 2.1-41. Anomalies (differences between the 1950–2010 mean and individual yearly values) of the average July water temperature at Bonneville Dam. Time periods corresponding to the 2008 BiOp's Base Period and more recent observations are indicated. Data obtained from Columbia River Data Access in Real Time (DART; http://www.cbr.washington.edu/dart/dart.html). Accessed November 2013.

Mean July water temperatures at Bonneville have increased since 1950, with temperatures predominantly higher than average since the early 1980s. Seven of 22 years (32%) averaged above 20°C during the 2008 BiOp's Base Period, while 5 of 12 recent years (42%) averaged higher than 20°C. The overall mean temperatures were nearly identical for the 2008 BiOp's Base Period (19.7 ±0.4°C) and the more recent observations (19.5 ±0.7°C).

2.1.4.2 Recent Information Regarding Climate Change

The 2008 BiOp included information on climate change that was published through 2007. The primary sources of information were the ISAB's review of climate change impacts on Columbia River basin fish and wildlife (ISAB 2007b), the ICTRT's ocean climate scenarios for use in quantitative analyses (ICTRT and Zabel 2007), and a modeling analysis of potential effects of climate change on freshwater stages of SR spring Chinook (Crozier et al. 2008). This information was used to assess effects of the RPA under climate change and to develop elements of the RPA that would implement climate change mitigation actions recommended by the ISAB (2007b) in the 2008 BiOp Section 8.1.3.

Section 2.2.1.3 of the 2010 Supplemental BiOp reviewed subsequently available climate change literature (through 2009) that was relevant to Pacific Northwest salmonids and made the following conclusions:

- New observations and predictions regarding physical effects of climate change were within the range of assumptions considered in the 2008 BiOp and the AMIP.
- New studies of biological effects of climate change on salmon and steelhead provided additional details on effects previously considered and suggest that the adult life stage may need particular attention through monitoring and proactive actions envisioned in the AMIP. (The 2010 Supplemental BiOp included amendments to the AMIP to address this point).
- The types of potentially beneficial actions identified by ISAB (2007b) and implemented through the RPA are consistent with the types of adaptation actions described in current literature.

This section briefly reviews the climate change effects considered in the 2008 BiOp and discusses additional information regarding climate change that has become available since the 2008 BiOp was issued. It concludes that, while additional details regarding observed and forecasted effects of climate change on Pacific Northwest salmonids have become available in recent years, the effects remain consistent with those described in the 2008 BiOp.

2.1.4.2.1 Review of Climate Change Effects Considered in the 2008 BiOp

The 2008 BiOp relied primarily upon the review of climate change effects on salmonids prepared by the NPCC's ISAB (2007b). This report summarized the key effects of climate change and related them to salmon life history in a figure that is reproduced here as Figure 2.1-42.

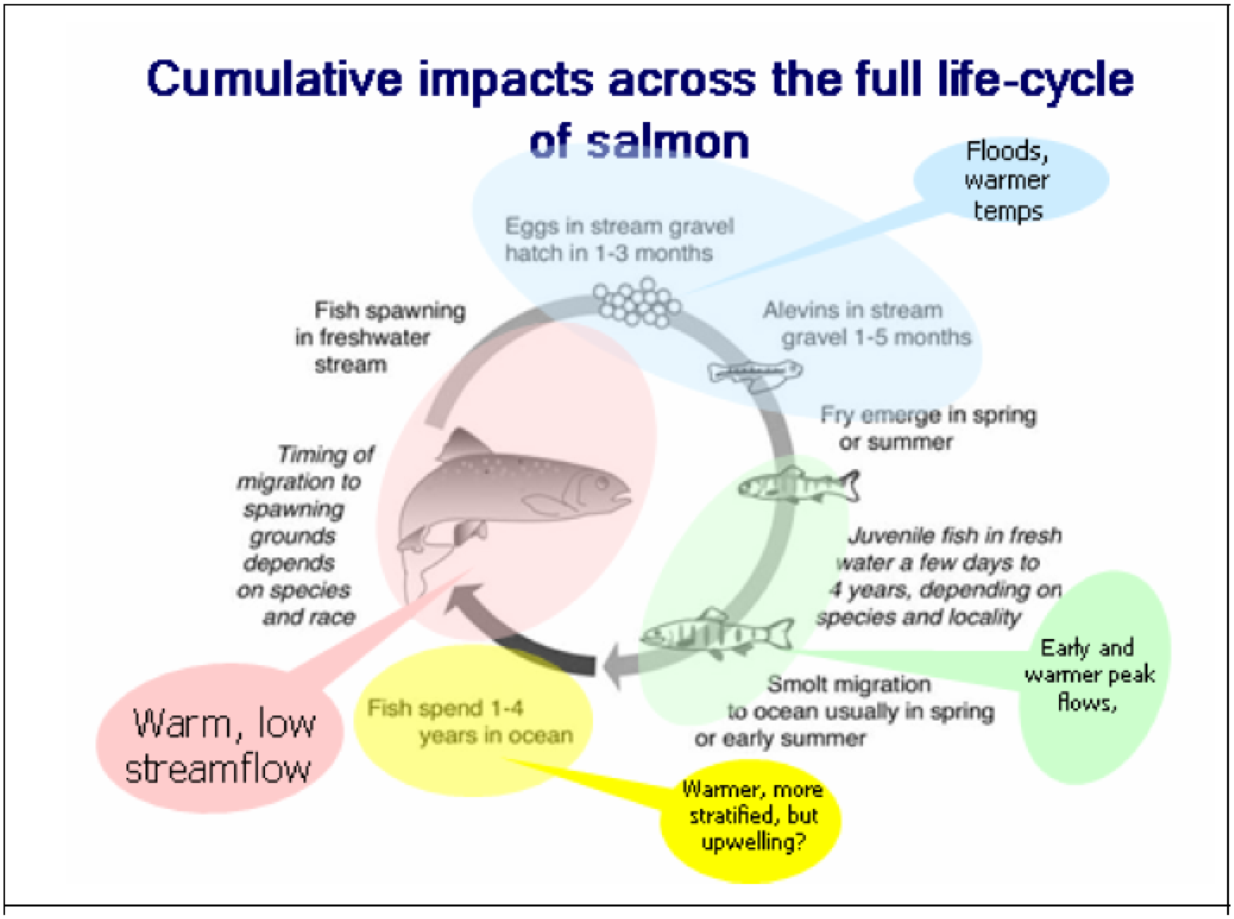

Figure 2.1-42. Illustration of the points in the salmon life history where climate change may have an effect. Reproduced from ISAB (2007b) Figure 24.

The effects of climate change that were summarized from ISAB (2007b) and other sources in the 2008 SCA Section 5.7.3, and incorporated by reference into the 2008 BiOp's description of the environmental baseline, included the following.

Freshwater Environment

Climate records show that the Pacific Northwest has warmed about 1.0°C since 1900 or about 50% more than the global average warming over the same period. The warming rate for the Pacific Northwest over the next century is projected to be in the range of 0.1°C to 0.6°C per decade. Although total precipitation changes are predicted to be minor (+ 1% to 2%), increasing air temperature will alter the snowpack, stream flow timing and volume, and water temperature in the Columbia River basin. Climate experts predict the following physical changes to rivers and streams in the Columbia basin:

- Warmer temperatures will result in more precipitation falling as rain rather than snow.
- Snowpack will diminish, and stream flow volume and timing will be altered.
  - More winter flooding is expected in transient[43] and rainfall-dominated basins.
  - Historically transient watersheds will experience lower late summer flows.
- A trend towards loss of snowmelt-dominant and transitional basins is predicted.
- Summer and fall water temperatures will continue to rise.

These changes in air temperatures, river temperatures, and river flows are expected to cause changes in salmon and steelhead distribution, behavior, growth, and survival. Although the magnitude and timing of these changes currently are poorly understood and specific effects are likely to vary among populations, the following effects on listed salmon and steelhead in freshwater are likely:

- Winter flooding in transient and rainfall-dominated watersheds may scour redds, reducing egg survival.
- Warmer water temperatures during incubation may result in earlier fry emergence, which could be either beneficial or detrimental depending on location and prey availability.
- Reduced summer and fall flows may reduce the quality and quantity of juvenile rearing habitat, strand fish, or make fish more susceptible to predation and disease.
- Reduced flows and higher temperatures in late summer and fall may decrease parr-to-smolt survival.
- Warmer temperatures will increase metabolism, which may either increase or decrease juvenile growth rates and survival, depending on availability of food.
- Overwintering survival may be reduced if increased flooding reduces suitable habitat.
- Timing of smolt migration may be altered such that there is a mismatch with ocean conditions and predators.

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[43] Transient watersheds have streamflow that is strongly influenced by both direct runoff from rainfall and springtime snowmelt because surface temperatures in winter typically fluctuate around the freezing point. Over the course of a given winter, precipitation in transient watersheds frequently fluctuates between snow and rain depending on relatively small changes in air temperature (Mantua et al. 2009).

- Higher temperatures during adult migration may lead to increased mortality or reduced spawning success as a result of lethal temperatures, delay, increased fallback at dams, or increased susceptibility to disease and pathogens.

The degree to which phenotypic or genetic adaptations may partially offset these effects is being studied but currently is poorly understood.

Estuarine Environment

Climate change also will affect salmon and steelhead in the estuarine and marine environments. Effects of climate change on salmon and steelhead in estuaries include the following:

- Warmer waters in shallow rearing habitat may alter growth, disease susceptibility, and direct lethal or sublethal effects.
- Increased sediment deposition and wave damage may reduce the quality of rearing habitat because of higher winter freshwater flows and higher sea level elevation.
- Lower freshwater flows in late spring and summer may lead to upstream extension of the salt wedge, possibly influencing the distribution of salmonid prey and predators.
- Increased temperature of freshwater inflows and seasonal expansion of freshwater habitats may extend the range of warm-adapted non-indigenous species that are normally found only in freshwater.

In all of these cases, the specific effects on salmon and steelhead abundance, productivity, spatial distribution, and diversity are poorly understood.

Marine Environment

Effects of climate change in marine environments include increased ocean temperature, increased stratification of the water column, and changes in intensity and timing of coastal upwelling. Hypotheses differ regarding whether coastal upwelling will decrease or intensify, but, even if it intensifies, the increased stratification of the water column may reduce the ability of upwelling to bring nutrient-rich water to the surface. There are also indications in climate models that future conditions in the North Pacific region will trend towards conditions during warm phases of the PDO. Hypoxic conditions observed along the continental shelf in recent years appear to be related to shifts in upwelling and wind patterns, which may be related to climate change.

These continuing changes are expected to alter primary and secondary productivity, the structure of marine communities (particularly the distribution of predators and prey), and in turn, the growth, productivity, survival, and migrations of salmonids, although the degree of impact on listed salmonids currently is poorly understood. A mismatch between earlier smolt migrations (because of earlier peak spring freshwater flows and decreased incubation period) and altered upwelling may reduce marine survival rates. Ocean warming also may change migration patterns, increasing distances to feeding areas.

In addition, rising atmospheric carbon dioxide concentrations drive changes in seawater chemistry, increasing the acidification of seawater. This reduces the availability of carbonate for shell-forming invertebrates (e.g., pteropods, which are prey for some species of salmon and prey for some forage fish that are consumed by salmon), reducing their growth and survival. This process of acidification is underway, has been well documented along the Pacific coast of the U.S, and is predicted to accelerate with increasing emissions.

2.1.4.3 Updated Climate Change Information Since the 2010 Supplemental BiOp

In addition to the 2007–2009 scientific literature on climate change that was reviewed in the 2010 Supplemental BiOp, NOAA Fisheries reviewed hundreds of scientific papers published from 2010 through 2012 that are relevant to effects of climate change on Pacific Northwest salmonids (Crozier 2011, 2012, 2013). The Crozier (2011 and 2012) reports were included as attachments to the Action Agencies' annual progress reports.[44] All three reviews (Crozier 2011, 2012, 2013) are included as Appendix D of this Supplemental Opinion. NOAA Fisheries will continue to update annual literature reviews as an element of AMIP implementation (see AMIP III.F), with a full review of 2013 literature available by summer 2014. NOAA Fisheries reviewed available 2013 scientific literature, examples of which are referenced in this section.

Other recent reviews of ongoing and expected changes in Pacific Northwest climate that are relevant to listed salmon and steelhead include the U.S. Global Change Research Program's national climate change impacts assessment (Karl et al. 2009; NCADAC 2013 DRAFT), the Washington Climate Change Impacts Assessment (CIG 2009), and the Oregon Climate Assessment (OCCRI 2010). The NCADAC (2013) includes a chapter that specifically reviews physical and biological climate change impacts in the Pacific Northwest (Dalton et al. 2013). These climate change assessments include empirical observations and climate model projections. The regional climate assessments include projections from the International Panel on Climate Change global climate models (IPCC 2007), which were then downscaled to reflect regional terrestrial and aquatic conditions (e.g., Salathe 2005) and ocean conditions (e.g., Stock et al. 2011). A new IPCC global climate assessment is currently underway, with new global climate projections expected by 2014.

Recent information concerning climate impacts on oceans and coastal resources is reviewed in Griffis and Howard (2012). Additional reviews of marine climate effects relevant to the Pacific Northwest, such as ocean acidification and sea level change, are included in the Oregon and Washington climate assessments (Huppert et al. 2009; Mote et al. 2010; Ruggiero et al. 2010). Key research on ocean acidification is reviewed in Feely et al. (2012) and includes Feely et al.

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[44] These reviews are also available on the Northwest Fisheries Science Center web site: http://www.nwfsc.noaa.gov/trt/lcm/docs/Climate%20Literature%20Review_py2011.pdf and http://www.nwfsc.noaa.gov/trt/lcm/docs/Climate%20Literature%20Review_py2010.pdf

(2008). Mote et al. (2009), Ruggiero et al. (2010), and NRC (2012) described observed sea level height changes along the Pacific coast and reviewed literature projecting sea level changes in the Pacific Northwest, which can affect rearing habitat of salmonids. Various localized studies of projected sea level height changes are also available (e.g., Glick et al. 2007; Sharp et al. 2013).

Recent reviews of the effects of climate change on the biology of salmon and steelhead in the Columbia River basin and the California Current region, subsequent to ISAB (2007b) and additional to Crozier (2011, 2012, 2013) reviews, include sections of the Oregon and Washington climate assessments (Huppert et al. 2009; Mantua et al. 2009, 2010; Hixon et al. 2010; Stout et al. 2010; Ford 2011). Adaptation strategies that contain measures to reduce impacts of climate change on Pacific Northwest salmon and steelhead include, in addition to ISAB (2007b), the interim Washington Climate Change Response Strategy (WDOE 2011); the Oregon Climate Change Adaptation Framework (ODLCD 2010); the National Fish, Wildlife, and Plants Climate Adaptation Strategy (NFWPCAP 2012); and the North Pacific Landscape Conservation Cooperative's reviews of marine and freshwater adaptation strategies (Tillmann and Siemann 2011a, 2011b). Beechie et al. (2012) produced an important description of best methods for restoring salmon and steelhead habitat in the face of climate change (see Section 2.1.4.5 for details). Several recent studies present recommendations for application of climate change information to management decisions, including McClure et al. (2013; multiple salmonid species), Wainwright and Weitkamp (2013; Oregon coast coho salmon), and Wade et al. (2013; Pacific Northwest steelhead).

Overall, new climate change information subsequent to the 2008 BiOp supports and adds detail to the information relied upon in that biological opinion. Crozier (2011, 2012, 2013; Appendix D in this Supplemental Opinion) describes results of hundreds of scientific papers relevant to effects of climate on Pacific Northwest salmon and steelhead that have been published since the literature reviewed in the 2008/2010 BiOps. *We refer the reader to those reviews for more information, but in the remainder of this section briefly describe a few examples of studies that are relevant to the current and future status of listed species, and relevant to expected effects of the RPA.*

2.1.4.4 Physical Effects of Climate Change

2.1.4.4.1 Recent Observations

In addition to the results displayed in Section 2.1.4.1, recent observations of climate trends in the scientific literature are generally consistent with expectations in the 2008 BiOp, and the capacity for monitoring these trends in the Pacific Northwest is increasing. For example, a variety of recent studies found significant trends in temperature, precipitation, and flow both within the Columbia River basin and over broader spatial scales.

Arismendi et al. (2012) and Isaak et al. (2012) found stream temperatures getting warmer within the Columbia River basin, although results were dependent upon length of the time series and whether the rivers were regulated or not. Arismendi et al. (2012) found significant warming trends when longer records were available—roughly 44% of streams with records prior to 1987 had significant warming trends. However, cooling trends predominated in the shorter time series, despite significant warming of air temperature in many cases. The authors noted a correlation between base flow and riparian shading with these cooling trends. Human-impacted sites showed less variability over time, likely due to flow regulation and reservoir heat storage. Isaak et al. (2012) demonstrated statistically significant warming trends from 1980 to 2009 on seven unregulated streams in the Pacific Northwest in summer (0.22ºC per decade), fall, and winter, producing a net warming trend annually despite a cooling trend in spring. Stream temperature trends correlated strongly with air temperature, showing the expected signal from regional climate warming. Trends in 11 regulated streams were in the same direction, but were not statistically significant, indicating that modified flows, in some cases explicitly for temperature management, can limit stream thermal response to climate drivers.

To increase the capability to monitor and project stream temperatures, Isaak and colleagues have assembled a Pacific Northwest stream temperature database[45] that was compiled from temperature records provided by hundreds of biologists and hydrologists working for numerous resource agencies. It contains more than 45,000,000 hourly temperature recordings at more than 15,000 unique stream sites. These temperature data are being used with spatial statistical stream network models to develop a more accurate and consistent baseline for describing current conditions and comparing the impact of future scenarios. NOAA Fisheries and Action Agency contributions to this regional database constitute the primary implementation of AMIP Amendment 3 (2010 Supplemental BiOp, Section 3.2; also see Section 3.9 of this Supplemental Opinion, *RPA Implementation to Address the Effects of Climate Change*).

As another example, consistent with the expectation of changes in hydrology, Jefferson (2011) found that transitional areas in 29 watersheds in the Pacific Northwest demonstrate significant historical trends of increasing winter and decreasing summer discharge. Snow-dominated watersheds showed changes in the timing of runoff (22 to 27 days earlier) and lower low-flows (5% to 9% lower) than in 1962.

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[45] NorWest: http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html

Crozier (2011, 2012, 2013) also reviewed studies of observed trends in the marine environment, including studies that

- Reviewed the chemistry of offshore waters near Vancouver Island and the Strait of Juan de Fuca, that indicated increases in dissolved carbon dioxide levels (associated with ocean acidification), which correlated with increases in atmospheric carbon dioxide.
- Described variable reports of trends in coastal upwelling intensity along the Pacific coast, with one recent comprehensive study concluding that upwelling events have become less frequent, stronger, and longer in duration off Oregon and California.
- Tracked low-oxygen (hypoxic) conditions in the Columbia River estuary that are associated with upwelling and Columbia River flow and may be exacerbated with climate change, and documented decreased oxygen levels off Newport, Oregon and a thickening of the oxygen minimum zone.
- Described changes in sea level height along the Pacific coast, including the effects of local geology and other factors.

2.1.4.4.2 Climate Change Projections

In addition to the reviews of observed changes in climate to date, a considerable body of literature has developed that uses models to project continuing climate change in the Pacific Northwest. These projections are generally consistent with expectations in the 2008 BiOp.

A particularly relevant example is a projection of mainstem Columbia River hydrology under climate change (Brekke et al. 2010; USBR et al. 2011). The Action Agencies are using these projections to plan for flood control, power management, and fish impacts (e.g., summer flow targets per RPA Action 4) in response to effects of climate change. Hydroregulations based on these climate projections also are being considered in the ongoing Columbia River Treaty review. Numerous other climate projections produced since the 2008 BiOp are included in the state and national climate assessments described above and in Crozier (2011, 2012, 2013).

There have also been advances in projecting tributary temperature and hydrologic changes. A recent example is Wu et al. (2012), who projected decreased summer streamflow (19.3% in 2020s to 30.3% in 2080s) in Pacific Northwest streams and increases in mean summer stream temperatures from 0.92°C to 2.10°C. The simulations indicate that projected climate change will have greater impacts on snow dominant streams, with lower summer streamflows and warmer summer stream temperature changes relative to transient and rain dominant regimes. Lower summer flows combined with warmer stream temperatures suggest a future with widespread increased summertime thermal stress for cold-water fish in the Pacific Northwest region.

An example of new projections of marine effects is Gruber et al. (2012), who estimated changes in ocean acidification in the California Current under two climate change scenarios. Their model projected that by the 2050s, 70% of the euphotic zone (top 60m) of nearshore (within 10km of the coast) habitat will be undersaturated for aragonite (the form of calcium carbonate generally used in shell formation) during the entire summer, and over 50% will be undersaturated year-round, regardless of emissions scenario.

The Pacific Northwest has increased its capacity to both develop downscaled climate projections and to interpret and apply them in recent years. In particular, two consortiums of academic and agency researchers have been formed to address Pacific Northwest climate research and outreach needs: the Climate Impacts Research Consortium[46] and the Northwest Climate Science Center.[47] The Interior Department has formed two Landscape Conservation Cooperatives[48] that generate applied climate research, outreach, and management planning for the Columbia River basin; and a variety of other public and private entities are providing and applying climate projections to support adaptation planning in the region.

2.1.4.5 Biological Effects of Climate Change on Salmonids

Recent scientific studies regarding biological effects of climate change are generally consistent with expectations in the 2008 BiOp; however, some studies provide new details and have implications that are particularly relevant to listed salmonids in the Columbia River basin. A few examples follow—details are in Crozier (2011, 2012, 2013) and Crozier and Zabel (2013).

A key piece of new information regarding likely effects of climate change on juvenile salmonid survival is Crozier and Zabel (2013). The 2008 BiOp Section 7.1.1 discussed an earlier version of this analysis (Crozier et al. 2008), which predicted an 18% to 34% decline in parr-to-smolt survival for spring Chinook in the Salmon River basin in 2040, compared to survival under current climate conditions, as well as a significant increase in extinction risk. We did not quantitatively apply these results to the 2008 BiOp analysis for reasons that included the time frame of the Crozier et al. (2008) analysis, but instead applied a qualitative approach to evaluating the adequacy of the RPA with respect to implementing ISAB (2007b) recommendations for climate adaptation actions (2008 BiOp Sections 7.1.2.1 and 8.1.3). The new Crozier and Zabel (2013) analysis updates both the expected climate conditions and the relationship between juvenile survival, summer stream temperature, and fall stream flow. The most recent climate downscaling and hydrological models predict that, although summer stream temperatures will increase, fall precipitation may also increase in the Salmon River basin,

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[46] The Climate Impacts Research Consortium is a NOAA-funded consortium of seven universities in Oregon, Washington, Idaho, and western Montana that provides information and tools for making decisions about landscape and watershed management in a changing climate. http://pnwclimate.org/

[47] The Northwest Climate Science Center is an Interior-Department–funded consortium of three universities in Washington, Oregon, and Idaho that develops climate science and decision support tools to address conservation and management issues in the Pacific Northwest Region. http://www.doi.gov/csc/northwest/index.cfm

[48] The Interior Department funds Landscape Conservation Cooperatives (LCC), which are public–private partnerships throughout the U.S. designed to respond to landscape-scale stressors, with an emphasis on climate change. Two LCCs cover most of the Columbia River basin: the Great Northern LCC (http://greatnorthernlcc.org/) and the North Pacific LCC (http://northpacificlcc.org/About).

reducing some of the impact from rising air temperatures. The analysis found that four of the nine populations evaluated responded negatively to warmer historical temperatures, four had neutral or slightly positive responses, and one population in a very cold stream showed a positive response in warmer years. In model projections that included climate change, abundance declined in five of the populations, but the remaining populations stayed about the same on average across models, or increased. The impact of population declines on the extinction risk within 25 years was minor for all but one population.

Crozier (2011, 2012, 2013) identifies many other recent studies relevant to effects of climate change on freshwater life stages of Pacific Northwest salmon and steelhead. These include studies elucidating effects of temperature and flow (coupled with density) on juvenile growth, survival, and migration timing, as well as projections of expected changes in response to climate change. Results of these studies add detail but are generally consistent with descriptions in ISAB (2007b) and the 2008 BiOp.

Additional information in the scientific literature, particularly for the Fraser River, continues to accumulate for the effects of increasing temperature on adult salmon migration and prespawning survival. Additionally, observations of high July through September 2013 Snake and Columbia River temperatures indicate dangerous conditions for adults migrating during that period (primarily SR fall Chinook, SR sockeye, SR steelhead, UCR steelhead, and MCR steelhead; but also the summer component of SR spring/summer Chinook). Preliminary information indicates unusually low survival of adult SR sockeye salmon through the FCRPS in 2013 (Crozier 2013), particularly for July and August migrants, which were exposed to the highest temperatures. The same is likely true for other species migrating at that time. Fish were delayed by high water temperatures in the fish ladder at Lower Granite Dam during 2013 for approximately 1 week in July and 1 week in September, as described in more detail in Section 3.3.3.1 *Adult Passage Blockages at Lower Granite Dam in 2013*.

As described in the 2010 Supplemental BiOp, higher mainstem temperatures during adult passage is a key area of concern requiring ongoing monitoring and evaluation and possibly additional actions to improve survival through the 2008 BiOp's adaptive management provisions. Amendments 1 through 4 to the AMIP were incorporated into the 2010 Supplemental BiOp to specifically address additional climate change concerns identified in that biological opinion, particularly those related to adult passage. Ongoing studies and actions to improve adult passage survival in light of higher temperatures and other factors include the following.

- As described in Section 3.3.3.1 *Adult Conversion Rate (Minimum Survival) Estimates*, adult survival rates in recent years have remained as expected, on average, for SR fall Chinook, UCR spring Chinook, and UCR steelhead. However, they have been lower than expected for other interior Columbia species. (Although, whether they are lower than Base Period survival rates is unclear). Several factors may explain these lower survival rates, including high water temperature in some years and for some parts of the run. The Action Agencies and NOAA Fisheries are initiating new studies to determine the explanation for lower adult survival estimates and, if appropriate, will develop modified actions to address contributing factors within the Action Agencies' jurisdiction and authority prior to 2018. Based in part on results of the studies implemented under AMIP Amendment 2, the Action Agencies are expanding the adult PIT tag detection capabilities to additional dams (The Dalles, Little Goose, Lower Monumental, and potentially John Day dams), continuing to provide environmental data to regional databases (AMIP Amendment 3), and are completing an active tag adult study in 2013, which can be compared directly to PIT tag estimates. As described in Section 3.3.1.1, together, these actions should be sufficient for NOAA to determine where within the longer reaches unexpected losses are occurring, and what factors are most likely responsible, so that a remedy can be formed and implemented.

- Studies to evaluate the feasibility of transporting adult sockeye salmon from Lower Granite Dam to the Sawtooth Valley to avoid high mortality in that reach per RPA Action 42, have resulted in a more detailed assessment of where adult losses are occurring along the entire Bonneville-to-Sawtooth migration route and a correlative analysis of factors, including water temperature, that may be responsible for adult sockeye mortality. This study is ongoing. The Corps also has completed the AMIP Amendment 1 evaluation of adult salmon thermal refugia in the lower Columbia and lower Snake rivers.
- In addition to releasing cool water from Dworshak to reduce lower Snake River temperatures per RPA Action 4, the Action Agencies are responding to the 2013 passage block at Lower Granite Dam by developing short-term measures to introduce cooler water from the reservoir forebay into the fish ladder to reduce the likelihood and severity of future instances. The Action Agencies are also identifying longer-term measures that, once implemented, should substantially reduce, if not eliminate, the possibility of future blocked passage at this project. Additional details are in Section 3.3.3.1 *Adult Passage Blockages at Lower Granite Dam in 2013*.

New projections of the effects of ocean warming on salmon marine distributions are an example of an effect generally considered in the 2008 BiOp, but which new information indicates may be greater than previously anticipated. As described in ISAB (2007b) and summarized in the 2008 BiOp, a major concern is the extent to which natural responses to climate change must include range shifts or range contractions, because the current habitat will become unsuitable. Abdul-Aziz et al. (2011) illustrate this point dramatically for Pacific Northwest salmon by showing that climate scenarios imply a large contraction (30% to 50% by the 2080s) of the summer thermal range suitable for chum, pink, coho, sockeye, and steelhead in the marine environment, with an especially large contraction (86% to 88%) of Chinook salmon summer range under two commonly used IPCC (2007) greenhouse gas scenarios. Previous analyses focusing on sockeye salmon (Welch et al. 1998) came to similar conclusions, but updated climate change projections and the multi-species perspective make this a particularly relevant study.

As described above, a considerable body of literature regarding actions to allow salmon and steelhead to persist in the face of climate change ("adaptation") has become available since the 2008 BiOp (e.g., the Oregon and Washington climate adaptation plans and the National Climate Adaptation Plan, referenced above). Additionally, new research such as Beechie et al. (2012) describes the best methods to apply for restoring salmon habitat in particular types of environments (e.g., streams in which the hydrology is determined by rainfall, melting snowfall, or a combination of the two). They found that restoring floodplain connectivity, restoring stream flow regimes, and reaggrading incised channels are the actions most likely to ameliorate stream flow and temperature changes and increase habitat diversity and population resilience. By contrast, they found that most restoration actions focused on instream rehabilitation[49] and controlling erosion and sediment delivery, while important for other reasons, are unlikely to ameliorate climate change effects. This study helps to focus our evaluation in Section 3.9 of the effectiveness of the RPA in promoting adaptation to climate change. Wade et al. (2013) reviewed the projected impacts of climate change on Pacific Northwest steelhead and concluded that habitat protection alone is insufficient to conserve this species. Coordinated, landscape-scale actions that both increase salmon resilience and ameliorate climate change impacts, such as restoring connectivity of floodplains and high-elevation habitats, will be needed. Other studies such as Donley et al. (2012) suggest methods and provide case studies for prioritizing recovery actions, such as restoring instream flow, in the face of climate change.

2.1.4.6 Relevance of Climate Information to the 2008/2010 BiOp's Analysis

New observations and predictions regarding physical effects of climate change, as described in Sections 2.1.4.1 and 2.1.4.2, continue to be within the range of assumptions considered in the 2008 BiOp and 2010 Supplemental BiOp. This information applies to both interior and lower Columbia basin salmon and steelhead.

- Ocean conditions considered in the 2008 BiOp extended through approximately 2001 (e.g., the ICTRT [2007] "Recent" ocean climate scenario represented climate conditions between 1980 and 2001). Climate patterns reflected in the PDO, El Niño indices, upwelling indices, and other ocean ecosystem indicators between 2002 and 2012 are within the range of the three ocean-climate scenarios considered in the 2008 BiOp.

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[49] Beechie et al. (2012) defined "instream rehabilitation" as adding stream meanders and channel realignment, addition of rock or wood structure, and adding gravel to streams. Although these are generally less effective at ameliorating climate change effects than other restoration actions, Beechie et al. (2012) did describe particular circumstances under which these actions could also contribute. In addition to the three most effective categories of restoration actions described above, other categories described by Beechie et al. (2010) that ameliorate effects of climate change include barrier removal and restoration of riparian functions (e.g., grazing removal and tree planting).

    - ◊ Average 2002 through 2012 conditions, as defined by the PDO, were more similar to the “Historical” climate scenario than to the “Recent” or “Warm PDO” scenarios, which are less favorable to salmon survival, for factors such as the PDO and El Niño indices. Recent El Niño and upwelling conditions either did not differ or were generally more favorable than the Recent and Warm PDO scenarios. Because the 2008 BiOp primarily relied upon the “Recent” climate scenario in the quantitative analysis for interior Columbia basin species, average ocean conditions to date have been similar or more favorable for salmon survival than assumed in the 2008 BiOp.
    - ◊ Although the average ocean conditions between 2002 and 2012 have been similar or more favorable for salmon survival than Base Period assumptions under the Recent climate scenario, poor ocean conditions still occurred during this period, particularly in 2003, 2004, 2005, and 2010.
- § Predictions of future ocean conditions as climate continues to change are also within the range of expectations in the 2008 BiOp. New information continues to add detail to the previous expectations, including predictions of northward-shifting isotherms, increasing ocean acidity, and higher sea levels. Some marine effects of climate change remain uncertain, such as the future pattern of upwelling (whether it will intensify or diminish) and the future pattern of broad-scale indices such as the PDO.
- § The 2008 BiOp did not include quantitative freshwater climate change scenarios or estimate resulting changes in salmon and steelhead survival. Instead, continuing Base Period (through approximately 2001) freshwater climate conditions were implicit in quantitative analyses for interior Columbia basin salmonids and future freshwater climate change was considered qualitatively. Some freshwater climate factors have remained consistent with observations during the 2008 BiOp’s Base Period, while others are more consistent with the 2008 BiOp’s qualitative expectations for future climate.
    - ◊ Average flow in the mainstem Columbia River since 2001 has been nearly identical to average Columbia River flow during the 2008 BiOp’s Base Period.
    - ◊ Average fall streamflow in the Salmon River basin since 2001 has been lower than the average fall streamflow during the 2008 BiOp’s Base Period, which is consistent with qualitative expectations under climate change in the 2008 BiOp.
    - ◊ Average summer stream temperature (as inferred from air temperature per Section 2.1.4.1.6) in the Salmon River basin since 2001 has been higher

    than the average temperature during the 2008 BiOp's Base Period, although the difference is not statistically significant. The higher summer stream temperatures were anticipated as a result of climate change in the 2008 BiOp.

    - ◊ Average July water temperature at Bonneville Dam since 2001 has been nearly identical to average water temperature during the 2008 BiOp's Base Period. Temperatures during both periods are higher than the 1950 to 2013 average, consistent with the description of expected climate effects in the 2008 BiOp.

- § More recent predictions of freshwater streamflow and temperature are generally unchanged from those included in the 2008 BiOp (e.g., increasing temperatures and changes in seasonal hydrology with higher winter and spring flows and lower summer and fall flows due to a decrease in the percentage of precipitation falling as snow).

New studies of biological effects of climate change on salmon and steelhead, as described in Section 2.1.4.5, are generally consistent with expectations in the 2008/2010 BiOps but provide additional details on those effects. Higher temperatures and modified adult migration timing and survival continue to be a concern and measures have been implemented to better understand and reduce this risk.

- § The 2008 BiOp indicated that warming stream temperatures could have positive or negative effects on juvenile salmonid growth, depending on available food and density. New studies provide a greater understanding of the interactions between stream temperature, food availability, fish density, and growth of juvenile salmonids, indicating the situations under which increasing stream temperatures will be beneficial, detrimental, or have little effect.
- § The 2008 BiOp generally assumed that parr-to-smolt survival of interior Columbia basin spring Chinook would decline substantially for most, if not all, populations. A new study indicates that this is most likely the case for populations with survival correlated primarily with summer stream temperatures. However, survival is likely to increase for populations more dependent upon fall stream flow. In this study, most of the Salmon River populations examined were in the first category. The impact of these projected survival changes on extinction risk was minor over the next 25 years for all but one of the nine populations in the study.
- § Juvenile studies confirm general expectations in the 2008 BiOp of changes in mainstem migration timing and life history strategies in response to higher temperatures.

- The new information on non-indigenous fishes provides additional detail to the general response of warm-water predators considered in the 2008 BiOp: their ranges are expected to expand and predation rates are likely to increase as temperatures warm.
- Most studies related to climate effects on estuary and ocean productivity offer new details on biological effects but do not differ substantively from factors previously considered in the 2008 BiOp. Examples include predictive modeling of reduced ocean salmon survival and a decline in fisheries as ocean temperatures warm and available marine habitat moves northward and becomes compressed and new predictive modeling of ocean acidification off Oregon and California.
- As described in the 2010 Supplemental BiOp, new studies and monitoring document effects of higher temperatures on modified adult migration timing and on reduced adult survival and spawning success in the Snake and Columbia rivers. These factors were considered generally in the 2008 BiOp, but new studies and observation of particularly high temperatures and temporary blocked passage at Lower Granite Dam in 2013 provide greater detail. Amendments added to the AMIP through the 2010 Supplemental BiOp and a new study implemented through the 2008 BiOp's adaptive management approach help to address this growing concern with adult migration. Additionally, short-term measures to reduce high fish ladder temperatures at Lower Granite Dam should ensure reduced likelihood and severity of blocked fish passage, such as that observed in 2013 (see Section 3.3.3.1 *Adult Passage Blockages at Lower Granite Dam in 2013*). Longer-term measures should substantially reduce, if not eliminate, the possibility of future blocked passage at the project.
- Tributaries in the lower Columbia are identified as containing thermal refugia for both steelhead and Chinook. Some new studies indicate that the utility of thermal refugia is reduced by harvest targeting fish in thermal refugia.

New research and plans for climate change adaptation are consistent with ISAB (2007b) and expectations of the 2008 BiOp. The types of monitoring and adaptation actions identified by ISAB (2007b) and implemented through the RPA are consistent with the types of adaptation actions described in current literature. New literature such as Beechie et al. (2012) provides additional guidance on the habitat restoration actions most likely to be effective in responding to climate change.

3.9 RPA Implementation to Address Effects of Climate Change

Assumptions about climate change informed the 2008 BiOp's assessment of whether the RPA actions would be sufficient to meet indicator metric targets (R/S, lambda, BRT trend, and extinction risk) for interior Columbia species. The 2008 BiOp did not quantitatively consider effects of climate change on survival for these species during freshwater life stages, as it did for survival during ocean residence (i.e., the Recent, Warm PDO, and Historic ocean climate scenarios applied in quantitative analyses. See Section 2.1.4 in this Supplemental Opinion). Reasons for not using the Crozier et al. (2008) paper to quantify freshwater effects of climate change and lack of other quantitative estimates are described on p.7-14 of the 2008 BiOp. Instead, the 2008 BiOp's approach to achieving indicator metric targets in the face of climate change affecting freshwater life stages relied on "a method of qualitative evaluation, based on ISAB recommendations for pro-active actions…" (2008 BiOp, p.7-14). That qualitative method considered effects of climate change qualitatively by determining "the degree to which the Prospective Actions implement recommendations by the ISAB (2007b) to reduce impacts of climate change on anadromous salmonids" (2008 BiOp, pp.7-32 to 7-35). The 2008 BiOp listed 20 RPA actions to implement ISAB recommendations and described expectations for those RPA actions relative to reducing impacts of climate change on pp.8-20 through 8-22. The 2008 BiOp concluded "that sufficient actions have been adopted to meet current and anticipated climate changes" and that we have sufficient flexibility to be sure that 2010 to 2018 habitat projects will also help to address climate change (2008 BiOp, pp.8-22 and 8-23).

The 2013 CE reviews progress implementing all RPA actions but does not specifically review the suite of actions described above in the context of climate change adaptation. The Action Agencies provided NOAA Fisheries with a separate document that explicitly reviews these RPA actions and that document is summarized in this section (Petersen 2013). NOAA Fisheries reviews these projects in the context of the ISAB (2007b) recommendations, as well as more recent literature on climate change adaptation (e.g., NFWPCAP 2012; Beechie et al. 2012; see Section 2.1.4.3 *Updated Climate Change Information Since the 2010 Supplemental BiOp*).

3.9.1 Planning Processes to Address Climate Change

The 2008 BiOp called for the Action Agencies to provide technical assistance for the regional RPA planning process, which takes the ISAB climate change adaptation recommendations into account for implementation, research, and monitoring. Examples of these planning activities include the following:

- NOAA Fisheries completed comprehensive reviews of recent climate science relevant to salmon (Crozier 2011, 2012), which the Action Agencies included in the 2010 and 2011 Progress Reports (Section 2.1.4.3 in this document). The Action Agencies also made the reports available to expert panels and others involved in restoration efforts. Expert Panels considered climate information within the context of limiting factors and the degree of uncertainty or severity of effects resulting from a shift in climate.
- The AMIP requires NOAA Fisheries to establish a regional stream temperature database and requires the Action Agencies to provide NOAA with past and future water temperature data from their existing monitoring stations to contribute to regional climate change evaluations. NOAA Fisheries and the Action Agencies are satisfying this requirement by submitting data to the USFS Rocky Mountain Research stream and air temperature database.[140] This project will provide "a mapping tool to help those in the western U.S. organize temperature monitoring efforts." See also Section 2.1.4.4 in this document.
- The Action Agencies, through the River Management Joint Operating Committee, conducted an extensive climate change modeling effort by developing a common and consistent dataset describing hydrology and reservoir water supplies under scenarios of climate change generated by the Intergovernmental Panel on Climate Change.

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[140] http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temperature.shtml

3.9.2 Tributary Habitat Mitigation to Address Climate Change

The ISAB (2007b) details a list of actions that can directly moderate impacts of climate change in tributary streams. Among actions to improve tributary habitat in a manner that will help salmon and steelhead adapt to effects of climate change, the 2008 BiOp highlighted water rights acquisition, riparian protection, barrier removal, and restoration of habitat connectivity to wetlands and floodplains that enhance flows and improve access to thermal refugia.

The BPA Fish and Wildlife program records aggregate metrics across multiple projects of riparian stream miles protected by land purchase; stream miles improved by restoration; acres of wetland habitat improved by various means; the number of culverts removed; and the number of fish screens installed at agricultural pumps. These treatments and associated metrics are indexed by project, contract requisition, year of completion, and geographic location.[141] The comprehensive report of physical metrics at the population level for tributary habitat measures completed with funding and technical assistance from BPA and Reclamation from 2007 to 2012 is summarized in the 2013 CE Section 3, Attachment 2, Table 1. A summary is included in the Citizens Guide to the Comprehensive Evaluation. Between 2007–2012, the Action Agencies opened up 2,053 stream miles of habitat to anadromous fish by removing culverts and water diversions; protected or restored 3,791 acres of estuary floodplain; and restored flow of 177,277 acre-feet of water to Columbia basin streams through water transactions and irrigation improvements.

An example of the Action Agencies' tributary habitat improvement projects relevant to climate change adaptation is illustrated by the work of The Freshwater Trust. The Freshwater Trust develops hydrographs for the rivers it works in, and uses them to determine when flow augmentation is most crucial for anadromous fish rearing and migration. As the period of low flow shifts, timing of water transactions will shift to reflect that. The Freshwater Trust also measures temperature on numerous projects to track temperature trends during the summer and predict the relative success of restoration efforts from a temperature standpoint.

The Lolo Creek watershed provides another example of actions to mitigate for the effects of climate change through passage improvement, riparian enhancement, and restoration of floodplain connectivity. Restoration efforts proposed for Lolo Creek that can buffer the effects of climate change on this drainage include culvert and bridge replacement to specifications that will accommodate a 100-year flow event and removing barriers in areas with suitable habitat that will allow for more diversity and the potential for fish to move to higher, cooler systems. Because heat budgets in streams are typically dominated by incoming solar radiation, shading from riparian vegetation plays an important role in buffering stream temperatures on small to medium-sized streams (Isaak 2012). Riparian plantings and floodplain restoration share many of the same benefits. Riparian plantings have the obvious

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[141] http://www.cbfish.org

effect of shading streams to reduce water temperatures. Floodplain restoration can help attenuate peak flows.

The North Fork John Day basin provides another example of how projects can reduce climate change impacts through protection, enhancement, and restoration of floodplain function and watershed process. Specific restoration actions address instream and riparian habitat and restoring floodplain function by eliminating passage barriers, native vegetation plantings, riparian fencing, and grazing management. The project also maintains conservation agreements that protect, enhance, and monitor floodplain and riparian habitat.

The Columbia Basin Water Transactions Program is continuing to work with its implementing partners at the state and local levels to incorporate considerations of climate change into its flow restoration program. Columbia Basin Water Transactions Program partners are taking climate change and best available science into account in working to address tributary flow issues at the subbasin and reach scales for the future. This is taking several forms, including the use of climate models to prioritize watersheds for restoration and to understand the possible long-term impacts to focal species, design flow restoration transactions to address anticipated changes in stream hydrology, and to restore ecological resiliency to streams where flow is a primary limiting factor for native fish. Lists of water transactions conducted in watersheds throughout the FCRPS are available in an online database.[142] Examples of transactions that have been identified, designed, and implemented with consideration for climate change include:

§ **Lemhi River (ID)—**The Idaho Department of Water Resources is using permanent easements and annual agreements negotiated with willing water rights holders to protect a base flow in the Lemhi River throughout the irrigation season. The transactions rely on senior water rights that have historically received their full diversion rate.

§ **Umatilla River (OR)—**The Freshwater Trust is utilizing stored water from McKay Reservoir in the upper Umatilla basin to restore instream flows. Working with stored water is an option for a warmer future where runoff amounts are similar but occur earlier in the year. This approach can help maintain the Umatilla River's fish runs even if the hydrograph sees a significant shift by allowing for late summer release of stored water that would otherwise have flowed out of the basin in the early summer months.

§ **Chewuch River (WA)—**Trout Unlimited is using a "trigger flow" mechanism to ensure flows in the Chewuch River, a key spawning and rearing tributary for steelhead and Chinook salmon, are maintained during the late summer and fall months when flows are expected to be more severely impacted by climate change. When the river drops below 100 cfs, a local irrigation district has

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[142] http://www.cbwtp.org/jsp/cbwtp/projects/index.jsp

agreed to reduce its diversion to ensure that base flows will be maintained. As the effects of climate change worsen, this agreement can help buffer the Chewuch River from declining water supplies and the associated habitat and water quality impacts.

3.9.3 Mainstem and Estuary Habitat Mitigation to Address Climate Change

The ISAB (2007b) recommended climate change adaptation actions in the estuary and mainstem Columbia River such as removal of levees or dikes to restore floodplain connectivity and tidal influence, restoring side channel habitat, and replanting and restoring riparian and wetland habitat along the mainstem.

The Corps sponsored a major study to identify the use and location of thermal refugia for adult steelhead and Chinook salmon in the lower Columbia and Snake rivers (USACE 2013b). This study provides a comparison of existing tributary and lower Columbia and lower Snake River temperature data; a summary of the Snake and Clearwater River confluence study/modeling operations and Dworshak project releases; and a compilation of the University of Idaho studies of temperature regimes during upstream migration and the use of thermal refugia by adult salmon and steelhead in the Columbia River basin.

Through the Columbia Estuary and Ecosystem Restoration Program (CEERP), the Action Agencies fund regional partners to identify habitat actions that will benefit outmigrating juvenile salmonids. These benefits are quantified by the ERTG and assigned an SBU score that captures the projected biological improvements for juvenile salmonids. The projects that score the highest are typically large projects that reconnect fragmented portions of the historical tidally influenced floodplain and restore natural ecological processes. This focus naturally enhances the resiliency and long-term sustainability of Action Agency habitat actions through time.

The following program components support continued efforts to minimize the impacts of climate change on Action Agency habitat projects:

- **Action Agency estuary habitat actions target restoration of natural ecosystem processes**. Hydrologic reconnections are increasingly at the core of most Action-Agency–funded estuary habitat restoration actions because they provide the greatest estimated benefits for fish and for the estuarine environment as a whole. Restoring connections to the historical floodplain allows for the reestablishment of native vegetation communities that require tidal inundation; increased refuge and rearing habitat for juvenile salmonids; export of organic material and prey items into the mainstem; and more natural temperature regimes in off-channel habitats. Fourteen dike breach actions in the Columbia River estuary are described in Petersen (2013).

- **U.S. Army Corps of Engineers Estuary Habitat Climate Change Pilot Study**. The Corps facilitated a series of interdisciplinary workshops (Action Agency representatives, scientists, and planners from the region) to consider climate change science relevant to Action Agency estuary habitat actions in the Columbia River estuary to evaluate if habitat action designs could incorporate additional elements to help maintain the habitat functions through time. Findings included the potential benefits of "ecotones" whereby vegetation communities may migrate to higher elevations if sea level rise becomes an issue in the lower estuary. This pilot is still ongoing.
- **Estuary modeling**. Over the past few years, BPA and others have helped fund a hydrodynamic numerical model of the Columbia River estuary and plume that can model water quality (e.g. dissolved oxygen, temperature) to help the Action Agencies project the climate change related effects of the changing ocean environment on the Columbia River estuary. These effects could include increased ocean acidification affecting the salt wedge in the estuary and more extensive hypoxic regions (seasonally) in the Columbia River estuary. This model is also being used in Columbia River Treaty evaluations of differing flow scenarios and their effects on these water quality parameters in the estuary (Columbia River Treaty evaluations also have a Climate Change Working Group).

3.9.4 Mainstem Hydropower Mitigation to Address Climate Change

The ISAB (2007b) recommended actions in the mainstem hydropower system that could help to mitigate for impending effects of climate change, such as addressing outflow temperatures, development and implementation of fish passage strategies, transportation, and predation management. Many RPA actions address these factors, including the following examples.

In the mainstem Columbia and Snake rivers there is fairly high confidence in the prediction that increased temperatures during the juvenile outmigration will have a negative effect on survival because the principal source of mortality during this stage is predation by piscivorous fish or birds. The activity level of predatory fish such as pikeminnow and bass has been documented to rapidly increase with increasing temperatures (e.g., Petersen and Kitchell 2001). Recent dam design improvements to help smolts efficiently move through the dam forebay, such as installation of surface passage and The Dalles spillway wall, are detailed under RPA Action 54.1-5 of Section 2 of the 2013 CE. The temporary spillway weir installed at Little Goose Dam in 2009 and the removable spillway weir installed at Lower Monumental in 2008 completed the program of installation of surface passage at all mainstem dams in the lower Snake and Columbia rivers. To reduce predation risk in the tailrace, the juvenile bypass outfalls were relocated at Lower Monumental Dam (RPA Action 23) and McNary Dam (RPA Action 21), and spill operations targeted at reducing eddies and time delays in the tailrace have also received study, including block tests of different operations during performance tests at the Lower Monumental Dam (RPA Action 23).

Travel speeds of yearling and subyearling Chinook, steelhead, and sockeye through the hydrosystem are monitored annually by NOAA Fisheries (BPA project 1993-029-00). Duration of travel from Lower Granite to Bonneville Dam is substantially faster during and after installation of surface passage routes compared to earlier equivalent flow years such as 2010 versus 2004; travel speeds are currently faster than they were in the early 1970s period when only four dams were installed in the mainstem river (Muir and Williams 2011). BPA continues to manage the Northern Pikeminnow Management Program (see program summary in 2013 CE Section 2, RPA 43). It has not been possible to test whether recent dam design changes will successfully improve survival during particularly warm or low flow years. Best water management protocols for ecosystem function have been discussed as part of the Dry Year Strategy (RPA Action 14). Detailed in the 2013 CE, Section 2, a “dry year” is defined as the lower 20th percentile of years for water supply. The FCRPS has not experienced a dry year under the technical definition since 2001,[143] and survival observations during the 2008–2012 period do not reflect dry year conditions.

A list of water management actions considered for the Dry Year Strategy are included in scenarios reviewed in the recently completed Columbia River Treaty Review Process. Through this process, modeling efforts considered future hydrological patterns driven by 70-year scenarios of climate change developed by the River Management Joint Operating Committee (RPA Actions 10 and 11). Adult salmon are expected to be particularly sensitive to high temperatures during migration during late summer (e.g., Hague et al. 2010). Adults are less sensitive to flow volumes in the mainstem river than juvenile salmon, however minimum flows for passage are required to negotiate fish ladders and small barriers in tributary streams.

Releases of water from large storage reservoirs in Canada (Arrow, Mica, etc.) and the FCRPS (Libby, Hungry Horse, Grand Coulee, Dworshak) may be managed to augment flows during the spring and summer juvenile migration seasons, and to enhance migration and spawning of fall-run Chinook and chum in fall. Under a climate future of more rapid snowmelt in spring or lower annual precipitation, the flow augmentation during these seasons can become competing needs given the maximum refill and storage capacity. The Action Agencies continue to conduct cold-water releases from Dworshak Dam, which is temperature stratified, to maintain temperatures in Lower Granite reservoir below 20°C in late summer. Recent research confirms the importance of this management practice for enhancing survival of fall-run Chinook from the Clearwater River, which may over-winter in reservoirs and then migrate the following spring as yearlings (see 2013 CE, Section 2, RPA 55.4).

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[143] As described in the 2013 CE, 2010 met the technical definition based on the May forecast. However, because of late spring precipitation, the actual runoff exceeded the dry year trigger.

3.9.5 Harvest Mitigation to Address Climate Change

The ISAB (2007b) recommended improvements in harvest and hatchery management, such as harvest reductions in years of poor climate conditions and targeting hatchery stocks or robust wild stocks. The Action Agencies have been able to coordinate several RME projects which shed light on appropriate management approaches under climate change. For example, the Action Agencies fund NOAA Fisheries' Ocean Survival of Salmonids project (see description under 2013 CE, Section 1 and Section 2, RPA 58.3), which produces an ocean indicators tool that has been successful in forecasting ocean survival rates of salmon useful for harvest management. The Ocean Ecosystem Indicator metrics may be a helpful tool for managers to adjust harvest during periods when poor ocean conditions will lead to low adult returns.

3.9.6 Summary of RPA Implementation to Address Effects of Climate Change

NOAA Fisheries continues to conclude that sufficient actions consistent with the ISAB's (2007b) recommendations for responses to climate change have been included in the RPA and are being implemented by the Action Agencies as planned. Section 2.1.1.2 of this Supplemental Opinion previously concluded that the ISAB (2007b) recommendations are consistent with new scientific literature regarding climate change adaptation for Pacific salmon and steelhead.

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Appendix D
Literature Reviews for Impacts of Climate Change on Columbia River Salmon

D.1 Impacts of climate change on Columbia River Salmon: Review of the scientific literature published in 2012

D.2 Literature review for 2010: Biological effects of climate change

D.3 Literature review for 2011: Biological effects of climate change

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Appendix D.1

Impacts of climate change on Columbia River Salmon: Review of the scientific literature published in 2012

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Impacts of climate change on Columbia River salmon

Review of the scientific literature published in 2012

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August, 2013

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Executive summary

Carbon emissions in 2012 (9.7 PgC) exceeded the previous record set in 2011 producing atmospheric CO_2 concentrations greater than 400 ppm at a majority of Arctic observation stations, although the global mean estimate is just shy of that benchmark at 392.6 ppm . A large number of GCMs have completed processing scenarios for a new IPCC 5th Assessment Report (AR5) to be released in fall 2013. A set of major reviews has also been completed in preparation for the National Climate Assessment, which is now in draft stage (NCADAC 2013). Preliminary reviews of these summaries indicate that they confirm most of the extent and impacts of climate change we have predicted in previous literature reviews. Although some models have revised certain estimates downward, we await the full synthesis to assess changes in projections from the previous IPCC report.

The bulk of the new information released in 2012 focused on sea level rise, sea ice extent, and glacier melting, which collectively was a weakness in the IPCC 4th Assessment Report. A National Academies Report projects global sea level to rise 13.5 cm by 2030 and 82.7 cm by 2100 (mean estimate), which is higher than the previous IPCC report, but comparable with other recent estimates. However, the uncertainty range reported here is much larger than other reports. Projections for Oregon and Washington are: –4 to 23cm by 2030, –3 to 48cm by 2050, and 10 to 143cm by 2100, compared with the 2000 level (Committee on Sea Level Rise in California et al. 2012). An analysis of climate extremes documents a historical and projected increase in extremely hot days, prolonged heat waves, and heavy precipitation events in many regions (IPCC 2012). Severe droughts are very likely to increase (Dai 2012), although the major drought of the 1930s has not been exceeded to date (IPCC 2012), overwhelming the historical trend.

Multiple reviews of historical trends in stream temperature in the Columbia River basin showed significant warming in unregulated streams with sufficiently long time series (mean summer warming of 0.22ºC per decade), although certain regulated streams and short records can show reversed trends (Arismendi et al. 2012; Isaak et al. 2012b). One important conclusion is that temperature mitigation through controlled releases from dams can successfully lower stream temperatures (Arismendi et al. 2012; Konrad et al. 2012; Macdonald et al. 2012). New models of streamflow and temperature across the Columbia River basin project that reductions in summer streamflow will increase stream warming to an even greater degree than those that considered increases in air temperature alone, particularly in snow-dominated basins such as the Salmon River basin and the Clearwater basin (Furey et al. 2012; Tang et al. 2012; Wu et al. 2012a). Marine studies showed declining dissolved oxygen and expanded oxygen minimum zones off the Oregon coast (Bjorkstedt et al. 2012; Pierce et al. 2012), and new models project these trends will continue and become more corrosive (Bianucci and Denman 2012; Gruber et al. 2012). Gruber et al. (2012) projected 70% of the euphotic zone in the California Current Ecosystem (CCE) will be undersaturated in aragonite by the 2050s.

Projected impacts of climate change on salmon are similar to those previously described. Multiple papers expanded our understanding of the marine distribution and links with physical drivers and food web processes specifically for Columbia River Chinook salmon (Bi et al. 2012; Pool et al. 2012; Rupp et al. 2012; Ruzicka et al. 2012; Yu et al. 2012), and cautioned that predator pressure might increase in the CCE (Hazen et al. 2012). Freshwater Columbia River basin studies described new information about salmon movement through dams in winter (Kock et al. 2012; Tiffan et al. 2012), the estuary (Harnish et al. 2012), and the ocean (Sharma and Quinn 2012). Multiple efforts to determine drivers of early marine survival produced somewhat contradictory results: some reports detected clear influences of the mainstem CR conditions (Haeseker et al. 2012; Holsman et al. 2012), but others concluded that early marine growth was much more important (Tomaro et al. 2012). Several studies of invasive species in the Columbia River basin showed smallmouth bass distribution is strongly temperature dependent, and that they are widespread in some tributaries, with negative impacts on native prey and salmon behavior (Hughes and Herlihy 2012; Kuehne et al. 2012; Lawrence et al. 2012). On a more optimistic note, evidence of rapid evolutionary responses in migration timing in Alaskan pink salmon (Kovach et al. 2012), and the utility of standing genetic variation for future local adaptation (Miller et al. 2012b) suggested there is adaptive potential in existing populations. Miller et al. (2012) showed that two relatively distantly related populations of *Oncorhynchus mykiss* have evolved rapid development rates using the same conserved genetic variation. This suggests that development rate might be capable of evolving faster in response to future climate warming than would generally be associated with *de novo* mutations. Similarly, successful artificial selection for heat tolerance in rainbow trout indicates that evolutionary processes can proceed quickly under the right conditions (Ojima et al. 2012; Tan et al. 2012).

On the policy side, a perspective on the Columbia River Treaty (Feeley et al. 2012) presented a cautionary note on the success of adaptive management in the Columbia River basin. Climate adaptation strategies are being piloted by the Forest Service with science-based partnerships (Littell et al. 2012), but climate change is still a relatively low priority in conservation actions (Ellenwood et al. 2012).

In conclusion, recent literature provides further support for continuing temperature mitigation actions and maximal population recovery by whatever restoration actions are possible because of continuing threats of rising stream temperature and declining summer flows, and extreme events with potentially negative impacts on cold-water fish.

Abbreviations and Acronyms

A1B, A2, B1	Carbon emission scenarios from AR4
AOGCM	Coupled Atmosphere-Ocean General Circulation Model
AR4	4th IPCC Assessment Report
AR5	5th IPCC Assessment Report
ENSO	El Niño-Southern Oscillation
GCM	General Circulation Model
Gt	gigatons
IPCC	Intergovernmental Panel on Climate Change
PDO	Pacific Decadal Oscillation
PgC	Petagram Carbon
VIC	Variable Infiltration Capacity Model
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
RCP	Representative Concentration Pathways (Emissions scenarios for AR5)
CCE	California Current Ecosystem
SLR	Sea Level Rise
WRF	Weather Research and Forecasting model
ROMS	Regional Ocean Modeling System
NPGO	North Pacific Gyre Oscillation

Goals and methods of this review

The goal of this review was to identify the literature published in 2012 that is most relevant to predicting impacts of climate change on Columbia River salmon listed under the Endangered Species Act. A large amount of literature related to this topic is not included, because almost anything that affects salmon relates to or is altered in some way by changes in temperature, stream flow, or marine conditions. We have tried to identify the most directly related papers by combining climatic and salmonid terms in search criteria. Thus, many general principles demonstrated in other taxa or with more general contexts in mind have been omitted. This review also does not include potentially relevant gray literature, because the search engine used only includes the major peer-reviewed scientific journals. In total, the methods employed involved review of over 1000 papers. Of these, 224 are included in this summary.

This search was conducted in ISI Web of Science in Jan and July, 2012. Each set of search criteria involved a new search, and results were compared with previous searches to identify missing topics. The specific search criteria all included PY=2012, plus:

1) TS=(climat* OR temperature OR streamflow OR flow OR snowpack OR precipitation OR PDO) AND TS=(salmon OR Oncorhynchus OR steelhead);
2) TS=(climat* OR Temperature OR Precipitation OR streamflow OR flow) AND TS=”Pacific Northwest”;
3) TS=(marine OR sea level OR hyporheic OR groundwater) AND TS=climat* AND TS=(salmon OR Oncorhynchus OR steelhead);
4) TS=(upwelling OR estuary) AND TS=climat* AND TS=Pacific;
5) FT=(“ocean acidification” OR “California current” OR “Columbia River”)
6) TS="prespawn mortality"

The review is organized by first considering physical environmental conditions (historical trends and relationships) and then model projections of future climate, snowpack, stream flow, temperature, ocean conditions, etc. A summary follows of the literature on ecosystem and then salmon-specific responses to these environmental drivers, in freshwater and marine environments, respectively.

2 Literature on the physical processes of climate change

Global or national climate analyses

State of the Climate 2012

Global CO_2 emissions from fossil fuel combustion and cement production exceeded the 2011 all-time record (9.5 ± 0.5 PgC in 2011, 9.7 ± 0.5 PgC in 2012), and a majority of Arctic station records of atmospheric CO_2 exceeded 400ppm for the first time . The final global mean estimate of atmospheric CO_2 is 392.6 ppm. Anthropogenic greenhouse gases together now represent a 32% increase in radiative forcing over a 1990 baseline.

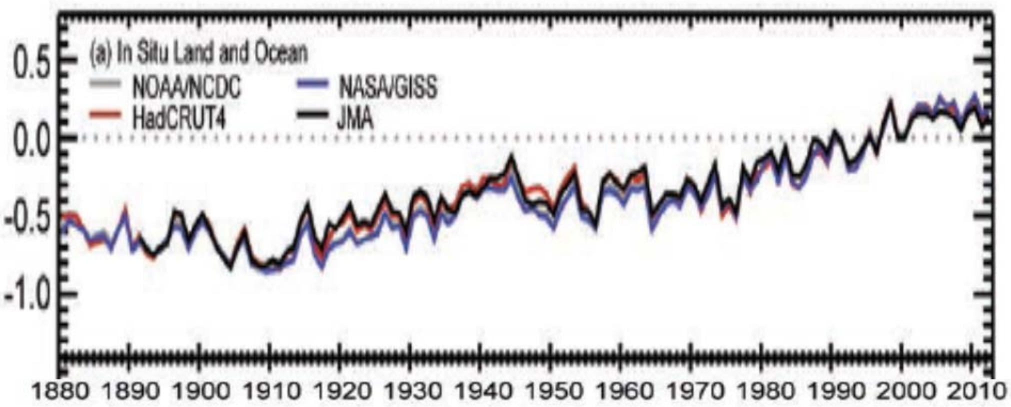

Figure 1. Global average surface temperature annual anomalies combining land and sea surface temperature (°C, 1981–2010 base period, Fig 2.1 in Blunden and Arndt 2013).

The year 2012 was among the 10 warmest years on record, continuing the decade-long phenomenon of above-average temperatures (all of these 10 warmest years occurred since 1998, Figure 1). More specifically, 2012 was 0.14°C to 0.17ºC above the 1981–2010 average globally (land was 0.24°–0.29°C and the ocean was 0.10°–0.14°C above average). The north and northeast Pacific, including the California Current Ecosystem (CCE), however, was cooler than average due primarily to a weak Aleutian Low, related in part to La Niña influences. Cumulatively, Earth is warming at a rate of 0.06°C per decade since 1880 and a more rapid 0.16°C per decade since 1970. However, there has been no trend since 2000, presumably reflecting the cooling effects of a high frequency of La Niña events in the period 1998–2012. Sea ice extent, Greenland ice sheet melting (97% of the ice sheet surface showed signs of melting), and permafrost warming attained new records, reflecting the long warming trends. The hydrological cycle is also more differentiated between dry and wet locations, with dry locations becoming drier and wet locations becoming wetter. Salinity also intensified (with salty areas getting saltier, and fresh areas getting fresher).

List of upcoming reports in 2013

General Circulation Models (GCMs) are producing new model runs of climate change for the 5th IPCC Assessment Report (AR5) to be released in fall 2013, called the Coupled Model Intercomparison Project Phase 5 (CMIP5). Chapters assessing impacts of climate change will follow in 2014. The CMIP5 developed new emission scenarios called Representative Concentration Pathways (RCP), which replace the 4th IPCC Assessment Report (AR4) scenarios (A2, A1B, B1, etc.). We will wait for the AR5 synthesis to comprehensively assess changes from the AR4 projections. However, the individual reports that turned up in our review did not suggest dramatic changes in the overall projections.

Global climate analyses

A major focus of the climate literature in 2012 was better understanding of sea level and sea ice, which was a weakness in AR4.

The National Academies produced a report focused on sea level rise (SLR) along the Washington, Oregon, and California coasts (Committee on Sea Level Rise in California et al. 2012). The report analyzed both the historical and projected trends of all the components to SLR. In conclusion, they projected a cumulative change in sea level globally of 8 to 23 cm by 2030 relative to 2000, 18 to 48 cm by 2050, and 50–140 cm by 2100. For the geographic region from northern California to Washington, they project a rise of –4 to 23 cm by 2030, –3 to 48 cm by 2050, and 10 to 143 cm by 2100. The large uncertainty for the Pacific Northwest (ranging from sea level *fall* to sea level *rise*) stems from complications in predicting regional geomorphic dynamics. Uplift of Washington and Oregon makes the regional projection lower than the global projection, and might cause local sea level to fall despite globally rising seas. However, the geological tension might also cause a massive subduction zone earthquake that would suddenly lower the land along the Pacific Northwest outer coast, but raise the land in Puget Sound.

The IPCC AR4 report tracked historical global sea level at 1.7 mm per year over the 20th century and recent (1993–2003) rates of 3.1 mm per year (p. 23). The higher recent rates might result from natural variability (especially ENSO), or global warming, or both. More recent reports produced similar estimates (Table 2.1 in the National Academy Report). For a 1 m rise by 2100, the recent rate would have to accelerate 3 to 4 times.

Damage along the coast occurs when large storms coincide with high tides. Some climate models predict that the winter storm track will move north over the 21st century, which would increase storm impact on the Oregon and Washington coasts. However, observational records (35 years) are not long enough to validate the drivers of historical trends and clarify the role of natural interdecadal and ENSO influences (Committee on Sea Level Rise in California et al. 2012).

In a separate paper, Boon (2012) reports accelerating SLR along the Atlantic coast of the US and Canada. It isn't clear whether this trend will continue, but if it does, they project a rise of 0.2 to 0.9 m above the long-term mean by 2050 in the Northeast region.

Valiela et al. (2012) documented freshening in estuarine, near-shore, and off-shore water in coastal Panama due to increased precipitation. Freshwater added to surface waters by rain increased stream erosion, uprooted stream-edge terrestrial and mangrove trees, increased mortality of benthic fauna, damped upwelling of denser, nutrient-rich water, and enriched nutrients in surface seawater.

Francis and Vavrus (2012) explained links between Arctic and mid-latitude weather, including projections of increased probability of extreme weather events due to the faster rate of warming in the Arctic. Lui et al. (2012) showed how decreases in Arctic sea ice played a role in recent cold and snowy winters in Europe and the mid- and eastern US. The seasonal timing of sea ice showed strong trends in both the Arctic (3 month *longer* ice-free period) and the Antarctic (2 month *shorter* ice-free period). Nonetheless, it is still unclear from the new CMIP5 simulations when the Arctic will be completely ice free due to high variability in natural climate fluctuations (Stroeve et al. 2012). Glaciers and ice caps lost mass at 148 ±30 Gt/yr from 2003 to 2010, raising sea level by 0.41 ± 0.08 mm/yr (Jacob et al. 2012), which is somewhat less than previously estimated.

Predicting sea level rise was a weakness of previous IPCC projections, which tended to underestimate recently observed rises. Nonetheless, in other respects, critical review showed that IPCC projections were very accurate at the global scale (Rahmstorf et al. 2012). Inconsistencies between ocean heat content estimates from different sources (Loeb et al. 2012) and heat release from warm ocean currents are being resolved (Wu et al. 2012b). Regional climate models still found local climates difficult to reproduce (Soares et al. 2012; Wehner 2013).

Using the new CMIP5 models, Gillett et al. (2012) reported results from the Canadian Earth System Model (CanESM2) with a new form of bias-correction based on regression of modeled and observed historical climates from 1851–2010. They confirm the signature of greenhouse gas forcing over the historical record reported by previous papers, but their estimate of past and projected forcing is lower than other estimates. They projected an overall range for global mean warming by 2100 of 1.2ºC to 4.3ºC, depending on the emissions scenario. Other papers reanalyzed the extent of historical warming. They found that the northern hemisphere warmed 1.12ºC and the southern hemisphere warmed 0.84ºC over the past century (Jones et al. 2012). Inputs from glaciers have been recalculated and are projected to raise sea level from 148 mm to 217 mm depending on RCP scenario by 2100 (Marzeion et al. 2012).El Niño analysis and modeling

Climate extremes

The IPCC Special Report (IPCC 2012) summarizes previous information on ENSO and other aspects of decadal variability, but concluded that the impact of global warming on these patterns is still highly variable among models in post-AR4 work. They described the shift toward more central rather than eastern equatorial Pacific El Niño, which we reported previously. They did not specifically focus on the PDO.

Specifically, ENSO studies included:(e.g., Carre et al. 2012; Dewitte et al. 2012; Li and Ren 2012; Li et al. 2012b; Ramesh and Murtugudde 2012; Zhang et al. 2012). Most of these studies are beyond the scope of this review, except for one that produced specific projections for future patterns in the frequency of El Niño events that would affect the California Current. Zhang et al. (2012) used two dynamic forecasting models, the Weather Research and Forecasting model (WRF, driven by GCMs ECHAM5 and CCSM3) and HadRM (driven by HADCM3) to model regional dynamics in the Pacific Northwest and southwest. Teleconnection patterns changed under future climate regimes, causing wet anomalies to dominate in both warm and cold phases of ENSO, unlike the canonical pattern associating wet conditions with cool phases, and dry conditions with warm phases.

Pacific Northwest

Historical analyses

A variety of studies published in 2012 found significant trends in temperature, precipitation and flow both within the Columbia River basin and over broader spatial scales. In brief, studies found stream temperatures getting warmer within the Columbia River basin (Arismendi et al. 2012; Isaak et al. 2012b) and interannual variability in stream flow increasing in the Fraser (Dery et al. 2012). In a few cases, no statistically significant trend emerged, specifically in a small set of regulated rivers (Isaak et al. 2012b) or over short time-series (Arismendi et al. 2012), and in snowfall in California (Christy 2012).

Stream temperature: an important limitation in our description and understanding of historical trends in stream temperature is the paucity of long-term data. Arismendi et al. (2012) conducted a very interesting analysis of the relationship between trends in temperature over time, and both the duration of the record and whether the stream was directly impacted by humans. Arismendi et al. (2012) found significant warming trends when longer records were available – roughly 44% of streams with records prior to 1987 had significant warming trends. However, cooling trends predominated in the shorter time series, despite significant warming of air temperature in many cases. The authors noted a correlation between base flow and riparian shading with these cooling trends. Human-impacted sites showed less variability over time, likely due to flow regulation and reservoir heat storage.

Isaak et al. (2012b) also compared temperature trends in unregulated and regulated streams. They demonstrated statistically significant warming trends from 1980 to 2009 on seven unregulated streams in the Pacific Northwest in summer (0.22ºC per decade), fall and winter, producing a net warming trend annually despite a cooling trend in spring. Stream temperature trends were strongly correlated with air temperature, showing the expected signal from regional climate warming. Trends in 11 regulated streams were in the same direction, but were not statistically significant, indicating that modified flows, in some cases explicitly for temperature management, limits stream thermal response to climate drivers.

Runoff: a study of interannual variability and total runoff within the Fraser River basin (Dery et al. 2012) found distinct trends of increasing interannual variability in spring and summer (the period of high flows) over the past 100 years. New datasets of snowfall records in California found no trend since 1878 or within the last 50 years (Christy 2012).

Fire frequency: previous analyses have projected an increase in fire frequency due to rising temperatures and longer fire seasons, but a new study (Holden et al. 2012) showed an added influence of the timing of snowmelt and annual streamflow. Annual area burned and severe-burn area corresponded closely to precipitation variability and total annual streamflow. Another study (Abatzoglou and Brown 2012) compared downscaling methods for future projections of wildfire danger, and found that a new method, the Multivariate

Adapted Constructed Analogs (MACA), outperformed other methods for the high demands of complex fire prediction.

Projected changes

An intensive model of stream flow and temperature in the Pacific Northwest was published in 2012 (Wu et al. 2012a). This group used a physical model of stream temperature based on a dominant river-tracing-based streamflow and temperature model (DRTT). Averaged across the Pacific Northwest, the model projected a 3.5% *decrease* in mean *annual* streamflow for the 2020s, despite a net increase in annual precipitation, but *increases* thereafter (0.6% and 5.5% increases for the 2040s and 2080s, respectively). However, *summer* streamflow decreased from 19.3% (2020s) to 30.3% (2080s). They projected increases in mean annual stream temperature from 0.55ºC (2020s) to 1.68ºC (2080s), while mean summer stream temperatures warmed from 0.92ºC to 2.10ºC.

The largest projected increases in stream temperature occurred near the mouth of the Columbia River, which rose 1.88°C (2020s) to 4.37°C (2080s). The simulations indicated that projected climate change will have greater impacts on snow-dominant streams, such as those found in the upper Columbia basin and Salmon and Clearwater basins, with lower summer streamflows acting synergistically with warmer summer stream temperature changes relative to transient- and rain-dominant regimes (Wu et al. 2012a).

Donley et al (2012) analyzed water availability for fish in the Columbia basin by taking output from the Climate Impacts Group downscaled projections (described in previous literature reviews) and incorporating reservoir management rules and human withdrawals for agriculture using the Water Evaluation and Planning System (WEAP). They analyzed four sub-basins (Okanogan, Methow, Wenatchee, and Yakima) under five scenarios (climate change alone, moderate or high increases in agricultural demands, and different potential conservation rules. They found the potential for very serious risks to salmonids unless substantial protections are put in place. They present a set of specific recommendations for each basin.

Kollat et al. (2012) modeled how human population growth and land use change would interact with climate change to dramatically increase the frequency of 100-year return period flood risk – up to 50%–60% in parts of the Pacific Northwest by 2100. This was a US-wide study, not locally downscaled, but the inclusion of the human dimension through impervious surfaces and changes in runoff reinforce previous results that showed the same trends but did not include these effects.

Six studies projected changes in streamflow or stream temperature at specific watersheds within the Columbia River basin. Lutz et al. (2012) focused on the Yakima River basin. They explored tree ring data over 366 years to characterize patterns of natural climate variability. They reconstructed five climate patterns and projected them under future climate change scenarios. The scenarios showed reductions in summer streamflow despite wetter meteorological conditions. The USGS completed projections using the Precipitation Runoff Modeling System (PRMS) for a number of watersheds across the country, including the Naches basin, which is a tributary to the Yakima (Markstrom et al. 2012). They predicted increased winter runoff and less spring and summer runoff due to shifts in precipitation falling as rain rather than snow.

Efforts to provide thermal refugia in the Snake River have relied on releases from the Dworshak Dam on the Clearwater River in Idaho. Furey et al. (2012) used a simple "conceptual" hydrological model to explore the combinations of temperature and precipitation change that would cause the most substantial shifts in streamflow. They found that increasing precipitation increased runoff if temperature stayed constant, but under warming scenarios annual streamflow declined.

Another sensitivity analysis of stream flow in the sister tributary, the Salmon River basin (Tang et al. 2012) produced similar responses with the more mechanistic Variable Infiltration Capacity (VIC) hydrological model. In response to incremental temperature increases, 1) annual flow decreased (November to February warming increased fall flows, whereas May to July warming decreased summer flows); 2) the timing of 50% of the annual flow shifted 10 to 30 days earlier with 2ºC warming, and 15 to 45 days earlier with 3ºC warming; and 3) flash flows increased, which tends to increase bank erosion.

The process of projecting the physical consequences of climate change in any given location involves many steps in modeling, and each step has its own uncertainty in model parameters and outcomes. Many studies include multiple GCMs and emission scenarios in their projections to represent these sources of uncertainty. Previous studies have found that sensitivity to uncertainty in different steps in the modeling process depends on such factors as the aspect of the hydrological cycle (wet or dry season) and geographic location of interest. For example, Jung et al. (2012) focused specifically on how a rain-dominated basin differed from a snow-dominated basin, both in the lower Willamette Valley, in sensitivity differences. They found that the snow-dominated basin was more sensitive to hydrological model parameter uncertainty because of difficulties in modeling snowmelt.

Surfleet et al. (2012) compared biases of three hydrological models (VIC, PRMS, and a site-specific GSFLOW model), in the Santiam River basin, a tributary to the Willamette River. They found biases in the large scale, VIC model, especially at small, unregulated sites, which they suspected reflected unmodeled groundwater influences. The models differed in their projected flows, mostly during low-flow periods of summer.

Additional studies developed detailed projections for the Boise and Spokane river basins (Jin and Sridhar 2012), Vancouver Island (Sobie and Weaver 2012) and British Columbia headwaters (but not the Columbia River Basin, Bennett et al. 2012). In general, these studies showed similar trends in responses and the importance of spatial variation in projections as has been reported for the Columbia River basin.

Marine

A report on "The state of the California Current System 2011-2012" focused mostly on 2011, because it was written in mid-2012 (Bjorkstedt et al. 2012). The report described spring 2012 as largely ENSO-neutral, with somewhat incoherent patterns in the PDO and multi-variate ENSO index, and latitudinal variability in the timing, strength, and duration of upwelling. The northern CCE had weaker than average and delayed upwelling. Bjorkstedt et al. (2012) also documented declines in dissolved oxygen, nutrient-enriched water below the mixed layer, and abundant jellyfish.

Climate models predict that **dissolved oxygen** will decrease and the oxygen minimum zone will thicken with global warming. Pierce et al. (2012) documented both of these trends since 1960 along the Newport line off central Oregon. Oxygen is decreasing between 100 and 550 m. The OMZ now occurs at ~800 m, and upwelled water is hypoxic on the Oregon shelf.

Analysis of historical time series found concordance of **upwelling** and the PDO, North Pacific Gyre Oscillation (NPGO) and ENSO at very low frequency especially in the southern half of the CCE (Macias et al. 2012b). Improved coupling of CCE with the atmosphere better reconstructs upwelling and small-scale phenomena (Li et al. 2012a). Iles et al. (2012) concluded that "upwelling events are becoming less frequent, stronger, and longer in duration" off Oregon and California. A new sensitivity analysis that used the Regional Ocean Modeling System (ROMS) model showed an increasing risk of coastal hypoxia and low pH off the Vancouver shelf (Bianucci and Denman 2012).

Literature on **ocean acidification** in 2012 focused on both physical dynamics of ocean acidification and biological sensitivities. A significant review was released by NOAA describing knowledge on this topic to date (Feeley et al. 2012). Papers that focused on physical dynamics to improve our understanding of ocean acidification included several that described historical and future **patterns in pH** in the California Current. This work developed empirical relationships and described recent trends and characteristics of pH and potential drivers (Alin et al. 2012; Wootton and Pfister 2012) and reconstructed ancient time series (Honisch et al. 2012). Wooton and Pfister (2012) found strong trends of declining pH (mean = –0.018 per yr) in the Strait of Juan de Fuca over about 15 years, which proved more consistent with rising atmospheric CO_2 rather than local drivers such as upwelling. Gruber et al. (2012) reported results from a high-resolution oceanographic model of the near-shore CCE simulating the A2 and B1 climate change scenarios from the IPCC AR4. Gruber et al. (2012) projected that by the 2050s, 70% of the euphotic zone (top 60m) of nearshore (10km) habitat will be undersaturated ($\Omega_{arag}<1$) the entire summer, and over 50% will be undersaturated year-round, regardless of emissions scenario. No areas were similarly acidic in pre-industrial times (~1750). Sea-floor habitat grew essentially entirely undersaturated by 2025 in the simulation.

Ecosystem responses to climate change

Literature reviews on marine ecosystems and fisheries

Recently, numerous reviews have published evidence for the fingerprints of climate change and projections of future trends in climate, including the IPCC Special Report on Extreme Events (Report 2012), a U.S. National Academy Report on sea level rise (Committee on Sea Level Rise in California et al. 2012), and a Royal Society of Canada report on climate change and marine biodiversity (Hutchings et al. 2012). More fish-centric reviews of impacts of these changes on fisheries are also available, especially for the UK (Cheung et al. 2012; Heath et al. 2012). Most comprehensively, Griffiths et al. (2013), Groffman and Kareiva (2013) and Staudinger et al. (2012) contributed technical input to the 2013 U.S. National Climate Assessment (NCADAC 2013) that reviewed the current state of knowledge on factors affecting oceans and freshwater resources. Doney et al. (2012) reviewed marine ecosystems globally. In the Pacific Northwest, Martins et al. (2012a) reviewed the physiological links between climate and sockeye salmon, with most data coming from the Fraser River. Rand et al. (2012) assessed sockeye extinction risk according to the International Union for the Conservation of Nature Red List criteria, and found that 27% of sockeye populations, mostly in British Columbia and Washington, are at very high risk of extinction, due partly to climate changes.

Ecosystem responses

Several studies focused on the connection between physical drivers and plankton communities. Historical shifts in primary production pointed to important environmental drivers. Chlorophyll-a concentration off central California increased, but north and south (the central North Pacific gyre and off southern Baja California) it decreased from 1996 to 2011 (Kahru et al. 2012). They associated the decrease in the North Pacific with enhanced vertical stratification, as predicted to result from global warming, and increases in upwelling. Other authors also linked the detailed mechanisms of upwelling to primary production (Lachkar and Gruber 2012; Macias et al. 2012a), and larger scale differences in the north and south Bering Sea (Stabeno et al. 2012). Phytoplankton cell size has been shrinking in Pacific equatorial and subtropical oceans, in addition to alternating with the ENSO cycle (Polovina and Woodworth 2012). Microcosm experiments indicated a shift in microzooplankton grazing rates (Chen et al. 2012). Bi et al. (2012) improved our understanding of local variation in effects of PDO on copepod communities in CCE, related in part to upwelling effects (near-shore communities were more responsive to PDO forcing than communities on the shelf slope). Freshwater influence and changing glacial melting rates also influenced community structure (Pirtle et al. 2012).

Two studies of links from physical drivers up the food chain focused specifically on salmon prey items. Ruzicka et al. (2012) developed an especially relevant food web model for Columbia River salmon for each of the 2003–2007 upwelling seasons for the northern California Current. They found that euphasiids were the most important link between primary productivity and fish productivity. In an alternative food web configuration, jellyfish dominated the biomass without providing much benefit to fish because jellyfish tended to sink to the bottom, causing nutrients to drop out of the pelagic food web. Jellyfish are very sensitive to environmental conditions, and these relationships drew more attention in 2012 (Lebrato et al. 2012; Suchman et al. 2012). Volkov (2012) linked Arctic cold-current patterns to the mass occurrence of the large hyperiid *Themisto libellula*. This species became a major food source for salmon in the Bering Sea from 2007 to 2011. In an alternative modeling approach, Blanchard et al. (2012) projected changes in potential fish production in all the major ecosystems world-wide, including the Pacific Northwest, employing a size-based food web model.

A study of phenological trends at four levels in the food web over 24 years in the North Sea failed to find much coherence among trophic levels (Burthe et al. 2012). Although they concluded a mismatch must be occurring, no adverse effects on breeding success in seabirds was apparent.

A study of top predators in the Pacific projected responses to climate change in 23 species (Hazen et al. 2012). They found that sharks, loggerhead turtles and blue whales were most at risk; California sea lions, elephant seals and tuna face little change or small increases; while sooty shearwaters and albatrosses might see large gains. Hazen et al. (2012) projected greater competition among top predators in the CCE, but also higher risk of anthropogenic impacts such as shipping and fisheries bycatch. The increasing oxygen minimum zones might make prey more vulnerable to air-breathing predators.

Impacts of climate change on salmon

Population declines attributed to climatic factors

Many salmonid populations have declined over the past century, and are currently threatened with extinction. Establishing causal links between declines and climate change presents a challenge because we generally lack the spatially specific and temporally appropriate data to document direct effects of environmental driving factors. Also, other human impacts are confounding factors. Inferential evidence comes from 1) concurrent changes in population and climate metrics, and 2) mechanistic models of habitat area (thermal niche models), population or individual growth models, or cumulative stress models. Several papers have taken each of these approaches.

Isaak et al. (2012a) and Zeigler et al (2012) described recent climate changes within the ranges of a variety of listed species of trout along the Rocky Mountains. They identified trends in air temperature and flow, and the primary climate stressors expected to affect each species. They discussed how observed changes exacerbate management challenges like increasing wildfires and movement of specific warm-adapted exotic species known to interact with the species of concern. Connors et al. (2012) evaluated a set of hypotheses for the decline of Fraser River sockeye salmon, including sea surface temperature and interactions among drivers in their hypotheses. They concluded that sea surface temperature is a significant contributing factor, either directly or through an interaction with farmed or pink salmon. They suggested that possibly "juvenile sockeye that are exposed to pathogens early in marine life are less able to compete for resources with pink salmon later in marine life. Alternatively, reduced food availability from competition with pink salmon might lead to disease expression in sockeye that are infected but not diseased. The antagonistic interaction between exposure to farmed salmon and oceanographic conditions during early marine life suggests that the effects of warmer sea surface temperature and exposure to farmed salmon production on sockeye productivity may be compensatory whereby some sockeye that die because of poor ocean conditions would have died because of diseases, and vice versa, but not because of both" (p. 310).

Transitioning to the more mechanistic quantitative models, two models involved European brown trout. In the first model, Almodevar et al. (2012) developed a habitat niche model based on presence and absence of brown trout in Iberian Peninsula. They found that suitable habitat has already declined by 12% per decade, which corresponds to 6% decline in population size per year. Under a B2 climate scenario, they expected 50% of the habitat will be lost by the 2040s, and the population will be extinct by 2100. In the second model, Lecomte and Laplanche (2012) developed a temperature-driven growth and production model for use in future population modeling.

Piou and Prevost (2012) developed an even more sophisticated growth and production model for Altantic salmon that includes genetic structure and microevolution. This versatile model will likely be quite useful in predicting plastic and evolutionary responses to climate change.

Other mechanistic models were more general in their application, but provided a common metric for integrating the net effect of different stressors through aerobic scope and energetic costs (Portner 2012; Sokolova et al. 2012).

Providing a larger temporal context for inferences of population decline due to warming, Turrero et al. (2012) took a paleoecological approach to document fluctuations between high and low salmon abundance and climate. Turrero et al. (2012) identified a longer generation time (more years at sea) in Atlantic salmon and brown trout during the Upper Palaeolithic period. They modeled population growth rates based on mutation rates and concluded that the shifts in life history were associated with a lower population growth rate.

Life-cycle modeling is a useful tool in conservation planning. Zeug et al. (2012) developed a stochastic life-cycle model for winter-run Chinook salmon in the Sacramento

River, California. A sensitivity analysis revealed that a 10% change in temperature had a much larger impact on escapement than comparable changes in other inputs.

Freshwater processes

Juvenile migration

McMillan et al. (2012) found that early maturation or smolting in *O. mykiss* depended on both body size and lipid levels: fatter fish tended to mature earlier, but they were more likely to smolt under warmer temperatures.

Arctic char propensity to go to sea was predicted by lake productivity (and hence growth potential) and the arduousness of the migration, suggesting locally adapted thresholds for anadromy (Finstad and Hein 2012).

Two studies of **in-river movement** behavior found that juveniles migrate past dams over winter. Juvenile fall Chinook move through the hydrosystem on the lower Snake River during winter more than previously thought, which has implications for dam operations, such as removal of fish screens to minimize loss in turbines (Tiffan et al. 2012). Similarly, coho move past Cowlitz Dam over winter (Kock et al. 2012). These behaviors increase as spring approaches. The effect of photoperiod and temperature on rheotactic behavior and swim speed in tanks confirms these mechanisms (Martin et al. 2012). Riley et al. (2012) found that artificial lights, such as those used at dams, can interfere with normal diel and perhaps seasonal behavior.

Migration routes through the Columbia River **estuary** vary, including both the navigation channel and off-channel areas (Harnish et al. 2012). Fish use tidal energy to facilitate migration. However, **ocean migration routes** of ocean-type (subyearling) and stream-type (yearling) Chinook are not differentiated as universally as was previously thought (Sharma and Quinn 2012). The traditional model posits that subyearling Chinook migrate nearer to shore while yearling Chinook go off-shore. They found this to be true for Chinook originating in snow-dominated rearing basins, e.g., the Upper Columbia, Snake River, and Upper Fraser. However, subyearling and yearling migrants from warmer natal environments in lower rivers and coastal areas overlap extensively in their ocean migration routes, contradicting the hypothesis.

Adult migration

Flow and temperature are regulating factors in upstream movement of salmonids. Exposure to high **temperature** is a paramount concern from California to British Columbia, as well as for Atlantic salmon (Moore et al. 2012). Moore et al. (2012) provide a conceptual overview on thermal impacts on the spawning migration. Empirical studies document actual temperatures experienced. Strange (2012) analyzed migration patterns and temperature exposure in the Klamath River in California. He tracked four run-timing groups: Klamath-Trinity spring, Trinity summer, Klamath fall and Trinity fall. Two runs avoided high temperatures by migrating before or after peak thermal maxima (the spring run and the Trinity fall run). One run avoided excessive cumulative thermal exposure by migrating very quickly (the Trinity summer run). However, the Klamath fall run stayed close to high temperature prior to migrating, which exposed them to moderately high thermal stress. The highest exposures occurred in spring-run fish that migrated very slowly, and hence got caught in summer temperatures for extended periods.

In the Puntledge River on Vancouver Island, BC, a study of biotelemetry plus animal-borne thermal loggers showed that summer-run Chinook are already exposed to temperatures exceeding their thermal limits and it is affecting their spawning migration (Hasler et al. 2012a). Cumulative thermal stress is strongly associated with mortality in early migrating Fraser River sockeye (Hinch et al. 2012), which might also have pre-existing conditions that make them vulnerable.

Flow is also a dominant factor controlling migration due to the energetic cost of migrating against a strong current. The optimal swimming path depends on the details of complex fluvial velocity fields (McElroy et al. 2012). Electromyogram recordings document a large amount of individual variation in the energetic cost of swimming through variation in swimming strategies, migratory behaviors, and habitat use, in addition to river environment drivers like temperature and water velocity (Hasler et al. 2012b). Bendall (2012) summarize multiple models of migration movement, including flow and olfactory signals, among other factors.

Direct effects of temperature

Papers detailing direct effects of temperature on salmonids fell into categories of 1) detailed physiology, 2) factors affecting maximum temperature tolerance, 3) thermal impacts on growth and consequences of various growth rates, 4) swimming performance 5) behavioral consequences of high temperature exposure, such as predator avoidance behaviors and spawn timing, 6) the use of cool water refugia, and 7) fish communities structured by adaptations to winter temperature. Martins (Martins et al. 2012a) reviewed the full range of effects of climate on growth, phenology and survival of sockeye salmon – but 83.4% of the papers reviewed focused on temperature.

Physiological responses to thermal stress include cellular effects, hormonal responses, cardiac function, reproductive capacity, gene expression, and fatty acid production (Anderson et al. 2012a; Anderson et al. 2012b; Arts et al. 2012; Casselman et al. 2012; Jeffries et al. 2012b; Keen and Gamperl 2012; Lahnsteiner and Kletzl 2012; Lahnsteiner and Mansour 2012; LeBlanc et al. 2012; Lewis et al. 2012; Reese and Williams 2012; Tan et al. 2012)

Factors that affected survival after a high temperature challenge included maternal effects (Burt et al. 2012b) and time to spawning, or maturation status -- with more mature fish having much lower survival, especially females (Jeffries et al. 2012a; Martins et al. 2012b). Size effects were somewhat contradictory, with smaller fish generally being more heat tolerant, favoring jacks over older males (Clark et al. 2012), but the effect was negligible or small in several species (Recsetar et al. 2012).

Temperature has a profound impact on growth rates, partially through altered behavior and appetite suppression (Folkedal et al. 2012a; Folkedal et al. 2012b; Hevroy et al. 2012). Atlantic salmon followed different growth trajectories after exposure to different acclimate temperatures, showing a surprising long-term effect of acclimation (Finstad and Jonsson 2012). Similarly, development temperatures produced different reaction norms for growth in cod (Hurst et al. 2012). This interannual variation in reaction norms in cod (Hurst et al. 2012) presents a significant challenge for modeling future responses to climate based on short-term experiments without a full understanding of interacting effects. But the net effects of different temperatures on growth, combined with density effects, produce predictable spatial patterns in body size (Parra et al. 2012). Bioenergetic models and dynamic energy budget models are used to model the impacts of different thermal regimes (Leach et al. 2012; Nisbet et al. 2012), and lead to theories of optimal energy allocation to storage tissue versus growth that varies depending on the length of the growing season and the severity of winter (Mogensen and Post 2012). Long-term consequences of thermally-induced differences in growth rate include reduced allocation to reproduction after compensatory growth following slow growth under cool temperatures (Lee et al. 2012).

Swimming performance in fry suffered after exposure to 16ºC (Burt et al. 2012a), but performance was sometimes inversely related to survival (i.e., there was a family effect on both, but a given family might have low survival but high performance). Different metrics of swimming performance showed different patterns in response to increasing temperature (Yan et al. 2012). Importantly, the maximum sustainable swim speed varies with temperature, which has implications for many studies that use this metric under novel thermal conditions.

Behavioral consequences of high temperature exposure were documented in adults and juveniles. Spawners waited to spawn, sometimes reducing net redd production, during warm years, in brook trout in New York over an 11-year study (Warren et al. 2012). Juvenile Chinook salmon produced stronger and more variable anti-predator behaviors in a laboratory experimental exposure to bass (Kuehne et al. 2012). Stenhouse (2012) summarized literature on coho temperature preferences, defining thermal ranges from optimal to detrimental.

Use of thermal refugia as streams warm has been difficult to predict, and several studies shed light on this behavior. Hillyard and Keeley (2012) showed that Bonneville Cutthroat trout used thermal refugia more in unregulated than regulated rivers, perhaps because the refugia were more abundant and closer together. Brook trout also move throughout a stream network in Appalachia differentially in mainstem or tributary habitat in response to high temperatures (Petty et al. 2012), and use of refugia depended also on cover. Coho salmon in the Klamath River congregated around the mouths of cool-water tributaries when mainstem temperatures approach 19ºC (Sutton and Soto 2012). If the refugia exceed 23ºC, they were no longer used, suggesting this temperature is too hot to provide any benefit.

Finally, Shuter et al. (2012) documents adaptations to winter temperatures that have evolved in different fish species, and emphasizes that this is an important time of year for structuring communities—it isn't all about summer maximum temperatures.

Local adaptation

Predicting evolutionary responses to future climate change relies on various lines of evidence, including: 1) study of existing phenotypic variation among populations exposed to different environmental conditions, 2) genomic studies revealing genetic differences among populations that might be adaptive, 3) measurements of current selection under different environmental conditions within populations, and finally, 4) optimality models that provide the theoretical basis for predicting evolutionary responses to selection under different environmental regimes.

Numerous studies measured **differences in thermal tolerance among populations**. Drinan et al. (2012a) evaluated embryonic survival, development rate, and growth rate at various temperatures in five populations of westslope cutthroat trout from Montana. Although the absolute survival at the highest temperature (14ºC) was not correlated with natal stream temperature, the decline in survival from 10ºC to 14ºC was consistent with stream rank temperature. They found that populations from warmer streams had more similar survival at 10ºC and 14ºC than populations from cooler streams. In a similar study, Colorado River cutthroat trout showed different thermal maxima, although the different acclimation responses appear to mediate the discrepancy rather than maximum possible heat tolerance under optimal acclimation conditions (Underwood et al. 2012). Larger fish were also less heat tolerant than smaller fish (Underwood et al. 2012). A comparison of hatchery strains of brook trout also showed genetic differences in thermal tolerance (McDermid et al. 2012).

Comparisons of natural populations exposed to different thermal regimes provide indirect evidence of selection on heat tolerance, but much more direct study of rapid evolution in this trait comes from **artificial selection**. A strain of rainbow trout has been artificially selected for heat tolerance, and several authors have studied the physiological mechanisms of this improved heat tolerance (Ojima et al. 2012; Tan et al. 2012).

Other examples of **local adaptation** to environmental conditions, specifically the **flow regime**, are fin length, body depth, body length, head shape, and eye size (Drinan et al. 2012b; Stelkens et al. 2012). Growth thresholds that determine the probability of smolting at a given age (Sogard et al. 2012), and tolerance of hypoxia (Cote et al. 2012) also appear to be locally adapted.

Distinguishing between phenotypic plasticity and genetic roots of these differences is not easy. Genetic differences among populations can be established with genomic techniques, and secondarily associated with selection (Limborg et al. 2012). Kovach tracked a change over time in a genetic marker in a population of pink salmon that he associated with direct selection on run timing (Kovach et al. 2012). Shorter term oscillations in selection on run timing were also detected in coho (Kodama et al. 2012). Miller et al. (2012b) concluded that most local adaptation in salmon stems from standing genetic variation rather than de novo mutations. This is a very important result because evolution proceeds much faster by this route. A specific quantitative trait loci has been associated with spawn timing in coho (Araneda et al. 2012).

Finally, a theoretical study of selection pressures demonstrated that given plasticity and a stochastic environment, the model predicts a “mismatch” in the timing of breeding and prey availability is optimal when cost of overshooting is more (or less) severe than the cost of the undershooting – in other words, when the fitness curve is asymmetric (Lof et al. 2012).

Invasive species: smallmouth bass and shad

A study of the relative abundance of alien piscivores and native prey species in seven Pacific Northwest (Hughes and Herlihy 2012) rivers found that native prey abundance was inversely related to the abundance of alien fish. They conclude that alien piscivores are present along the entire length of the Okanogan and John Day rivers. They suspect that declines of native prey species can be attributed to these invasions, especially smallmouth bass.

Another study (Lawrence et al. 2012) focused specifically on smallmouth bass invasion of the John Day River. They found extensive overlap in bass and subyearling Chinook habitat in early summer. Both species shifted upstream as temperatures warmed seasonally, but a high-gradient portion of the river might limit bass. Because temperature constituted the primary determinant of bass presence, rising stream temperatures will very likely bring more bass. Restoration activities could focus specifically on maintaining bottlenecks to discourage further upstream movement of bass.

A third study (Kuehne et al. 2012) conducted experiments on bass predation of juvenile Chinook salmon at various temperatures. They found salmon had stronger and more variable antipredator responses at warmer temperatures, which they thought might limit growth.

American shad have become the most abundant migratory species in the Columbia River. Hasselman et al. (Hasselman et al. 2012) considered the potential ecological effects of shad on coastal ecosystems and salmonids.

Diseases

The *Ceratomyxa shasta* parasite is thought to be inhibiting recovery of Chinook and coho salmon in California. Although it is not currently recognized as driving significant mortality in the Columbia River, morbidity and mortality in salmon is temperature dependent, and is likely to increase as a threat in warmer climates. Hallett et al. (2012) tested spatial and temporal dynamics of disease progression in the Klamath River. They found that coho was more sensitive than Chinook salmon to parasite density and temperature. Ray et al. (2012) tested the effect of temperature on lethality in a laboratory study, and found a positive correlation (higher mortality and faster progression to death at higher temperatures). In the field, parasite density varied from year to year; this also influenced the timing and magnitude of field mortality. The spatial distribution of an intermediate polychaete host for the parasite also affects parasite density, and is itself sensitive to discharge rates (Malakauskas and Wilzbach 2012). Thus these studies indicate that climate change might change disease risk through direct temperature effects on the fish, temperature effects on parasite growth rates, and through flow effects on other hosts.

Contaminants

Studies of the impacts of contaminants covered two focal areas. First, increased mobilization of historically stored pollutants through glacial melting (Elliott et al. 2012) or intensification of flooding. Although Cofalla (2012) focused specifically on modeling managed floods that have the potential to mobilize contaminants stored in sediment, the principle applies similarly to climate change-induced flood intensification. Second, contaminant effects depend strongly on the mixture of contaminants and their interaction with temperature and salinity. Brooks et al. (2012) provide an overview of interacting effects. Others compared the toxicity of different metals with temperature (Terzi and Verep 2012) and their impact on the expression of heat shock proteins (Soyut et al. 2012). Daley et al. (2012) studied the seasonal progression of bioamplification and depletion of persistent organic pollutants in Chinook embryos and larvae. They found that the highest concentrations of POPs occurred in later yolk-sac larvae, before exogenous feeding.

Marine processes

Studies of the effects of climate variability on salmon in their marine stage addressed salmon spatial distribution, growth, survival, and age at maturity. Highlights for Columbia

River fish include greatly improved ocean models (Gruber et al. 2012) and physical-trophic links (Pool et al. 2012; Yu et al. 2012), and mixed results on the importance of freshwater conditions for marine survival of Columbia River Chinook (Haeseker et al. 2012; Holsman et al. 2012; Tomaro et al. 2012).

Spatial distribution

A combination of physical drivers (upwelling, current strength, temperature) and prey distribution shape salmon distribution.Several papers described predictors of juvenile salmon in the California Current to differentiate the role of physical and biological processes that determine salmon distribution. The strength of along-shore currents influences the proportion of smolts that head south versus north from the Columbia River (Yu et al. 2012). Sea surface temperature, chlorophyll-*a* concentration, and copepod indices predict the local density of Chinook yearlings north of the Columbia, but chorophyll-*a* was the only strong predictor to the south. This latter result was confirmed by Pool (Pool et al. 2012), who further found that coho density was related to decapod larval distribution, salinity and neuston biomass (surface plankton).

Several studies clarified variation in the habitat and migration routes of Atlantic salmon (Mork et al. 2012; Sheehan et al. 2012). These studies also found that wind forcing was the primary driving factor because salmon largely followed current strength, but that the fish also have a tendency to swim toward warmer and saltier water, which likely keeps them in prey-rich areas (Mork et al. 2012).

Growth

Studies of salmon marine growth focused on biological factors, such as maternal effects (Todd et al. 2012), prey densities (Atcheson et al. 2012a; Atcheson et al. 2012b; Dixon et al. 2012; Johnson and Schindler 2012; Sturdevant et al. 2012), and competition with other salmonids (Atcheson et al. 2012b; McKinnell and Reichardt 2012). Many studies also identified significant physical predictors of salmon growth, such as sea surface temperature (Friedland and Todd 2012), the Northern Oscillation Index (Satterthwaite et al. 2012) or climate regime (Huusko and Hyvarinen 2012; McKinnell and Reichardt 2012; Urbach et al. 2012). In general, these papers are consistent with earlier work showing that large-scale physical drivers set up conditions with high or low productivity depending on the location, and if currents are favorable for salmon to reach these prey-rich locations, they grow well. These papers provide much detail on local prey condition and preference, salmon stock-specific responses to physical drivers, and strong density-dependence, principally through competition with pink salmon.

Age at maturation

Long-term trends in spawner age have motivated identification of the factors driving the change. Studies of Altantic salmon often find a correlation between sea surface temperature and age at maturity, but the direction of this effect is not consistent. For example, two papers from Norway produced opposite results. A laboratory study showed that salmon mature earlier in response to good growth in their first year and warmer winter temperatures (Jonsson et al. 2012). But another analysis of a long-term trend toward older spawners also attributed this trend to warmer water in fall (Otero et al. 2012). Interestingly, a study with a paleological perspective showed that warmer climates are associated with earlier maturation, and lower population growth rates (Turrero et al. 2012).

Growth conditions also influence the probability of repeat spawning: the probability of Altantic salmon repeat spawning in the Miramichi River in eastern Canada is correlated with small-fish biomass in nearby ocean waters (Chaput and Benoit 2012). However, when salmon migrated to less prey-rich areas, they were less likely to spawn multiple times.

Survival

The relationship between good growth conditions (high prey quality) and survival is complicated. Most studies have found consistent links from **physical drivers** that provide high levels of nutrients, such as upwelling, tend to transfer the nutrients predictably up the food chain – i.e., high raw nutrients leads to higher primary and secondary production, followed by higher salmon growth and survival (Beaugrand and Reid 2012; Thompson et al. 2012; Tomaro et al. 2012; Trueman et al. 2012). Correlations between physical conditions and salmon survival are generally assumed to be mediated via this mechanism. For example, Rupp found the 4-year average PDO to be a strong predictor of coho survival (Rupp et al. 2012), and more diverse physical predictors (Miller et al. 2012a) and regime shifts seem to drive ocean carrying capacity (Kaeriyama et al. 2012). However, McKinnell and Reichardt (2012) did not see declines in survival when growth rates declined after the 1977 regime shift, possibly because intra- or inter-specific competition reversed the relationship in some years.

Several papers argued that **predator** densities are a major driving force in long-term declines in salmon abundance. For example, Mantyniemi (2012) attributed salmon declines to increasing grey seal populations at longer time scales, although interannual variation at shorter time scales responded to herring abundance. A combination of wind patterns affecting the migration route and causing pelagic piscivores (silver and red hake, *Urophycis chuss*, spiny dogfish) to overlap spatially with the migration suggest Gulf of Maine salmon decline might be driven by predation (Friedland et al. 2012). Holsman et al. (2012) also found predator densities to be a highly weighted predictor of smolt to adult survival of Columbia River Chinook salmon, along with prey density, lipid-rich copepod biomass, upwelling, temperature, and freshwater factors (river flow, transportation through the hydrosystem and hatchery- versus wild-origin).

Anoxic conditions resulting from strong upwelling combined with large respiring fish populations drove a major fish kill in California in 2011 (Stauffer et al. 2012), which indicates that coincidentally interacting events are likely to drive dramatic events in the future as well.

A long-standing question of interest is the extent to which **freshwater conditions affect marine survival**. As mentioned above, Holsman et al. (2012) found significant effects of smolt migration conditions (especially flow and whether the fish was transported) on smolt to adult survival. Haeseker et al. (2012) also analyzed the Columbia River. They found that spill through dams and water travel time (related to total discharge) were significant predictors of estuarine and marine survival. However, neither body size at the time of ocean entry nor the timing of ocean entry were correlated with adult returns in another Columbia River Chinook analysis (Tomaro et al. 2012). In that study, marine growth rate was the best predictor. However, two studies of Atlantic salmon do attribute long-term declines to smolt quality, which includes both timing and body condition (Russell et al. 2012; Todd et al. 2012). The latter study (Todd et al. 2012) tied poor smolt condition back to maternal effects of poor-condition spawners, positing a multi-generational condition cascade. Fortunately, the recent trend of increased ultraviolet radiation exposure during freshwater life stages (from ozone depletion) does not increase marine mortality (Melnychuk et al. 2012).

Ocean acidification – biological impacts

Numerous groups continue to probe biological sensitivities and evidence of negative impacts of recent trends in ocean acidification. I summarize here only work on pteropods and copepods because of their important role in the food chain. A study of pteropod shell characteristics in the Southern Ocean found that these planktonic mollusks already show signs of shell deterioration (Bednarsek et al. 2012). A laboratory study of Arctic Ocean pteropods determined the pH levels that would erode shells (Comeau et al. 2012a), and Comeau et al. (2012b) projected that under the A2 emissions scenario *Limacina helicina* will be unable to calcify shells over much of the Arctic by the end of the century. Flynn et al. (2012) pointed out that the boundary layer around plankton has much lower pH than surrounding water, and that the ability of seawater to buffer this microenvironment effect will decrease. Lischka and Riebesell (2012) studied field measurements in Svalbard over winter. They concluded that winter undersaturation, in combination with low food supply, might become the population bottleneck for Arctic pteropods.

The proportion of lipid-rich copepods in the plankton is a strong indicator of salmon survival for Oregon coho and Columbia River Chinook (see marine survival section). Some copepods might be only subtly affected by direct effects of pH – for example, *Calanus glacialis* showed no effect on egg production, but possible delayed or reduced success in hatching (Weydmann et al. 2012). However, indirect effects of acidification via the food web presents an additional threat to salmon that has not previously drawn much attention. Rossoll et al. (2012) found a decline in fatty-acid production in copepods in response to changes in their diatom prey.

An important consideration for biological effects of ocean acidification is that many factors interact to drive primary productivity, and under global change, some will enhance productivity while others will counteract these changes. For example, Gao et al. (2012) described the both stimulatory and inhibitory effects of changes in photosynthetically active radiation and ultraviolet exposure, as well as stratification, freshening, and changes in metabolic rates with temperature and nutrient availability. They cautioned against over interpretation of single-factor experiments.

Several authors argued that multiple sources of biological stressors need to be considered together. Pörtner (2012) followed up earlier work with further elaboration of the utility of "oxygen and capacity dependent thermal tolerance" as an index that integrates disparate stressors into a physiological unit: pollutants, hypoxia and thermal stress interact to challenge aerobic scope and energy budgets.

Conservation in practice

Beechie et al. (2012) developed a **decision support framework** to guide restoration planning to incorporate climate change. They provide a list of which restoration actions mitigate for which sorts of climatic factors, and rank various actions for their effectiveness in ameliorating for specific climate threats projected for the Pacific Northwest. Littell et al. (2012) described the **adaptation strategies** identified by science-based partnerships being piloted by the **National Forest Service**. The strategies include increasing resilience, considering limitations, prioritizing treatments from a pragmatic point of view, adaptive management, and a focus on structure and composition as a primary goal. Mainstone et al. (2012) reviewed conservation of river flows in the UK. They recommended maintaining a natural flow regime as the best defense against climate change.

A joint adaptation strategy document (National Fish Wildlife and Plants Climate Adaptation Partnership 2012) was published for a number of U.S. agencies responsible for fish and wildlife (NOAA, USFWS, and a collection of state and tribal representatives). The strategy describes seven major goals. They recommend conserving and connecting habitat, reducing non-climate stressors, enhancing management capacity, increasing awareness and motivate action, supporting adaptive management, increasing knowledge and information, and managing species and habitats. They make specific recommendations for cold-water fish, such as reconnecting channels with floodplains and protecting deep stream beds and riparian shade cover to limit temperature increases.

James et al. (2012) discuss **Ecosystem-based Management in Puget Sound**. They describe the initial framework for selecting and ranking indicators. Review of **prescribed dam releases** in the Sustainable Rivers Project as a conservation strategy showed benefits but the need for longer-term evaluations (Konrad et al. 2012). MacDonald et al. (Macdonald et al. 2012) reviewed the **water temperature management of the Nechako River**, which involves forecasting meteorological conditions and responding to high air temperatures with controlled water releases to avoid critical maximum water temperature during spawning migrations. They concluded that the program successfully reduced thermal exposure of fish, and prevented prespawn mortality. Cooke et al. (2012) reviewed how science has benefitted management of Fraser River sockeye. They found that recovery from fishery capture has improved, and that thermal tolerances and genomic signatures could be used to predict migration success. Cosens and Williams (2012) reviewed the history of flow management in the Columbia River and the **Columbia River Treaty**.

Economic trade-offs: In a case study of Shasta River management, Null and Lund (2012) optimized out-migrating coho salmon against restoration costs for a diverse set of restoration options, constrained by a total budget. Radeloff (2012) assessed the ability of four policy scenarios to affect land-use change in the U.S. by 2051. All scenarios showed dramatic increases in urban land and loss of agricultural land, but variable increases in forest, depending on the scenario. They suggested that urbanization will increase and should be taken into account when planning.

Priority of climate change in decision-making: Evaluation of decision-making processes in three major sectors in Colorado (forests, biofuels and grazing) revealed that although there is interest in and discussion of climate change issues, threats from climate remain a lower priority than other issues (Ellenwood et al. 2012). From a more general perspective on climate science, Lemos et al. (2012) discussed the gap between information that scientists produce that they think is useful, and the information that decision-makers actually use. They focused on users' perceptions of how well the information fits, interplay with existing types of information, and the quality of the interaction between scientists and users. They recommended varying levels of interaction, customizing the information, and repackaging existing information to meet multiple users' needs.

General conservation principles: For conserving native trout, Hakk and Williams (2012) recommended protecting genetically pure populations across the historical range, restoring life-history diversity, and protecting large, stronghold populations. They advised that larger populations are needed for long-term persistence. Conservation in coastal zones is complicated by a multiple relevant spatial and temporal scales, spatially-diffuse footprints of human actions, and the potential for large consequences from small human decisions (Swaney et al. 2012)

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Appendix D.2
Literature review for 2010: Biological effects of climate change

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Literature review for 2010 citations for BIOP: Biological effects of climate change

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August, 2011

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1 Executive summary

Nationally and globally, the climate of 2010 continued trends of global warming, being one of the two warmest years on record. New analyses of observational data were generally consistent with previously reported historical trends of climate change. Climate, oceanographic, hydrologic, and stream-temperature models continue to be developed, tested, improved, and applied. Most of their assessments and projections indicated worsening physical conditions for salmon in mid-latitude regions, consistent with previous analyses: rising air temperature, moderately rising precipitation, declining snowpack, declining stream flow (partly due to water withdrawals), and rising sea surface temperature (although at reduced rates in upwelling regions). However, a few of the results could have either beneficial or negative implications for salmon. Historical analyses and predictions of net changes in primary productivity are spatially variable, and increases in the intensity of coastal upwelling (see below) could have positive or negative impacts. New studies on the biological effects of most of these processes were consistent with previous analyses, and showed that where salmon are limited by cool temperatures, warming is beneficial, at least over the short term, but in areas that are already relatively warm or where floods or low flows have negative impacts, climate change scenarios consistently project declines in salmon. In the ocean, several new studies pointed to the importance of sea surface temperature for early marine survival (as opposed to the Pacific Decadal Oscillation or smolt condition), but there were large differences among populations included in the study, and the single Columbia River population included did not show a strong ocean effect in this analysis (Sharma et al. 2009). The most geographically relevant papers include stream temperature analyses of the Boise River Basin (Isaak et al. 2010), the Wenatchee River Basin (Cristea and Burges 2010), and the Touchet Basin (Wiseman et al. 2010); and numerous climatological analyses of the Columbia Basin (see sections 4 and 5).

Several new papers documented historical and projected increases in upwelling intensity in the California Current (Bakun et al. 2010; Garcia-Reyes and Largier 2010; Wang et al. 2010). Although stronger upwelling has been positively associated with Columbia River salmon survival in the 20th century, Bakun et al. (2010) presented some possible scenarios (exacerbated by bad fisheries management) in which anoxia, toxic gas eruptions and jellyfish take over. Furthermore, although increased primary productivity predicted by some models would be expected to benefit salmon, most ecosystem models predict declines in salmon productivity south of the Arctic. Arctic conditions were expected to improve for salmon based on increased nitrate concentration (Rykaczewski and Dunne 2010), primary productivity (Kahru et al. 2010; Steinacher et al. 2010), and fisheries catches generally (Cheung et al. 2010; MacNeil et al. 2010).

A few emerging potential threats were documented for Fraser River salmon, with unknown potential for affecting Columbia River salmon. Algal blooms lowered survival of Chilko sockeye smolts (Rensel et al. 2010), and apparently increasing aggregations of sharks might be increasing predation on returning adults (Williams et al. 2010).

One other highly novel study found that gene flow increased during unfavorable river conditions, suggesting that straying might increase in response to rising temperatures (Valiente et al. 2010).

Three studies documented strong trends in salmonid phenology (one smolt-timing and two spawn-timing studies). Two of these studies also involved declining populations, and the authors suggested that part of the problem was a mismatch between rates of temperature change either in fresh- or saltwater (Kennedy and Crozier 2010) or between spring and summer (Wedekind and Kung 2010). In the 2010 BIOP we mentioned a trend toward earlier smolting in Snake River spring Chinook (Achord et al. 2007), so attention to potential phenological mismatches seem warranted. Several other studies attributed population decline more directly to environmental deterioration (Clews et al. 2010; Wiseman et al. 2010).

A large number of recent studies on Fraser River sockeye found negative impacts of high temperatures on adult migration survival and throughout the life cycle, and warned that a majority of populations within the Fraser River Basin are highly vulnerable to extinction due to climate change, based on both quantitative (Hague et al. 2011; Martins et al. 2011) and qualitative analyses (Jacob et al. 2010; McDaniels et al. 2010). McDaniels et al. (2010) considered possible management actions, but found they were limited. One study found individual variation in the use of thermal refugia during migration that depend on individual condition (Donaldson et al. 2010), while another study found that thermal refuge use corresponded to higher survival (Mathes et al. 2010). Disease morbidity and mortality is being exacerbated by warmer temperatures (Braden et al. 2010; Bradford et al. 2010; Marcos-Lopez et al. 2010) and artificial propagation (especially fish farms, Krkosek 2010; Pulkkinen et al. 2010).

Several theoretical papers described new mathematical methods of detecting impending extinction due to environmental deterioration (Drake and Griffen 2010; Ovaskainen and Meerson 2010) and elevated risks from environmental impacts at particular time scales and life stages (Worden et al. 2010).

Several studies demonstrated strong maternal effects on larval survival, compared with stronger genetic effects on juvenile growth and survival. These studies could possibly imply that negative effects of the hydrosystem could persist into the next generation, whereas evolution might modify juvenile growth and survival.

New studies provided additional details on adaptation strategies, such as those previously described in ISAB (2007), for Pacific salmon. For example, Cristea and Burges (2010) found that the cooling potential of riparian vegetation restoration is likely to postpone stressful temperatures for salmonids in Wenatchee River tributaries through the end of the century. However, vegetation restoration did not significantly reduce temperature in the mainstem Wenatchee. Such studies need to be site specific, because, for example, Null et al (2010) found that restoring and protecting cool springs was more beneficial than increasing riparian shading in the Shasta River. Several papers provided more information on adaptation strategies in general and the practical social and technical considerations for implementing them (e.g., Binder et al. 2010; Brekke et al. 2010).

In conclusion, new information from 2010 publications was generally consistent with previous analyses in reporting ongoing trends in climate consistent with climate change projections and negative implications for salmon at mid-latitudes. Modeling techniques continue to improve. A few studies focused on areas that did not receive much attention in our previous report, and thus provide new information. These areas include predicted and observed intensification of upwelling (compared with various similar and contradictory reports published previously), reduced salmon survival due to algal blooms, climate-induced straying, and climate change-induced mismatches in phenology associated with population declines. Numerous new studies of Fraser River sockeye warn of very severe risk from climate change. Finally, several theoretical papers augment our toolbox for anticipating extinction due to environmental deterioration.

2 Table of acronyms

AO	Arctic Oscillation
BPA	Bonneville Power Administration
CCS	California Current System
ENSO	El Niño-Southern Oscillation
ESU	Evolutionarily Significant Unit
GCM	General Circulation Model
IPCC	Intergovernmental Panel on Climate Change
NPI	North Pacific Index
NPGO	North Pacific Gyre Oscillation
NO	Northern Oscillation
OA	Ocean Acidification
PDO	Pacific Decadal Oscillation
SO	Southern Oscillation or Southern Annual Mode
SST	Sea surface temperature
VIC	Variable Infiltration Capacity model
WACCA	Washington State Climate Change Assessment
WRF	Weather Research and Forecasting

3 Goals and methods of this review

The goal of this review was to identify the literature published in 2010 that is most relevant to predicting impacts of climate change on Columbia River salmon listed under the Endangered Species Act. A large amount of literature related to this topic is not included, because almost anything that affects salmon at all relates to or is altered in some way by changes in temperature, stream flow or marine conditions. We have tried to identify the most directly related papers by combining climatic and salmonid terms in my search criteria. Thus many general principles demonstrated in other taxa or with more general contexts in mind have been omitted. This review also does not include potentially relevant gray literature, because the search engine used only includes the major peer-reviewed scientific journals. Additional references were solicited from NOAA staff and independent scientists who specialize in freshwater habitat, estuary behavior, marine ecosystems, ocean acidification, and climate-fish dynamics in other species. In total, the methods employed involved review of over 800 papers. Of these, 223 are included in this summary.

This search was conducted in ISI Web of Science in June, 2011. Each set of search criteria involved a new search, and results were compared with previous searches to identify missing topics. The specific search criteria all included PY=2010, plus:

1) TS=(climat* OR temperature OR streamflow OR flow OR snowpack OR precipitation OR PDO) AND TS=(salmon OR Oncorhynchus OR steelhead);

2) TS=(climat* OR Temperature OR Precipitation OR streamflow OR flow) AND TS="Pacific Northwest";

3) TS=(marine OR sea level OR hyporheic OR groundwater) AND TS=climat* AND TS=(salmon OR Oncorhynchus OR steelhead);

4) TS=(upwelling OR estuary) AND TS=climat* AND TS=Pacific;

5) FT=("ocean acidification" OR "California current" OR "Columbia River")

6) TS="prespawn mortality"

The review is organized by first considering physical environmental conditions (historical trends and relationships) and then predictions of future climate, snowpack, stream flow, temperature, ocean conditions, etc. A summary follows of the literature on salmonid responses to these environmental conditions, progressing through the life cycle.

4 National Climate Summary of 2010

Nationally and globally, 2010 was at or near record-breaking levels in many respects, based on NOAA’s Annual State of the Climate Report (Blunden et al. 2011) Strong El Niño-Southern Oscillation (ENSO), Arctic Oscillation (AO), and Southern Annular Mode (SO) conditions drove very dramatic weather events in many parts of the world, while we emitted greenhouse gases at very high levels (above the average over the past 30 years). Trends consistent with global climate change reported in the 2010 Supplemental Biological Opinion (NMFS 2010) continued: 1) 2010 was one of the two warmest years on record; 2) average global sea surface temperature was the third warmest on record and sea level continued to rise; 3) ocean salinity variations at a global scale showed intensification of the water cycle; and 4) Arctic sea ice shrank to the third smallest area on record, the Greeland ice sheet melted at the highest rate and over the largest area since at least 1958, and alpine glaciers continued to melt.

5 Historical analysis of terrestrial climate, stream flow and stream temperature in the western US and British Columbia

A number of new papers have conducted historical analyses of trends over the past half century or so in air temperature (rising), precipitation (rising), snowpack (declining) and stream flow (declining). Trends in ocean conditions and El Niño events are discussed in the ocean section. These results are generally consistent with trends described in the 2010 Biological Opinion (NMFS 2010). Further, several papers have analyzed how broad-scale climatic conditions such as the Pacific Decadal Oscillation (PDO) and ENSO drive variation in processes with significant biological implications, such as drought, forest fire, landslides, and coastal fog.

Specifically, Fu et al. (2010) showed that in Washington State from 1952 to 2002, annual mean air temperature increased 0.61ºC (daily mean), 0.24ºC (daily maximum), and 0.93ºC (daily minimum), on average (or at a rate of 0.122, 0.048, and 0.185ºC, respectively, per 10 years). Despite increasing annual precipitation, stream flow decreased at a rate of -4.88 cms/yr, with the largest effects in May and June on the west side of the Cascade Mountains. Temperature increased throughout the year (except October and December) across the state, with a small area of maximum temperature cooling in the central-eastern portion of the state. Minimum temperatures rose more than maximum temperatures. To explain the declines in streamflow, the authors suggested that human water use and increased evaporation rates due to rising temperature and more surface area exposure (e.g., from reservoirs) play important roles. Ryu et al. (2010) showed a positive relationship between a drought index based on streamflow and El Niño in the Pacific Northwest. Bumbaco and Mote (2010) studied the role of winter and summer precipitation and temperature in causing three droughts in Washington and Oregon (2001, 2003, and 2005), and found a different driver in each case (low winter precipitation in 2001, low summer precipitation in 2003, and warm winter temperatures during key precipitation events in 2005).

Corresponding to the lower availability of water for biological processes, Meyn et al. (2010) showed that summer drought correlates strongly with the forest area burned in British Columbia. The PDO index the previous winter was related to summer drought in some areas of British Columbia, but is not a very strong driver over most of the province. Johnstone and Dawson (2010) tracked a new index of climate not mentioned in our previous report, which is the frequency of coastal fog along the California coast. They showed that fog levels are correlated with the strength of upwelling and have declined 33% from 1951 to 2008, increasing drought stress for plants.

Intense precipitation events, predicted to increase in winter with climate change, exacerbated by rain on snow events and high wind also increase the risk of landslides (Guthrie et al. 2010).

Average snow depth decreased widely across the western United States, especially at lower-elevation stations (<1000 m, Grundstein and Mote 2010). The vast majority of lower-elevation stations (80%) and a majority of mid-elevation stations (2000-3000m, 62%) showed significantly negative trends. Snow depth was strongly related to the PDO and the North Pacific Index (NPI).

Streamflow reflects both climatic factors and local habitat. For example, recent papers discussed the impact of glacier runoff and projected changes (quantified on Mt Hood by Nolin et al. 2010), and combinations of snow fall and forest integrity, whether due to harvest or fire. Specifically, Jones and Perkins (2010) studied how rain-on-snow events and harvest differentially affected different sized basins, while Eaton et al. (2010) examined changes in peak flows and the timing of the freshet, in addition to channel morphology following fire.

Wetlands are highly dynamic environments. Large scale variability in climate such as oscillations of the PDO can dramatically change local environmental conditions. After the regime shift of 1976, a wetland in southern California experienced a dramatic increase the frequency of extreme storms and floods due to a shift in the storm track across the Pacific. Zedler (2010) classified the types of events and their ecological consequences (mostly for plants) in terms of their relationships, for example, whether the ordering of events matters (e.g., river-mouth closure followed by a drought, that killed many more plants than additive effects would predict. They suggested focusing restoration actions on preparing ecosystems for likely future climates rather than restoring past communities necessarily.

6 Projected changes in terrestrial climate for the 21st century

Some of the most relevant projections of climate change conditions within the Columbia Basin were summarized in the 2010 BIOP based on reports produced for the Washington State Climate Change Assessment (WACCA), but were published in formal climate journals in 2010. In this category, Mote and Salathé (2010) described climate changes in the Pacific Northwest predicted by general circulation models produced for the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report. Salathé et al. (2010) described changes predicted by the regional dynamical climate model Weather Research and Forecasting (WRF) Model. Elsner et al. (2010) summarized the regional hydrological implications of the global model predictions, and Mantua et al. (2010) described projected increases in peak winter flows, lower late summer flows, and high summer stream temperatures that will threaten salmon. A few other sections of the WACCA report were not mentioned in the BIOP, and are summarized in this report.

Predictions of how rising greenhouse gases will affect climate depend on how functional relationships are modeled. A large body of work describes tests and improvements of the climate models, and are mostly beyond the scope of this review. It is worth noting here that work is ongoing on many aspects with especially large levels of uncertainty at the moment, such as the extent of intra-model variability compared with inter-model variability (over half of the variation between models can be explained by variation within models, Deser et al. 2010), how the global circulation models drive ENSO variability (An et al. 2010) and regional downscaling -- i.e., how to convert the large-scale global model output (~200km^2 resolution) to the regional scale (~8 km^2 resolution, Ainslie and Jackson 2010). There are important differences in predictions made by different downscaling approaches. Qian et al. (2010) compare predictions from two dynamical downscaling methods, a subgrid parameterization and a regional climate model. They found that both methods greatly improved the modeled snowpack compared with observations over simpler downscaling methods, but the regional model captured precipitation and snowpack along the coastal mountains much better because of the importance of mountain orientation for wind direction. This model predicted a greater change in snowpack under climate change scenarios than the subgrid approach.

Predictions of changes in snowpack are very sensitive to how temperature changes with elevation. Minder et al. (2010) clarified spatial and temporal variation in the lapse rate in the Cascades, and Minder (2010) studied the effect of different determinants of the snow melting level in physical models. Minder (2010) predicted a loss of 14.8%-18.1% of Cascade snowfall per degree of warming, assuming precipitation increases, and 19.4%-22.6% loss per degree without precipitation increases, with profound impact on accumulated snowpack.

6.1 Stream flow

Many hydrological projections are based on the Variable Infiltration Capacity model (VIC). Wenger et al. (2010) conducted a test of this model in the Pacific Northwest. They found that model predictions were relatively accurate for center of flow timing and mean annual and summer flows, and the frequency of winter floods. However, modeled frequencies of low flows and groundwater-impacted streams did not match observations closely.

Chang and Jung (2010) projected the hydrology of the Willamette River Basin. They considered predictions from 8 general circulation models (GCMs), and downscale to 1/16th degree resolution for their hydrological model. Like previous projections, the models predicted increased winter flow, decreased summer flow, reduced snowpack, and earlier runoff. The different GCMs varied significantly in their predictions, especially later in the century. There was also substantial variation at the subbasin scale, indicating important local controls in hydrology. A new analysis by the Climate Impacts Groups for the Bonneville Power Administration (BPA) showed similar spatial variation, uncertainty, and general trends. This was a comprehensive study in draft form in 2010 (Brekke et al. 2010). It will be summarized more thoroughly in the 2011 report.

Three papers focused on changes in precipitation or hydrologic extremes. Tohver and Hamlet (2010) analyzed shifts in extreme streamflow statistics at 297 sites in the Columbia Basin, based on the Columbia Basin Climate Change Scenarios Project. First they described the same results previously reported: there was a general shift from weakly snow-dominant basins to transient basins, and from transient basins to rain-dominant basins, such that no snow-dominant sources remained in the US portion of the Columbia Basin by 2080, under the A1B scenario, and extremely few even in the highly optimistic B1 scenario. However, they found significant differences between the two downscaling methods employed in flood projections. The "hybrid delta" method predicted flooding increases throughout the Columbia Basin, whereas in Mantua et al. (2010) and the "composite delta" method, increased flooding is more spatially variable. The hydrid delta method is thought to be more accurate in this regard, reflecting the spatial distribution of warming and precipitation increases better than the composite method. Higher winter temperatures and precipitation regimes increase flooding most in transient and rain-dominant basins, but also in snow-dominant basins, despite the reduced accumulation of snowpack. Even greater increases in flooding could be caused by increasing spring storm intensity and more precipitation falling as rain rather than snow. Increased flooding in transitional and rain-dominated basins followed from increased winter precipitation. Low flow risk increased most in rain-dominant and transient basins due to rising summer temperatures and evapotranspiration rates. Snow-dominant basins, so important in the Columbia and Snake tributaries, were relatively resilient to this effect in this analysis possibly because the lowest flows tend to occur in winter, and they did not separate out summer low flows.

Rosenberg et al. (2010) examined precipitation extremes for stormwater infrastructure. They found that uncertainty in projections is too large to make engineering preparations, but that some potential outcomes could be very serious. Towler et al. (2010) similarly examined extreme precipitation events and secondary effects, in this case, turbidity, important for Portland's water supply. They developed a technique for applying climate change scenarios to detect the impacts of predicted shifts in extreme events.

A study in California (Meyers et al. 2010) found that +2ºC and +4ºC climate warming and altered precipitation are likely to shift floods from spring to winter, and increase the frequency and intensity of floods. Such a change would negatively affect brook trout more than rainbow trout, which would then experience less competition from brook trout.

Another study (Moradkhani et al. 2010) explored climate change scenarios in the Tualatin River in Oregon using a different hydrological model and found that the 50-year floods and the riparian ecotone decreased in low emissions scenarios, but increased in high emissions scenarios. Thus well-established trees along the riparian corridor were flooded in the high-emission scenarios.

Some streams are currently fed by significant amounts of glacier meltwater. Nolin et al. (2010) studied a stream on Mt Hood that currently derives 41-73% of its late summer flow from glaciers. Under climate change scenarios, glaciers retreated, ultimately reducing summer flow.

7 Historical analyses and projections of ocean conditions

A number of studies published in 2010 provided insight into areas of profound importance for salmon that have been especially uncertain in prior climate change analyses. Two papers indicated that over the 20th century, upwelling in the California Current System (CCS) and the Humboldt Current System have become more intense, which is consistent with a new analysis of GCM projections that predicted it will continue to intensify with global warming. Papers focusing on historical sea surface temperatures (SST) addressed previous criticisms that observed trends are due to instrument bias, re-established the global pattern of decadal oscillations overlaid upon a background of rising SST, and documented the shifting character of El Niño events and their impact on long-term SST trends.

7.1 Upwelling

Upwelling dynamics along the Washington and Oregon coasts are a key element in Columbia River salmon marine survival and growth. The impacts of climate change on upwelling dynamics are among the most uncertain of all the predictions of climate change models. Conflicting predictions stem from 1) changes in the various driving processes that affect upwelling are expected to act in opposite directions, necessitating quantitative comparisons for determining net effects (i.e., rising SST should reduce upwelling, while increasing alongshore winds should increase upwelling) and 2) the spatial resolution of both climate models and empirical datasets have generally been too coarse to accurately capture upwelling dynamics.

Two papers published in 2010 basically supported the intensification prediction by documenting empirical trends over the 20th century, and a 3rd paper analyzed GCM reconstruction and projections of upwelling dynamics over the next century. Garcia-Reyes and Largier (2010) analyzed hourly buoy data off the California coast to describe the historical trend at an appropriate spatial and temporal scale. They found strong evidence for intensification of upwelling from 1982 to 2008, especially in central California (35ºN-39ºN). Specifically, they documented trends in the upwelling index (based on pressure fields), the strength of upwelling winds (based on alongshore wind speed), SST directly within the upwelling region (hence a negative trend in absolute temperature during the upwelling season), the number of days of upwelling within the season, a lengthening of the upwelling season (more days in March and October, hence earlier spring and later fall transition), and increased variability in upwelling winds (an increase in the 90th percentile and a decrease in 10% percentile), indicating stronger upwelling alternated with more relaxation in winds. They also found correlations of magnitude 0.6 or 0.7 between upwelling winds and the Northern Oscillation and the North Pacific Gyre Oscillation (NPGO), and between SST and the PDO and ENSO.

The second paper (Bakun et al. 2010) reviewed the basic argument that increasing land temperatures will intensify the pressure gradient between ocean and land, and hence intensify the alongshore wind stress, which initiates upwelling. Bakun et al. (2010) then reviewed previous tests of the hypothesis, and described a new test focusing on the relationship between water vapor and upwelling off Peru. This test showed significant correlations most of the time. Because water vapor acts as a greenhouse gas, they concluded this was consistent with a prediction of intensifying upwelling with rising greenhouse gas concentrations. One very important point they made in this paper, however, is that intensification of upwelling is not necessarily good for fish. They described scenarios in which excessive upwelling advects zooplankton offshore too quickly for effective phytoplankton control. If omnivorous fish such as sardines are overfished or not present for some reason, there could be an ecosystem regime shift toward that currently found off Namibia, in which unconsumed phytoplankton sink and generate hypoxic zones and toxic gas eruptions, which kill fish and leave an ecosystem dominated by jellyfish.

In the third paper, Wang et al. (2010) analyzed the performance of all the major GCMs produced for the 4th IPCC assessment using a number of criteria, including PDO variation across the Pacific and upwelling near the mouth of the Columbia River. Twelve of the 23 GCMs had a reasonable representation of the PDO over the 20th century (i.e., had a spatial correlation coefficient of the first Empirical Orthogonal Function of winter SST of at least 0.7). Half of these models predicted that SST would exceed the variability of the PDO within 50 years under the A1B emissions scenario (the reminder predicted it would happen within 90 years). Averaged over 10 models, SST in the CCS was expected to increase 0.26ºC per decade in the 21st century. Although the GCMs were not designed to characterize dynamics at the spatial scale of coastal upwelling, these models did remarkably well at capturing the seasonality of upwelling, even if they overestimated seasonal variation somewhat. Representation of the California Current was better than the Humboldt Current. In the CCS, 17 models predicted increases in July upwelling while only two models predicted decreases.

7.2 Ocean temperatures

Three studies analyzed historical trends in ocean temperatures. Carson and Harrison (2010) examined the impact of instrument bias in previously reported interdecadal trends at the ocean surface, 50m, 100m, and 300m temperatures. They found coherent signals of interdecadal variability at multiple depths, even with bias correction and comparisons of different datasets. This contrasts with recent work on the global average temperature, which showed reduced decadal variability after bias correction. Schwing et al. (2010) describe global atmospheric and oceanic teleconnections (e.g., the PDO, AO, NO, SO, and major current systems) and the major factors driving large marine ecosystems. Atmospheric teleconnections synchronize much of the decadal variability in the California and Humboldt Current Systems, as well as the Gulf of Alaska. Schwing et al. (2010) showed a persistent warming trend of 1-2ºC over 100 years in SST in all large marine ecosystems, although the rate of warming was weaker in the upwelling (or downwelling) dominated coastal region. The general patterns (overall trend and decadal fluctuations) were similar to global mean surface temperature, despite some regional differences. The western Pacific showed roughly similar trends, but lags behind the eastern Pacific by about 10 years, and was driven by quite different physical processes. Thus they predicted similarities among the eastern Pacific large marine ecosystems in responses to climate change, but less so between eastern and western Pacific large marine ecosystems. Another paper (Moore et al. 2010), made a very interesting point, which is that ENSO warm water events usually only affect winter temperature in Pacific Northwest waters, while the PDO warm phase often persists through summer and fall. This has important implications for the salmonid life stage that is affected by these events, which then has implications for impacts on population dynamics (Worden et al. 2010), as described below in the Population Dynamics Modelling Section.

Finally, Lee and McPhaden (2010) paper parsed out sea surface temperature increases in the central Pacific during El Niño events, and found that the increasing frequency and intensity of these events in this region drove most of the overall trend in sea surface temperature (SST). SST during El Niño events warmed by 0.24ºC/decade, whereas SST warming in neutral and La Niña years was positive, but much smaller (0.05-0.07ºC/decade) and not statistically significant over the 1982-2008 time frame. The reason for this shift in the position of the maximum warm anomaly is not known, but increasing intensity and frequency of El Niño events has been predicted to follow from rising greenhouse gases (Yeh et al. 2009), as cited in the 2010 Biological Opinion.

7.3 Ocean acidification

Two papers found that measured declines in pH near urban areas are faster than expected from CO_2 uptake alone and partially reflect nutrient loading (in the Hood Canal of Puget Sound, Washington, Feely et al. 2010; along the Dutch coast, Provoost et al. 2010). Wong et al. (2010) studied trends in pCO_2 in seawater along line P out from Vancounver Island, and found that it has risen in the oceanic zone at a rate of 1.36 μatm per year, tracking the atmospheric growth rate. The coastal zone pCO_2 rose at a similar rate in winter, but spring levels showed no trend.

8 Impact of stream temperature and flow on juvenile salmon

8.1 Effects of temperature on embryo development

There has been much concern that warmer winter temperatures will increase embryo mortality, cause ealier fry emergence, smaller fry size, and a mismatch between larval needs and food supply. In an experiment on coho survival, Lohmus et al. (2010b) found the optimal temperature for hatching and alevin survival was a relatively high 12ºC; they found substantial survival (40%) still at 16ºC, but very low survival at 18ºC (2.5%). In a review article, Teletchea and Fontaine (2010) found a strong positive relationship between egg size and larval energy reserves, and a strong negative relationship between temperature and time to first mixed feeding (i.e., requiring external food supply) among Pacific salmon. Thus although Pacific salmon have relatively large eggs and hence more flexibility in temporally matching food availability than other fish, higher temperatures are likely to produce smaller, less flexible fry. Janhunen et al. (2010) found that alevins hatched at the higher temperature were developmentally less advanced.

If either egg or larval survival is reduced under future climatic conditions, it is theoretically possible that they might evolve in response to selection. Several studies showed that populations from different climates have locally adapted development rates and thermal tolerances. Narum et al. (2010) found evidence of selection for differing climates by comparing genetic markers in redband trout: temperature was strongly correlated with allele frequencies. And Kavanagh et al. (2010) found evidence of local adapation to cool temperatures and reduced critical maximum temperatures in European grayling within 22 generations. However, Evans et al. (2010) and Janhunen et al. (2010) found similar results in Chinook salmon and Arctic charr, respectively, that genetic variation was relatively weak for embryo survival, but was slightly greater for larval length. Maternal effects were strong in both studies especially at the earlier developmental stages, indicating that adult migration and prespawn condition could have long-lasting effects through the next generation.

The effect of temperature during development might have more complicated effects beyond body size and emergence time. In sticklebacks, developmental temperatures and consequent compensatory growth affected skeletal and muscle morphology, with potential effects on locomotor performance (Lee et al. 2010). In zebra fish, brief exposures to cool developmental temperatures affected dorsal, anal, caudal, and pelvic fin positions, as well as gill cover and the position of the lower jaw (Georga and Koumoundouros 2010). It is not clear whether these shape changes have functional implications, but they were preserved through adulthood. Zabel et al. (2010) showed that different Chinook salmon ESU (fall vs spring/summer life history types) had different otolith/fish length relationships, demonstrating differences in morphology that are not simply explained by different growth rates. The populations do rear in very different environments, but the role of environmental temperature requires further study.

Other effects of high temperature during development include sex reversal. Magerhans and Horstgen-Schwark (2010) reported an experiment that showed that sensitivity to temperature in sex determination in rainbow trout is substantial and heritable. The initial population had a sex ratio of 51.9% female when eggs were reared at 18ºC, and 49.3% female when reared at 12ºC. After one generation of selection, they produced a sex ratio of either 57.6% or 44.5% female at 18ºC, indicating a heritability of 0.63 for this trait. Stelkens and Wedekind (2010) reviewed the various mechanisms of sex determination and sex reversal in teleost fish.

8.2 Effects of temperature and flow on juvenile growth and survival

Many papers have continued to demonstrate strong effects of temperature and flow on juvenile salmon growth and survival. Most papers are consistent in showeding improved growth when relatively cool habitat warms up: spring in Massachusetts, (Xu et al. 2010a), fall in Idaho (Jenkins and Keeley 2010); and a long-term trend of larger smolts in the Baltic (Vainikka et al. 2010). However, negative effects of warming were typical during summer (Xu et al. 2010b) and winter (Xu et al. 2010a), when consumption cannot compensate for increased metabolic demands. In northern Europe, the net effects are expected to still be positive except under the warmest climate change scenario examined (+4ºC). This prediction was consistent with observations of increased size at age over 23 years in Baltic Sea Altantic salmon, although hatchery practices and size-selective fishing also affect these populations. In more southerly locations, the negative effects were predicted to outweigh positive effects even in moderate warming scenarios (Xu et al. 2010a). Changes in growth rates might affect the timing of vulnerability to predators such as bass, which are very size selective (Christensen and Moore 2010).

Similarly, several papers showed that higher flow has positive effects when it is relatively low to start with (e.g., in spring in the heavily water-withdrawn Lemhi Creek, in fall in the more natural Marsh Creek, and higher spring flows in the Columbia for both populations of Chinook salmon (Arthaud et al. 2010), and throughout the brook trout growing season in Massachusetts, (Xu et al. 2010a), and in bringing in more insect drift to cutthroat trout in Jenkins and Keeley (2010), and increasing Atlantic salmon habitat volume (Teichert et al. 2010). However, the highest flows (floods) had negative effects (Hayes et al. 2010; Xu et al. 2010a). Hayes et al. (2010) found that relaxed density-dependent mortality over the following season compensated for the immediate negative effects on brown trout, thus there was no net effect in this case.

The rest of this section provides more detail on the papers mentioned in the previous two paragraphs. Xu et al. (2010a) tracked individual brook trout growth over an 8 year study. They found strongly interacting effects of temperature, flow, season, and density. Highest growth rates occurred in spring, and were positively correlated with temperature and flow. In the warmest season, summer, temperature was negatively correlated with growth. Flow was generally positively correlated with growth, except in winter. Furthermore, density had greater negative effects at high temperatures. Because current climate predictions indicated the greatest increases in temperature and flow are in the winter, and that flow decreases in the summer, the net prediction based on their data was a decrease in mean fish spawner size and fecundity under a moderate (1.5ºC) warming scenario.

Davidson et al. (2010) studied the same study system as Xu et al. (2010a), but analyzed Atlantic salmon growth instead of brook trout growth, and included the impacts of the density of both Atlantic salmon and brook trout. Using a linear mixed model, they found that environmental effects (both temperature and discharge) were much more important than density in driving variation in growth. Warmer temperatures within a season generally had a very small negative effect, while high discharge had a strong positive effect. Interestingly, they found that more variability in temperature (the second principle component in temperature) had a negative impact at low discharge, but a positive impact at high discharge.

Habitat quality depends in part on food availability and the cost of aquiring it, which in turn depend on flow and temperature. Jenkins and Keeley (2010) found that cutthroat trout foraging location matched that predicted by the amount of energy gained (net energy intake NEI), with habitat type (pool versus riffle) and temperature explaining most of the variation among sites. Using an energetic model, they concluded that warmer temperatures will have negative effects on smaller fish, but will lengthen the growing season for larger fish.

Hayes et al. (2010) used changes in the relationship between weight and density in a New Zealand brown trout population over time to assess the impact of unusually low flows and one flood on population dynamics. They argued that although the flood caused substantial emigration or mortality, survival after the flood was higher than in other years (i.e., reduced density-dependent mortality), such that the population recovered quickly. The low-flow events had no effect on survival or biomass.

Arthaud et al. (2010) examined how well variation in flow during freshwater stages affected egg-smolt and egg-adult rates in a pristine stream (Marsh Creek, Idaho) and a stream subject to very high rates of water withdrawal (Lemhi Creek, Idaho). In

Lemhi Creek, water withdrawals are so severe that spring flows during the parr year strongly limited production and drove variation in both egg-smolt and egg-adult survival. In Marsh Creek, egg-smolt survival was correlated with parr-year August flow, but the cumulative impact on egg-adult survival was much weaker. In both populations, smolt-adult return rates were best predicted by Columbia River spring flow and ENSO.

Rising temperatures increase not only the metabolic rate of salmonids, but that of their predators, and potentially the risk from warm-adapted invasives such as bass. Christensen and Moore (2010) documented levels of bass predation on stocked rainbow trout in Twin Lakes, Washington.They found that trout sizes in fall (100-160mm) made them vulnerable to predation by large largemouth bass, but larger trout (>210mm) escaped predation. This suggests that changing growth rates due to temperature might affect not just total predation, but also the temporal period salmon are vulnerable to bass predation.

Westley et al. (2010) considered the affects of dispersal of anadromous fish through lake systems and discover a consequent lag in the community response to environmental forcing, in addition to habitat change and fishing mortality. By examining fish composition over 46 years, they found an immediate response and a 1-year time lagged response to the PDO in an upper lake where sockeye rear their first year, but just a 1-year time-lagged response in a lower lake. They emphasized these processes are important for anticipating the impact of environmental variability on community composition.

Lohmus et al. (2010a) studied variation in juvenile growth among wild-type and growth-enhanced coho salmon at 3 temperatures. They saw little evidence of compensatory growth, perhaps because fish were fed to satiation, so rank order in size was relatively consistent throughout the experiment. The fish grew more at 16ºC than at 12ºC, which is consistent with previous studies that found 15ºC to be the optimal temperature for growth.

8.2.1 Local adaptation/genetic control in growth rates

Growth rate in general and the growth response to temperature in particular is a heritable trait, and several papers showed differences between populations consistent with a history of different selection pressures. Latitudinal gradients are especially useful for demonstrating evolutionary effects of different thermal regimes. In general, colder temperatures slow growth rate within populations, producing a latitudinal gradient of smaller size at age in cooler locations (Chavarie et al. 2010; Morita and Nagasawa 2010). However, over evolutionary time populations in cooler environments have compensated for this effect by evolving faster growth rates and better tolerance of adverse conditions at northern latitudes. Chavarie et al. (2010) demonstrated these higher growth rates in northern populations across 66 populations of lacustrine Arctic charr in eastern North America, although their anadromous forms did not showed the same strong effect. Finstad et al. (2010) showed that compared to southern Norwegian populations, northern populations of Atlantic salmon have adapted higher feeding activity and reduced metabolic expenditures to sustain them over a longer winter.

Although these patterns prove that fish evolve to different thermal regimes over long time periods, potential evolutionary responses to rapid climate change are a very different matter. Understanding the roles of phenotypic plasticity, genetic variability, and maternal effects controlling larval survival and fry growth is key to predicting plastic and evolutionary responses to climate change. In a carefully controlled breeding design plus translocation experiment, Evans et al. (2010) quantify the strengths of these various effects in Chinook salmon from Quinsam and Big Qualicum rivers. They found that all processes were important for explaining their results, but that maternal effects were the most important process for larval survival, while additive genetic effects dominated fry survival and fry growth. These results suggest that maternal condition is very important for cross-generational effects, and that there is substantial genetic variation available for an evolutionary response to environmental change.

Van Doorslaer et al. (2010) explored rapid evolution in Daphnia, which are a major prey item of lake-dwelling salmonids, to increased temperature through artificial selection. They compared these newly evolved populations to Daphnia from a historically warmer climate. After only six months of exposure to unusually warm conditions, size at maturity had evolved. In this semi-natural experiment, the intrinsic population growth rate did not evolve. However, in a previous study (Van Doorslaer et al. 2009a) they showed the reverse effect, where population growth rate evolved but not size at maturity, demonstrating that either response is feasible, depending on ecological conditions. Furthermore, another previous study (Van Doorslaer et al. 2009b) showed that *in situ* evolution might reduce the competitive advantage and hence likelihood of invasion of more southerly, warm-adapted genotypes.Thus rapid evolution is possible, at least in Daphnia and perhaps other planktonic prey of salmonids, but it remains to be seen how this will pan out in natural communities and longer-lived species like salmon.

8.2.2 The timing of growth

In addition to total growth in a season being important, the rate of growth early in the season can have complex repercussions for smolting decisions, negative consequences of compensatory growth, and the ability to capitalize on ephemeral resources with large potential benefits. By manipulating the timing of food supply for California steelhead, Beakes et al. (2010) confirmed previous work indicating that the decision whether to smolt in a given year is based on growth rates the previous year, and that early size advantages are maintained over the year. Lee et al. (2010) showed that in three-spined sticklebacks, compensatory growth after cool temperature-induced slow growth negatively impacted swimming endurance, especially when it occurred near to the breeding season. Armstrong et al. (2010) found that juvenile coho salmon in the Wood River system in Alaska can only benefit from eating sockeye eggs if they are large enough to swallow them. Because growth rates are very temperature-dependent, coho juveniles in warmer streams were able to exceed the 70mm size limit necessary for eating the highly nutritious eggs. This enormous nutrient gain led to a highly non-linear response of growth rate to temperature.

8.2.3 Assessment of survival and growth risks from climate change in European salmonids

Elliott and Elliott (2010) reviewed the temperature limits for European salmonids in regard to survival, feeding and growth. They did not found evidence of local adaptation (within species) in temperature tolerance, although there were marked differences in the upper thermal limits among species. They described the relationship between the North Atlantic Oscillation and emergence dates and adult return ages and rates. Using a growth model under climate change conditions, they predicted improved growth and earlier smolting in brown trout (age 1 instead of 2) except under the most extreme conditions (>4ºC), but suggested eggs of Arctic charr in some streams in southern Britain and Ireland might be at risk from high temperatures and low oxygen content. They noted several examples in which fish preferred cooler temperatures despite low oxygen levels over warmer temperatures with more oxygen, and emphasized the importance of maintaining deep pool refugia.

8.3 Behavioral and survival responses to winter conditions

Several papers described *in situ* behavioral responses to environmental conditions, especially concealment behavior and nocturnality. Winter (cold) temperatures tend to induce concealment behavior in both Grande Ronde River Chinook salmon (Van Dyke et al. 2010) and Oregon steelhead (Reeves et al. 2010), but Reeves et al. (2010) found that the response was stronger in a montane population than a coastal population. Reeves et al. (2010) also found an increase in nocturnality was more pronounced in winter in the montane population. Orpwood et al. (2010) found that riparian cover increased concealment and nocturnality in both summer and winter, regardless of food supply.

Linnansaari and Cunjak (2010) found that juvenile Atlantic salmon mortality or emigration over winter in New Brunswick, Canada was highest in early winter, before ice formation, and mortality was low during ice cover. They noted that this suggests that warmer winters that have shorter ice cover will not necessarily improve survival. Furthermore, they found that high discharge events and early maturation lowered apparent survival, although the latter might have been related to spawning-related dispersal.

One additional study (Pettersson et al. 2010) compared the suitability of different diets for aquaculture, but found that swimming ability at low temperature can be greatly impaired by an inadequate composition of fatty acids. This could have implications for wild fish if prey availability changes.

8.4 Juvenile residency, migration timing and straying responses to growth and environmental conditions

Life history diversity is a profoundly important issue in relation to environmental variability, both in facilitating a rapid response to directional environmental change and in maintaining bet-hedging strategies in case of unpredictable environmental conditions. One key trait in salmonids that is very sensitive to environmental conditions is the decision of whether to migrate to sea or not, and if they do migrate, when do they do it, and do they return to the natal rearing grounds to spawn or do they stray to a new location. Papers published in 2010 addressed all of these issues.

Johnson et al. (2010) showed that resident and migratory life-history forms of cutthroat trout were not genetically differentiated in two lower Columbia River tributaries (Abernathy Creek and the Chinook River). This study showed that resident and migratory families were not reproductively isolated, but not whether there is genetic basis to the behavior (a genetic basis has been found with brook and rainbow trout). Thus it is still not completely resolved whether the long-term trend in these populations toward residency is an evolutionary or plastic response.

Steelhead/rainbow trout also have significant variation among populations in the probability of migrating to sea. Satterthwaite et al. (2010) built on previous models to argued that reduced smolt survival is the most important vital rate that could drive anadromous populations toward residency. The next most important rate was freshwater survival and growth.

Reed et al. (2010a) also found a strong relationship between smolt size and timing and growth opportunities. They found that sockeye salmon outplants from the same hatchery smolted earlier and at a larger size when they reared in a more productive lake, despite negative density dependence. They also had higher marine survival.

Morita and Nagasawa (2010) focused on the rate of maturation of age 0+ males and females in relation to temperature and latitude within Japan. Masu salmon matured as parr at higher rates in warmer streams, and May stream temperature was the best predictor of maturation rates across 12 populations. Furthermore, masu matured at smaller sizes in warmer streams.

8.5 Freshwater ecosystem processes

A variety of studies explored the effects of changes in temperature and flow on freshwater plankton communities. For example, raising the temperature reduced mean body size and prevalence of smaller phytoplankton, and total phytoplankton biomass (but not zooplankton, Yvon-Durocher et al. 2010), affected trophic dynamics (predator impact) and carrying capacities in bacteria-protist mesocosms (Beveridge et al. 2010) and increaseed overall productivity (Stich and Brinker 2010). Variation in the seasonality of flow (increased winter and decrease summer flow) increased phytoplankton abundance (Jones et al. 2010).

Moore and Schindler (2010) showed that insects in Alaskan streams with large salmon populations have adapted to salmon phenology by developing faster than insects in non-salmon streams so that they emerge prior to spawning, and the enormous habitat disturbance salmon create by digging redds.

McDermott et al. (2010) studied the development of hyporheic communities in recently de-glaciated streams in Alaska. These communities were negatively affected by redd-digging.

9 Environmental impacts on salmon marine stages and marine ecosystems

9.1 Smolt timing and early ocean survival

When salmon migrate from fresh to saltwater, they must balance the opportunities and constraints in both habitats. As discussed above, growth rates strongly influence whether and when to smolt from a freshwater perspective, and better growth might lead to earlier smolting or larger smolts (or both, e.g., Reed et al. 2010a). Similarly, some interference with the natural growth or behavioral pattern by stocking at an inappropriate time can lead to delayed smolting (Skilbrei et al. 2010). Kennedy and Crozier (2010) showed a trend from 1978 to 2008 toward earlier smolting in wild Atlantic salmon in the River Bush, Northern Ireland. The emigration has shifted 10-14 days (depending on whether one tracks the start of the emigration or the peak emigration date), which correlates with the 5th day of river temperatures over 10ºC. Nonetheless, marine survival has declined dramatically (from 30-35% early in the time series to 5-10% more recently), which the authors attributed to increasing disparity between river and ocean temperatures. Thus despite apparent tracking of some thermal cue for smolting, river temperatures still increased too fast to avoid a potentially dangerous differential (2.5ºC) between river and ocean temperatures. It is not clear whether other aspects of marine conditions could be driving the population decline.

Smolt timing is well-known to be population-specific, presumably reflecting adaptation to the particular balance of trade-offs between freshwater and marine growth and survival at a given location. Spence and Hall (2010) analyzed the large scale geographic patterns in smolt timing across 53 coho populations from Alaska to central California, and found very strong geographic clustering of smolt timing, duration and variability with oceanographic zones. They suggested links to the predictability of ocean conditions. Because climate change might directly alter the timing of maximal ocean productivity and predictability, meaning specifically interannual variation in the optimal arrival time for smolts, these observations have important implications. Spence and Hall (2010) found that high latitude (mostly Alaskan) populations smolt relatively late, over a short temporal window, and with very little variability from year to year. They argued this is adaptive given the high predictability of the photoperiod-driven increases in productivity characteristic of the Arctic ocean. Southern populations (mostly Oregonian and Californian) that migrate into an ocean dominated by upwelling dynamics tend to enter earlier, but over a much larger temporal window. They argued that this is a bet-hedging strategy given the high interannual variability and unpredictability (from freshwater locations) of the spring transition. They also identified a third cluster in a transitional area mostly from British Columbia and Washington that were intermediate in smolt characteristics, and mostly migrated into buffered areas of Puget Sound and the Strait of Georgia. Although they also discussed alternative explanations and additional important factors, such as natal site elevation, migration distance, and watershed and stream size, these other factors are less likely to change with climate change.

What determines optimal ocean arrival timing is not well understood. Nonetheless, juvenile salmon survival is correlated with forage fish abundance, possibly because they provide alternative prey for predators. Zooplankton or food supply has also been identified as important. Kaltenberg et al. (2010) described the phenology and patterns of variability of forage fish and mesozooplankton populations near the Columbia River plume in 2008 and 2009. Kaltenberg et al. (2010) found a very sudden appearance in mid-May both years of large schools of forage fish which corresponded with similar sea surface temperature, salinity, and river flow (from the Columbia) each year. Zooplankton peaks occurred throughout the spring and summer as fronts passed over the sampling stations, and thus did not showed strong seasonality compared with the forage fish. Litz et al. (2010) found that forage fish switched from eating mainly dinoflagellates early in 2005, during the very delayed upwelling season, to a mostly diatom-based food source after the more normal upwelling season of 2006. They based this conclusion on lipid and fatty acid composition of the forage fish.

Chittenden et al. (2010) analyzed the survival of coho from Seymour and Quinsam Rivers, British Columbia 2007-2009, as a function of release date and marine plankton productivity. They found that coho stayed in the estuary during low marine productivity. Fish that arrived during zooplankton blooms passed quickly through the estuary and had the highest marine detection rates and smolt-adult survival (1.5-3x higher). The optimal time in both years was intermediate among the release groups.

MacFarlane (2010) measured growth in the San Fransisco Bay estuary and coastal ocean over 11 cohorts. They found that the first month following ocean entry was critical for subyearling Chinook. They found very little growth accrued in the estuary, but far better growth upon arrival in the ocean. Higher salinity and lower freshwater outflow produced better growth in the estuary, while cooler temperatures, lower sea level, and greater upwelling improved growth in the ocean. They concluded that climate change conditions would yield reduced growth.

Juvenile salmon presumably do not always encounter adequate food resources. To develop a reference point for interpreting the amount of deprivation that marine fish experience, Fergusson et al. (2010) conducted a laboratory starvation experiment and compared various indices of condition with that usually observed in wild-caught Southeast Alaskan chum salmon in 2003. They found that whole body energy content, percent moisture content, and condition residuals were better indicators of starvation than weight or length, and that after 10-15 days of starvation, laboratory fish fell outside the range normally observed in wild fish.

Two studies found that sea surface temperatures during the first year in the ocean best explained adult returns. Focusing on 24 stocks of northwest Pacific Chinook salmon, Sharma and Liermann (2010) found that the PDO and ENSO indices explained much less variation in recruitment than local sea surface temperatures, which were strongly affected by the strength of upwelling and hence reflected more information about ocean productivity than basin-wide average temperatures. They simulated the effect of a 1ºC change in SST, and found a 13% decline in productivity on average across populations. However, the only one population from the Columbia River was included in this analysis, Deschutes River fall Chinook, and this population showed a minimal effect of ocean predictors (SST, PDO and ENSO). Saito et al. (2010) studied the factors that best predicted smolt-adult return rates of chum salmon in Nemuro Strait in Hokkaido, Japan, 1999-2002. They found that somatic condition and growth rates during the coastal residency period (first 2-3 months in the ocean) did <u>not</u> predicted adult returns. Instead, sea surface temperatures during the first year (especially winter) in the ocean and the size of smolts at release best explained variation in smolt-adult returns.

Petrosky and Schaller (2010) found that warm ocean conditions in March, reduced upwelling in April, and slower river velocity (or additional trips through powerhouses at dams) during the spring migration period were the best predictors of poor ocean survival for both Chinook and steelhead. They recommended increasing spill to help compensate for lower flows and poorer ocean conditions due to climate change.

9.1.1 Algal bloom lowers survival

Although most studies of early marine survival focused on food availability and predation, algal blooms can cause high mortality in Fraser River sockeye salmon. Rensel et al. (2010) found that earlier and larger spring and early summer Fraser River flows were linked to major blooms of harmful raphidophyte flagellate *Heterosigma akashiwo* in the Strait of Georgia. Chilko sockeye salmon survival declined from 10.9% in non-bloom years to 2.7% in bloom years.

9.2 Marine habitat usage

Several studies have focused on ocean habitat usage, especially thermal preference. NOAA scientists have documented a strong aversion to temperatures over 19ºC in the Columbia estuary. This is a strong limitation on habitat usage in the late summer, when juvenile salmon were once abundant (Dan Bottom, personal comm., technical reports). Peterson et al. (2010) synthesized 15 years of survey data to describe the distribution of yearling coho and Chinook salmon distribution and abundance in June and September (after leaving the estuary). The species differed in depth preference and distance offshore. Higher catches correlated positively with chlorophyll and copepod biomass in both species, and with temperature in Chinook salmon. Duffy et al. (2010) described Chinook salmon diet and habitat usage in Puget Sound. "At nearshore sites, insects (all months) and gammarid amphipods (July) were dominant prey sources, whereas in offshore diets decapods (primarily crab larvae; July) and fish (September) were most important." They emphasized that the terrestrial sources of many of the prey items demonstrates an important link between waterfront landuse and salmon survival.

Based on trawl data, Morita et al. (2010a) found that larger and older adult sockeye, chum, and pink salmon inhabited cooler areas than smaller and younger salmon. Using this information, Morita et al. (2010b) developed a bioenergetic model explaining this pattern as a function of the optimal temperature for growth decreasing with body size, which was validated with a laboratory experiment. They concluded that the negative effects of climate warming on growth will be more severe for larger fish. Radchenko et al. (2010) described the results from surveys in the eastern Pacific, documenting the location of salmon and many other ecosystem components in 2009.

Using a combined bioenergetic-ecosystem model, Kishi et al. (2010) explained trends of declining body size in chum from 1970 to 2000 in terms of reduced densities of zooplankton and rising sea surface temperatures. They then characterized suitable potential ocean habitat for Hokkaido chum as 8-12ºC in the summer and 4-6ºC in the winter, based on survival studies and relationships between CPUE and SST. Using global circulation models to simulate global warming conditions, they predicted future distribution shifts: loss of habitat in the eastern North Pacific (Gulf of Alaska), and a northward shift in the Arctic Ocean. Furthermore, they predicted a lower carrying capacity in several areas. Finally, they predicted the current migration route to the Sea of Okhotsk will become unsuitable by 2050. Somewhat along similar lines, Genner et al. (2010) analyzed trends in size and abundance in the English Channel from 1911 to 2007, and found that smaller-sized fish fluctuated in abundance with temperature, showeding quick responses to environmental change. Larger-sized fish, however, showed persistent declines in the larger size classes and overall abundance, perhaps due to size-selective overharvesting.

9.3 Biological Implications of ocean acidification

Literature on how ocean acidification (OA) will affect marine species and communities is exploding, making a complete review beyond of the scope of this report. A recent meta-analysis of the impacts of OA on marine species indicated that there is significant variation in how sensitive marine species are to OA, and, if sensitive, what aspect of organismal biology changes in the face of low pH (Kroeker et al. 2010). However, in general, when all taxa are pooled, OA had negative impacts on survival, calcification, growth and reproduction (Kroeker et al. 2010). Here, we focused on laboratory experiments that explored the sensitivity of fish and salmon prey to OA.

Given the paucity of research, it is impossible to concluded whether the direct and indirect impacts of OA on salmon prey, as a whole, will be positive, negative, or neutral. Development timing of amphipods increased in response to low pH conditions, which may negatively impact population dynamics of this important food source (Egilsdottir et al. 2009; Hauton et al. 2009). Pteropod calcification rate declined with ocean pH, although pteropods can calcify below an aragonite saturation state of 1 (Comeau et al. 2010a; Comeau et al. 2009a; Comeau et al. 2009b; Comeau et al. 2010b). Pteropods in the laboratory survived without shells (Comeau et al. 2010a), though their ability to do this in the field is unknown. How OA affects pteropod population dynamics is also unknown, but energetic challenges (e.g., respiration rates) increase (Comeau et al. 2010b). A study on Antarctic krill indicated that OA is unlikely to affect the progression of early development until CO_2 levels exceed 1000ppm (effect observed at 2000ppm; Kawaguchi et al. 2011). Surface oceans may reach this level by 2100, though deep, cold water may exceed it sooner. The impact of OA on copepods varied with species and life stage, but includes evidence for increased nauplius mortality and decreased egg hatching rate (Kurihara and Ishimatsu 2008; Kurihara et al. 2004a; Kurihara et al. 2004b; Mayor et al. 2007; Pascal et al. 2010). In addition, high CO_2 levels countered some toxic effects of cadmium and copper ions on benthic copepods (Pascal et al. 2010). However, mercury and silver accumulation in *Loligo* squid paralarvae increased with CO_2 levels, which has implications for transfer of metals through food webs (Lacoue-Labarthe et al. 2011).

The role of gelatinous zooplankton in North Pacific ecosystems is steadily increasing. Analysis of time series data from the North Sea showed a negative correlation between gelatinous zooplankton and pH (Attrill and Edwards 2008; Richardson et al. 2009; Richardson and Gibbons 2008), although asexual reproduction and polyp survival in *Aurelia labiata* were not affected by OA in the laboratory (Winans and Purcell 2010).

The direct impacts of OA on salmonids are uncertain, especially because the species group spends its early life stages in fresh, not marine, waters. In the last BiOp, we reported no effect of pH 7.0 on *Salmo salar* mortality, growth, condition, metabolism, or plasma pH, hematocrit, sodium, or chloride (Fivelstad et al. 1998) and impairment of olfactory abilities in tropical clownfish (Dixson et al. 2010; Munday et al. 2009b). Recent research provides more insight on how fishes may respond (or not) to OA: 1) increased otolith size in some but not all species (Checkley Jr. et al. 2009; Franke and Clemmesen

2011; Munday et al. 2011a; Munday et al. 2011b), 2) erosion of auditory based behavior and induction of behavior linked with higher mortality due to predation in a tropical clownfish (Munday et al. 2010; Simpson et al. 2011), 3) decrease in aerobic scope in two tropical coral reef fishes (Munday et al. 2009a), 4) upregulation of some proteins in stickleback and cod and RNA expression in Atlantic herring (Franke and Clemmesen 2011), 5) no impact on early development (survival, growth, skeletal deveopment) in a tropical damselfish and Atlantic herring (Franke and Clemmesen 2011; Munday et al. 2011a).

Two recent modeling papers explored the ecological impacts of OA and other aspects of climate change. Ainsworth et al. (2011) predicted that ocean acidification may cause salmon landings to decrease in Southeast Alaska and Prince Williams Sound food webs and increase in Northern British Columbia and Northern California Current food webs. However, when the authors applied five impacts of global change to these food webs simultaneously (primary productivity, species range shifts, zooplankton community size structure, ocean acidification, and ocean deoxygenation), projected salmon landings decreased in all locales (Ainsworth et al. 2011). Incorporating ocean acidification and ocean deoxygenation into bioclimatic envelop models for harvested fishes in the Northeast Atlantic caused 20-30% declines in projected future harvest, likely due to reduced growth performance and faster range shifts (Cheung et al. 2011). This study is informative to Pacific salmon management as it indicates how changes in physiological performance of finfishes due to ocean acidification may impact harvested populations.

9.4 Ocean ecosystem effects

9.4.1 Evidence of changes in Arctic marine ecosystems

Of the global reviews of documented changes in biota that appear to be responses to climate change, very few have focused on marine ecosystems. Thus the review of the “footprint” of climate change in Arctic marine biota by Wassmann et al. (2010) fills a very important hole. Wassmann reviewed 13 studies of benthos, 9 studies of fish (5 on cod, 2 on pollock, 1 each for turbot and pipefish), 7 studies of birds (5 species), 9 studies of polar bears, 2 seals and 1 whale. Responses ranged from behavioral to growth to range shifts and community reorganization (Greenland cod and shrimp). Most observations are consistent with predictions from climate change simulations: increased primary productivity, declines in endemic, ice-associated species, and invasions or increases in more temperate zone species. One study documenting a change in primary producers was Kahru et al. (2010), who showed that the annual phytoplankton bloom maximum has advanced by up to 50 days in certain areas of the Arctic, with significant trends in 11% of the Arctic Ocean, primarily reflecting the reduction in sea ice. Bloom timing has also advance in the North Pacific.

9.4.2 Ecosystem models

Several very complex models explored the ocean ecosystem dynamics of climate forcing and climate change. Popova et al. (2010) focused on the Arctic Ocean under current conditions, and found that two key processes drove variability in primary production: the extent of winter mixing and short-wave radiation at the ocean surface, which controls phytoplankton blooms.

Two studies analyzed climate change simulations. Rykaczewski and Dunne (2010) used NOAA's Geophysical Fluid Dynamics Laboratory earth system model to study changes in nutrient supply and productivity of the California Current Ecosystem. They focused on nitrate because it is the main nutrient limiting primary production in the CCE. The model predicted a 2ºC rise in ocean temperatures across the basin from 1860 to 2100 under the SRES A2 scenario. They found weaker wind-stress curl, which reduced the strength of upwelling (and downwelling, in the subtropical gyre), but other changes produced a modest increase in upwelling. They note, however, that global models might not have sufficient resolution to fully represent upwelling dynamics. Despite increased stratification, they predicted an 80% increase in nitrate concentration by 2100 in the upper 200m of the CCE, but decreases elsewhere in the Pacific. The increased nitrate concentration in the CCE comes mainly from longer transit times of deep water that are subsequently upwelled.This water is also more depleted in oxygen (18%) and more acidic (0.5 pH units). This produced a net increase in productivity of 10% in the CCE presumably benefitting surface feeding fish, but more frequent hypoxic events threatening benthic and mid-water fauna.

Steinacher et al. (2010) compared four coupled global carbon cycle-climate models that incorporated marine biogeochemcial-ecosystem models. All four models predicted a decreasing trend in global net primary production and particulate organic carbon export. The models all predicted increasing temperature and stratification in all regions and increasing light in the Arctic where sea ice retreats. The high-latitude ocean retained sufficient nutrients to increase primary production and particulate organic carbon export (with increases in the Bering Sea). Nonetheless, they still projected declines in biomass throughout the north Pacific. They discussed differences among the models compared in quantitative predictions. Despite broad agreement on a regional scale, none of the models appear to do exceptionally well at modeling the coastal Pacific Northwest and Alaska (hence the upwelling-specific analyses described previously). Brown et al. (2010a) also predicted increases in primary productivity around Australia, benefitting fisheries and threatened turtles and sharks. They cautioned that the ecological benefit is sensitive to species interactions, which could reverse the benefit for some species.

Several studies in the San Francisco Bay estuary described complex physical and biological processes. MacNally et al. (2010) analyzed the factors affecting the decline of four pelagic fish in the San Francisco estuary. A combination of physical and food web driven factors suggested a diverse array of factors are responsible, but changes in freshwater flow and water clarity had strong effects. The results suggested a relatively good understanding of the ecosystem, but few management options. Cloern et al. (2010) described strong effects of the PDO and the NPGO on demersal fish, crabs and shrimp in San Francisco Bay. They emphasized the interconnectedness of the estuary in linking oceanography and watershed hydrology.

9.4.3 Seabirds, rockfish, and sharks

Several studies explored potential impacts of climate on seabird populations. Wolf et al. (2010) predicted 11-45% declines in Cassin's auklet in response to climate change. Ainley and Hyrenbach (2010) explored bottom-up and top-down drivers of a large number of seabird species in the California Current. Black et al. (2010) analyzed ocean drivers of seabird and rockfish dynamics, emphasizing the importance of February ocean conditions.

Williams et al.(2010) documented very large aggregations of 20,000 sharks in the western Queen Charlotte Sound, British Columbia in a 2004-2006 study. Although it is not absolutely certain that this is a new phenomenon, it has not been documented until recently, and they suggested that the aggregations might be a response to rising sea temperatures. The sharks might present a "feeding gauntlet" deadly for Fraser River salmon, that typically prefer the northern migration route through Queen Charlotte Sound during warm years.

In addition to sharks, other marine fish are likely to shift their distribution in response to rising ocean temperatures. In Australia, coral reef fishes usually limited by winter temperature are predicted to survive as far south as Sydney by 2080 (Figueira and Booth 2010).

9.5 Effects on fisheries

Cheung et al. (2010) combined models that predicted increases in primary productivity with bioclimatic envelop models of species distribution to predicted the impact of climate change on fisheries catch for 1066 species of fish and invertebrates (assuming the geographic location of the fishery doesn't change). They predicted a 30–70% increase in high-latitude catches, including Alaska, a decline of about 10% in the contiguous US, and a drop of up to 40% in the tropics. MacNeil et al.(2010) similarly concluded that Arctic fisheries will benefit from invasions of southern species and increased primary productivity, while there will be species turnover in the temperate zone and significant losses in the tropics.

9.6 Review of hypotheses/frameworks for ocean climate forcing fish populations

Two papers present overviews of the prevailing physical and ecological hypotheses or conceptual frameworks currently in the literature on climate-ocean interactions. Ottersen et al. (2010) focused on three major oceanographic phenomena that drive variability in fish recruitment: temperature, mixing, and advection. They discussed the debate on bottom-up versus top-down population regulation, and trophic cascades, and the key role of forage fish as having both effects. They described immediate and delayed effects of climate, and factors that differentiate local climate drivers from large-scale climate processes such as the NAO and the PDO. They discussed direct, indirect, integrated (i.e., processes that occur over longer time scales than a particular extreme climate event) and translation (i.e., organism movement) effects of climate drivers. Any of these responses might be linear or nonlinear, at the individual or community level. They then detailed specific geographic regions and their particular climate-ecological dynamics. In the Northeast Pacific they emphasized ENSO and the PDO and biological responses. They finally discussed teleconnections and regional differences between the Atlantic and the Pacific.

Bakun (2010) reviews a number of different concepts of population regulation, such as the match-mismatch hypothesis, issues with schooling fish, and the predation risk-nutrient level trade-off (which he calls "loopholes"). Bakun emphasized three major physical processes that provided favorable conditions for fish: nutrient enrichment through upwelling or mixing, concentration through convergence or front formation, for example, and retention processes, such as eddies. Overall this paper emphasized that oceans are complex adaptive systems, and cautioned against assuming simpler concepts from the terrestrial literature adequately capture their complexity.

10 Impact of temperature and flow on adult migrants

10.1 Migration bioenergetic cost

Upstream migrating salmon face several additional stresses due to climate change. Most importantly, rising temperatures increases the metabolic cost of swimming and holding prior to spawning. Cumulative energetic costs or acute thermal stress also increase prespawn mortality. Several papers studied the bioenergetics of migration, which are relevant for calculating these costs. Clark et al. (2010) developed a biologging tag technique for measuring energy expenditure and heart rate in actively migrating sockeye. Cook and Coughlin (2010) found that rainbow trout alter their kinematics around obstructions in the water in a way that improves their efficiency. Forgan and Forster (2010) explored the physiology of oxygen consumption in different tissues. Nadeau et al. (2010) analyzed the relative costs of swimming in the lab against low and high flows that span much of the range typical for Fraser River sockeye. They found that higher flows elevated stress, but not mortality. However, overall females had higher mortality than males. Roscoe et al. (2010) studied the behavior of natural migrants through a lake with cooler bottom water. They found that more mature females with lower energy content preferred the cooler water, while other females and males showed less preference. They posited that use of the thermal refuge slowed maturation and helped maintain energy reserves.

10.2 Migration survival and timing

Migrating upstream is an energetic and thermal bottleneck for many salmon populations. New papers clarified the role of temperature in stimulating upstream migration in a very warm river (the Klamath), and the relationship between timing, temperature, flow, and survival in the cooler Fraser River. Projections in the Fraser River of the consequences of warming over the next century are especially dire.

In the Klamath River, Strange et al. (2010) found that Chinook volitionally migrated through much warmer water than previously thought. Chinook initiated migration at 21.8-24ºC. These high river temperatures produced a mean average body temperature of 21.9ºC, and mean average maximum body temperature of 23.1ºC over the first week of the migration. These temperatures usually cause migration blockages in the Columbia River, but apparently reflect adaptation to the much warmer conditions in the Klamath. Declining temperatures triggered migration, even when the river was still very hot. It is not known whether these fish experienced high prespawn mortality or reduced fecudity or fertility. In the Fraser River, several new papers showed a positive correlation between river temperature and mortality. MacDonald et al. (2010) developed a forecasting model for fisheries managers to facilitate real time predictions of migration survival for various groups of populations. They found that temperature, flow, the timing of entry relative to the average for that population, and fish abundance were good predictors of migration survival. Interestingly, the best predictors did not necessarily match the *a priori* prediction based on the absolute environmental conditions. For example, temperature was an important predictor for Early Stuart sockeye, even though these fish encounter relativley lower temperatures than other fish. The authors point out that these fish still encounter high temperatures upstream, and that they might have lower thermal tolerances than other populations.

Several papers simulating future conditions in the Fraser River predicted signficant declines in sockeye salmon. Hague et al. (2011) found that a 1.0 °C increase in average summer water temperature tripled the number of days per year exceeding critical salmonid thermal thresholds (i.e. 19.0 °C). Martins et al. (2011) found evidence of thermal stress-induced mortality during the migration in three of the four stock-aggregates examined. Under warming scenarios, migration survival in these stocks was projected to decline 9-16%.

Particular attention has focused on the unusual behavior among some Fraser River sockeye populations of migrating much earlier than the historical norm. The early migrants experience much higher temperautres than normally-timed fish, and have significantly lower survival. Mathes et al. (2010) found that early migrants that utilized cool lake habitat as a thermal refuge during their migration had much higher survival than fish that took the river corridor directly to spawning grounds. The early-entry river migrants accumulated extraordinarily high cumulative temperatures and none survived. The early-entry lake migrants had similar cumulative thermal exposure to normally-timed fish that stayed in the river, and similar survival. Donaldson et al. (2010) compared physiological responses to stress (gillnet capture), migration rate and survival in Adams-Shuswap and Chilko populations. The unusually early migrants of the former migrate at the same time as the normal-timed migrants of the latter population. They found delayed effects (near spawning grounds) on survival that differed between the populations. Although the two groups had similar physiological condition when they entered the river, survival among the early-entry Adams-Shuswap group correlated with migration rate (slower migrants had lower survival) and physiological condition (metabolic and osmoregulatory impairment), but not among the Chilko fish.

In the Columbia River, Jepson et al. (2010) studied the migration timing of fall Chinook. They found clear differentiation between the Upper Columbia River and Hanford Reach populations, but Deschutes, Yakima, and Snake River populations migrated throughout the season. They also found harvest was concentrated in late August and early September, and preferentially selected larger fish.

10.2.1 Traditional tribal knowledge and effects of climate change on migration survival and timing

Jacob et al. (2010) described the effects of changes in the salmon runs on native people, and the very serious long-term implications of climate change for both people and fish. Through interviews, they identified changes in salmon abundance (diminished), timing (later in summer and fall), and condition (much less healthy, both in fat content and disease prevalence) from people's recollections of traditional conditions. They discussed potential adaptations, but predicted relatively poor prospects for both people and fish.

11 Impact of high temperatures on prespawn mortality and spawning behavior

11.1 Diseases

The prevalence and virulence of many diseases in fish are much more severe under warmer conditions, and several papers reported disease spread over recent years. Marcos-Lopez et al. (2010) reviewed the increasing risk from a number of diseases (e.g. enteric red mouth, furunculosis, proliferative kidney disease and white spot) due to climate change. The risk from some exotic pathogens that prefer cool water declines (e.g., viral haemorrhagic septicaemia (VHSV), infectious haematopoietic necrosis virus (IHNV) and spring viraemia of carp virus (SVCV), while the risk from warm-loving exotic pathogens (epizootic haematopoietic necrosis and epizootic ulcerative syndrome) increases. They recommended revising management actions to control disease to take into account changing risk levels due to climate change.

Braden et al. (2010) reported spread of proliferative kidney disease (PKD) in natural populations of pink salmon in Quinsam river, Vancouver Island. Bradford et al. (2010) reported widespread prevalence (70% of samples) of the myxozoan parasite *Parvicapsula minibicornis* throughout the Fraser River watershed, and a very advanced stage of infection in most fish on spawning grounds. Ray et al. (2010) quantified levels of *Ceratomyxa shasta* that kill juvenile Chinook salmon in the Klamath River, improving our understanding of this disease. Tonteri et al. (2010) found selection on immune related genes more common than selection on non-immune-related genes in Atlantic salmon, and that allelle frequencies were related to temperature and latitude, suggesting an important role of climate in driving this selection pressure.

Although not directly related to climate change, Koel et al. (2010) reported that Great Blue herons are viable vectors of whirling disease, which affects salmonids in 25 states. Krkosek (2010) warned that sea lice are an increasing threat from farmed salmon in the Pacific, and that the abiotic and biotic factors affecting this disease are not well studied. Pulkkinen et al. (2010) found that fish farms actually select for more virulent strains of *Flavobacterium columnare*, a disease exacerbated by warmer temperatures.

11.2 Prespawn behavior and mortality

Keefer et al. (2010) documented a strong correlation between prespawn mortality in Willamette River Chinook and water temperature and fish condition. Mortality ranged from 0-90%, depending on year and release group. Fish in poor or fair condition had twice the mortality risk of fish in good condition. These fish were transported above a dam, and thus do not represent a natural migration. Nonetheless, they do reflect a dramatic increase in risk due to high temperatures.

Young et al. (2010) found that over summer, brown trout adults in New Zealand tended to hold in deep pools, and only moved during higher flow events and cooler temperatures (below 19ºC). A severe flood killed 60-70% of the tagged population.

11.2.1 A correlation between gene flow and the NAO

Valiente et al. (2010) addressed the population genetic consequences of increased male parr maturation in response to climate change. In addition to describing effects on maturation, they discovered a strong pattern in straying. Specifically, they found a strong correlation between the North Altantic Oscillation Index and immigration from a neighoring stream. I believe that this is the first study system to document this phenomenon, and hence is especially interesting. They found that straying increased linearly when conditions in the natal stream deteriorated (became too warm). This paper is also especially notable in referring specifically to adverse conditions induced by global warming at the southern edge of a species range.

11.3 Spawning behavior

The timing of reproduction is often crucial in determining successful population growth. How climate change will affect spawn timing raises concern because of high risks of prespawn mortality with lengthening freshwater residence, extreme sensitivity of eggs to high temperature (compared to other life stages), and the potential for a mismatch between emergence suitable environmental conditions for fry. Two studies documented long-term shifts in spawn timing in freshwater fish. Wedekind and Kung (2010) showed that European grayling have advanced their spawn timing by more than 3 weeks since 1948, which they attributed to rising temperature. However, a difference between spring and summer warming rates exposed fry to inappropriate temperatures, possibly contributing to population decline. Schneider et al.(2010) showed that walleye are now spawning up to 2 weeks earlier throughout Minnesota (26 populations), with a 0.5-1 day advance for every 1 day advance in ice break up.

Several studies explored the stimulus for spawning. Wilkinson et al. (2010) experimentally manipulated temperature and photoperiod for rainbow trout, and found that under natural photoperiods, elevated winter-spring temperatures only slightly increased maturation rates. Under advanced photoperiod, temperature had a much larger relative effect, but the overall maturation rate was much lower. O'Malley et al. (2010) studied the genetic basis of variation in spawn timing. They compared geographical variation in a gene (OtsClock1b) associated with photoperiod among 53 populations of chum, coho and pink salmon. Combined with a previous study of Chinook salmon, they found that daylength at spawn timing explained much of the variation in allele frequencies of OtsClock1b in chum and Chinook, but not coho and pink salmon.

In addition to affecting juvenile survival and migration success, temperature and flow affect access to and quality of spawning sites. Taylor et al. (2010) documented the distribution of redds over 12 years in a Nova Scotia stream in relation to the timing and intensity of fall rains and beaver dams. They found that stream usage by salmon was linearly related to precipitation, except when blocked by beaver dams. Moir and Pasternack (2010) described a strong positive relationship between substrate coarseness and faster flow in Chinook salmon spawning site selection, demonstrating interactions between habitat characteristics that are not always included in habitat suitability analysis.

12 Direct heat stress

Several papers studied direct heat stress, population variation in heat tolerance, and its genetic basis. Bellgraph et al. (2010) found that juvenile Chinook salmon survived temperatures up to 23.2ºC. The fish increased swimming behavior and heart rate under higher temperatures. Brook char reduced swimming performance at temperatures over 15ºC, especially in combination with ammonia (Tudorache et al. 2010). Feldhaus et al. (2010) found that redband trout amplify production of heat shock proteins (hsp70) between 19 and 22ºC, indicating thermal stress. Healy et al. (2010) studied the genetic basis of variation in the heat shock response in killifish, and found a fairly complicated pattern. They concluded that variation among subspecies must be due to more than simple upregulation of a particular regulator, but involves evolution in a variety of genes. In a comprehensive review, Pankhurst and King (2010) explained the physiological processes mediating the negative effects of high temperature on reproduction.

Sublethal temperature effects interact with other stressors. Boyd et al. (2010) found higher mortality after catch-and-release under elevated temperatures in the evening in rainbow trout. A very large fish kill (25,000 carp) occurred in the St. Lawrence River in 2001, which Ouellet et al. (2010) attributed to a combination of high air temperature and low flow, which depleted oxygen in the lake. They also discussed indirect effects of long-term stress, such as immunosuppression.

Pörtner (2010) reviewed the concept of oxygen supply to the tissues being the fundamental process that determines thermal windows, and as a means for understanding the synergistic effects of multiple stressors. Ocean hypercapnia and acidification interact with warming temperature to further reduce oxygen availability. On the other hand, exposure to high CO_2 also depresses metabolic rates, which might help tolerate reduced availability of oxygen.This fundamental process is general, and hence not species-specific. Seebacher et al. (2010) made an analogous argument that the fundamental limiting factor is cellular damage from the production of reactive oxygen byproducts of metabolism.

13 Higher-level processes

13.1 Population-dynamics modeling

Key to understanding the factors regulating salmon populations (which is essential for predicting effects of climate change) is an appreciation of how different scales of variability interact with the internal periods of variation inherent in populations with overlapping generations. Worden et al. (2010) studied the frequencies of population variability as a function of 1) environmentally-induced variation in survival in the first ocean year only, 2) environmentally-induced variation in survival in all ocean years, and 3) environmentally-induced variation in the age at reproduction. They considered these effects within the larger context of increased variability due to fishing mortality, and different censusing techniques. They found different patterns of fluctuations in all the different scenarios explored. Salmon are more sensitive to some time scales of environmental variability than others, and with fishing they are doubly sensitive to low frequency environmental variability. Long-term changes in climate could thus interact with additional fishing-induced variability to induce fluctuations that pose much greater risks of population collapse than that induced by reduced abundance alone.

Two papers focused on the mathematical properties of population decline to extinction when environmental factors are driving the decline, and provide tools for identifying this trajectory. Drake and Griffen (2010) identified an early warning signal that anticipates a tipping point, beyond which extinction is almost inevitable. The early warning signal is a “critical slowing down”. They demonstrated the statistical properties of this signal using an experimental Daphnia population. A reliable baseline prior to environmental degradation is crucial for successful application of this technique. Ovaskainen and Meerson (2010) reviewed recent advances in theoretical physics that characterized the properties of stochasticity useful for determining mean extinction times under various conditions.

Animals often compensate for environmental variability through phenotypic plasticity, i.e., modifying their behavior or physiology in response to environmental conditions. Reed et al. (2010b) focused on the adaptiveness of phenotypic plasticity. Specifically, they demonstrated that plasticity is only adaptive when there is a reliable cue that anticipates environmental conditions. When the cue becomes less reliable (which might result from different aspects of climate changing at different rates, for example), plasticity shifts from being adaptive to increasing population extinction risk. They emphasized that population models will need to explicitly incorporate plasticity to include this potential effect.

13.2 Population-level effects

13.2.1 Population declines attributed to climatic factors

Clews et al. (2010) studied how environmental variation correlated with population fluctuations of Atlantic salmon and brown trout in Wales from 1985 to 2004. Local catchment processes were not useful in explaining population decline, but broader scale climatic variables correlated strongly with population densities. They found that weather conditions in the previous summer explained most of the variation. Specifically, a principle component analysis showed that reductions in density were highest following hotter, sunnier, and drier conditions. Over the course of the study, summer stream temperatures were estimated to have increased by 0.5ºC in headwaters and 0.6ºC in larger tributaries, and in winter by 0.7ºC and 1ºC, respectively. This amount of warming could explain on the order of a 40% decline in density (or ~3-3.5 fewer salmon per 100m^2), based on the principle component score (which also includes discharge). Winter warmed more than summer due in part to trends in the NAO, but was not strongly correlated with salmon abundance. The similarity in response between the anadromous salmon and freshwater resident brown trout indicates that freshwater indices are either driving the declines in both species, or are correlated with ocean phenomena in salmon.

After a comprehensive physical and biological assessment, Wiseman et al. (2010) found that warm water tempeature and sedimentation were the primary drivers of habitat decline in the Touchet River in Washington, contributing to contraction of spring Chinook, summer steelhead, and bull trout.

Robinson et al. (2010) reported that stressful summer temperatures (determined by cumulative degree days over 20ºC measured at the bottom of an Adirondack lake) reduced stomach fullness, reproductive activity, and survival of brook trout over one year old, and especially fish over two years old. Like Crozier et al. (2010), they found a positive correlation between temperature and growth at low fish density, and a negative correlation at high fish density.

13.2.2 Expert judgment of overall risks to Fraser River sockeye

A synthetic, expert-opinion analysis of the threat of climate change over the entire life cycle of Fraser River sockeye salmon (McDaniels et al. 2010) found that the cumulative threats are very high. A substantial proportion of responses indicated the fish were highly vulnerable (the highest threat level) at all life stages except the overwintering fry stage. They identified the most vulnerable life stages to be the egg and returning adult stage for populations throughout the Fraser River drainage, especially under a +4ºC warming scenario. They also considered the prospect of reducing the threat through management quite limited.

13.2.3 Paleological perspective

Finney et al. (2010) conducted a major review of the paleological literature on fluctuations in fish abundance (including salmon) over thousands of years. The most relevant topics focused on positive correlations between SST and salmon abundance in Alaska both recently and over most of the past 300 years and again over 2500 years based on sedimentary collection of marine-derived nitrogen carried into freshwater by anadromous salmon. Anomalies in the SST-salmon correlation occurred in several sections of the long-term record, which the authors attributed to changes in ocean-atmosphere circulation during these periods, producing alternate patterns of North Pacific climate variability relative to the PDO and variation in the Aleutian Low. The longer time series showed a bimodel pattern of fluctuations between low and high abundance, with high abundance during the 1250-1890 AD cooler period of the Little Ice Age. This suggests different longer term patterns than suggested from recent data. They also discussed patterns driving anchovy, sardines, and other major ecosystem players throughout the world, and synchronous shifts in all ecosystems. However, specific relationships varied across the time series between in-phase and out-of-phase correlations, indicating alternative modes of climatic forcing of ecosystem dynamics.

13.3 Trends in phenology worldwide

Worth noting here is that phenological responses to climate change have been observed across all taxa, worldwide. A new review out in 2010 (Thackeray et al. 2010) assessed 25,532 rates of phenological change for 726 UK terrestrial, freshwater, and marine taxa. Most taxa showed earlier spring phenomena at rates higher than previously reported. They separated out taxa at different trophic levels, and found that secondary consumers were responding the slowest, and hence were at most risk of a mismatch in timing between predator and prey. Because this trend was so widespread and not restricted to individual species, it highlights a growing risk of the disruption of ecosystem function and services.

14 Habitat

14.1 Stream flow habitat models

Quite a few papers used models of stream flow (or temperature, covered in the next section) to quantify habitat availability for salmonids. Hilker and Lewis (2010) developed a theoretical model of how water velocity affects potential prey populations subject to advection and diffusion downstream, and the minimum flow requirements for drift-feeders like juvenile salmon. Cover et al. (2010) examined the impact of debris flows and debris floods on headwater stream communities. They found that debris flows raised stream temperature, reduced large wood and benthic communities and most vertebrates, with the exception of rainbow trout, which were abundant in recent debris-flooded areas. Escobar-Arias and Pasternack (2010) developed a functional flows model based on shear stress dynamics to characterize fall Chinook spawning habitat; the model could be parameterized for other species. High flow events provided access to new habitat, which can have both positive and negative impacts on salmon. Access to a floodplain that contains pollutants could be detrimental for juvenile salmon. Henery et al. (2010) showed that growth was higher in free swimming Chinook that utilized the Yolo Bypass floodplain than fish that stayed in the Sacramento River, but that the fish in the floodplain accumulated 3.2% more methylmercury per day than fish in the river.

A large group of scientists worked on a new framework for assessing environmental flow needs for many streams and rivers simultaneously to foster development and implementation of environmental flow standards at the regional scale (Poff et al. 2010), and this can be a basis for initiating an adaptive management program.

14.2 Thermally-suitable habitat models and trends

Enhancing riparian vegetation is a major conservation tool recommended for reducing maximum stream temperatures. Two studies showed strong empirical effects of vegetation on stream temperature. In response to high temperature-induced disease-related fish kills, Roth et al. (2010) developed a physical model of stream temperature in Switzerland. They found that existing vegetation (mostly in-stream reeds) lowered the expected temperature by 0.7ºC, but a further decrease of 1.2ºC could be achieved by a mature riparian forest. Brown et al. (2010b) found that coniferous forest plantations lowered summer temperatures in a comparison of 3 forested and 3 moorland sites in northern England.

Statistical models of stream temperature have been used to quantify habitat area that meets particular criteria for species of interest, and to track trends in habitat area over time. Larnier et al. (2010) developed and compared models to identify conditions in the Garonne River in France that are thermally stressful for salmonid migration and survival. Isaak et al. (2010) developed a spatial autocorrelation model to predicted stream temperature throughout the 2500 km^2 upper Boise River Basin in Idaho based on temperatures measured at particular sites. The model performed well against observed temperatures. Historical analysis showed a trend of mean basin stream temperature from 1993 to 2006 rising at a rate of 0.27ºC/decade, and maximum temperatures rose by 0.34ºC/decade. They detected a strong thermal signature of wildfires in the basin: stream temperatures in affected reaches rose 2-3 times more than the basin average due largely to increases in radiation. Rising temperatures shifted rainbow trout habitat to slightly higher elevations but caused 11-20% loss of bull trout habitat.

High temperature already threatens some populations in warmer climates. Null et al. (2010) explored restoration alternatives to migitate stressful temperatures in California’s Shasta River. They found that a focused on restoring and protecting cool springs provided the most benefit for salmon (much greater benefit than increasing riparian shading, for example). This conclusion might apply to regions anticipating increasing temperature stress.

14.3 Habitat projections

Wiley et al. (2010) developed a series of models to explore the effects of land cover and climate change on fish habitat in the Great Lakes. They found very significant climate change impacts, and that these impacts were very sensitive to land management. Increasing forest cover and limiting urban development had very large impacts on projected flows, temperatures, and consequently modeled fish habitat. Nonetheless, even the best-case land use scenarios involved destabilization of 57%-76% of the channel system by the end of this century due to increasing rainfall and discharge rates. Summer temperatures rose sharply, with severe consequences for cold-water fish. They projected a loss of ~74% of adult Chinook habitat (but little impact on juvenile Chinook habitat), and the reverse for steelhead: a loss of ~50% of juvenile steelhead habitat, but only ~15% loss of adult habitat. They projected large benefits of climate change for smallmouth bass and walleye.

Several papers explored the potential for riparian vegetation to mitigate future warming. Cristea and Burges (2010) explored climate change impacts in the Wenatchee watershed, a tributary to the Columbia River. They found greater potential for mitigation in smaller tributaries (-1.5ºC in Icicle Creek and -2.8ºC in Nason Creek) compared with the mainstem Wenatchee River (-0.3ºC), due to stream width. The cooling benefit of vegetation restoration will be surpassed by climate change by the 2020s in the mainstem, but postpone stressful temperatures for salmonids in the tributaries until the end of the century, which is a significant benefit.

A study in Scotland (Hrachowitz et al. 2010) produced a comparable result. In this case, however, the highest mean weekly temperatures currently occur in small exposed streams, and these streams are projected to reach extremely stressful temperatures for salmonids in a + 4ºC climate change scenario, which raised the catchment-wide mean stream temperature by 1.4ºC. They suggested that vegetation restoration would ameliorate these stresses.

Hill et al. (2010) showed that certain pristine and environmentally heterogeneous areas in northern coastal British Columbia with salmon have high potential resilience, but relatively low productivity, and hence might not be sufficient to maintain a "salmon stronghold".

14.4 Temperature-driven air pollution

Although mountain areas often support relatively pristine habitat, they are vulnerable to transport of pollutants generated long distances away. In particular, they are especially vulnerable to chemicals that are globally distributed by atmospheric deposition in a temperature-dependent way. Persistent organic pollutants, polycyclic aromatic hydrocarbons, and organochlorine compounds are concentrated in alpine streams because of the strong temperature gradients over short distances. Jarque et al. (2010) studied the reponse to organochlorine compounds in brown trout from the Pyrenees to Norway. They found biologically significant concentrations of pollutants in fish muscle correlated negatively with lake temperature, but biological activity might increase their negative consequences for fish with climate change

15 Policy/human social factors

Several papers addressed policy and management issues in adapting to climate change. All emphasized the need for more applied science and dialogue between researchers, managers, and the public. Some discussed specific climatic and biological information gaps and agreement, and the need for priority setting (Wilby et al. 2010), while others focused more on human social processes (Perry et al. 2010; Slaughter et al. 2010).

More specifically, Wilby et al. (2010) claim there is a lot of confusion about how best to proceed due to uncertainty in regional climate projections, biological responses, and environmental objectives. They emphasized that certain taxonomic groups are underrepresented in baseline data and impact studies, such as macrophytes, and that whole ecosystem responses need to be understood. Environmental objectives differ across managers, the public, conservation groups, etc., who further have different time frames of concern. They argued that even standard advice, such as increasing riparian shading to lower water temperatures and reducing abstraction from river flows, needs site-specific analysis and comparison with alternative actions before implementation. They argued that information gaps include site-specific information, underrepresented taxa, ecosystem goods and services, and risks and definitions of invasive species, given recommendations for increased connectedness. Overall they recommended more applied interdisciplinary research, adaptive management and cost-benefit analysis, in addition to reevaluation of goals and priorities.

Binder et al. (2010) summarized implications for adapation based on the Washington State Climate Change Assessment. They summarized key ingredients in successful adaptation planning, such as political leadership, money, stakeholder engagement, actionable science, tiggering extreme climatic events that motivate action and a long-term perspective. To adapt to changing water resources, they recommended expanding and diversifying water supplies, reducing demand, implementing operational changes, increasing summer drought and winter flood preparedness. To protect salmon, they recommended reducing summer stream temperatures, increasing minimum stream flows, and reducing peak winter flows by various means. They warned that these actions will involve more tradeoffs between water for fish and people.

Perry et al. (2010) emphasized that marine ecosystems and human behaviors are interconnected and showed similar features such as variability at many time scales. They suggested that fisheries focused on opportunistic species (e.g., anchovy) provide a model of flexibility that should be adopted by fisheries focussed on traditionally more stable species (e.g., cod) to adapt to increasing variability due to climate change. They cautioned that spontaneous human responses to increasing ocean variability might further de-stabilize marine ecosystem (e.g., switching to un-fished species). They recommended proactive, flexible management and communication among a broad group of stakeholders to prepare for the diversity of stresses coming to marine ecosystems.

Slaughter et al. (2010) argued that the free market (and reduced subsidies) is a better way to address over-allocation of Pacific Northwest water resources than court or regulator mandates in some respects, although both will be necessary.

The Washington State Integrated Climate Change Response Strategy: Species, Habitats and Ecosystems (Brekke et al. 2010) outlines an integrated approach to climate adaptation strategies that applies to a very wide range of ecosystems and threats. They focused on three conceptual approaches – resistance, resilience and response to faciliate natural system responses, and then building scientific and institutional readiness to support adaptation.

In their book, Climate Savvy, Hansen and Hoffman (2010) considered how a wide range of resource conservation issues—such as managing invasive species, harvest management, or ecological restoration—will need to change in response to climate change. Climate responses of ecosystems or organisms can be one of three types: resistance (stays the same), resilience (recovers after a disturbance), and response (e.g., movement or change). Key adaptation strategies for managing ecosystems in a changing climate included (1) protect adequate and appropriate space, (2) reduce non-climate stressors, (3) manage for uncertainty, (4) reduce local and regional climate effects, and (5) reduce the rate and extent of global climate change.

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Appendix D.3
Literature review for 2011: Biological effects of climate change

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Literature review for 2011 citations for BIOP: Biological effects of climate change

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July, 2012

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1 Executive summary

In 2011, the accumulation of more “fingerprints” of global warming continues (Blunden and Arndt 2012). CO_2 concentrations in the atmosphere broke new records, driving radiative forcing to 30% above 1990 levels. Rapid warming in high latitudes produced record losses of snow and ice from ice sheets and sea ice. Average summer temperatures throughout the U.S. were the second warmest on record, and despite the typically cool La Niña, 2011 was one of the 15 warmest years on record in the US, contributing to a very active wildfire season. The rise in 30-year average daily temperatures, reflected in the U.S. “Normals” for 1981-2010, was several degrees above that for the 1971-2000 period, reflecting the longer trends (Arguez et al. 2012). The frequency of extreme precipitation events (1-day and 5-day events) has increased over much of the Northern Hemisphere, despite natural forcing toward a decrease, thus presenting another “fingerprint” of the effects of anthropogenic forcing (Min et al. 2011).

In the PNW, hydrological impacts of warming have been strongest in rain-snow transient watersheds, where discharge has increased in the winter and decreased in the summer, producing earlier peak flows and lower low flows since 1962 (Jefferson 2011). New projections of hydrological responses in the PNW are consistent with the observed historical trends in hydrology (Cuo et al. 2011) and fire frequency and severity (Rogers et al. 2011), and emphasize the additional sensitivity in our region to higher projected rates of summer warming compared with winter warming for total annual discharge (Das et al. 2011). A statistically significant rise in summer sea level over the past century reflects larger patterns of sea level rise, while controlling for the effects of El Niño in winter (Komar et al. 2011). Similarly, summer upwelling intensity at 39º-42ºN has increased (Black et al. 2011), and upwelling has advanced earlier in the year, with a shorter upwelling period off British Columbia (Foreman et al. 2011). Hypoxia in the Columbia River estuary has been linked to upwelling events (Roegner et al. 2011b), and frequently reaches stressful levels for fish (2mg/L, Roegner et al. 2011a). Although some models project that hypoxic water from upwelling will decrease with climate change (Glessmer et al. 2011), sensitivity to hypoxia is much greater in warmer water, so it continues to present a serious risk (Vaquer-Sunyer and Duarte 2011). Numerous papers explore the hydrodynamics of the Columbia River, including sediment transport which might affect salmon survival (Jay et al. 2011; Jay and Naik 2011; Naik and Jay 2011b; Naik and Jay 2011a). Ecological fingerprints of climate change include a strong signal of long-term trends and regime shifts in marine ecosystems, described in a recent review of 300 time series in waters around the UK (Spencer et al. 2011).

A major concern is the extent to which natural responses to climate change must include range shifts or range contractions, because the current habitat will become unsuitable. The rate of range shifts and phenological shifts necessary to track climate change might be significantly larger in the ocean than on land, despite the slower absolute rate of warming in the ocean, due to shallower spatial and temporal gradients in temperature (Burrows et al. 2011). Abdul-Aziz et al (2011) illustrate this point dramatically for PNW salmon by showing that climate scenarios imply an enormous contraction (30-50% by the 2080s) of the summer thermal range suitable for chum, pink, coho, sockeye and steelhead in the marine environment, with an especially large contraction (86-88%) of Chinook salmon summer range (A1B and A2 scenarios). Previous analyses focusing on sockeye salmon (Welch et al.

1998) came to similar conclusions, but updated climate change projections and the multi-species perspective make this a particularly relevant paper.

Most of the other impacts of climate change on salmon reported in 2011 are consistent with the direction of previous studies. Copeland and Meyer (2011) found a positive effect of flow on juvenile Chinook density in the Salmon River Basin. Although demonstrated in Atlantic salmon (Marschall et al. 2011), observations that very long delays at dams can lead to exposure to extremely high river temperatures during smolting also could apply to the Columbia River. Bi et al (Bi et al. 2011a; Bi et al. 2011b) found strong correlations between marine distribution and growth and cold-water flow from the north, which presumably will decline with rising SST.

Numerous papers on adult migration demonstrate that migration timing is both genetically and plastically determined, and that changes in timing have already occurred (e.g., an evolutionary response in Columbia River sockeye, Crozier et al. 2011) and will continue with climate change. Projections of warming in the Fraser River produced much lower estimates of migration survival than occur now (Hague et al. 2011; Martins et al. 2011), although they aren’t expected to drive the populations extinct on their own (i.e., acting on this life stage alone, Reed et al. 2011). Much of the current mortality might be due to diseases as yet unidentified (Miller et al. 2011a).

Several papers emphasize that focusing exclusively on effects of individual life stages gravely unrepresents the cumulative impacts of climate change on salmon (Healey 2011; Pankhurst and Munday 2011). Analyses of the factors correlated with salmon extinctions in California (Zeug et al. 2011) and Japan (Fukushima et al. 2011) point to changes in flow regimes and rising air temperatures.

The risk of diseases throughout the life cycle is probably one of the least well quantified areas of concern (e.g., little is known about virus responses to climate change, Danovaro et al. 2011). The best way to protect salmon from disease risk is to maintain large population sizes with high genetic diversity (de Eyto et al. 2011). Species interactions are also poorly predicted, although recent work shows that competition among trout species can significantly alter predicted effects of climate change (Wenger et al. 2011).

On the positive side, some papers found less negative impacts of rising temperatures than expected (e.g., high tolerance of Snake River fall Chinook for 23ºC, Geist et al. 2011), and substantial genetic variation (and thus theoretically, the potential for evolution) in growth parameters, smolt behavior, migration timing, cardiac performance and heat tolerance. However, the existence of genetic variation and local adaptation in physiological traits does not support much optimism that evolution is likely to rescue Chinook salmon from risk of lowered survival due to climate change (unlike migration timing, as mentioned above). Typically, evolution relies on large population sizes and plenty of time. This is especially true if fisheries selection, e.g., on age at return, opposes adaptive responses to climate change or enhances population variability in response to environmental forcing (Botsford et al. 2011; Rouyer et al. 2011).

Adaptation plans for responding to climate change in the Pacific Northwest are being developed (e.g., review in National Wildlife Federation 2011). However, several papers emphasize that institutional barriers are a serious impediment to proactive climate change adaptation in water management (Farley et al. 2011b; Hamlet 2011; Safford and Norman 2011).

In conclusion, new information from 2011 publications was generally consistent with previous analyses in reporting ongoing trends in climate consistent with climate change projections and negative implications for salmon. A few studies focused on areas that did not receive much attention in our previous report, and thus provide new information. These areas include the expected loss of significant portions of the marine distribution, albeit it mainly in the second half of this century, the current risk of hypoxia in the Columbia River estuary, as well as documented and projected rates of evolutionary changes in migration timing. Disease impacts on migration survival documented in Fraser River sockeye warn of the potential for a very rapid decline in survival, unlike the linear projections generally forecasted, with little managerial recourse. Several papers demonstrated how cumulative effects of climate change over the entire life cycle are likely to be much higher than previously predicted from effects on individual life stages. Finally, new adaptation plans for the PNW are being developed but institutional barriers to climate change adaptation for some agencies and water use sectors create challenges for effective response.

Table of acronyms

A1B, A2, B1	Carbon emission scenarios from IPCC Fourth Assessment Report
AOGCM	Coupled Atmosphere-Ocean General Circulation Model
ENSO	El Niño-Southern Oscillation
GCM	General Circulation Model
IPCC	Intergovernmental Panel on Climate Change
PDO	Pacific Decadal Oscillation
PNW	Pacific Northwest
SST	Sea surface temperature

2 Goals and methods of this review

The goal of this review was to identify the literature published in 2011 that is most relevant to predicting impacts of climate change on Columbia River salmon listed under the Endangered Species Act. A large amount of literature related to this topic is not included, because almost anything that affects salmon at all relates to or is altered in some way by changes in temperature, stream flow or marine conditions. We have tried to identify the most directly related papers by combining climatic and salmonid terms in search criteria. Thus many general principles demonstrated in other taxa or with more general contexts in mind have been omitted. This review also does not include potentially relevant gray literature, because the search engine used only includes the major peer-reviewed scientific journals. In total, the methods employed involved review of over 500 papers. Of these, 135 are included in this summary.

This search was conducted in ISI Web of Science in July, 2012. Each set of search criteria involved a new search, and results were compared with previous searches to identify missing topics. The specific search criteria all included PY=2011, plus:

1) TS=(climat* OR temperature OR streamflow OR flow OR snowpack OR precipitation OR PDO) AND TS=(salmon OR Oncorhynchus OR steelhead);
2) TS=(climat* OR Temperature OR Precipitation OR streamflow OR flow) AND TS=”Pacific Northwest”;
3) TS=(marine OR sea level OR hyporheic OR groundwater) AND TS=climat* AND TS=(salmon OR Oncorhynchus OR steelhead);
4) TS=(upwelling OR estuary) AND TS=climat* AND TS=Pacific;
5) FT=(“ocean acidification” OR “California current” OR “Columbia River”)
6) TS="prespawn mortality"

The review is organized by first considering physical environmental conditions (historical trends and relationships) and then predictions of future climate, snowpack, stream flow, temperature, ocean conditions, etc. A summary follows of the literature on salmonid responses to these environmental conditions, progressing through the life cycle.

3 Climate

3.1 Global, national, regional climate

3.1.1 1981-2010 U.S. "Normals"

NOAA released a new set of "Normal" temperatures, i.e., 30-year average temperatures for the U.S for the 1981-2010 period (Arguez et al. 2012). The new normals include some methodological and station changes, and thus are not recommended for describing long-term trends in climate. Nonetheless, there is a striking increase in most of the indices. January minimum temperature has risen 2-4ºF throughout the north-central US, with nearly the entire central US seeing at least 1ºF increases compared with 1971-2000 normals. July maximum temperatures have increased at least 0.5ºF in the entire West.

3.1.2 State of the Climate 2011

Despite the cooling effect of La Niña, 2011 was still one of the 15 warmest years on record and above the 1981-2010 average (Blunden and Arndt 2012). Global sea surface temperature (SST) was 0.1ºC cooler than El Niño-driven 2010, but the global upper ocean heat content was still higher than for all prior years. Atmospheric CO_2 concentrations increased by 2.1ppm in 2011, exceeding 390ppm for the first time since instrumental records began. Together with increases in other greenhouse gases, radiative forcing is now 30% higher than in 1990. Ocean uptake of CO_2 was 12% below the long-term average. The Arctic continued to warm at twice the rate of lower latitudes, continuing extreme surface warming and net snow and ice loss on the Greenland ice sheet and the greatest loss in the Canadian Arctic since Gravity Recovery and Climate Experiment satellite measurements began. Arctic sea ice extent in September 2011 was the second-lowest on record, and 4-5yr old ice set a new record minimum of 19% of normal. Similar records were set in Antarctica.

The nationally-averaged summer temperature was the second warmest on record, but the Pacific Northwest (PNW) was cooler than average. The tornado season was one of the most destructive and deadly recorded, and historic flooding soaked much of the central US, surpassing the great floods of the 1920s and 1930s. The US also had a very active wildfire year (Blunden and Arndt 2012).

Observations of weather over the past 60 years (shifts in the position of warm and cold fronts across US) are consistent with projections of climate change associated with elevated greenhouse gas concentrations. The overall shift toward cold fronts and away from warm fronts across the northern US arises from a combination of an enhanced ridge over western North America and a northward shift of storm tracks throughout the mid-latitudes (Hondula and Davis 2011).

3.1.3 Extreme events

General circulation models (GCM) predict that anthropogenic forcing will increase the frequency of extreme events, such as heavy precipitation events, that cause massive flooding in the PNW. Min et al (2011) identified positive trends in extreme precipitation events in GCM projections. These trends were most consistent in the anthropogenic-forcing experiment only (without natural forcing), because natural forcing over the 20th century would have led to decreases in extreme precipitation events in many areas, thus producing a weaker observed signal of the anthropogenic fingerprint (i.e., without correction for natural forcing). Statistical comparisons of model representations and observed data show that coarse-resolution models are not capable of capturing the frequency of extreme events, but regional climate models nested within them greatly improve the dynamics (Duliere et al. 2011). Note that in 2012 the Intergovernmental Panel on Climate Change (IPCC) released a thorough analysis of changes in the frequency of extreme events, which will be included in the 2012 literature review.

3.1.4 El Niño analysis and modelling

The 2009-2010 El Niño differed from classical El Niño because it exhibited a “Modoki phenomenon”, or a “warm-pool” El Niño, with most warming in the central Pacific but a rapid transition to La Niña in 2011. Kim et al (2011) postulate the “fast phase transition” is due to a very warm Indian ocean and record-high SST in the central Pacific (see also Barnard et al. 2011).

Much work has been dedicated to improving the oceanographic data going into climate models, e.g., from autonomous gliders (Todd et al. 2011), and the spatial resolution of coupled atmosphere-ocean general circulation models (AOGCM) (Dawson et al. 2011), so that the next round of the IPCC’s Fifth Assessment Report models should have better representation of El Nino-Southern Oscillation (ENSO).

The importance of El Niño modeling has been emphasized in many papers, particularly for the PNW. Paleological data indicates that the recent century has been unusually wet in the perspective of much longer time-series. Long-term droughts have occurred throughout the last 6000 years, especially during the last 1000 years. Shifts in the severity of both wet and dry multidecadal events appear to be driven by changes in the ENSO pattern, and its effect on the Pacific Decadal Oscillation (PDO) (Nelson et al. 2011).

3.2 Terrestrial

3.2.1 Historical trends in streamflow in PNW

Like previous studies, new analyses of historical trends in streamflow in the PNW emphasize the sensitivity of transitional watersheds (i.e., where precipitation falls as both snow and rain) and transitional elevations within watersheds to recent (and projected) warming. Specifically, in an analysis of 29 watersheds in the PNW (Jefferson 2011), transitional areas demonstrate the most significant historical trends (i.e., greater winter and lower summer discharge). Snow-dominated watersheds showed changes in the timing of runoff (22-27 days earlier) and lower low flows (5-9% lower) currently than in 1962. Peak flows increased in the more heavily snow-dominated watersheds exposed to more frequent rain-on-snow events at higher elevations, but there was no trend in most of the transient or rain-dominated watersheds.

A series of papers on the impact of climate, dams, water withdrawal, and other human impacts on the Columbia and Willamette Rivers demonstrate that 1) human factors dominate the change in outflow of the Columbia River over the 20th century (Jay and Naik 2011; Naik and Jay 2011a), 2) climate factors, especially ENSO and the PDO, but also more fine-scale details about the timing of winter storms and spring warming rates also drive significant changes in the annual flow, as well as the detailed flow profile and winter and spring freshets (Naik and Jay 2011a) , 3) sediment loads have been strongly reduced due mostly to flow management and withdrawals, but climate-driven flow reductions also lower sediment transport, which has negative impacts on juvenile salmon survival (Jay and Naik 2011; Naik and Jay 2011a).

Many papers explore how habitat generally and flow in particular are related to juvenile salmonid density or growth. We focus here only on those in the Columbia River Basin.

In the lower Columbia, low flows in summer and fall through a tidal channel in the lower Columbia River (from Portland, OR to Vancouver, WA) have gotten lower and tidal range has increased due to both tidal changes and river flow and harbor modifications (Jay et al. 2011).

In Idaho, water diversion patterns vary with water availability in the Snake River Plain over the past 35 years from 1971 to 2005 (Hoekema and Sridhar 2011). Overall trends of declining mid- and late-season diversion is due to lack of water supply due to lower summer flows. Diversions have increased in April in response to unusually wet springs.

In a study of temporal variability in stream habitat characteristics over nine years in 47 headwater streams, Al-Chokhachy et al (2011) used landscape, climate, and disturbance attributes as explanatory factors. Although the factors were significant, most of the variability was difficult to explain.

A high proportion of groundwater input to a basin significantly affects the flow regime. Streams in the Klamath Basin with major groundwater inflow have a smoother and delayed response to snowmelt. However, July to September baseflows decrease under climate change scenarios much faster than mostly surface-input streams (Mayer and Naman 2011).

3.2.2 *Projected changes in stream flow and ice-cover*

An analysis of how land-cover and climate change in the Puget Sound basin will drive hydrological change (Cuo et al. 2011) showed that land use, leading to younger vegetation and urbanization will likely have more impact at lower elevations than climate change alone. In the rain-snow transition zone, increased winter precipitation and less snow led to earlier winter and spring runoff, with increases in these seasons due to projected increases in precipitation. Reductions in late spring and summer runoff followed, but the net change was a slight increase in annual runoff. Land-cover change had greater impact on the total runoff, especially at lower elevations, due to an increase in impervious surfaces and loss of mature vegetation in forested areas.

Das et al (2011) explore the sensitivty of streamflow across the Columbia Basin (and three other basins) to the seasonality of warming. They find that annual streamflow is much more sensitive to warming in the summer than in the winter. This is because winter warming causes an initial increase in streamflow that partly compensates for the later low flows in the summer. Summer warming dries out soil immediately through greater evapotranspiration rates with no compensation during the next rainy season. Because the A2 scenario predicts greater summer warming (5ºC) than winter warming (3ºC), this has a greater impact than uniform warming or a bias in the other direction would have. Application of a 2ºC cool season warming and 4ºC warm season warming produced a decline in annual streamfow of 9.8% in the Columbia Basin (Das et al. 2011). Work continues (Bohn, Sonessa et al. 2010) on the Variable Infiltration Model hydrology model, downscaling bias correction, and understanding how best to use multi-model ensembles compared with best-fitting individual models.

Scenarios of climate change in the Willamette Basin predicted increases in flows in winter (September through February), and decreases in summer (March through August, Jung and Chang 2011). The spring freshet is expected to advance seasonally, the 7-day low flows decrease, and peak flows increase due to winter flooding, especially at higher elevations.

Similar to watersheds and elevations in the rain-snow transition zone, lakes where winter ice cover is short with winter minimum temperatures closer to 0ºC are most sensitive to warming. Weyhenmeyer et al (2011) predict that "3.7% of the world's lakes larger than 0.1 km^2 are at high risk of becoming open-water systems in the near future."

In an analysis of uncertainty around flooding in urban areas, Jung et al (2011) explicitly focus on the uncertainty at all levels of modeling, from GCM model and emissions scenarios to land use change to hydrological model parameters and natural variability in climate. The development versus conservation land use scenarios in watersheds around Portland, OR made little difference to the overall projections, especially in the more developed watershed. In that watershed, hydrological parameters drove much more uncertainty than in the more pristine watershed. Uncertainty from GCM model structure (i.e., different GCMs) was larger than hydrological model uncertainty, and natural varibility was larger still, especially at long flood frequencies. Overall, flood frequencies are expected to increase by the 2050s.

3.2.3 Fire

Simulations of PNW fire frequency in future climates predict large increases in the area burned (76%-310%) and burn severities (29%-41%) by the end of the twenty-first century (Rogers et al. 2011). The changing fire regime lowers carbon storage west of the Cascades in the absence of fire suppression, but raises it in the dry eastern PNW.
Fire frequency is expected to increase in most areas of the PNW. Fire has a profound effect on steam temperature and nutrient input. An analysis of historical stream changes and trout response in burned and unburned areas of Montana showed stream temperatures increased 2-6ºC right after the fire, but recovery by fish was generally swift (Sestrich et al. 2011).

3.3 Marine

3.3.1 ENSO

State of the California Current System 2010-2011: The 2009-2010 El Niño was relatively weak and short-lived, and it was quickly followed by La Niña. La Niña produced some record-breaking cool conditions throughout the California Current system, with anomalously strong upwelling in summer 2010. Impacts of both El Niño and La Niña were weaker and the transition between them was less abrupt off southern California compared with off Washington and Oregon. Productivity in the pelagic ecosystem enhanced with La Niña off central and southern California, but El Niño-condition copepod assemblies persisted later in the northern California Current system (Bjorkstedt et al. 2011).

Heinemann et al (2011) developed a simplified ENSO and ecosystem (nutrient-phytoplankton-zooplankton) model that demonstrates how the ecosystem itself could moderate ENSO variability by the effect of phytoplankton on the absorption of shortwave radiation in the water column. This biological feedback to the climate system leads to (1) warming of the tropical Pacific, (2) reduction of the ENSO amplitude, and (3) prolonging the ENSO period. In a somewhat similar analysis, Lin et al (2011) showed that the spatial distribution of chlorophyll-a actually influences the mean state of the ocean in the tropical Pacific. Because chlorophyll-a blocks solar radiation to some extent, a shallow thermocline and stronger currents lead to decreased annual mean SST in the eastern equatorial Pacific. They conclude that the seasonal cycle of chlorophyll-a can dramatically change the ENSO period in the coupled model.

3.3.2 Sea Level Rise, wind speed and wave height

Sea level varies seasonally and with significant ocean phenomena, such as El Niño events. Determining whether there has been a significant rise in sea level must first, therefore, account for this effect. Komar et al (2011) separated out the seasonal trends in sea level in the PNW. Strong El Niño events dominate the winter record, but the more stable summer sea levels show statistically significant trends toward higher sea level.

Using satellite data, Young et al (2011) documented increasing oceanic wind speeds and wave height over 23 years globally, with a higher rate of increase in extreme events.

3.3.3 Upwelling

Most analyses published in 2011 found that upwelling has become more intense over the past century. The California Current System demonstrates two seasonal upwelling “modes” (Black et al. 2011). Summer upwelling shows longer frequency variation, reflecting multi-decadal processes. Significant linear trends over 64 years show the intensity of summer upwelling has increased at 39ºN to 42ºN. Winter upwelling reflects North Pacific Index and ENSO cycles. Chinook salmon growth-increment chronology correlated significantly with the summer upwelling mode (Black et al. 2011). Similarly, upwelling off British Columbia (Foreman et al. 2011) starts later and ends earlier, based on trends over the past 50 years. Nonetheless, cumulative upwelling and downwelling has significantly increased, because of the increase in intensity. The intensity of coastal upwelling off California, however, has not increased over the past 60 years (Pardo et al. 2011), based on SST and the upwelling index from the National Centers for Environmental Prediction/ National Center for Atmospheric Research reanalysis project database.

The effects of upwelling off the coast extend into the Columbia River estuary. Roegner et al (2011b) investigated whether the source of chorophyll in the estuary was freshwater or marine. High flows in spring brought freshwater chlorophyll into the estuary, although production was relatively low. In the summer, upwelling winds transported chlorophyll from the ocean. Tidal cycles determined stratification, which was higher during neap tides than spring tides.

3.3.4 Oxygen mimium zones and O_2 sensitivity

Oxygen minimum zones (OMZs), have been expanding over the 20th century. Studies of a 2.4-4.5ºC warming event in the Miocene indicates that similar low oxygen conditions occurred at that time as have recently been observed (Belanger 2011). An analysis of anchovy and sardine oscillations indicates that oxygen levels, rather than temperature or food availability could be the primary factor driving anchovy/sardine oscillations in the Peruvian upwelling region (Bertrand et al. 2011).

The Columbia River estuary experiences low oxygen conditions (2mg/L) when strong upwelling combines with neap tides (Roegner et al. 2011a). Mortality caused by low oxygen is significantly increased by warmer water. In a meta-analysis, Vaquer-Sunyer and Duarte (2011) found that increasing temperature reduced marine benthic macrofauna survival times and increased minimum oxygen thresholds for survival by 74%, and 16%, respectively, on average. They project that 4ºC ocean warming will lower survival times by 35.6% and raise minimum oxygen concentrations by 25.5%, potentially causing many more die-offs in the future.

A separate model of upwelling in an AOGCM predicts a reduction in the impact of OMZs from upwelling. Glessmer et al Glessmer, Park et al. 2011) found that 25% less low oxygen water reached the surface in their double CO_2 scenario, compared with the current climate.

3.3.5 Ocean acidification

Ocean pH is often thought of as being fairly static, but Hofmann et al (2011) demonstrate very high spatial and temporal variability in diverse marine habitats. Others (Joint et al. 2011) similiarly argue that natural variability is very high, pointing out that pH can change much more in freshwater lakes. Models of future pH and biological responses and feedbacks are still challenging (Tagliabue et al. 2011).

Much work has continued on the sensitivity of different organisms and life stages to ocean acidification. Gruber (2011) published an overview of the combined threats of ocean acidification, rising temperatures, and lowered oxygen levels. Many species have been studied in 2011, including herring (Franke and Clemmesen 2011), coral reef fishes (Munday et al. 2011a), clownfish (Munday et al. 2011b), an intact invertebrate community (Hale et al. 2011), crustaceans (Whiteley 2011) plus many studies on pteropods (Lischka et al. 2011) and phytoplankton (Low-DÉCarie et al. 2011). The results are mixed, but many stages and species are not especially sensitive. Pteropods are a concern for salmon because they are a prey item and have an aragonitic shell. They are sensitive to temperature increases in addition to rising acidity (Lischka et al. 2011).

3.3.6 Ecosystem effects

Large-scale climate factors and ocean chemistry drive the distribution and productivity of the entire marine biota. Factors such as the PDO, ENSO, and Northern Oscillation Index are strong predictors of larval fish concentration and diversity in the northern California Current (Auth et al. 2011). Upwelling indices are a significant predictor of herring and surf smelt catches in the Skagit River estuary (Reum et al. 2011). The Aleutian Low Pressure Index is correlated with seabird productivity and timing (Bond et al. 2011). Long-term trends in community composition this past century have been documented in a majority of time series of marine ecosystems. In a study of 300 biological time series from seven marine regions off western Europe, Spencer et al (Spencer et al. 2011) found most regions showed both long-term trends and regime shifts. Pollock, for example, changed its role in the food web during warm periods (Coyle et al. 2011). Regime shifts (i.e., a step in some measure of biological response over a short temporal interval or in response to a small physical change) are also widespread, although they might be overestimated by failure to account for temporal trends (Spencer et al. 2011).

Predicting how ecosystems will change with the climate typically relies on environmental correlates of organism distribution. Lenoir et al (2011) developed a model that explains observed shifts in the distribution of eight exploited fish in the North Atlantic, and projects that these species should continue to move northward, but some might be hindered by barriers and rate limitations. Finally, mesocosm experiments show how warming accelerates the phytoplankton bloom timing by about 1 day/ºC, and decreases biomass (Sommer and Lewandowska 2011).

Using NOAA’s Geophysical Fluid Dynamics Laboratory Earth System Model, Polovina et al (2011) project shifts in large marine ecosystems. They use modeled phytoplankton density to distinguish 3 biomes in the North Pacific. Under the A2 emissions scenario, the model predicts that temperate and equatorial upwelling biomes will occupy 34 and 28% less area by 2100. The subtropical biome, on the other hand, expands. Extending this change in area to primary productivity and fisheries catches, they expect a 38% decrease in the temperate biome, and a 26% increase in the subtropical biome catch.

An additional concern throughout the ecosystem is the increasing prevalence of persistent organic pollutants, especially polycyclic aromatic hydrocarbons from fossil fuel burning (De Laender et al. 2011). This direct source of pollution is a major concern for salmon, especially coho, in urban areas, but might become a more widespread marine phenomenon.

Jones (2011) discusses the potential for increasing marine productivity by enriching the oceans artificially with macronutrients (the Haber-Bosch process). He argues that phosphorus appears to limit the carbon storage capacity of nitrogen and hence additional new primary production.

3.3.7 Viruses

A typically overlooked consequence of global change is a potential increase in the impacts from viruses. Danovario et al (2011) review the very large impacts viruses have on phytoplankton, especially, but also throughout the ecosystem. They point out many positive correlations between temperature (and other expected changes in ocean chemistry) and viral abundance, but the relationships are complicated and more work is needed.

3.4 Comparing rates of climate change in marine and terrestrial environments

Burrows et al (2011) compared the rates of historical climate change in marine and terrestrial environments. Focusing on the rates of temperature change that organisms might be expected to track through either range shifts or phenological change, they calculated the velocity of temperature change in terms of the latitudinal distance an isotherm has shifted (km/year), and the seasonal shift in spring and fall temperatures (days per year). These two quantities are ratios of the long-term temperature trend and either the spatial or temporal gradients across the landscape. Using these metrics, they found that although the absolute rate is a little slower in the ocean, because the spatial and seasonal gradients in temperature are shallower, the overall velocity and seasonal rates of change are faster for marine than terrestrial ecosystems, implying faster range shifts will be needed to track cliamte change. The ocean also differs from land because many ocean areas are cooling, especially in areas where upwelling has intensified, generating a bimodal distribution of rates of temperature change.

4 Salmon life-stage effects

4.1 Freshwater stages

4.1.1 Juvenile behavior and survival

Copeland and Meyer (2011) studied the correlations in juvenile salmonid density since 1985 in the Salmon and Clearwater River Basins. Densities in all six species were positively correlated, and flow and Chinook salmon redds were correlated with densities overall. For Chinook salmon, models with spawner density combined with either annual mean discharge or drought (Palmer Drought Severity Index) had similar Akaike information criterion (AIC) weights, and explained 52% of the variation.

Hypoxia limits the suitability of many nesting sites, and is often affected by changes in flow via deposition rate of fine sediments or flushing and groundwater infiltration. Malcolm et al (2011) found that interstitial velocity is not a good predictor of hyporheic dissolved oxygen. Miller et al (2011b) explore how rainbow trout compensate for low oxygen by altering their cardiac ontogenic program.

Heat tolerance varies by life stage in salmon. Breau et al (2011) show that differences in thermal-refuge-seeking behavior between age 0+ and age 1+ and 2+ Atlantic salmon stems from higher tolerance in respiration and cardiac performance in younger fish.

Given the dramatic changes in winter temperature expected throughout the PNW, it is a concern that winter ecology is not well understood. Stream environments create complicated ice dynamics that are very sensitive to fine scale variation in temperature and flow (Brown et al. 2011). Fish responses to thermally elevated areas overwinter (e.g., near nuclear power plants) sometimes have negative consequences for reproduction, but likely responses to long-term, gradual changes throughout the stream are not clear. Undercut banks are critical winter habitat for brook trout in small mountain stream, affected only slightly by winter flow reductions (Krimmer et al. 2011).

4.1.2 Juvenile growth

Salmon growth rates depend on temperature both directly because of temperature-governed chemical reaction rates, and indirectly because of elevated energetic demands of higher metabolic rates. Increased consumption can sometimes compensate for higher metabolic rates, leading to an interaction between ration and temperature effects. Geist et al (2011) tested the growth rate of Snake River fall Chinook below Hells Canyon Dam, and found high tolerance to short periods of high temperature (23ºC) even at relatively low rations (down to 4% of body weight). However, at 1% ration, fish grew better at constant cool temperatures, suggesting that this low consumption rate was insufficient to cover metabolic costs of high temperatures. Natural consumption rates at this location are unknown. Steelhead in Los Angeles County grow year-round and produce large smolts, despite spending a week each year at mean temperatures over 22ºC (Bell et al. 2011). It is important to note that although growth is sensitive to temperature, other factors, such as negative effects of fish density, can be more limiting (Bal et al. 2011).

Bioenergetic models are a primary means of analyzing changes in stream quality on growth. A crucial element of these models is the interaction between metabolic rate and energy supply through food consumption. Individual variation in bioenergetic parameters is generally ignored, but Armstrong et al (2011) show through a modelling exercise that this variation can significantly affect the impact of flow and food variability on growth.

Energetic rates were measured in rainbow trout exposed to various flows in a natural environment. The crucial difference between their environment and a typical laboratory set up was the existence of refuges from high flows, which allowed swim speed to decline at peak flows (Cocherell et al. 2011). Taguchi and Liao (2011) also explored how microhabitat utilization can be very energetically efficient.

By coupling a bioenergetic model with a simplified stream temperature model, Beer and Anderson (2011) demonstrate potential changes in Chinook and steelhead growth rates as a sensitivity analysis of change in mean air temperature and change in snowpack. They describe 4 characteristic stream types in the PNW -- warm winter and cool summer (North Santium); cold stream with high snowpack (Clearwater); warm summer with high snowpack (Salmon River) and warm summer with low snowpack (Snake River). They found that in the streams with cooler summers, warming and loss of snow increased growth rates, but in the warmer-summer streams, growth decreased.

4.1.3 Smolt behavior and survival

Bjornsson et al (2011) review physiological characteristics of smolting and environmental drivers. Acidification, as well as endocrine disruptors and other contaminants could lower survival through interferring with this carefully controlled process. Perkins and Jager (2011) created a development model for Snake River fall Chinook salmon that proposes a mechanism by which delayed growth leads to a yearling smolt behavior.This type of behavioral switch could make a big difference in population responses to climate change, but is hard to predict ahead of time. Other studies (Hayes et al. 2011) of California steelhead document different hormone levels between fish that smolt at different times over the season, and some fish that return upstream before smolting the following year. This rich variety of behavior will be crucial to effective responses to climate change.

Many anthropogenic habitat modifications have the potential to exacerbate effects of climate change on stream temperature. Smolt survival is often reduced at high temperatures, and due to direct and indirect effects of dam passage. Marschall et al (2011) explicitly modeled the interaction between delays at dams and exposure to high temperatures during smolt migration. Assuming that a threshold temperature causes fish to initiate migration in spring, they explore the range of initiation temperatures likely to ensure a successful migration with and without delays caused by dams. They find that even short delays at dams greatly reduce this window of opportunity. Particularly dangerous were irregular warm river sections that occurred downstream, and caused high delayed mortality (i.e., after successful passage through a dam) in late migrants. Their model is based on temperatures, flows, and migration distances measured in the Connecticut River for Atlantic salmon, but bears high relevance to Columbia River salmonids. Finally, conditions during smolting can affect maturation age. Exposure to elevated temp (16ºC) and continuous light can trigger early maturation in male Atlantic salmon (Fjelldal et al. 2011).

4.1.4 Adult migration

The return to freshwater to spawn is a delicately timed behavior. Each population has adapted the timing of return to minimize mortality in freshwater prior to spawning, and to maximize fecundity which depends on marine growth and energetic expenditure during the migration, among other things. Migration mortality is closely tied to environmental conditions, especially temperature, experienced during the migration. Many papers published in 2011 explore the genetic and behavioral controls on timing and resulting morality.

Adult migration timing in sockeye has been progressing earlier in the year in the Columbia River over the 20th century. Crozier et al (2011) explore how changes in river temperature and flow, as well as ocean conditions might be driving this advance. They found evidence that this trait evolved genetically due to mortality of late migrants exposed to higher Columbia River temperatures during the historical migration period. The fish also show a strong annual response to river flow, such that they migrate earlier in low-flow years. These two processes combined suggest both plastic and evolutionary responses are involved in an adaptive shift likely to continue in response to climate change. Genetic studies have identified candidate genetic markers in Columbia River adult Chinook salmon associated with run-timing (Hess and Narum 2011). Liedvogel et al (2011) review the genetics of migration more broadly.

Early migration in Adams and Weaver Creek sockeye in the Fraser River has a very different explanation and result, however. Early migrants in the Fraser experience very high temperatures and have high mortality, so the sudden change in behavior that began in 1995 has been hard to explain. Thomson and Hourston (2011) correlated early entry timing with weaker wind stress for Adams River stocks, and with lower surface salinity for Weaver Creek stocks. They postulate that both factors lead physiologically to earlier entry because the former entails easier swimming against weaker currents and the latter entails earlier osmoregulatory adaptation to freshwater, noting that early migrants were exposed to relatively fresh water earlier in the year.

Several genetic studies of Fraser River sockeye have found that gene expression varies systematically over the course of the migration (Evans et al. 2011), and that certain gene expression patterns were strongly correlated with mortality during the migration (Miller et al. 2011a). The genes that were upregulated are associated with the immune defense system, and the authors propose that viral infection might be to blame for the low survival. Other papers developed statistical correlates of migration survival for in-season fisheries management, in which temperature and flow were strong predictors of survival for some stocks, especially those exposed to harsher conditions (Cummings et al. 2011). Warmer water lowers catch-and-release survival (Gale et al. 2011), and might be important in interpreting tagging studies. A comparison of migration survival of fish tagged at sea versus those tagged in freshwater (which is much warmer) found that those tagged at sea had much higher survival (Martins et al. 2011).

The timing of the adult migration among Yukon River Chinook salmon is correlated with SST, air temperature and sea ice cover. As these factors change with climate change, migration is expected to occur earlier (Mundy and Evenson 2011).

Projected adult migrant survival

Several papers used observed survival of migrating Fraser River sockeye to project survival under future climate scenarios. Martins et al (2011) modeled 9-16% declines by the end of the century. Hague et al (2011) quantified the number of day per year that migrating fish will experience less optimal temperatures. They found that the number of days over 19ºC tripled, reducing their aerobic scope to zero in some cases. They found that exposure varied within each run, such that there is potential for shifts in run-timing to drive adaptive responses to rising temperature. An individual-based simulation model of the evolutionary response to rising river temperatures with climate change showed that Fraser River sockeye with a reasonable heritability (0.5) would theoretically shift their migration 10 days earlier in response to 2ºC warming. Nonetheless, this study did not generally predict extinction of these populations even if they did not respond to selection (Reed et al. 2011). But evolution in run timing has clearly occurred in Chinook salmon introduced to New Zealand, where populations from a common ancestry have diverged 18 days in their spawning-migration (Quinn et al. 2011).

Local adaptation and acclimation in heat tolerance

Evolution in response to rising temperatures could occur in adult migration timing, as discussed above, or in heat tolerance. Eliason et al (2011) studied variation in cardiac tissue. Local adaptation in thermal optima for aerobic, cardiac tissue and performance among populations migrating at different times through the Fraser River. They argue that the heart has adapted to population-specific migration temperatures, in addition to the length of migration. This is consistent with interspecific differences. Pink salmon have higher heat tolerance during migratory stages than sockeye (Clark et al. 2011). Similar differences can also reflect acclimation. Studies of cardiac tissue in rainbow trout identified very distinct morphology and tissue composition in distinct cold-acclimated and warm-acclimated fish (Klaiman et al. 2011).

4.2 Marine stage

4.2.1 Marine survival

Because ocean survival is the strongest correlate of population growth rate for most populations, understanding the factors that drive marine survival has been a high priority for decades.

The primary factors thought to govern survival are growing conditions, which are generally correlated with overall ocean productivity. In a new paper confirming and refining previously recognized patterns for PNW salmon, Bi et al (2011b) explore the relationship between coho early marine survival, copepod species composition, water transport in the California Current, and larger climatic indices (the PDO). Cold copepod biomass correlates with coho survival. Seasonally, they found that lipid-rich copepods associated with cool water are less abundant in the winter, when the current is coming predominantly from the south (“positive alongshore current”) and more abundant in summer, when current is coming from the north (“negative alongshore current”). At the annual and decadal scale, when the PDO is positive, more water comes from the south in winter; when PDO is negative, more water comes from north during summer. In a separate paper, Bi et al. (2011a) confirmed the spatial relationships between yearling Chinook and coho distributions and copepod assemblages. Both species are strongly positively correlated with the cold copepod assemblage and chlorophyll a concentration. Yearling coho had similar relationships, but also positively correlated with temperature. Nonetheless, the adult migration does not necessarily track annual varation in zooplankton location. Bristol Bay sockeye do not seem to vary their migration route among years in response to variation in marine productivity and temperature (Seeb et al. 2011).

Salmon growth and survival often correlates with SST (e.g., Norwegian Atlantic salmon growth at sea is positively correlated with SST in the Barents and Norwegian Seas (Jensen et al. 2011), and Japanese chum salmon growth is positively correlated with summer/fall SST in coastal areas while fish stay near shore, and off-shore temperatures later in the year (Saito et al. 2011). Much of the mortality is size-selective, with smaller fish having higher mortality rates. Size-selective mortality could stem from either an energetic constraint (insufficient resources to survive harsh conditions) or size-selective predation. In Alaskan sockeye, Farley et al (2011a) found that the energetic status of juvenile sockeye was adequate to survive winter, and suggest predation-avoidance behavior as a better explanation for size-selective mortality and ongoing energy loss. They suggest that higher temperatures in climate projections might lead to declines in age-0 pollock, a high quality prey for salmon, and lead to lower winter survival.

Marine survival is tightly linked to ocean conditions at the time of smolting. The Rivers Inlet sockeye population in British Columbia has been depressed since the 1990s. High flows in this river decrease marine productivity because the river is nutrient-poor. Thus the negative correlation between high river flow and marine survival appears to result from the impact of low nutrient, brackish water depressing marine plankton growth (Ainsworth et al. 2011b). This system-specific impact on marine productivity explains the difference between a positive correlation for high-nutrient rivers, like the Columbia, and low-nutrient rivers like Rivers Inlet.

More broadly, salmon survival is often correlated with broader indicators of ecosystem productivity. Lower trophic level productivity generally supports better growth and survival all the way up the food chain. Borstad et al (2011) found that regional chlorophyll abundance in April, timing of spring wind transition and phytoplankton bloom are important for survival of Canadian Triangle Island sockeye salmon, sandlance and rhinoceros auklets.

4.2.2 Projected future marine habitat availability

In an important paper, Abdul-Aziz et al (2011) constructed maps of potential salmon marine distributions under climate change scenarios. They developed thermal niche models for summer and winter separately for five Pacific salmon species and steelhead based on high-seas catch records over the last 50 years. These are not mechanistically-determined range limits, e.g. through physiological constraints, and thus might not correlate with future distributions exactly the way they do now. It is likely that changes in the distribution of food availability will play a very large role in future distributions, which might depend on many factors. However, they do indicate how projected changes in SST translate into one characterization of potential salmon habitat. Historical analysis showed that salmon thermal habitat, using observed temperature ranges, changed very little over the 20th century. However, under the A1B and A2 emissions scenarios, the multi-model ensemble average SST imply a reduction in summer habitat for coho 5-32%, where the range goes from the 2020s to the 2080s, Chinook habitat declines 24-88%, and Steelhead habitat area declines 8-43%. Winter habitat area shows much less effect in these species, ranging from 0 to 10% for the 3 species and three future time periods. Sockeye had much greater sensitivity in their winter range, reducing from 6-41%. The B1 scenario had a similar result for 2020s and 2040s, but was less severe by 2080 (-66% for Chinook summer habitat, -21 to -24% for coho and steelhead summer, and 0 to -7% for all three species in winter). One reason for the high percentage reduction in Chinook summer habitat was that their historical absolute area was estimated to be much smaller in summer than the other species (7 million km^2 compared with 10-11 million km^2). But the projection is for a complete loss of Gulf of Alaska habitat by the 2040s, and complete loss of Okhotsk Sea and Subarctic subdomains, and most of the Bering Sea habitat. There is a small extension into the Arctic Ocean that is not currently occupied, but net reductions vastly outweighed this potential expansion.

4.2.3 Ocean acidification

Two recent modeling papers explored the ecological impacts of ocean acidification and other aspects of climate change. Ainsworth et al. (2011a) predicted that ocean acidification may cause salmon landings to decrease in Southeast Alaska and Prince Williams Sound food webs and increase in Northern British Columbia and Northern California Current food webs. However, when the authors applied five impacts of global change to these food webs simultaneously (primary productivity, species range shifts, zooplankton community size structure, ocean acidification, and ocean deoxygenation), projected salmon landings decreased in all locales (Ainsworth et al. 2011a). Incorporating ocean acidification and ocean deoxygenation into bioclimatic envelope models for harvested fishes in the Northeast Atlantic caused 20-30% declines in projected future harvest, likely due to reduced growth performance and faster range shifts (Cheung et al. 2011).

5 Higher-level processes

5.1 Population-level effects

Warming temperatures in Alaska have opened up potential habitat for colonization. Pink salmon and Dolly Varden were among the first fish to colonize one such stream in Glacier Bay (Milner et al. 2011). The stream community has developed over the past 30 years. Having robust populations at the edge of the current range to provide colonists faciliates range expansion.

5.2 Diseases

The negative impact of multiple stressors, such as UV-B exposure and high temperatures, on immune function, together with predicted increases in pathogen load in warmer waters resulting from global climate change, suggest an increased risk of diseases in fishes (Jokinen et al. 2011). De Eyto et al (2011) show that selection on immunological adaptation at the major histocompatibility genes in Atlantic salmon varied with life stage and were strongly correlated with juvenile survival. They emphasize the importance of maintaining genetic diversity to evolve in response to novel disease pressures expected to result from climate change.

Many diseases are more prevalent or virulent at warmer temperatures. Salmonid parasites often require intermediate hosts, and parasite risk to fish can be lower in areas unsuitable for the other host. *Tubifex tubifex*, the host of whirling disease, cannot tolerate very hot streams affected by geothermal processes in Yellowstone National Park, thus reducing infection of rainbow trout in these reaches (Alexander et al. 2011). However, some expected negative effects of rising temperatures have not been detected. In an Alaskan stream summer water temperature has increased 1.9ºC over the past 46 years. However, the presumed increase in consumption rates in sockeye has not led to an increase in tapeworm load (Bentley and Burgner 2011). Algal blooms are affected by environmental conditions, and can kill large numbers of fish. When an algal bloom moved through a fish farm in New Zealand, a large fish kill occurred (MacKenzie et al. 2011). The extent to which wild fish could have avoided the bloom is unknown.

5.3 Population declines and variability attributed to climatic factors

A fairly rare but important element of evaluating the importance of environmental effects is a comparison between environmental and anthropogenic or a variety of alternative hypotheses. Most studies look at only a single type of explanation – i.e., they just compare environmental effects. But Otero et al (2011) conducted a comprehensive analysis of the catch of Atlantic grilse over the whole length of the Norwegian coast as a function of environmental effects during the smolt stage and the return migration, marine, and anthropogenic (fish farms, fishery, dams) potential driving factors. They find water temperature and flow interact with dams to shape catches, and aquaculture and fisheries have negative effects.

Many spring and fall run Chinook salmon populations have been extirpated from the Central Valley of California. Migration barriers completely explain Central Valley California fall Chinook extirpation, but for spring Chinook, habitat loss and altered flow regimes, especially enhanced summer flows, predicted extirpation (Zeug et al. 2011). An analysis of population extinction of Sakhalin taimen (*Parahucho perryi*) in Japan showed that in comparing populations that ranged from extinct to endangered to extant, lower air temperatures and minimal agricultural development set extant populations apart. Lagoons also provided refugia (Fukushima et al. 2011).

When fisheries alter the age structure of a population, it can lose some of its resiliency to environmental variation. Long-term shifts toward a shorter generation time, and reduced age overlap within the population adds variability to population growth rates. Environmental conditions driving that variability thus become more important. Cod show increasing sensitivity to environmental fluctuations, which could ultimately make climate impacts more severe (Rouyer et al. 2011). Age structure can also be important if generation time coincides with the periodicity of a key environmental driving factor. Age-structured models with periodic environmental forcing and fishing pressure generate the cohort resonance effect, which can drive much more variability in population abundance than predicted by an ecosystem or stage-structured model if the frequency of the forcing factor is close to the mean age of reproduction (Botsford et al. 2011).

5.4 Projected cumulative effects throughout the life cycle

A holistic perspective demonstrates that climate change will pose significant stress not just on one or two stages, but potentially on every life stage. Healy (2011) outlines adverse impacts throughout the life cycle, as well as pointing out how responses in one stage can carry over and affect survival or growth in a subsequent stage, and even suequent generations. Cumulatively, he argues they pose enormous risk for Fraser River sockeye. Healy also lists management and policy responses that would reduce these stresses by life stage.

Elevated tempeatures often inhibit reproduction. Pankhurst and Munday (2011) review the entire suite of known endocrine effects in salmonids, as well as the diverse sensitivities in juvenile stages as well. They emphasize that the ramifications of chemical, thermal and hydrological change will be complex and pervasive throughout the life cycle and geographic range of these fish.

5.5 Species interactions

Wenger et al (2011) used thermal criteria, flow frequency, and interaction strengths with other salmonids to predict habitat availability for all trout in the interior west under climate change scenarios. Under A1B scenarios, average habitat decline across all species is 47%. Brook trout loses the most habitat (77%) and rainbow trout the least (35%). Species interactions shaped the outcome negatively for some species and positively for others. It does demonstrate that considering species interactions could significantly alter predicted responses to climate change.

Temperature gradients cause variation in salmon behavior that can either enhance ecosystem productivity, or reduce it. The large spread in Alaskan sockeye salmon spawn timing due to thermal differences among streams supports most of the growth in rainbow trout, who eat salmon eggs over a relatively long temporal window in the fall (Ruff et al. 2011). On the other hand, a study of paleoecological and recent lake productivity in Tuya Lake, British Columbia revealed an interaction between salmon consumption and warming, such that salmon enhanced climate-induce nitrogen deficiencies (Selbie et al. 2011). They emphasize that ecosystem structure is very sensitive to temperature.

6 Human adaptation

Extensive work explores adaptation responses to climate change. This literature is mostly beyond the scope of this review, but we just highlight a few examples here. Several papers concentrate on human responses to climate change. A comprehensive review of marine and aquatic vulnerabilities, adaptation strategies, and existing adaptation plans in the PNW was drafted in 2011 (National Wildlife Federation 2011). This report identified common elements of adaptation plans in the PNW and elsewhere, including: remove other threats and reduce non-climate stressors that interact negatively with climate change or its effects; establish or increase habitat buffer zones and corridors; increase monitoring and facilitate management under uncertainty, including scenario-based planning and adaptive management. The report includes additional approaches from available literature in the broad areas of information gathering and capacity building; monitoring and planning; infrastructure and development; governance, policy, and law; and, conservation, restoration, protection and natural resource management. This information is intended to guide development of climate change adaptation strategies through the North Pacific Landscape Conservation Cooperative. At the national level, adaptation strategies have been proposed for ecosystems including coastal and aquatic systems affecting salmonids (USFWS et al. 2011). The draft inland aquatic ecosystems strategy focuses on protecting and restoring existing habitat; maintaining ecosystem functions that will continue to provide benefits in a changing climate; reducing impacts of non-climate stressors; and including climate considerations in resource management planning, monitoring, and outreach programs. A final national adaptation strategy is expected in 2012. Safford and Norman (2011) describe the institutional forces that shape the way recovery planning groups in Puget Sound develop plans to manage water to improve salmon survival. They found that asymmetrical roles (e.g., tribal veto power), coupled with lack of explicit support for tribal sovereignty (which might reduce the likelihood of tribal vetoes) contribute to institutional problems. Similarly, allowing technical planners to also contribute to citizen committees reduces the ability of the planning groups to achieve diverse social and technical objectives. The lack of broader participation has generally led to calls for increasing water supply for salmon, but there has been a lack of concrete recommendations for accomplishing this. Farley et al (2011b) describe capacity for institutional responses to climate change among four water sectors in Oregon's McKenzie River basin and found that some sectors have more flexibility (e.g., fish habitat recovery and flood control) than others (e.g., municipal water and fishing guides) for responding to climate change. Hamlet (2011) also examines institutional capacity for water management adaptation, and finds that, although existing institutions have resources to deal with moderate changes, substantial obstacles to climate change adapation exist for large and complex systems such as the Columbia River basin. Lack of a centralized authority for water management decisions, layers of existing laws and regulations, and lack of specificity in some management plans contribute to this concern. He suggests that the most progress in large systems may be expected at smaller geographical scales such as subbasins. He does note that in the last several years, significant progress has been made in surmounting some of these obstacles, and the PNW region's water resources agencies at all levels of governance are making progress in addressing the fundamental challenges inherent in adapting to climate change. Thorpe and Stanley (2011) emphasize that restoration goals must focus on building resilient functioning ecosystems with the capacity to respond to climate change, rather than historical models. Two papers project stress on regional and urban water supplies (House-Peters and Chang 2011; Traynham et al. 2011). House-Peters and Change (2011) identify potential solutions through dense development in urban areas and tree planting. Koehn et al (2011) review the major impacts of climate change on fishes, and step through potential adaptation measures. Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment is a document produced by the NWF that provides an overview of species and ecosystem sensitivity, exposure, and vulnerability to climate change. They propose a systematic approach to evaluating risks and selecting conservation measures that most efficiently address those risks (Glick et al. 2011).

6.1 Human impact on stream temperature

A review paper (Hester and Doyle 2011) on human impacts on stream temperature describes the most common actions with thermal impacts and calculates the mean temperature change reported. The actions summarized are: loss of riparian shading, loss of upland forest, reductions of groundwater exchange, increased width-to-depth ratio, input of effluent discharges, diversion of tributary input, releases from below the thermocline of reservoirs, and global warming. Cold water reservoir releases in summer were the primary means of cooling streams, although diverting warm tributaries can also lower stream temperatures. Hester and Doyle (2011) also collected thermal performance curves for stream and river species. They summarized the amount of temperature change from the thermal optimum to 50% performance (growth, development, reproductive activity, or survival) both above and below the optimum. They found that most performance curves are asymetrical, and that most species are more sensitive to temperatures above the optimum (typical breadth from optimum to 50% for fish is about 4ºC above the optimum, and 6ºC below the optimum). Most human impacts shift temperature less than 5ºC, but reservoir releases, riparian shading and changes in groundwater exchange can change stream temperature up to 12-14ºC.

In a review of the impact of logging on stream temperature in the Oregon Coast Range, Groom et al (2011b) found that maximum, mean, minimum, and diel fluctuations in summer stream temperature increased with a reduction in shade, longer treatment reaches, and low gradient. Shade was best predicted by riparian basal area and tree height. In a separate paper, Groom et al (2011a) found that typical logging practices on private land generally caused streams to exceed water quality thresholds, but that recent management rules successfully lowered this probability greatly.

Some rivers have management options for lowering stream temperature over a short period of time, which can be crucial for preventing lethal temperatures for fish. For example, Lewiston Dam can release cold water into the Klamath; water can also be protected from withdrawals. These methods can be effective if they are timed precisely. A simulation study found short-term (7-10 day) water temperature forecasts prove useful for increasing fish production in the Klamath and John Day Rivers (Huang et al. 2011).

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