2.2 Habitat Conditions and Ecological Interactions Affecting Salmon & Steelhead

2.2.1 Climate Change and Ocean Conditions

2.2.1.1 2008 FCRPS BiOp and AMIP Methods:

The primary resource for evaluating effects of climate change on listed species was the ISAB (2007a) review. This was incorporated by reference and summarized in 2008 BiOp Sections 7.1.1, 7.1.2, and 8.1.3, and Section 5.7.3 of the SCA. Other references, particularly regarding El Niño and the Pacific Decadal Oscillation (PDO), and studies incorporating climate change into life-cycle modeling were also included in Sections 5.7.1 and 5.7.2 of the SCA, and Section 7.1.1 of the 2008 BiOp. RPA Actions related to climate change were summarized in 2008 BiOp Section 8.1.3. The AMIP included additional monitoring for climate effects, including development of a model that incorporates the latest climate change information, development of an annual report to review new climate change information relevant to listed species in the Columbia River basin, and enhanced population and habitat monitoring to detect effects of climate change. No additional climate change literature was cited in the AMIP.

2.2.1.2 2010 Voluntary Remand Methods:

As described in the introduction to Section 2, NOAA Fisheries released a list of references it was considering for the 2010 Remand to other parties in the NWF v NMFS litigation and to the ISAB. Citations from this process were included under several topics, with 191 listed under "Climate Change." In addition, NOAA Fisheries performed a literature search for climate change using two database search engines. The first was CSA Illumina, which searched Aquatic Sciences and Fisheries Abstracts, Oceanic Abstracts, Meteorological and Geoastrophysical Abstracts, Water Resources Abstracts, Conference Papers Index, and BioOne Abstracts and Indexes using the search term "(salmon OR steelhead OR Oncorhynchus) AND (climate OR temperature)" for all fields. A total of 1,020 citations from 2007-2010 were displayed and the titles and some abstracts were reviewed to reduce this list to the 139 documents (including several duplicates) on climate change that appeared most relevant to Columbia River basin salmon and steelhead. When it was noticed that some conservation biology journals were poorly represented in this search, a second search was performed using the ISI Web of Knowledge database search engine and the same search term. The most common journals displayed in the first literature search were excluded. The second search produced 875 documents, some of which were duplicates from the first search. Inspection of titles and abstracts, and in some cases full articles, led to an additional 50 citations that appeared most relevant to climate change impacts on Columbia River basin salmon and steelhead. The initial federal Climate Change Collaboration in the Pacific Northwest (C3) database and recommendations by NOAA Fisheries staff yielded additional citations of potential relevance.

NOAA Fisheries reviewed the collected citations on climate change to determine relevance to effects on listed Columbia River basin salmon and steelhead. New studies that specifically addressed climate observations and projections in the Columbia River basin and the California Current or biological effects of those observations and predictions to listed Columbia River basin salmon and steelhead were considered most relevant to this review. Studies from other regions or studies that focused on other species generally were considered less relevant. However, many of these studies were included in the review because they appeared to be representative of effects that may be experienced by Columbia River basin salmon and steelhead. After summarizing the new information, NOAA Fisheries determined whether it changed the way the 2008 BiOp considered effects of the RPA on listed species or their critical habitat or if it changed the discussion of adaptive management actions in the AMIP.

2.2.1.3 New Information Relevant to the 2008 FCRPS BiOp and AMIP

This section reviews new reports on the potential physical and biological effects of climate change on salmon in the Columbia River. The climate change summary can be found in section 2.2.1.4 and 2.2.1.5. In general this section covers:

- Recent observations and future expectation of physical effects of climate change in the Pacific Northwest (2.2.1.3.1)
- Observations and future expectations of biological effects of climate change in the Pacific Northwest (2.2.1.3.2)
- Effectiveness of climate change mitigation and adaptation actions (2.2.1.3.3)
- Monitoring climate change and species responses (2.2.1.3.4)

2.2.1.3.1 Recent Observations and Future Expectations of Physical Effects of Climate Change in the Pacific Northwest

2.2.1.3.1.1 Global Climate Projections

ISAB (2007a) relied upon global climate information and projections from the Intergovernmental Panel on Climate Change (IPCC 2007). There has not been a subsequent IPCC report with updated global projections.

2.2.1.3.1.2 Air and Stream Temperature

Approach in 2008 FCRPS BiOp and AMIP:

ISAB (2007a) and the 2008 BiOp (Section 7.1.1) noted that average air temperature has risen approximately 1ºC in the last century and is predicted to rise approximately 0.1-0.6ºC per decade. The 2008 BiOp also described Crozier et al. (2008a) estimates of summer stream temperature changes in the interior Columbia River basin, based on downscaled global climate model results.

New Information Relevant to the 2008 FCRPS BiOp and AMIP:

Northern hemisphere anomalies from NASA indicate that average northern hemisphere temperatures went down slightly in 2007-2008 compared to the previous three years, but were still approximately 0.8ºC higher than the 1951-1980 average[1]. Schwartz et al. (in press) found that global temperatures have risen only 40% as quickly as expected over the industrial era, indicating that significant uncertainties remain regarding the rate of future increases. Recent projections for future temperature changes in the Pacific Northwest remain 0.1-0.6ºC per decade (Mote and Salathe 2009) as described in the 2008 BiOp. More than 200 stations have been used to model stream temperature projections by basin for Washington State (Mantua et al. 2009a). Maximum weekly water temperatures are expected to increase generally <1ºC by 2020s, but 2-5ºC by the 2080s, such that >40% of stations (double the current number) in eastern Washington will exceed 21.5ºC, a critical threshold for juveniles, including much of the lower Columbia Basin. Thermal migration barriers in the Columbia, Yakima, and Snake Rivers of temperatures over 21ºC are predicted to increase in duration from 1-5 weeks in the 1980s, to 10-12 weeks by 2080s.

Kaushal et al. (2010) analyzed historical records from 40 sites throughout the US (none in the Columbia Basin) and found that 20 major streams and rivers have shown statistically significant, long-term warming. Annual mean water temperatures increased by 0.009–0.077°C per yr, and rates of warming were most rapid in, but not confined to, urbanizing areas. Long-term increases in stream water temperatures were typically correlated with increases in air temperatures.

2.2.1.3.1.3 Precipitation

ISAB (2007a) indicated an expectation of small changes in total precipitation, indistinguishable from natural variability until the late 21st century, but with more falling as rainfall than snowfall because of increased temperatures. Recent projections continue to indicate a small (+1-2%) expected change in total precipitation in the Pacific Northwest, although some models also predict an enhanced seasonal cycle with wetter autumns and drier summers (Mote and Salathe 2009).

2.2.1.3.1.4 Hydrology (Stream Flow) and Other Freshwater Predictions

Approach in 2008 FCRPS BiOp and AMIP:

ISAB (2007a) and the 2008 SCA (Section 5.7.3) indicated 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. The 2008 SCA also described Crozier et al. (2008a) estimates of late summer stream flow changes in the Salmon River basin, based on downscaled global climate model results.

[1] http://data.giss.nasa.gov/gistemp/tabledata/NH.Ts.txt

New Information Relevant to the 2008 FCRPS BiOp and AMIP:

Several papers have documented declines in snowpack over the 20th century. Stewart (2009) found that globally mid-elevation regions have reduced snowpack due to decreasing snow-to-rain ratios, but higher elevations have increased snowpack due to precipitation increases. Casola et al. (2009) attribute 8-16% of the decline in spring snow-water equivalent in the Cascades to global warming, and project another 11-21% by 2050. However, these projections are statistically indistinguishable from background variation with only 30 years of data. Mote et al. (2008a) found 15-35% declines since mid-century, and argue that a long-term effect of rising temperature is inevitable, but it is not yet possible to quantify exactly how much of the trend is due to anthropogenic effects. Stoelinga et al. (in press) assembled a longer dataset, back to the 1930s, and found that spring snowpack in the Cascades has declined 23%, which is nearly statistically significant. The recent decline since 1948 of 48% is significant, but is due largely to variation in the PDO. Importantly, the residual after correcting for the effect of the PDO, indicates a steady loss of 2%/decade, or 16% since 1930. Most snow (90%) now melts 5 days earlier than in the 1930s, but the trend is not significant. This model predicts that snowpack will decline 11% per degree rise in air temperature. Yarnell et al.(2010) presents a conceptual model of general effects of changes in snowmelt magnitude (mostly abiotic, channel effects) and timing (mostly biotic effects) vs the rate of change in both.

Corresponding changes in streamflow have also been observed. Kalra et al. (2008) found evidence of a step change in streamflow in the Pacific Northwest corresponding with the 1976/1977 regime shift in the PDO. Luce and Holden (2009) found that dry years (i.e., 25% flows) have been getting drier since 1948, although there has been no change in mean or median annual flow. Woo and Thorne (2008) determined that streamflow in the Pacific Northwest is more strongly correlated with decadal shifts (e.g., PDO) than with the long-term climate trend. Dai et al. (2009) found that annual discharge from the Columbia River exhibited a significant decrease in trend over time and claimed that year-to-year variability is related to ENSO-type events, and overall trends are consistent with widespread drying but are not necessarily due to human influence (i.e., water withdrawals). Van Kirk and Naman (2008) compared changes in Klamath base flows caused by climate vs water withdrawals and concluded that water withdrawals had a greater impact.

Predictive modeling of the effects of climate change are consistent in direction. Modeling by Hamlet and Lettenmaier (2007), Mantua et al. (2009a) and Elsner et al. (2009) project more winter flooding in transitional and rainfall-dominated basins, and historically transient runoff watersheds will experience lower late summer flows throughout Washington State. Mantua et al. (2009a) project a steady trend toward an entire loss of snowmelt-dominant basins in Washington State, and predict that only 10 basins will remain as transient between snowmelt and rainfall-dominated basins by 2080. The Columbia and Snake Basins are predicted to remain snowmelt dominant, but shift toward more transitional behavior (Elsner et al. 2009). April 1 snowpack is projected to decrease by 28% in Washington State by the 2020s (Elsner et al. 2009). Mastin (2008) modeled hydrology of the Yakima basin using two estimates of increased future air

temperatures. Lee et al. (2009) refined an existing optimization/simulation procedure for rebalancing flood control and refill objectives for the Columbia River Basin for anticipated global warming of 2ºC.

Numerous new analyses of projected changes in stream temperature and flow in the Columbia Basin either are or will soon be available. Detailed models of flow and temperature have been completed for specific salmon studies in small watersheds using the Distributed Hydrology Soil Vegetation Model (e.g., Battin et al. 2007). New analyses apply this model to various sites in the Wenatchee Basin and Salmon River Basin. A large new dataset with historical naturalized and projected future streamflows for the Columbia Basin is now available from the Climate Impacts Group on the Columbia Basin Climate Change Scenarios Project website[2]. This data set applies a new "hybrid delta" downscaling technique, which combines the advantages of the simple delta approach with the statistical controls of the Bias Corrected and Statistical Downscaling approach. A new dataset that models stream temperatures as well as flows throughout the range of Pacific salmon under various climate change scenarios is being prepared by Nate Mantua and colleagues for the Moore Foundation and the National Center for Ecological Analysis and Synthesis (NCEAS).

The Reservoir Management Joint Operating Committee (Bureau of Reclamation, Bonneville Power Administration (BPA), and U. S. Army Corps of Engineers (Corps)), in cooperation with the University of Washington Climate Impacts Group, has been developing climate and hydrology datasets to simulate effects of future climate on mainstem Snake and Columbia River hydrology. This research is scheduled for completion in 2010.

The National Science Foundation is also funding a major initiative for interdisciplinary study of water resources in Idaho, focusing on the Salmon River Basin and Snake River Plain. Research will include extensive hydrological, biological, economic and social modeling.

2.2.1.3.1.5 Pacific Decadal Oscillation (PDO)

Approach in 2008 FCRPS BiOp and AMIP:

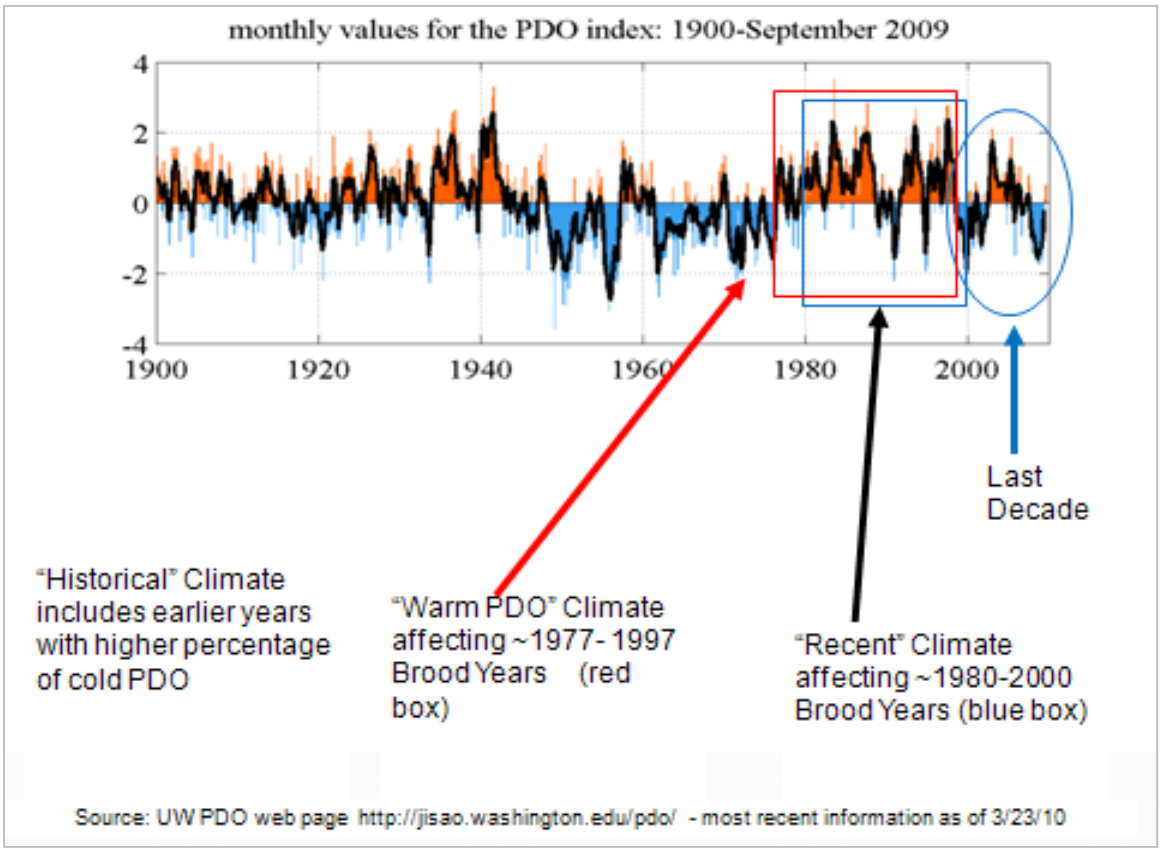
The PDO is a measure of north Pacific sea surface temperature variability, but the index is correlated with both terrestrial and oceanic climate effects. The 2008 SCA included a general discussion of the PDO in Section 5.7.2 and Figure 5.7.1-2 displayed a time series of estimates through Jan 2008. ISAB (2007a) also included a general discussion of PDO observations and stated that future effects of climate change in coastal ecosystems may be "similar or even more severe than those experienced during past periods of...warm PDO." The 2008 BiOp Section 7.1.1 referred to an e-mail from the ISAB chair clarifying that, in referring to general circulation models that predict increased global warming in the future, "We are not referring to regional models for ocean conditions in the Northeast Pacific that predict future conditions (5-10 years from now) such as the frequency and intensity of PDOs and ENSOs and coastal upwelling that

[2] www.hydro.washington.edu/2860/

will affect ocean survival of Columbia River salmonids. We are not aware of any such models." The Interior Columbia River Technical Recovery Team (ICTRT and Zabel 2007) and the 2008 BiOp considered three historical time periods with different average PDOs to reflect a reasonable bound on future climate conditions (see Section 2.2.1.3.2.7 for details).

New Information Relevant to the 2008 FCRPS BiOp and AMIP:

The most recent available information is displayed below. There has been a much larger percentage of cool PDO conditions (i.e., values less than zero in blue shading) during the last decade than occurred in either the "Recent" or "Warm PDO" periods used for modeling future ocean survival in the 2008 BiOp.



2.2.1.3.1.6 El Niño-Southern Oscillation (ENSO)

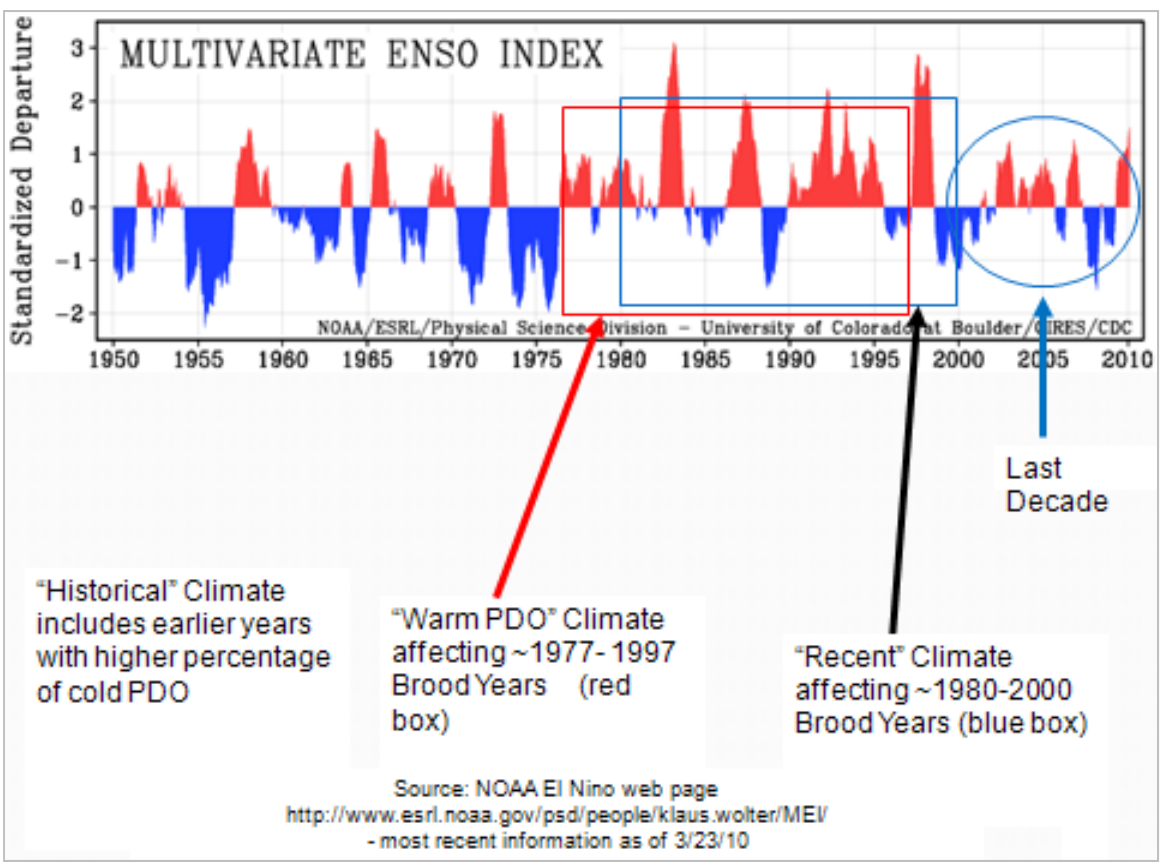
Approach in 2008 FCRPS BiOp and AMIP:

The Multivariate ENSO Index is a measure of differences in atmospheric pressure across the Pacific. El Niño conditions result in warm surface waters in the California Current and affect Pacific Northwest weather patterns. The 2008 SCA included a general discussion of the ENSO Index in Section 5.7.2 and Figure 5.7.1-1 displayed a time series of estimates through November 2007. ISAB (2007a) also included a general discussion of El Niño observations and stated that future effects of climate change in coastal ecosystems may be "similar or even more severe than those experienced during past periods of strong El Niño effects."

New Information Relevant to the 2008 FCRPS BiOp and AMIP:

The most recent available information is displayed below. An El Niño is currently occurring but is dissipating. El Niño conditions weakened during April 2010 and temperature anomalies decreased across the equatorial Pacific. According to NOAA's Climate Prediction Center's May 6, 2010 report, nearly all models predict decreasing sea surface temperature anomalies in the Niño-3.4 region through 2010, with an April-June transition followed by ENSO-neutral conditions through the end of 2010. Nearly a third of model predictions indicate the development of cold La Niña conditions later in the year[3].

El Niño conditions in the past decade (i.e., positive values and red shading in figure) have not been as strong as the El Niños that occurred in either the "Recent" or "Warm PDO" periods used for modeling future ocean survival in the 2008 BiOp. General circulation models still produce conflicting projections regarding whether increasing greenhouse gases will increase, decrease, or have no effect on ENSO patterns. Although none of the models have simulated so-called "tipping-point" behavior in this phenomenon, abrupt shifts in biological responses to incremental changes in ENSO have been observed, and cannot be ruled out (Latif and Keenlyside 2009). Yeh et al. (2009) found that El Niños have shifted in character in the late 20th century, such that Central Pacific El Niños have become more predominant than the classical Eastern Pacific El Niños. Their models predict that this trend will continue with climate change due to flattening of the thermocline.



2.2.1.3.1.7 Alaskan Gyre, North Pacific Gyre Oscillation (NPGO)

Approach in 2008 FCRPS BiOp and AMIP:

ISAB (2007a) generally discussed the effect of Alaskan gyre oscillations on Pacific Northwest salmon survival: strong Aleutian Low winters are favored during warm PDO and El Niño conditions.

New information relevant to the 2008 FCRPS BiOp and AMIP:

DiLorenzo et al. (2008) describe the North Pacific Gyre Oscillation (NPGO) as a climate pattern that emerges as the 2nd dominant mode of sea surface height variability in the Northeast Pacific. The NPGO tracks changes in strength of the central and eastern branches of the North Pacific gyres and of the Kuroshio-Oyashio Extension and is significantly correlated with previously unexplained fluctuations of salinity, nutrients and chlorophyll-a measured in long-term observations in the California Current and Gulf of Alaska. DiLorenzo et al. (2009) evaluated the long-term time series of upper ocean salinity and nutrients collected in the Alaskan Gyre along Line P and found significant decadal variations that are shown to be in phase with variations recorded in the Southern California Current System. The fact that large-amplitude, low-frequency fluctuations in salinity and nutrients are spatially phase-locked and correlated with a measurable climate index (the NPGO) open new avenues for exploring and predicting the effects of long term climate change on marine ecosystem dynamics.

2.2.1.3.1.8 Other Local and Regional Physical Indicators of Salmon Marine Survival in the California Current

Approach in 2008 FCRPS BiOp and AMIP:

ISAB (2007a) and the 2008 SCA (Section 5.7.3) generally discussed the importance of other ocean climate factors, such as coastal upwelling, and their importance to salmon survival and described possible effects of climate change on these factors.

New Information Relevant to the FCRPS BiOp and AMIP:

NOAA Fisheries' Northwest Fisheries Science Center established a web page that summarizes local and regional ocean conditions relevant to survival of listed, stream-type salmon (spring Chinook and coho), including sea surface temperature anomalies, coastal upwelling, timing of the physical spring transition, dissolved oxygen levels, and deep–water temperature and salinity[4]. Peterson et al. 2010 documents this information through 2009. Colder than normal surface temperatures off Oregon, which had been observed for the previous two years, switched to warmer than normal temperatures in the late summer and fall of 2009. Mote and Salathe (2009) estimate that by 2030-2059 Pacific Northwest ocean temperatures are expected to be 1.2C greater than the 1970-99 average. April observations off Oregon indicate that normal sea surface temperatures have returned in northern California current waters[5].

[4] http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/a-ecinhome.cfm
[5] http://coastwatch.pfel.noaa.gov/cgi-bin/elnino.cgi

Checkley and Barth (2009) reviewed forcing mechanisms for the California Current System (CCS), considered variability characteristic of the CCS, and concluded by considering future change. High surface production results in deep and bottom waters depleted in oxygen and enriched in carbon dioxide. Future climate change will differ from past change and thus prediction of the CCS requires an understanding of its dynamics. Of particular concern are changes in winds, stratification, and ocean chemistry.

Peterson et al. 2010 also noted that upwelling anomalies between May-September were generally positive between 2001-2006, but have been negative in 2007-2009. In 2009, this was a result of five makor events during which upwelling relaxed and warm water was transported onshore. Peterson et al. (2010) also noted that the spring transition to upwelling was later than normal in 2008 and 2009, following four years of earlier transitions. An early transition is associated with increased ecosystem productivity.

Rykaczewski and Checkley (2008) discuss mechanisms of upwelling that may be affected by climate change. Two atmospheric conditions induce different types of upwelling in coastal upwelling ecosystems: coastal, alongshore wind stress, resulting in rapid upwelling (with high vertical velocity, w); and wind-stress curl, resulting in slower upwelling (low w). The authors show that the level of wind-stress curl has increased and that production of Pacific sardine (*Sardinops sagax*) varies with wind-stress curl over the past six decades. The extent of isopycnal shoaling, nutricline depth, and chlorophyll concentration in the upper ocean also correlate positively with wind-stress curl.

2.2.1.3.1.9 Sea Level Height

Approach in 2008 FCRPS BiOp and AMIP:

Increasing sea level height was discussed generally in ISAB (2007a) and 2008 SCA (Section 5.7.3). ISAB (2007a) describes a predicted 0.18-0.59 m rise for the world ocean by the end of the 21st century.

New Information Relevant to the 2008 FCRPS BiOp and AMIP:

Mazzotti et al. (2008) found an average 1.8 mm/year rise in sea level height over the 20th century. They predict 20-38cm rises by 2100 at various locations including Seattle, Astoria, and Newport. Abeysirigunawardena and Walker (2008) described an annual average mean sea level trend of a 1.4 mm/yr increase in sea level height observed in British Columbia for the period (1939-2003), as opposed to a lower longer term trend. This suggests that a possible acceleration in sea level rise occurred during the latter half of the twentieth century. Sea level height in coastal areas of Washington state is now expected to be 0.35-0.55m higher by 2050 and 0.88-1.28 m higher by 2100, depending on location (Mote and Salathe 2009; Mote et al. 2008b). Glick et al. (2007) modeled sea level rise at several specific sites in Washington and Oregon using the Sea Level Affecting Marshes Model (SLAMM).

2.2.1.3.1.10 Ocean Acidification

Approach in 2008 FCRPS BiOp and AMIP:

Increasing acidification and decreased carbonate ion availability from the increasing concentration of CO2 dissolved in ocean waters was discussed generally in ISAB (2007a) and the 2008 SCA (Section 5.7.3).

New Information Relevant to the FCRPS BiOp and AMIP:

Since the start of the industrial revolution, the oceans have absorbed about a third of anthropogenic carbon dioxide emissions (Sabine et al. 2004). New information indicates that, globally, ocean pH has dropped about 0.1 due to ocean acidification (reviewed in Feely et al. 2008). Samples from the continental shelf of North America have confirmed this 0.1 pH drop (Feely et al. 2008; Hauri et al. 2009). Ocean acidification also decreases the amount of carbonate ions available to organisms that build calcium carbonate shells. The saturation state for one type of calcium carbonate widely used by marine organisms has decreased 0.5 in the California Current System (Hauri et al. 2009). Ocean acidification is expected to accelerate in the near-term future given continued carbon dioxide emissions (Byrne et al. 2010; Caldeira and Wickett 2003; Doney et al. 2009).

2.2.1.3.2 Recent Observations and Future Expectations of Biological Effects of Climate Change in the Pacific Northwest On Listed Columbia River Basin Salmon and Steelhead

2.2.1.3.2.1 Impacts of Climate Change on Salmon in Columbia Basin Tributaries (Spawning and Egg-to-Emergence Survival)

Approach in 2008 FCRPS BiOp and AMIP:

ISAB (2007a), summarized in the 2008 SCA (Section 5.7.3), noted that increased winter flooding can reduce egg survival, some redds might be dewatered, spawners may change to less productive timing or areas for spawning, there may be earlier fry emergence which may cause lower survival, there may be smaller fry size at emergence, and increased temperatures could cause direct egg mortality or susceptibility to disease.

New Information Relevant to the 2008 FCRPS BiOp and AMIP:

Spawner Distribution:

Geist et al. (2008) determined that chum salmon and fall Chinook spawning distribution below Bonneville Dam is influenced by hyporheic temperatures and gradients. Variability of temperature was increased by load-following (fluctuations in power production). Connor et al. (2003) found that Snake River fall Chinook egg development time was well-predicted by thermal units, and sites outside the current spawning distribution appeared limited by cold temperature. If cold winters are the primary limiting factor for these populations, new sites might become suitable with warmer winters. Angilletta et al. (2008) examined how dams changed thermal regimes on the Willamette, Rogue, and Cowlitz Rivers (cooler summer, warmer fall and winter),

and postulated that resultant changes in emergence time could drive evolution in spawn timing. Hanrahan (2008) found that variation in operations at Hells Canyon Dam had minimal impact on hydraulic and temperature gradients between the river and riverbed at nearby Snake River fall Chinook spawning sites.

Spawner Success:

Yates et al. (2008) determined that climate change will exacerbate effects of warm temperatures on poor spawning success in the Sacramento River, but reservoirs such as Shasta provide a cool-water pool through the summer that may help counter this effect.

Methods for Assessing Climate Change:

Groves et al. (2008) found that surface water temperature predicts intra-redd temperatures for salmon embryo developmental timing in the Snake River, facilitating models of development time and potential spawning distribution.

2.2.1.3.2.2 Impacts of Climate Change on Salmon in Columbia Basin Tributaries (Fry-Smolt Rearing)

Approach in 2008 FCRPS BiOp and AMIP:

ISAB (2007a), summarized in the 2008 SCA (Section 5.7.3), noted that reduced flows may impact quality and quantity of rearing habitat, strand fish, or make fish more susceptible to predation. Warmer spring-fall temps may reduce quality and quantity of rearing habitat, cause a reduction in size (hence survival) if habitats are food-limited or an increase in size if habitats are not food-limited, and increase predation rates. In colder high-elevation streams, higher temperatures may be beneficial and result in larger fish. Higher winter temperatures may increase fish size and survival, but may also increase predation rates. Higher winter flows are likely to increase mortality if winter flood refuge habitat is not available.

Crozier et al. (2008a; 7-14, 2008 SCA) predicted an 18-34% decline in parr-smolt survival of SR spring/summer Chinook populations by 2040. This information was not used to adjust quantitative 2008 BiOp metrics because the time period was outside that of 2008 BiOp, there was uncertainty about direct comparison to the 2008 BiOp base condition, and uncertainty about the way to treat partial density-dependent compensation described by Crozier et al. (2008a).

<u>New Information Relevant to the 2008 FCRPS BiOp and AMIP:</u>

Survival:

Geist et al. (2010) described mainstem temperature tolerances of juvenile Snake River fall Chinook, finding high survival over 30 days at constant temperatures up to 22ºC, and moderately high survival (83-88% over 30 days) when daily maximum temperatures reached 27ºC.

Growth:

Crozier et al. (2010) found positive effects of warmer temperatures on parr growth in Salmon River Basin Chinook at low fish densities, but the effect reversed at higher densities. Boughton et al. (2007) found negative effects of warm temperatures on growth in California steelhead in field enclosures, and an interaction with food availability, although in some analyses these

effects were not significant. Rundio and Lindley (2008) found that, unlike many temperate streams where terrestrial inputs provide an alternate prey source when aquatic invertebrate abundance is low, terrestrial inputs to two California streams with Mediterranean climate apparently provide a year-round additional source of prey. The terrestrial prey (like aquatic prey) peaks when water temperature is warmest and hence when fish growth potential is high. Beauchamp (2009) analyzed the bioenergetics of allometric relationships between fish size, temperature, and ration, and found that smaller fish have higher optimal and maximum temperatures for growth relative to larger fish, and that improving food quality (composite energy density) can raise the optimal temperature for growth. Beauchamp concluded that juveniles are more likely to be limited by prey quality and quantity than temperature directly, whereas adults will be more sensitive to temperature change. McCarthy et al. (2009) predicted decreased steelhead growth rate in the Trinity River under three climate scenarios based on bioenergetic analyses.

Behavior:

Spina (2007) showed that California steelhead occupy relatively hot pools and remain active over summer. Apparently thermal refugia cannot be found or are not available.

Disease:

Dionne et al. (2007) found that among Atlantic salmon in eastern Canada along 12º of latitude, allelic diversity within the Major Histocompatibility Complex is correlated with pathogen and bacterial diversity, which in turn is correlated with thermal regimes. Thus warmer temperatures are associated with more diverse and virulent pathogen communities, which in turn has presumably selected for greater immune resistance. Bowden (2008) found that an increase in temperature, salinity, pH, particulates, oxygen and light increases immune function. Kocan et al. (2009) found that swimming stamina was reduced above 15ºC in rainbow trout exposed to ichthyophoniasis infection, and argue that the high migration mortality observed in Yukon River Chinook might be caused by this interaction between disease and high temperature exposure.

2.2.1.3.2.3 Impacts of Climate Changes on Multiple Life Stages in Tributaries

New Information Relevant to the 2008 FCRPS BiOp and AMIP

Nelitz et al. (2009) modeled climate change impacts on potential Chinook habitat in the Cariboo-Chilcotin region of southern British Columbia. They generated climate change scenarios by inputting downscaled temperature and precipitation projections into a hydrological model, and classifying historic and future potential habitat using temperature and flow criteria, as well as other habitat criteria, such as access barriers, channel characteristics, etc. They found that habitat suitability is likely to decrease due to rising temperatures and decreasing flow in the northeastern portion of the study region, but increase in the southern section, where certain areas are currently considered too cold for Chinook. Although the results are site-specific, the methods are relevant to studies in the Columbia Basin.

Some ongoing studies of tributary restoration and recovery potential are also of interest. NWFSC staff (T.Cooney and D. Holzer) are working with R. Carmichael (Oregon Department of Fish and Wildlife) to develop maps of vulnerability to climate change for interior Columbia

steelhead populations. Cooney and Holzer have developed relatively simple models to relate summer stream temperatures in steelhead rearing habitats to projections based on the general climate change models. Carmichael has adapted available regional assessments of stream flow characteristics to incorporate into the assessment. The combined analyses will be used to identify sensitivity of recovery strategies to current climate model projections, highlight watersheds within each population that are particularly vulnerable, and compare these with recovery strategies.

Christine Petersen with the Moore Foundation/ NCEAS workgroup is working on population viability analyses of the Wenatchee Basin and the Grande Ronde Basin, identifying critical life history stages threatened by climate change. Preliminary results suggest that for Wenatchee Basin Chinook, mainstem Columbia summer temperatures are likely to have negative impacts on summer runs, although probably not in the next 25 years, whereas spawning habitat is more likely to constrain some spring Chinook populations. For Grande Ronde populations, thermally suitable summer holding areas may already be limiting population recovery, and this constraint will intensify with warmer temperatures.

Tributary Habitat Effects:

Dunham et al. (2007) showed that physical stream habitats can remain altered (for example, increased temperature) for many years following wildfire, which is predicted to increase with climate change, but native aquatic vertebrates can be resilient. Pollock et al. (2009) showed that stream temperatures are significantly correlated with the percent of harvest in watersheds.

Thermal Refugia for Multiple Life Stages:

Reid (2007) described thermal refugia for adult spring Chinook and juvenile Chinook and steelhead in the Rogue River. Refugia were approximately 2° C cooler than adjacent areas and current levels of motor boat activity had minor effects on water temperature, fish behavior, and fish metabolism.

Effects of Temperature on Population Distribution:

Lindley et al. (2007) used results of downscaled global climate models, linked to a regional hydrologic model, to predict that the forecast rise in summer stream temperatures may allow spring-run Chinook salmon to persist in some California streams, but make other areas unsuitable. At the upper end of predictions, very little spring-run Chinook habitat is expected to remain suitable.

2.2.1.3.2.4 Impacts of Climate Change on Mainstem Juvenile Migrations and Mainstem Spawning

Approach in 2008 FCRPS BiOp and AMIP:

ISAB (2007a), summarized in the 2008 SCA (Section 5.7.3), noted that fall Chinook and chum salmon will have similar egg-fry effects in the mainstem as described above for warmer, low-elevation, streams. Yearling smolts may reach the estuary earlier because of high spring flows and warm temperatures and there may be mismatch with ocean conditions and predators. Higher temperatures may cause earlier migration (which could be an advantage or disadvantage), may

cause higher predation rates, and may cause higher mortality of reservoir-type SR fall Chinook. Warm temperatures may favor food competitors of juvenile fall Chinook, such as American shad. Higher temperatures also stress fish so that they are more susceptible to disease and infection from pathogens. Reduced flow in the late spring and summer may lead to delayed migration of fall Chinook smolts, higher predation in dam forebays, and changes in vertical distribution that could lead to reduced dam passage survival.

New Information Relevant to the 2008 FCRPS BiOp and AMIP:

Genetics and Life History Strategy:
Williams et al. (2008) document a potential evolutionary adaptation to the altered thermal regime and reservoirs created by Snake River dams. Currently, nearly half of returning SR fall Chinook adults employed a yearling juvenile residence pattern, which differs from dominant historical pattern of subyearling migration. Models indicate that this shift is due to thermal changes caused by dams.

Juvenile Migration Timing and Triggers:
Achord et al. (2007) found earlier smolting of SR Chinook in warmer years. Sykes et al. (2009) found similar patterns among Chinook from Central British Columbia. Sykes and Shrimpton (2010) clarified experimentally that temperature and photoperiod trigger smolting.

Juvenile Migration Survival:
Zabel et al. (2008) found lower migration survival at temperatures over 13ºC for both Chinook and steelhead, in addition to flow effects.

2.2.1.3.2.5 Impacts of Climate Change on Mainstem Adult Migrations

Approach in 2008 FCRPS BiOp and AMIP:

ISAB (2007a), summarized in the 2008 SCA (Section 5.7.3), noted that higher temperatures may increase mortality or reduce spawning success through direct mortality at lethal temperatures, delayed migration or delay entering fish ladders, increased fallback past dams, and loss of energy reserves because of increased metabolism. Higher temperatures may also cause higher mortality or reduced spawning success due to susceptibility to disease and pathogens.

New Information Relevant to the 2008 FCRPS BiOp and AMIP:

Adult Migration Survival:
Keefer et al. (2008a) and Fryer (2007, 2008, 2009) found that late-migrating Columbia sockeye are less likely to survive migration than early-migrating fish due most likely to high river temperatures. Mann (2007) found low migration success in Chinook exposed to the highest temperatures (sometimes >23ºC). Keefer et al. (2009) show that steelhead that migrate during high temperature periods are 8% less likely to successfully home to natal tributaries, but suggest it is likely due to high harvest in thermal refugia in the lower Columbia River tributaries, rather than direct exposure to high temperatures. The latest migrants are more likely to overwinter in the hydrosystem (Keefer et al. 2008b), where they have higher survival than in tributaries. The timing and location of harvest thus has a very strong impact on the utility of thermal refugia.

Clabough et al. (2008) quantified the actual temperatures experienced by salmon and steelhead at Columbia and Snake River dams and found that summer and fall Chinook and steelhead frequently encounter stressful temperatures (>20ºC). Wood et al. (2008) analyzed the evolutionary history of major sockeye ecotypes, arguing that climate change likely will put the anadromous types at greatest risk because of increased river temperatures experienced during migration.

Mann et al. (2008) described the influence of sublethal temperatures on spawning success. SR fall Chinook and SR steelhead exposed to the highest temperatures during migration had the lowest embryo viability. There is evidence, however, that adult Chinook and steelhead use cooler water within the Lower Granite Reservoir that comes from releases from Dworshak to lower their body temperatures (Clabough et al. 2006)

Physiological Effects of High Temperatures on Adult Migration:

Recent studies have elucidated mechanisms by which high temperature lowers survival of adult salmonids. Farrell et al. (2008) and Farrell (2009) show aerobic scope varies among populations as a function of migration temperature, with unusually high temperatures for a given population resulting in collapse of aerobic scope. A model of aerobic scope vs. temperature successfully predicts the collapse of Fraser sockeye in 2004. Crossin et al. (2008) and Steinhausen et al. (2008) conducted physiological studies to elucidate mechanisms of high adult mortality during high temperature events in Fraser River sockeye salmon.

Timing of Adult Migrations:

Keefer et al. (2008c) found that different Chinook salmon populations in the Columbia River migrate in a consistent order each year. Annual variation in timing reflects earlier migration in years of low flow or high temperature, with secondary effects of ocean conditions, as characterized by the PDO and North Pacific Index. Quinn et al. (2007a) described a shift to earlier adult sockeye migration in Alaska that was correlated with fishing pressure selection, not temperature. Crozier et al. (2008b and in prep) show advancing migration timing in Columbia River Basin spring/summer Chinook and sockeye salmon, and later migration in fall Chinook, consistent with adaptation to avoid high temperatures. Using genetic data on fitness, Ford and Ellis (2006) showed selection for an earlier optimum migration timing compared with the historical timing in a coastal population of coho. However, this population is currently migrating earlier than the optimum due to hatchery selection.

Prespawn mortality:

Quinn et al. (2007b) showed that pre-spawning mortality in some Alaskan sockeye salmon populations correlated with both density and warm temperature (average August daily maximum up to 20.6ºC) in holding habitat. Keefer et al. (in press) found that Chinook transported to potential spawning habitat above dams in the Willamette River basin had much higher prespawn mortality (up to 93%) when released during higher temperature periods (mean July and August temperatures at some locations exceeded 22ºC). Mann (2007) observed a correlation between pre-spawn mortality and daily temperature fluctuations in summer Chinook that spawn in the South Fork of the Salmon River Basin in 2003.

2.2.1.3.2.6 Impacts of Climate Change on Estuary Migration and Rearing

Approach in 2008 FCRPS BiOp and AMIP:

ISAB (2007a), summarized in the 2008 SCA (Section 5.7.3), noted that there may be physiological effects of warmer waters in shallow estuary habitats, including changes in growth, disease susceptibility, direct lethal or sublethal effects. Arrival and residence time of adults and juveniles may be altered, predator community structure may change, there may be reduced shallow habitat in spring and increased habitat in fall/winter, and a possible decrease in upriver detritus input to the estuary food chain. Sea level height increase and storm surges could change effectiveness of restoration actions such as dike breaching and culvert placements.

New Information Relevant to the 2008 FCRPS BiOp and AMIP:

The Estuary chapter describes new information about the Columbia River estuary. Although most of the studies do not directly address climate change the new information about fish behavior, habitat use and survival have implications relative to climate change factors such as sea level height. Additionally, that section reviews information regarding effectiveness of mitigation actions and concludes that reconnecting shallow water estuarine habitat to cold water refugia is expected to protect juveniles against expected impacts of climate change.

2.2.1.3.2.7 Impacts of Climate Change on Survival in the Oceans

Approach in 2008 FCRPS BiOp and AMIP:

ISAB (2007a), summarized in the 2008 SCA (Section 5.7.3), noted that if the regional impacts of global warming are expressed in El Niño-like and warm PDO-like ways, there is likely to be decreased production of salmon in the Pacific Northwest. Warming increases stratification which results in decreased primary production and abundance of zooplankton. Peak upwelling may be delayed, causing a mismatch with timing of salmon ocean entry. O_2 content of upwelled waters may decline, reducing productivity. Global warming may change coastal wind patterns, resulting in hypoxic areas on the Oregon and Washington shelf that affect salmon prey. Ocean acidification may reduce some types of salmon prey. Ocean warming may change migration patterns, increasing migration distances to feeding areas. Higher temperatures may increase metabolism, reducing growth if food is limited and possibly changing maturation rates.
The 2008 BiOp also described the ICTRT's simulation of ocean survival under three possible future climate conditions for recovery planning purposes (ICTRT 2007; ICTRT and Zabel 2007). The three future scenarios represented ocean conditions experienced by 1978-1999 complete brood cycles ["recent"; also representing 1980-2001 outmigration years], 1975-1997 brood years ["warm PDO"], and approximately 1937-1997 brood years ["historical"; first year varies by availability of specific index data]. The 2008 BiOp explicitly modeled these future climate scenarios and the results were considered in the 2008 BiOp. The "warm PDO" assumption reduced survival by 2-12%, compared to the "recent" assumption, depending upon species. The "historical" assumption increased survival by 11-44%.

New Information Relevant to the 2008 FCRPS BiOp and AMIP:

Effects of juvenile migration conditions on ocean survival:
Scheuerell et al. (2009) studied predictors of smolt to adult return rate as a function of juvenile migration conditions and timing, finding that generally early arrival at Bonneville Dam and cooler river temperatures were better for marine survival, but the optimal arrival date varied by year. Ongoing studies are working to tease apart potential mechanisms driving the day and year effects.

Forecasts of Marine Survival:
The NWFSC's webpage[6] summarizes local and regional ocean conditions (Section 2.2.1.3.1.8) and biological factors indicative of marine salmon survival. Peterson et al. (2010) documents this information through 2009 and includes predictions for coho and Chinook salmon. Local and regional biological information affecting salmon survival includes copepod biodiversity, the prevalence of highly nutritious copepod species vs. less nutritious warm-water species, indices of the prey community and the biological spring transition to the summer copepod community and catches of yearling Chinook and coho salmon in ocean surveys. The combination of physical and biological indicators in 2008 were the highest of the 12 years surveyed, indicating high ocean survival of juvenile Chinook that entered the ocean that year and which will mainly return to spawn in 2010. Ocean conditions in 2009 were the 6th best of the 12 years surveyed, suggesting intermediate returns in 2011.

Marine migration behavior and survival:
Weitkamp (2010) noted that Chinook ocean migration patterns appear very stable between years despite wide variation in ocean conditions. Teo et al. (2009), contrary to other studies, did not find an inverse survival relationship between Alaska and California Current hatchery coho salmon. Chittenden et al. (2009) reviewed current knowledge on the relationship between climate and salmon, and emphasize the importance of modern technology, especially acoustic and physiological and environmental monitoring tags for improving our understanding of the effects of environmental change on salmon survival and behavior.

Marine Growth:
Wells et al. (2007, 2008) found that growth during ocean residence of a northern California Chinook population was negatively correlated with summer sea surface temperature and other factors indicative of a strong and productive California Current. Growth of Alaska Chinook populations was positively correlated with winter sea surface temperature and other factors indicative of a strong and productive Alaska Current. Puget Sound Chinook grew best in conditions in which the transition zone was dominated by neither the Alaska Current nor California Current.

Ocean Acidification:
Understanding the impact of ocean acidification on marine organisms is still in its infancy. At least one study that has tested the response of a salmonid, *Salmo salar*, to ocean acidification (Fivelstad et al. 1998). In this study, post-smolts exposed to pH of 7.0 for 41 days did not differ

[6] http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/a-ecinhome.cfm

from the control group in their mortality, growth, condition, metabolism, or plasma pH, hematocrit, sodium, or chloride. Work on another fish species has found that ocean acidification impairs olfactory ability (Dixson et al. 2010; Munday et al. 2009). Should this olfactory impairment occur in salmon, it could impact their ability to home to their natal river networks and avoid swimming predators. Ocean acidification is likely to impact salmon via trophic interactions. Experimental work has shown that many invertebrate species on which salmon prey (e.g., pteropods, euphausiids, copepods) suffer direct effects of ocean acidification on development, calcification, and mortality (Comeau et al. 2009; Dupont and Thorndyke 2009; Kurihara 2008; Kurihara et al. 2004a; Kurihara et al. 2004b; Mayor et al. 2007; Nicol 2008; Orr et al. 2005). Brodeur et al. (2007) noted that pteropods and copepods were important prey of juvenile coho salmon in the northern California current during weak upwelling or El Niño years.

Patterns in Plankton:

Coyle et al. (2008) argue that if climate on the Bering Sea shelf continues to warm, the zooplankton community may shift from large to small taxa which could strongly impact apex predators and the economies they support. Moran et al. (2010) found a strong relationship between temperature and phytoplankton body size in the North Atlantic, which is consistent with common ecological relationships between temperature, body size, and population abundance. They predict a gradual shift towards smaller primary producers as temperatures warm. Mackas et al. (2007) analyzed variation in plankton in the North Pacific from 1979-2004. They found that under warm conditions, copepod distributions shift northward and life cycle timing of *Neocalanus plumchrus* is advanced by several weeks. They caution that with consistent warming, life cycle events might become mismatched with food supply. Johannessen and Macdonald (2009) review potential risks of climate change combined with other anthropogenic stressors for the Strait of Georgia ecosystem.

Trophic interactions:

Ocean predators such as Pacific hake, jack and chub mackerel, are more abundant in the Pacific Northwest in warmer years (Emmett et al. 2006), which might lower salmon survival (Emmett and Sampson 2007). Emmett and Sampson (2007) found that the abundance of Pacific hake and forage fish, combined with Columbia River flows and possibly ocean turbidity can explain much of the annual variation in marine survival of fall Chinook and coho, but that sea surface temperature upon ocean entry is the best predictor of survival in spring/summer Chinook salmon. Okey et al. (2007) suggest that warmer temperatures might have favored salmon shark along the Alaska coast, increasing their predation of salmon. However, many of these species interactions are not well understood and predicting effects with climate change remains speculative.

Life-history comparisons:

Yatsu et al. (2008) compare population-dynamic responses to climate of five marine species with contrasting life-history characteristics. Marine climatic regime shifts may influence recruitment by changing local environmental conditions, phenological shifts in zooplankton life-history, and stochastic episodic events in both top-down and bottom-up processes. Species differed in the direction, extent and timing of their response, implying very individualistic responses to climate change. Fisher et al. (2007) reviewed information on the first-year ocean distribution of salmon

and note that different species go to different places (e.g., ocean-type Chinook are more coastal while steelhead are further offshore), which would lead to an expectation of different effects of ocean climate change on different species.

Carrying Capacity:

Mantua et al. (2009b) describe life-cycle modeling results that represent interactions among salmon stocks, including wild versus hatchery. They conclude that models that contained density-dependent interactions in the ocean fit the historical data better, indicating the existence of an ocean carrying capacity, particularly in the North Pacific. Kaeriyama et al. (2009) found that large-scale climate forcing such as the PDO can influence carrying capacity of the North Pacific for some species of salmon.

2.2.1.3.2.8 Impacts of Climate Change on Multiple Life Stages

New Information Relevant to the 2008 FCRPS BiOp and AMIP:

Evolutionary responses to climate change:

Because environmental conditions have such a profound effect on fitness, in response to climate change salmon will either evolve, modify traits by phenotypic plasticity, shift their geographic range or go extinct. Although phenotypic plasticity is well documented in Pacific salmon (e.g., Beckman and Dickhoff 1998), its limits are not. Similarly, Pacific salmon have been shown to have a heritable component to the expression of many life history traits (reviewed by Carlson and Seamons, 2008). However, we lack a general understanding of how rapidly and under what conditions, evolutionary change can be expected to occur. Conover et al. (2009) found that environmental and genetic influences may work together to accentuate phenotypic adaptations or may cancel each other out to reduce adaptations. Orr and Unckless (2008) examined the response of populations to sudden shifts in climate and, based on theoretical models, concluded that it will be difficult for populations to adapt to sudden changes in the environment via the mechanism of mutations at single or few loci. However, they note that these conclusions may be somewhat limited because they do not consider the possibility of mutations at multiple loci. In general, the larger the effective population size and the larger the number of loci that can mutate, the greater the capacity of a population to adapt to sudden environmental changes. Waples et al. (2008) document the diverse ways in which the hydropower system has changed the selective pressures on Columbia River salmon. Many of these changes are similar in direction and sometimes larger in magnitude than near-term changes imposed by climate change (e.g., reduction in magnitude and earlier peak flows). Crozier et al. (2008b) reviewed potential evolutionary and plastic responses to climate change in different life history stages. Although climate change might produce conflicting selection pressures in different life stages, most of the expected plastic responses to climate change are likely to be adaptive, and reduce the demographic cost of selection on salmon. Importantly, some anthropogenic impacts impose selection in the opposite direction as climate change (e.g., hatchery selection for earlier spawning when later spawning would be adaptive in a warmer climate, Quinn et al. 2002). Morbey and Hendry (2008) and Beechie et al. (2008a) describe diversity in salmonid life history, morphology and behavior, which reflects adaptations to spawning habitats and review these adaptations.

Changing climate might cause a mismatch between local adaptations and environmental conditions.

Survival Patterns and Climate Effects:
McKinnell (2008) determined that the main factors explaining lowered Fraser River sockeye productivity since 1989 occurred in freshwater habitat, including density-dependent fecundity, and that climate is of lesser importance. They also found that stormier winters (more intense winter Aleutian lows) are associated with lower productivity rather than higher productivity, contradicting previous studies.

Sublethal temperature effects:
McCullough et al. (2009) reviewed new thermal research and found that recent studies move away from evaluating lethal tolerances to more emphasis on growth, disease, gene expression, etc. Noyes et al. (2009) found that elevated water temperatures may alter the biotransformation of contaminants to more bioactive metabolites and impair homeostasis.

Invasive species:
Please see the chapter on non-indigenous fishes (Section 2.2.5.2) for additional information. Several major native (e.g., pikeminnow) and non-native (e.g., smallmouth and largemouth bass, Channel catfish, walleye) predators of salmon in the Columbia River are currently limited by cool temperatures (Sanderson et al. 2009a), and are likely to expand geographically (Sharma et al. 2009a; Sharma and Jackson 2008; Sharma et al. 2009b; Sharma et al. 2007) or increase their predation rates within their current distribution as water temperatures warm. For example, Channel catfish require spawning temperatures above 21ºC (Sanderson et al. 2009a), so potential spawning areas could increase as more of the Columbia Basin exceeds this threshold. Bass are more active when temperatures exceed 15ºC (Tabor et al. 2007), so predation rates tend to rise in this range. Rahel and Olden (2008) list numerous mechanisms and processes by which climate change might increase threats from invasive species, including advantages from altered flow or thermal regimes, loss of ice cover for native fish, increased salinity, and anthropogenic activities in the water. Not all invasive species will benefit from climate change, but a few can be extremely influential.

2.2.1.3.3 Effectiveness of Climate Change Mitigation and Adaptation Actions

Approach in 2008 FCRPS BiOp and AMIP:

The 2008 BiOp, Section 8.1.3 included mitigation options for various life stages that were recommended by ISAB (2007a). These ISAB recommendations include:

Planning Actions

1. Assessing potential climate change impacts in each subbasin and developing a strategy to address these concerns should be a requirement in subbasin plan updates. Providing technical assistance to planners in addressing climate change may help ensure that this issue is addressed thoroughly and consistently in the subbasin plans.

2. Tools and climate change projections that will aid planners in assessing subbasin impacts of climate change are becoming more available. Of particular interest for the Columbia Basin is an online climate change streamflow scenario tool that is designed to evaluate vulnerability to climate change for watersheds in the Columbia Basin. Models like this one can be used by planners to identify sensitivities to climate change and develop restoration activities to address these issues.

3. Locations that are likely to be sensitive to climate change and have high ecological value would be appropriate places to establish reserves through purchase of land or conservation easements. Landscape-scale considerations will be critical in choice of reserve sites, as habitat fragmentation and changes of habitat will influence the ability of such reserves to support particular biota in the future. These types of efforts are already climate change concerns.

Tributary Habitat

1. Minimize temperature increases in tributaries by implementing measures to retain shade along stream channels and augment summer flow
   - Protect or restore riparian buffers, particularly in headwater tributaries that function as thermal refugia
   - Remove barriers to fish passage into thermal refugia
2. Manage water withdrawals to maintain as high a summer flow as possible to help alleviate both elevated temperatures and low stream flows during summer and autumn
   - Buy or lease water rights
   - Increase efficiency of diversions
3. Protect and restore wetlands, floodplains, or other landscape features that store water to provide some mitigation for declining summer flow
   - Identify cool-water refugia (watersheds with extensive groundwater reservoirs)
   - Protect these groundwater systems and restore them where possible
   - May include tributaries functioning as cool-water refugia along the mainstem Columbia where migrating adults congregate
   - Maintain hydrological connectivity from headwaters to sea

Mainstem and Estuary Habitat

Remove dikes to open backwater, slough, and other off-channel habitat to increase flow through these areas and encourage increased hyporheic flow to cool temperatures and create thermal refugia

Mainstem Hydropower

1. Augment flow from cool/cold water storage reservoirs to reduce water temperatures or create cool water refugia in mainstem reservoirs and the estuary
   - May require increasing storage reservoirs, but must be cautious with this strategy
   - Seasonal flow strategy
2. Use of removable spillway weirs (RSW) to move fish quickly through warm forebays and past predators in the forebays.
   - Target juvenile fall Chinook salmon
3. Reduce water temperatures in adult fish ladders
   - Use water drawn from lower cool strata of forebay
   - Cover ladders to provide shade
4. Transportation
   - Develop temperature criteria for initiating full transportation of juvenile fall Chinook salmon
   - Explore the possibility of transporting adults through the lower Snake River when temperatures reach near-lethal limits in later summer
   - Control transportation or in-river migration of juveniles so that ocean entry coincides with favorable environmental conditions
5. Reduce predation by introduced piscivorous species (e.g., smallmouth bass, walleye, and channel fish) in mainstem reservoirs and the estuary

Harvest

1. Harvest managers need to adopt near-and long-term assessments that consider changing climate in setting annual quotas and harvest limits
   - Reduce harvest during favorable climate conditions to allow stocks that are consistently below sustainable levels during poor phase ocean conditions to recover their numbers and recolonize areas of freshwater habitat

- Use stock identification to target hatchery stocks or robust wild stocks, especially when ocean conditions are not favorable

Hatcheries

- Control juvenile migration to ensure that ocean entry coincides with favorable ocean conditions

Those ISAB recommendations that were incorporated into the RPA are described in the same section. Section 7.1.2.1 in the 2008 BiOp explains that the degree to which the RPA incorporates ISAB recommendations is one of the factors upon which the RPA was evaluated. The 2008 BiOp also described the work of Battin et al. (2007), which looked at effectiveness of different restoration actions in face of climate change in Puget Sound.

New Information Relevant to the 2008 FCRPS BiOp and AMIP:

Appropriate Management Responses to Climate Change:
Waples et al. (2009) report that over the past two centuries, anthropogenic changes to salmon ecosystems have altered disturbance regimes outside the range of the historical template, so resilience of salmon populations might be compromised. The authors discuss appropriate management responses such as actions that release constraints on processes that sustain habitat diversity, actions that attenuate anthropogenically exaggerated disturbance regimes and reduce the frequency of high mortality events, and actions that restore emigration pathways to historical habitats to increase the diversity of habitats available to salmon. These are consistent with adaptation recommendations for a variety of taxa. For example, Mawdsley et al. (2009) reviewed 16 broad adaptation strategies for climate change, applicable to a range of species.

A number of studies have recommended responses to climate change in tributary salmonid habitat. Bisson (2008) is a web site that reviews recent literature and makes the following management recommendations for responding to climate change in aquatic environments: maintain river flow in low flow periods; maintain floodplain connections; maintaining habitat connections among suitable habitat sites; protect and enhance riparian forests. Forest management recommendations from Bisson (2008) include: minimizing anthropogenic increases in water temperature by maintaining well-shaded riparian areas; maintaining a forest stand structure that retains snow, reduces the "rain on snow" effect associated with forest openings, and promotes fog drip; disconnecting road drainage from the stream network to soften discharge peaks during heavy rainstorms; ensuring that fish have access to seasonal habitats, e.g., off-channel wintering areas or summer thermal refugia; and protecting springs and large groundwater seeps from development and water removal, as these subterranean water sources will become increasingly important when surface flows are altered by climate change. Bisson et al. (2009) provide similar advice on restoration approaches to maintain natural diversity and resilience to factors such as climate change.

Ward et al. (2008a) found that effects of watershed restoration on salmonid populations were detectable in the Keogh River basin of British Columbia. The authors conclude that habitat restoration may help salmon respond to climate shifts. Jorgensen et al. (2009) found that prespawning and incubation stream temperatures were especially sensitive to total forest cover, impervious surface area, and mean annual precipitation in the Wenatchee River Basin. The percent of fine sediment in the water was also sensitive to precipitation, and had the greatest role in population declines. Thus restoration actions focusing on improving forest cover and impervious area produced the greatest increase (or prevented the greatest loss) in population productivity (Honea et al. 2009).

Schindler and Rogers (2009) recommended preserving life-history diversity within and among populations to respond to enhanced juvenile growth and accelerated juvenile life histories in response to warming water temperature.

Palmer et al. (2008, 2009) reviewed climate effects on freshwater ecosystems, projected changes in river flow under various climate change scenarios, and determined that impounded rivers will be impacted more than free-flowing ones. Parts of the Columbia River basin will probably need intervention in the future. Suggested actions in the mainstem and tributaries include: stormwater and sediment management, channel reconfiguration, dam removal/retrofit, floodplain restoration, water-quality management, groundwater/surface-water management, enhanced fish passage, flow modification, bank stabilization, riparian management, and in-stream habitat improvements.

Schindler et al. (2008) note that there is considerable uncertainty in predicting climate change effects on salmon, so an appropriate management response, similar to those in the studies cited above, is needed. Lawler et al. (2010) discuss strategies for management under uncertain future climate. Their main recommendations for making salmon populations more resilient to climate change are to: 1) develop adaptive management plans with prescribed alternative strategies; 2) implement actions to remove other threats to populations, such as removing non-indigenous species and maintaining habitat connectedness and availability; and 3) conduct extensive monitoring of climate conditions and population's response to climate.

Management Responses to Climate Change in the CVP/SWP BiOp:

The June 4, 2009, biological opinion on "Long-Term Operations of the Central Valley Project and State Water Project" (CVP/SWP BiOp) (NMFS 2009a) developed a reasonable and prudent alternative that includes a number of measures to reduce impacts of the projects in the face of climate change. These include managing water releases from storage reservoirs to maintain cool temperatures downstream, developing new models and decision-support tools for determining appropriate reservoir operations, specifying minimum end-of-season storage to ensure that a minimum volume of cool water is available for the next year in the event of a multi-year drought, and developing or improving temperature-control devices at dams. The CVP/SWP BiOp concludes that these measures may not be sufficient to reduce temperature-related mortality of fish and eggs below the projects in light of climate change through 2030 action duration, so studies and pilot programs to evaluate and implement reintroduction above impassible dams are

required. The 2008 BiOp contains similar measures to manage water temperature such as flow provisions as described below.

Progress Implementing Climate Change Mitigation Actions in the 2008 FCRPS BiOp:
Action Agency progress in implementing actions to reduce temperatures and implement other measures that respond to climate change are detailed in Appendix E. These measures include cold-water releases from Dworshak reservoir in July and August to maintain temperatures at or below 68°F at Lower Granite Dam; lowering reservoir elevations at the Snake River projects to minimum operating pool to reduce heating; project operations such as spill, use of spillway weirs, and bypass systems to reduce exposure of juveniles to warm temperatures; and development of a Water Management Plan and in-season management procedures to ensure that water is released and stored in a manner that optimizes survival of listed species. Progress is also well under way to develop a long-term Columbia Basin hydrology data set to be used to model climate change through various reservoir regulation models and tools and link this to biological models such as COMPASS. Appendix F also documents Action Agency progress in implementing tributary actions that will reduce impacts of climate change (e.g., Methow project improving access to spring-fed thermal refugia) and temperature monitoring to improve the ability to select future habitat improvement projects.

2.2.1.3.4 Monitoring Climate Changes and Species Responses

Approach in 2008 FCRPS BiOp and AMIP:

The 2008 BiOp and the AMIP described a general monitoring program to detect climate changes and species responses. This includes fish status and habitat action effectiveness monitoring, Intensively Monitored Watersheds, and forecasting and water management assessments related to climate change. In addition, under the AMIP, NOAA Fisheries will update and enhance a life-cycle model for Columbia and Snake River species, specifically to address climate change information. Under the AMIP, NOAA Fisheries will provide the Action Agencies with a climate change report each year for use in adaptively managing RPA actions. All of these actions are ongoing or under development.

New Information Relevant to the 2008 FCRPS BiOp and AMIP:

See the Research, Monitoring, and Evaluation chapter for a review of new information related to this subject. Other new information relevant to monitoring climate change effects includes Fleming and Quilty's (2007) risk-based approach to establishing screening-level, site-specific water temperature objectives and Doyle et al.'s (2010) protocol for monitoring climate change in Pacific Northwest National Parks and forests. Beamish et al. (2009a) developed a Long-term Research and Monitoring Plan (LRMP) for the North Pacific Anadromous Fish Commission that synthesized past research and identified critical areas for new research to understand impacts of future climate and ocean changes on the population dynamics of Pacific salmon. This study identified six climate change issues involving ecological resources that are important for integrated ecosystem assessments: 1) determining climate signals (long term change versus natural variation) impacting ecosystems; 2) the impact of ocean warming on distribution and

productivity of living marine resources; 3) the impacts of loss of sea ice on living marine resources; 4) ocean acidification impacts on marine biota; 5) freshwater supply and resource management; and 6) sea level rise. Beamish et al. (2009b) produced a bibliography of papers describing climate effects on Pacific salmon that accompanies Beamish et al. (2009a).

2.2.1.4 Relevance to 2008 FCRPS BiOp Analysis and AMIP

New observations and predictions regarding physical effects of climate change, as described in Section 2.2.1.3.1, are within the range of assumptions considered in the 2008 BiOp and the AMIP.

- Temperature and precipitation projections for the Pacific Northwest have not changed in the last two years.
- A great deal of new information is available, or will soon become available, on flows in Columbia basin tributaries and the mainstem Snake and Columbia Rivers as temperatures warm. This new information will allow predictions at the watershed scale to be coupled with biological models. The new flow information available to date, however, does not appear to fundamentally differ from general regional patterns previously considered (i.e., higher winter and spring flows in transitional and rainfall-driven basins; lower summer and fall flows in most basins).
- Broad-scale climate patterns reflected in the PDO and Multivariate ENSO index indicate that conditions during the past decade have clearly been within the range, and below the average, of both the base period and the "Warm PDO" climate conditions considered in 2008 BiOp modeling. We are currently experiencing a weakening El Niño condition, and most models predict a return to ENSO-neutral conditions by summer. To date, predictive models of longer-term effects of climate change on the PDO and El Niño provide conflicting results.
- Other ocean indicators are also within the range considered in the 2008 BiOp.

New studies of biological effects of climate change on salmon and steelhead, as described in Section 2.2.1.3.2, provide 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.

- ISAB (2007a), which was the basis for most of the climate information considered in the 2008 BiOp, indicated that warming temperatures could have positive or negative effects on juvenile growth, depending on available food and density. New studies confirm a range of responses and provide greater details regarding responses, but do not provide substantively different information than that considered in the 2008 BiOp.
- New studies are in progress which should help to elucidate potential responses of juveniles to climate change at the watershed level. At this time, however, the

available information does not differ substantively from that available in the 2008 BiOp.

- Juvenile studies confirm general expectations in the 2008 BiOp of changes in mainstem migration timing and life history strategies in response to higher temperatures. As previously noted and incorporated into 2008 BiOp modeling, arrival timing in the estuary is at least as important as cool temperatures in predicting smolt-to-adult survival for Snake River Chinook and steelhead.
- The new information on non-indigenous fishes (Section 2.2.5.2) provides additional detail to the general response of warm-water predators considered in the 2008 FCRPS BiOp: their ranges are expected to expand and predation rates are likely to increase as temperatures warm.
- Several new studies 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 provide greater detail. 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.
- A new area of study investigates recent historical and potential future evolutionary responses and phenotypic plasticity in juvenile and adult salmon and steelhead migration timing and life history strategy, suggesting that major shifts in run and spawn timing may accompany continuing climate change. While the direction of phenotypic adaptation is generally known, the degree to which it will occur is not clear at this time. Some studies document that the timing of harvest and collection for hatchery broodstock can either undermine or accelerate evolutionary responses.
- A major initiative launched by NOAA (Fisheries, Pacific Marine Environmental Laboratory, and Office of National Marine Sanctuaries) the West Coast Ocean Acidification Research Plan, will greatly improve our understanding of the effects of ocean acidification in the coming decade.
- Most studies related to climate effects on estuary and ocean productivity indicate that, while new information on biological effects in these areas is available, it does not differ substantively from factors previously considered in the 2008 BiOp.

New information indicates that RPA actions that should help to monitor and mitigate climate change are being implemented as expected per the 2008 BiOp and the AMIP. The types of potentially beneficial actions identified by ISAB (2007a) and implemented through the RPA are consistent with the types of adaptation actions described in current literature.

The new information concerning climate change indicates the potential for the functioning of PCEs in spawning and rearing areas, juvenile and adult migration corridors, and areas for growth and development to adulthood (i.e., the estuary) to change over time due to increased temperatures (water quality) and altered seasonal flows related to shifts in the timing of precipitation (water quantity). However, the physical effects are likely to be within the range considered in the 2008 BiOp. A number of actions in the mainstem migration corridor and in tributary and estuarine areas will proactively address the effects of climate change. Some of these improvements have already been implemented and others are scheduled for implementation over the term of the RPA (Appendices E and F).

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