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

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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).

7 Literature cited

Abdul-Aziz, O. I., N. J. Mantua, and K. W. Myers. 2011. Potential climate change impacts on thermal habitats of Pacific salmon (Oncorhynchus spp.) in the North Pacific Ocean and adjacent seas. Canadian Journal of Fisheries and Aquatic Sciences 68:1660-1680.

Ainsworth, C. H., J. F. Samhouri, D. S. Busch, W. W. L. Chueng, J. Dunne, and T. A. Okey. 2011a. Potential impacts of climate change on Northeast Pacific marine fisheries and food webs. ICES Journal of Marine Science 68:1217-1229.

Ainsworth, L. M., R. Routledge, and J. Cao. 2011b. Functional Data Analysis in Ecosystem Research: The Decline of Oweekeno Lake Sockeye Salmon and Wannock River Flow. Journal of Agricultural Biological and Environmental Statistics 16:282-300.

Al-Chokhachy, R., B. B. Roper, E. K. Archer, and S. Miller. 2011. Quantifying the Extent of and Factors Associated with the Temporal Variability of Physical Stream Habitat in Headwater Streams in the Interior Columbia River Basin. Transactions of the American Fisheries Society 140:399-414.

Alexander, J. D., B. L. Kerans, T. M. Koel, and C. Rasmussen. 2011. Context-specific parasitism in Tubifex tubifex in geothermally influenced stream reaches in Yellowstone National Park. Journal of the North American Benthological Society 30:853-867.

Arguez, A., I. Durre, S. Applequist, R. S. Vose, M. F. Squires, X. Yin, R. R. Heim et al. 2012. NOAA s 1981–2010 U.S. Climate Normals: An Overview. Bulletin of the American Meteorological Society.

Armstrong, J. D., K. J. Millidine, and N. B. Metcalfe. 2011. Ecological consequences of variation in standard metabolism and dominance among salmon parr. Ecology of Freshwater Fish 20:371-376.

Auth, T. D., R. D. Brodeur, H. L. Soulen, L. Ciannelli, and W. T. Peterson. 2011. The response of fish larvae to decadal changes in environmental forcing factors off the Oregon coast. Fisheries Oceanography 20:314-328.

Bal, G., E. Rivot, E. Prevost, C. Piou, and J. L. Bagliniere. 2011. Effect of water temperature and density of juvenile salmonids on growth of young-of-the-year Atlantic salmon Salmo salar. Journal of Fish Biology 78:1002-1022.

Barnard, P. L., J. Allan, J. E. Hansen, G. M. Kaminsky, P. Ruggiero, and A. Doria. 2011. The impact of the 2009-10 El Nino Modoki on US West Coast beaches. Geophysical Research Letters 38.

Beer, W. N., and J. J. Anderson. 2011. SENSITIVITY OF JUVENILE SALMONID GROWTH TO FUTURE CLIMATE TRENDS. River Research and Applications 27:663-669.

Belanger, C. L. 2011. Coastal dysoxia accompanies Early Miocene warming based on benthic foraminiferal and sedimentary records from Oregon. Marine Micropaleontology 80:101-113.

Bell, E., S. M. Albers, J. M. Krug, and R. Dagit. 2011. Juvenile growth in a population of southern California steelhead (Oncorhynchus mykiss). California Fish and Game 97:25-35.

Bentley, K. T., and R. L. Burgner. 2011. An assessment of parasite infestation rates of juvenile sockeye salmon after 50 years of climate warming in southwest Alaska. Environmental Biology of Fishes 92:267-273.

Bertrand, A., A. Chaigneau, S. Peraltilla, J. Ledesma, M. Graco, F. Monetti, and F. P. Chavez. 2011. Oxygen: A Fundamental Property Regulating Pelagic Ecosystem Structure in the Coastal Southeastern Tropical Pacific. Plos One 6.

Bi, H. S., W. T. Peterson, J. Lamb, and E. Casillas. 2011a. Copepods and salmon: characterizing the spatial distribution of juvenile salmon along the Washington and Oregon coast, USA. Fisheries Oceanography 20:125-138.

Bi, H. S., W. T. Peterson, and P. T. Strub. 2011b. Transport and coastal zooplankton communities in the northern California Current system. Geophysical Research Letters 38.

Bjorkstedt, E. P., R. Goericke, S. McClatchie, E. Weber, W. Watson, N. Lo, B. Peterson et al. 2011. State of the California Current 2010-2011: Regionally variable responses to a strong (but fleeting?) La Nina. California Cooperative Oceanic Fisheries Investigations Reports 52:36-68.

Bjornsson, B. T., S. O. Stefansson, and S. D. McCormick. 2011. Environmental endocrinology of salmon smoltification. General and Comparative Endocrinology 170:290-298.

Black, B. A., I. D. Schroeder, W. J. Sydeman, S. J. Bograd, B. K. Wells, and F. B. Schwing. 2011. Winter and summer upwelling modes and their biological importance in the California Current Ecosystem. Global Change Biology 17:2536-2545.

Blunden, J., and D. S. Arndt. 2012. State of the Climate in 2011. Bulletin of the American Meteorological Society 93:S1-S282.

Bond, A. L., I. L. Jones, W. J. Sydeman, H. L. Major, S. Minobe, J. C. Williams, and G. V. Byrd. 2011. Reproductive success of planktivorous seabirds in the North Pacific is related to ocean climate on decadal scales. Marine Ecology-Progress Series 424:205-U218.

Borstad, G., W. Crawford, J. M. Hipfner, R. Thomson, and K. Hyatt. 2011. Environmental control of the breeding success of rhinoceros auklets at Triangle Island, British Columbia. Marine Ecology-Progress Series 424:285-302.

Botsford, L. W., M. D. Holland, J. F. Samhouri, J. W. White, and A. Hastings. 2011. Importance of age structure in models of the response of upper trophic levels to fishing and climate change. Ices Journal of Marine Science 68:1270-1283.

Breau, C., R. A. Cunjak, and S. J. Peake. 2011. Behaviour during elevated water temperatures: can physiology explain movement of juvenile Atlantic salmon to cool water? Journal of Animal Ecology 80:844-853.

Brown, R. S., W. A. Hubert, and S. F. Daly. 2011. A Primer on Winter, Ice, and Fish: What Fisheries Biologists Should Know about Winter Ice Processes and Stream-Dwelling Fish. Fisheries 36:8-26.

Burrows, M. T., D. S. Schoeman, L. B. Buckley, P. Moore, E. S. Poloczanska, K. M. Brander, C. Brown et al. 2011. The Pace of Shifting Climate in Marine and Terrestrial Ecosystems. Science 334:652-655.

Cheung, W. W. L., J. Dunne, J. L. Sarmiento, and D. Pauly. 2011. Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. ICES Journal of Marine Science: Journal du Conseil 68:1008-1018.

Clark, T. D., K. M. Jeffries, S. G. Hinch, and A. P. Farrell. 2011. Exceptional aerobic scope and cardiovascular performance of pink salmon (Oncorhynchus gorbuscha) may underlie resilience in a warming climate. Journal of Experimental Biology 214:3074-3081.

Cocherell, S. A., D. E. Cocherell, G. J. Jones, J. B. Miranda, L. C. Thompson, J. J. Cech, and A. P. Klimley. 2011. Rainbow trout Oncorhynchus mykiss energetic responsesto pulsed flows in the American River, California, assessed by electromyogram telemetry. Environmental Biology of Fishes 90:29-41.

Copeland, T., and K. A. Meyer. 2011. Interspecies Synchrony in Salmonid Densities Associated with Large-Scale Bioclimatic Conditions in Central Idaho. Transactions of the American Fisheries Society 140:928-942.

Coyle, K. O., L. B. Eisner, F. J. Mueter, A. I. Pinchuk, M. A. Janout, K. D. Cieciel, E. V. Farley et al. 2011. Climate change in the southeastern Bering Sea: impacts on pollock stocks and implications for the oscillating control hypothesis. Fisheries Oceanography 20:139-156.

Crozier, L. G., M. D. Scheuerell, and R. W. Zabel. 2011. Using Time Series Analysis to Characterize Evolutionary and Plastic Responses to Environmental Change: A Case Study of a Shift toward Earlier Migration Date in Sockeye Salmon. American Naturalist 178:755-773.

Cummings, J. W., M. J. Hague, D. A. Patterson, and R. M. Peterman. 2011. The Impact of Different Performance Measures on Model Selection for Fraser River Sockeye Salmon. North American Journal of Fisheries Management 31:323-334.

Cuo, L., T. K. Beyene, N. Voisin, F. G. Su, D. P. Lettenmaier, M. Alberti, and J. E. Richey. 2011. Effects of mid-twenty-first century climate and land cover change on the hydrology of the Puget Sound basin, Washington. Hydrological Processes 25:1729-1753.

Danovaro, R., C. Corinaldesi, A. Dell'Anno, J. A. Fuhrman, J. J. Middelburg, R. T. Noble, and C. A. Suttle. 2011. Marine viruses and global climate change. Fems Microbiology Reviews 35:993-1034.

Das, T., D. W. Pierce, D. R. Cayan, J. A. Vano, and D. P. Lettenmaier. 2011. The importance of warm season warming to western US streamflow changes. Geophysical Research Letters 38.

Dawson, A., A. J. Matthews, and D. P. Stevens. 2011. Rossby wave dynamics of the North Pacific extra-tropical response to El Nino: importance of the basic state in coupled GCMs. Climate Dynamics 37:391-405.

de Eyto, E., P. McGinnity, J. Huisman, J. Coughlan, S. Consuegra, K. Farrell, C. O'Toole et al. 2011. Varying disease-mediated selection at different life-history stages of Atlantic salmon in fresh water. Evolutionary Applications 4:749-762.

De Laender, F., J. Hammer, A. J. Hendriks, K. Soetaert, and C. R. Janssen. 2011. Combining Monitoring Data and Modeling Identifies PAHs as Emerging Contaminants in the Arctic. Environmental Science & Technology 45:9024-9029.

Duliere, V., Y. X. Zhang, and E. P. Salathe. 2011. Extreme Precipitation and Temperature over the U.S. Pacific Northwest: A Comparison between Observations, Reanalysis Data, and Regional Models. Journal of Climate 24:1950-1964.

Eliason, E. J., T. D. Clark, M. J. Hague, L. M. Hanson, Z. S. Gallagher, K. M. Jeffries, M. K. Gale et al. 2011. Differences in Thermal Tolerance Among Sockeye Salmon Populations. Science 332:109-112.

Evans, T. G., E. Hammill, K. Kaukinen, A. D. Schulze, D. A. Patterson, K. K. English, J. M. R. Curtis et al. 2011. Transcriptomics of environmental acclimatization and survival in wild adult Pacific sockeye salmon (Oncorhynchus nerka) during spawning migration. Molecular Ecology 20:4472-4489.

Farley, E. V., A. Starovoytov, S. Naydenko, R. Heintz, M. Trudel, C. Guthrie, L. Eisner et al. 2011a. Implications of a warming eastern Bering Sea for Bristol Bay sockeye salmon. Ices Journal of Marine Science 68:1138-1146.

Farley, K. A., C. Tague, and G. E. Grant. 2011b. Vulnerability of water supply from the Oregon Cascades to changing climate: Linking science to users and policy. Global Environmental Change-Human and Policy Dimensions 21:110-122.

Fjelldal, P. G., T. Hansen, and T. S. Huang. 2011. Continuous light and elevated temperature can trigger maturation both during and immediately after smoltification in male Atlantic salmon (Salmo salar). Aquaculture 321:93-100.

Foreman, M. G. G., B. Pal, and W. J. Merryfield. 2011. Trends in upwelling and downwelling winds along the British Columbia shelf. Journal of Geophysical Research-Oceans 116.

Franke, A., and C. Clemmesen. 2011. Effect of ocean acidification on early life stages of Atlantic herring (Clupea harengus L.). Biogeosciences 8:3697-3707.

Fukushima, M., H. Shimazaki, P. S. Rand, and M. Kaeriyama. 2011. Reconstructing Sakhalin Taimen Parahucho perryi Historical Distribution and Identifying Causes for Local Extinctions. Transactions of the American Fisheries Society 140:1-13.

Gale, M. K., S. G. Hinch, E. J. Eliason, S. J. Cooke, and D. A. Patterson. 2011. Physiological impairment of adult sockeye salmon in fresh water after simulated capture-and-release across a range of temperatures. Fisheries Research 112:85-95.

Geist, D. R., Z. Q. Deng, R. P. Mueller, V. Cullinan, S. Brink, and J. A. Chandler. 2011. The Effect of Fluctuating Temperatures and Ration Levels on the Growth of Juvenile Snake River Fall Chinook Salmon. Transactions of the American Fisheries Society 140:190-200.

Glessmer, M. S., W. Park, and A. Oschlies. 2011. Simulated reduction in upwelling of tropical oxygen minimum waters in a warmer climate. Environmental Research Letters 6.

Glick, P., B. A. Stein, and N. A. Edelson. 2011. Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment. Washington, D.C., National Wildlife Federation.

Groom, J. D., L. Dent, and L. J. Madsen. 2011a. Stream temperature change detection for state and private forests in the Oregon Coast Range. Water Resources Research 47.

Groom, J. D., L. Dent, L. J. Madsen, and J. Fleuret. 2011b. Response of western Oregon (USA) stream temperatures to contemporary forest management. Forest Ecology and Management 262:1618-1629.

Gruber, N. 2011. Warming up, turning sour, losing breath: ocean biogeochemistry under global change. Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences 369:1980-1996.

Hague, M. J., M. R. Ferrari, J. R. Miller, D. A. Patterson, G. L. Russell, A. P. Farrell, and S. G. Hinch. 2011. Modelling the future hydroclimatology of the lower Fraser River and its impacts on the spawning migration survival of sockeye salmon. Global Change Biology 17:87-98.

Hale, R., P. Calosi, L. McNeill, N. Mieszkowska, and S. Widdicombe. 2011. Predicted levels of future ocean acidification and temperature rise could alter community structure and biodiversity in marine benthic communities. Oikos 120:661-674.

Hamlet, A. F. 2011. Assessing water resources adaptive capacity to climate change impacts in the Pacific Northwest Region of North America. Hydrology and Earth System Sciences 15:1427-1443.

Hayes, S. A., M. H. Bond, C. V. Hanson, A. W. Jones, A. J. Ammann, J. A. Harding, A. L. Collins et al. 2011. Down, up, down and "smolting" twice? Seasonal movement patterns by juvenile steelhead (Oncorhynchus mykiss) in a coastal watershed with a bar closing estuary. Canadian Journal of Fisheries and Aquatic Sciences 68:1341-1350.

Healey, M. 2011. The cumulative impacts of climate change on Fraser River sockeye salmon (Oncorhynchus nerka) and implications for management. Canadian Journal of Fisheries and Aquatic Sciences 68:718-737.

Heinemann, M., A. Timmermann, and U. Feudel. 2011. Interactions between marine biota and ENSO: a conceptual model analysis. Nonlinear Processes in Geophysics 18:29-40.

Hess, J. E., and S. R. Narum. 2011. Single-Nucleotide Polymorphism (SNP) Loci Correlated with Run Timing in Adult Chinook Salmon from the Columbia River Basin. Transactions of the American Fisheries Society 140:855-864.

Hester, E. T., and M. W. Doyle. 2011. Human Impacts to River Temperature and Their Effects on Biological Processes: A Quantitative Synthesis. Journal of the American Water Resources Association 47:571-587.

Hoekema, D. J., and V. Sridhar. 2011. Relating climatic attributes and water resources allocation: A study using surface water supply and soil moisture indices in the Snake River basin, Idaho. Water Resources Research 47.

Hofmann, G. E., J. E. Smith, K. S. Johnson, U. Send, L. A. Levin, F. Micheli, A. Paytan et al. 2011. High-Frequency Dynamics of Ocean pH: A Multi-Ecosystem Comparison. Plos One 6.

Hondula, D. M., and R. E. Davis. 2011. Climatology of winter transition days for the contiguous USA, 1951-2007. Theoretical and Applied Climatology 103:27-37.

House-Peters, L. A., and H. Chang. 2011. Modeling the impact of land use and climate change on neighborhood-scale evaporation and nighttime cooling: A surface energy balance approach. Landscape and Urban Planning 103:139-155.

Huang, B., C. Langpap, and R. M. Adams. 2011. Using instream water temperature forecasts for fisheries management: an application int he Pacific Northwest. Journal of the American Water Resources Association 47:861-876.

Jay, D. A., K. Leffler, and S. Degens. 2011. Long-Term Evolution of Columbia River Tides. Journal of Waterway Port Coastal and Ocean Engineering-Asce 137:182-191.

Jay, D. A., and P. K. Naik. 2011. Distinguishing human and climate influences on hydrological disturbance processes in the Columbia River, USA. Hydrological Sciences Journal-Journal Des Sciences Hydrologiques 56:1186-1209.

Jefferson, A. J. 2011. Seasonal versus transient snow and the elevation dependence of climate sensitivity in maritime mountainous regions. Geophysical Research Letters 38.

Jensen, A. J., P. Fiske, L. P. Hansen, B. O. Johnsen, K. A. Mork, and T. F. Naesje. 2011. Synchrony in marine growth among Atlantic salmon (Salmo salar) populations. Canadian Journal of Fisheries and Aquatic Sciences 68:444-457.

Joint, I., S. C. Doney, and D. M. Karl. 2011. Will ocean acidification affect marine microbes? Isme Journal 5:1-7.

Jokinen, I. E., H. M. Salo, E. Markkula, K. Rikalainen, M. T. Arts, and H. I. Browman. 2011. Additive effects of enhanced ambient ultraviolet B radiation and increased temperature on immune function, growth and physiological condition of juvenile (parr) Atlantic Salmon, Salmo salar. Fish & Shellfish Immunology 30:102-108.

Jones, I. S. F. 2011. Contrasting micro- and macro-nutrient nourishment of the ocean. Marine Ecology-Progress Series 425:281-296.

Jung, I. W., and H. J. Chang. 2011. Assessment of future runoff trends under multiple climate change scenarios in the Willamette River Basin, Oregon, USA. Hydrological Processes 25:258-277.

Kim, W., S. W. Yeh, J. H. Kim, J. S. Kug, and M. Kwon. 2011. The unique 2009-2010 El Nino event: A fast phase transition of warm pool El Nino to La Nina. Geophysical Research Letters 38.

Klaiman, J. M., A. J. Fenna, H. A. Shiels, J. Macri, and T. E. Gillis. 2011. Cardiac Remodeling in Fish: Strategies to Maintain Heart Function during Temperature Change. Plos One 6.

Koehn, J. D., A. J. Hobday, M. S. Pratchett, and B. M. Gillanders. 2011. Climate change and Australian marine and freshwater environments, fishes and fisheries: synthesis and options for adaptation. Marine and Freshwater Research 62:1148-1164.

Komar, P. D., J. C. Allan, and P. Ruggiero. 2011. Sea Level Variations along the U.S. Pacific Northwest Coast: Tectonic and Climate Controls. Journal of Coastal Research 27:808-823.

Krimmer, A. N., A. J. Paul, A. Hontela, and J. B. Rasmussen. 2011. Behavioural and physiological responses of brook trout Salvelinus fontinalis to midwinter flow

reduction in a small ice-free mountain stream. Journal of Fish Biology 79:707-725.

Lenoir, S., G. Beaugrand, and É. Lecuyer. 2011. Modelled spatial distribution of marine fish and projected modifications in the North Atlantic Ocean. Global Change Biology 17:115-129.

Liedvogel, M., S. Akesson, and S. Bensch. 2011. The genetics of migration on the move. Trends in Ecology & Evolution 26:561-569.

Lin, P. F., H. L. Liu, Y. Q. Yu, and X. H. Zhang. 2011. Response of Sea Surface Temperature to Chlorophyll-a Concentration in the Tropical Pacific: Annual Mean, Seasonal Cycle, and Interannual Variability. Advances in Atmospheric Sciences 28:492-510.

Lischka, S., J. Budenbender, T. Boxhammer, and U. Riebesell. 2011. Impact of ocean acidification and elevated temperatures on early juveniles of the polar shelled pteropod Limacina helicina: mortality, shell degradation, and shell growth. Biogeosciences 8:919-932.

Low-DÉCarie, E., G. F. Fussmann, and G. Bell. 2011. The effect of elevated CO2 on growth and competition in experimental phytoplankton communities. Global Change Biology 17:2525-2535.

MacKenzie, L. A., K. F. Smith, L. L. Rhodes, A. Brown, V. Langi, M. Edgar, G. Lovell et al. 2011. Mortalities of sea-cage salmon (Oncorhynchus tshawytscha) due to a bloom of Pseudochattonella verruculosa (Dictyochophyceae) in Queen Charlotte Sound, New Zealand. Harmful Algae 11:45-53.

Malcolm, I. A., A. F. Youngson, C. Soulsby, C. Imholt, and R. J. Fryer. 2011. Is Interstitial Velocity a Good Predictor of Salmonid Embryo Survival? Transactions of the American Fisheries Society 140:898-904.

Marschall, E. A., M. E. Mather, D. L. Parrish, G. W. Allison, and J. R. McMenemy. 2011. Migration delays caused by anthropogenic barriers: modeling dams, temperature, and success of migrating salmon smolts. Ecological Applications 21:3014-3031.

Martins, E. G., S. G. Hinch, D. A. Patterson, M. J. Hague, S. J. Cooke, K. M. Miller, M. F. Lapointe et al. 2011. Effects of river temperature and climate warming on stock-specific survival of adult migrating Fraser River sockeye salmon (Oncorhynchus nerka). Global Change Biology 17:99-114.

Mayer, T. D., and S. W. Naman. 2011. Streamflow response to climate as influences by geology and elevation. Journal of the American Water Resources Association 47:724-738.

Miller, K. M., S. R. Li, K. H. Kaukinen, N. Ginther, E. Hammill, J. M. R. Curtis, D. A. Patterson et al. 2011a. Genomic Signatures Predict Migration and Spawning Failure in Wild Canadian Salmon. Science 331:214-217.

Miller, S. C., T. E. Gillis, and P. A. Wright. 2011b. The ontogeny of regulatory control of the rainbow trout (Oncorhynchus mykiss) heart and how this is influenced by chronic hypoxia exposure. Journal of Experimental Biology 214:2065-2072.

Milner, A. M., A. L. Robertson, L. E. Brown, S. H. Sonderland, M. McDermott, and A. J. Veal. 2011. Evolution of a stream ecosystem in recently deglaciated terrain. Ecology 92:1924-1935.

Min, S. K., X. B. Zhang, F. W. Zwiers, and G. C. Hegerl. 2011. Human contribution to more-intense precipitation extremes. Nature 470:378-381.

Munday, P. L., M. Gagliano, J. M. Donelson, D. L. Dixson, and S. R. Thorrold. 2011a. Ocean acidification does not affect the early life history development of a tropical marine fish. Marine Ecology-Progress Series 423:211-221.

Munday, P. L., V. Hernaman, D. L. Dixson, and S. R. Thorrold. 2011b. Effect of ocean acidification on otolith development in larvae of a tropical marine fish. Biogeosciences 8:1631-1641.

Mundy, P. R., and D. F. Evenson. 2011. Environmental controls of phenology of high-latitude Chinook salmon populations of the Yukon River, North America, with application to fishery management. Ices Journal of Marine Science 68:1155-1164.

Naik, P. K., and D. A. Jay. 2011a. Distinguishing human and climate influences on the Columbia River: Changes in mean flow and sediment transport. Journal of Hydrology 404:259-277.

—. 2011b. Human and climate impacts on Columbia River hydrology and salmonids. River Research and Applications 27:1270-1276.

National Wildlife Federation. 2011. Climate Change Effects and Adaptation Approaches in Marine and Coastal Ecosystems of the North Pacific Landscape Conservation Cooperative Region: A Compilation of Scientific Literature. Phase 1 Draft Final Report. http://www.nwf.org/~/media/PDFs/Global-Warming/Reports/NPLCC%20Reports/NPLCC_Marine_Climate-Effects_Draft-Final_FullReport.ashx

Nelson, D. B., M. B. Abbott, B. Steinman, P. J. Polissar, N. D. Stansell, J. D. Ortiz, M. F. Rosenmeier et al. 2011. Drought variability in the Pacific Northwest from a 6,000-yr lake sediment record. Proceedings of the National Academy of Sciences of the United States of America 108:3870-3875.

Otero, J., A. J. Jensen, J. H. L'Abee-Lund, N. C. Stenseth, G. O. Storvik, and L. A. Vollestad. 2011. Quantifying the Ocean, Freshwater and Human Effects on Year-to-Year Variability of One-Sea-Winter Atlantic Salmon Angled in Multiple Norwegian Rivers. Plos One 6.

Pankhurst, N. W., and P. L. Munday. 2011. Effects of climate change on fish reproduction and early life history stages. Marine and Freshwater Research 62:1015-1026.

Pardo, P. C., X. A. Padin, M. Gilcoto, L. Farina-Busto, and F. F. Perez. 2011. Evolution of upwelling systems coupled to the long-term variability in sea surface temperature and Ekman transport. Climate Research 48:231-246.

Perkins, T. A., and H. I. Jager. 2011. Falling Behind: Delayed Growth Explains Life-History Variation in Snake River Fall Chinook Salmon. Transactions of the American Fisheries Society 140:959-972.

Polovina, J. J., J. P. Dunne, P. A. Woodworth, and E. A. Howell. 2011. Projected expansion of the subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming. Ices Journal of Marine Science 68:986-995.

Quinn, T. P., M. J. Unwin, and M. T. Kinnison. 2011. Contemporary divergence in migratory timing of naturalized populations of chinook salmon, Oncorhynchus tshawytscha, in New Zealand. Evolutionary Ecology Research 13:45-54.

Reed, T. E., D. E. Schindler, M. J. Hague, D. A. Patterson, E. Meir, R. S. Waples, and S. G. Hinch. 2011. Time to Evolve? Potential Evolutionary Responses of Fraser River Sockeye Salmon to Climate Change and Effects on Persistence. Plos One 6.

Reum, J. C. P., T. E. Essington, C. M. Greene, C. A. Rice, and K. L. Fresh. 2011. Multiscale influence of climate on estuarine populations of forage fish: the role of coastal upwelling, freshwater flow and temperature. Marine Ecology-Progress Series 425:203-215.

Roegner, G. C., J. A. Needoba, and A. M. Baptista. 2011a. Coastal Upwelling Supplies Oxygen-Depleted Water to the Columbia River Estuary. PLoS ONE 6 e18672.

Roegner, G. C., C. Seaton, and A. M. Baptista. 2011b. Climatic and Tidal Forcing of Hydrography and Chlorophyll Concentrations in the Columbia River Estuary. Estuaries and Coasts 34:281-296.

Rogers, B. M., R. P. Neilson, R. Drapek, J. M. Lenihan, J. R. Wells, D. Bachelet, and B. E. Law. 2011. Impacts of climate change on fire regimes and carbon stocks of the U.S. Pacific Northwest. Journal of Geophysical Research-Biogeosciences 116.

Rouyer, T., G. Ottersen, J. M. Durant, M. Hidalgo, D. A. G. Ø. Hjermann, J. Persson, L. C. Stige et al. 2011. Shifting dynamic forces in fish stock fluctuations triggered by age truncation? Global Change Biology:no-no.

Ruff, C. P., D. E. Schindler, J. B. Armstrong, K. T. Bentley, G. T. Brooks, G. W. Holtgrieve, M. T. McGlauflin et al. 2011. Temperature-associated population diversity in salmon confers benefits to mobile consumers. Ecology 92:2073-2084.

Safford, T. G., and K. C. Norman. 2011. Water water everywhere, but not enough for salmon? Organizing integrated water and fisheries management in Puget Sound. Journal of Environmental Management 92:838-847.

Saito, T., T. Kaga, E. Hasegawa, and K. Nagasawa. 2011. Effects of juvenile size at release and early marine growth on adult return rates for Hokkaido chum salmon (Oncorhynchus keta) in relation to sea surface temperature. Fisheries Oceanography 20:278-293.

Seeb, L. W., J. E. Seeb, C. Habicht, E. V. Farley, and F. M. Utter. 2011. Single-Nucleotide Polymorphic Genotypes Reveal Patterns of Early Juvenile Migration of Sockeye Salmon in the Eastern Bering Sea. Transactions of the American Fisheries Society 140:734-748.

Selbie, D. T., J. N. Sweetman, P. Etherton, K. D. Hyatt, D. P. Rankin, B. P. Finney, and J. P. Smol. 2011. Climate change modulates structural and functional lake ecosystem responses to introduced anadromous salmon. Canadian Journal of Fisheries and Aquatic Sciences 68:675-692.

Sestrich, C. M., T. E. McMahon, and M. K. Young. 2011. Influence of Fire on Native and Nonnative Salmonid Populations and Habitat in a Western Montana Basin. Transactions of the American Fisheries Society 140:136-146.

Sommer, U., and A. Lewandowska. 2011. Climate change and the phytoplankton spring bloom: warming and overwintering zooplankton have similar effects on phytoplankton. Global Change Biology 17:154-162.

Spencer, M., S. N. R. Birchenough, N. Mieszkowska, L. A. Robinson, S. D. Simpson, M. T. Burrows, E. Capasso et al. 2011. Temporal change in UK marine communities: trends or regime shifts? Marine Ecology-an Evolutionary Perspective 32:10-24.

Tagliabue, A., L. Bopp, and M. Gehlen. 2011. The response of marine carbon and nutrient cycles to ocean acidification: Large uncertainties related to phytoplankton physiological assumptions. Global Biogeochemical Cycles 25.

Taguchi, M., and J. C. Liao. 2011. Rainbow trout consume less oxygen in turbulence: the energetics of swimming behaviors at different speeds. Journal of Experimental Biology 214:1428-1436.

Thomson, R. E., and R. A. S. Hourston. 2011. A matter of timing: the role of ocean conditions in the initiation of spawning migration by late-run Fraser River sockeye salmon (*Oncorhynchus nerka*). Fisheries Oceanography 20:47-65.

Thorpe, A. S., and A. G. Stanley. 2011. Determining appropriate goals for restoration of imperilled communities and species. Journal of Applied Ecology 48:275-279.

Todd, R. E., D. L. Rudnick, R. E. Davis, and M. D. Ohman. 2011. Underwater gliders reveal rapid arrival of El Nino effects off California's coast. Geophysical Research Letters 38.

Traynham, L., R. Palmer, and A. Polebitski. 2011. Impacts of Future Climate Conditions and Forecasted Population Growth on Water Supply Systems in the Puget Sound Region. Journal of Water Resources Planning and Management-Asce 137:318-326.

USFWS, NOAA-Fisheries Service, and Association of Fish and Wildlife Agencies. 2011. National Fish, Wildlife and Plants Climate Adaptation Strategy, Agency Review Draft, November 2011. http://www.wildlifeadaptationstrategy.gov:153

Vaquer-Sunyer, R., and C. M. Duarte. 2011. Temperature effects on oxygen thresholds for hypoxia in marine benthic organisms. Global Change Biology 17:1788-1797.

Welch, D. W., Y. Ishida, and K. Nagasawa. 1998. Thermal limits and ocean migrations of sockeye salmon (*Oncorhynchus nerka*): long-term consequences of global warming. Canadian Journal of Fisheries and Aquatic Sciences 55:937-948.

Wenger, S. J., D. J. Isaak, C. H. Luce, H. M. Neville, K. D. Fausch, J. B. Dunham, D. C. Dauwalter et al. 2011. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. Proceedings of the National Academy of Sciences of the United States of America 108:14175-14180.

Weyhenmeyer, G. A., D. M. Livingstone, M. Meili, O. Jensen, B. Benson, and J. J. Magnuson. 2011. Large geographical differences in the sensitivity of ice-covered lakes and rivers in the Northern Hemisphere to temperature changes. Global Change Biology 17:268-275.

Whiteley, N. M. 2011. Physiological and ecological responses of crustaceans to ocean acidification. Marine Ecology-Progress Series 430:257-271.

Young, I. R., S. Zieger, and A. V. Babanin. 2011. Global Trends in Wind Speed and Wave Height. Science 332:451-455.

Zeug, S. C., L. K. Albertson, H. Lenihan, J. Hardy, and B. Cardinale. 2011. Predictors of Chinook salmon extirpation in California's Central Valley. Fisheries Management and Ecology 18:61-71.