Impacts of Climate Change on Salmon of the Pacific Northwest

A review of the scientific literature published in 2017

Lisa Crozier and Jared Siegel

Fish Ecology Division
Northwest Fisheries Science Center
National Marine Fisheries Service, NOAA
2725 Montlake Boulevard East
Seattle, Washington 98112

July 2018

Contents

Highlights

Global annual temperatures in 2017 were the third highest on record since 1880, exceeded only by 2015 and 2016, and contributing to a long-term increase of 0.07°C/decade (NOAA 2018). The Pacific Northwest was 0.72°C warmer than average, but substantially cooler than in 2015.

A new analysis of sea surface temperature anticipates warming of 2°C above the 1900-1975 baseline by 2025 across the California Current Large Marine Ecosystem (Alexander et al. 2018). Alexander et al. (2018) found a continued warming trend of 0.36°/decade on average across the latest global climate models (GCM) under the RCP 8.5 emissions scenario (business as usual).

A new summary of anticipated changes in upwelling predicts increased upwelling during spring in the northern California Current, but decreased upwelling in more southerly regions and during other seasons by mid- to late-century (Brady et al. 2017). Simulated changes were estimated from 1920 to 2100 using monthly output from 40 members of the Community Earth System Model Large Ensemble Project, which captures internal variability within a single GCM rather than across GCMs.

Dissolved oxygen in the ocean is expected to decline rapidly in response to anthropogenic forcing. However, high levels of natural variability and poor observation ability has made detecting expected trends and evaluating model performance difficult. In a “time of emergence” analysis, Long et al. (2016) found that the "signal" from anthropogenic effects should have already exceeded the "noise" from natural variability in some southern and tropical oceans, and should be widespread by the 2030s-2040s.

By 2063, a decline of 0.2 units in pH is expected during the summer upwelling season in the California Current. Using the end-to-end ecosystem model Atlantis, Marshall et al. (2017) projected dramatic effects for epibenthic invertebrates, including economically and ecologically important species (e.g., crabs and shrimp) and some demersal fish due to both direct and indirect mechanisms. Pteropods are already near an ecological threshold and may be among the first species facing extirpation due to acidification (Bednarsek et al. 2017).

Various analyses were published in 2017 on "The Blob," a marine heat wave observed from January 2014 through August 2016 in the California Current and Gulf of Alaska. Researchers evaluated physical drivers, plankton response, and harmful algal blooms associated with "The Blob."

Retrospective analyses of climate and streamflow in the Pacific Northwest found trends of decreasing precipitation, contrary to trends seen in the rest of the U.S. (Mallakpour and Villarini 2017; Roque-Malo and Kumar 2017). Historical trends in the Pacific Northwest may reflect the high variability in precipitation on a decadal scale, which delays the signal of directional climate change, as well as the changes in the spatial characteristics of precipitation, for example, those caused by shifts in the location of the jet stream. As in previous analyses, projections of future conditions point to increasing winter precipitation, higher wet-season flows, decreasing summer precipitation, lower low flows, and increasing drought (Ahmadalipour et al. 2017a; Ahmadalipour et al. 2017b; Huang and Ullrich 2017; Marlier et al. 2017; Rupp et al. 2017a; Rupp et al. 2017b).

Increased winter precipitation in some areas will intensify flooding that typically occurs during the salmon incubation period. Flooding is generally considered a risk factor for incubating eggs, but data showing strong impacts on salmon survival are rare. Thus, the empirical study of Hood Canal chum salmon by Weinheimer et al. (2017) is noteworthy. They showed an egg-to-fry survival decline from ~45% to near 0% as peak flows increased from <1 to 5 m^3/s.

Key aspects of salmon response to climate change depend on genetic adaptation and plasticity in both migration timing and thermal tolerance. Juvenile migration timing was shown to be plastic and related to rearing temperatures in chum from Salmon Creek, Washington (Weinheimer et al. 2017), but chum from arctic waters were found less plastic than expected (Vega et al. 2017).

Smolt migration temperatures through the Columbia River hydrosystem were shown to predict survival of spring/summer Chinook salmon in a temperature challenge experiment (Gosselin and Anderson 2017). A combination of migration date and juvenile transportation history were similarly predictive of how long smolts survived at 23.5˚C. The authors concluded that temperatures experienced during migration affect juvenile condition, and thus have a carryover effect on marine survival.

Because early marine survival is highly variable and strongly related to environmental conditions, it is often a key element in climate impact studies for salmon. Historically, salmon have migration timing matched periods of high ocean productivity and its predictability (Spence and Hall 2010). We therefore assume climate change could alter selection pressure on migration timing. However, it has been difficult to demonstrate modern selection and evolutionary response on marine entry timing.

In an interesting re-evaluation of genetic change previously shown in pink salmon in Alaska, Manhard et al. (2017) proposed that it was selection on the juvenile stage rather than the adult stage that drove the shift in adult migration timing. They argue that a strong selection event on juvenile migration timing in a single year caused the near-permanent shift in adult run timing as a byproduct of the correlation between juvenile and adult behavior.

Although genetic responses to climate change clearly occur and can be adaptive, we lack standardized tools for predicting which populations have more adaptive capacity than others. Wade et al. (2017) compared different metrics for adaptive capacity (habitat condition, population status, and genetic diversity), and found that they produced different vulnerability rankings for bull trout and steelhead in the Pacific Northwest.

Numerous habitat factors and management actions affect salmon survival during the freshwater life stages. Habitat restoration showed potential for ameliorating future climate-induced warming of streams in a modeling study of the Grande Ronde (Justice et al. 2017) and John Day Rivers (McHugh et al. 2017).

Along with habitat restoration, flow control specifically for temperature management will be increasingly necessary to mitigate climate change impacts. Temperature control devices have been shown to reduce thermal stress compared with historical dam management techniques. Presently, the most advanced mechanisms of temperature control through selective reservoir releases are applied at Shasta Dam in the Sacramento River of California. Unfortunately, even these tools may not be sufficient to reach future temperature targets due to competing demands on hydrosystem operations (Sapin et al. 2017). Similar problems may emerge in some Pacific Northwest watersheds, where some dams may not be able to reach flow targets for temperature control (McGrath et al. 2017).

Effects of temperature on salmon rearing habitats are more complex than often suggested by climate impact studies. In fact, thermal heterogeneity itself is valuable to fish, even outside habitats that remain within a tolerable temperature range. In the Klamath River, California, steelhead migrated in and out of warm water to take advantage of high prey availability there, but retreated to cooler refugia for digestion (Brewitt et al. 2017).

Bioenergetic costs increase for fish in warmer water, and few studies are available that can quantify the ability of salmon to actually consume the needed calories. Haskell et al. (2017) estimated the ability of fall Chinook to meet energetic demands by eating high-quality prey (American shad) in reservoirs. They concluded that consumption rates would have to be much higher than historically observed for fish to achieve positive growth rates. Thus despite the high abundance of prey available, consumption rates might not be able to compensate for higher energetic costs (Haskell et al. 2017).

Increased fish mortality at warmer temperatures is often mediated by disease rather than resulting from direct temperature-induced physiological collapse. Bailey et al. (2017a) compared immune responses of rainbow trout challenged by proliferative kidney disease at 15 and 12°C. They found that it was not only a breakdown in immune capability, but a shift in immune response strategy that characterized the effect of temperature on the fish immune system. Temperature also can act via oxygen limitation, which could be the mortality agent for summer-incubating winter Chinook salmon eggs (Martin et al. 2017).

Myers et al. (2017) reviewed the literature on documented and projected effects of climate change on inland fishes. They identified management strategies proposed to address climate impacts on community composition, abundance, distribution, phenology, and adaptive capacity (Table 4, Myers et al. 2017). They concluded that temperature might be over-emphasized in the research to date, and risks from other climate drivers need to be more fully appreciated.

In conclusion, climate conditions continue to follow trends predicted previously by GCMs, and projections for the future are consistent with previous model results. Very rapid warming in the ocean now appears highly likely, although uncertainty remains whether the northeast Pacific will track global trends (Johnstone and Mantua 2014). New evidence supports previous observations of negative effects of climate change on salmon in all life stages. Habitat and management actions can help reduce the impacts of warming on salmonids, as shown in examples of habitat restoration and altered dam management strategies. Nonetheless, there are many limitations on the maximum benefits of these actions.

Objective and Methods

This review was conducted to identify literature published in 2017 that is most relevant to prediction and reduction of climate change impacts on Columbia River salmon listed under the Endangered Species Act. Our literature search focused on peer-reviewed scientific journals included in the *Web of Science* database, although we occasionally included highly-influential reports outside that database.

To capture the most relevant papers, we combined climatic and salmonid terms in our search criteria. This excluded studies of general principles demonstrated in other taxa or within a broader context. In total, we reviewed over 500 papers, 151 of which were included in this summary.

Literature searches were conducted in May 2018 using the Institute for Scientific Information (ISI) *Web of Science* indexing service. Each set of search criteria involved a new search, and results were compared with previous searches to identify potential missing topics. Because many articles appear online before the print version, some citations appeared online in 2017 and hence were included in our search but subsequently changed to 2018. We used specific search criteria that included a publication year of 2017, plus:

1) A topic that contained the terms climate,[1] temperature, streamflow, flow, snowpack, precipitation, **or**[2] PDO, **and** a topic that contained salmon, *Oncorhynchus*, or steelhead, but **not** aquaculture or fillet
2) A topic that contained climate, temperature, precipitation, streamflow or flow **and** a topic containing "Pacific Northwest"
3) A topic that contained the terms marine, sea level, hyporheic, or groundwater **and** climate, **and** salmon, *Oncorhynchu*s or steelhead
4) Topics that contained upwelling **or** estuary **and** climate **and** Pacific
5) Topics that contained ocean acidification **and** salmon, *Oncorhynchus* or steelhead
6) Topics that contained upwelling **or** estuary **or** ocean acidification **and** California Current, Columbia River, Puget Sound or Salish Sea
7) A topic that contained prespawn mortality

[1] The wildcard (*), was used to search using "climat*" to capture all forms of the word "climate."
[2] Boolean operators used in the search are shown in boldface.

This review is presented in two major parts. The first considers changes to the physical environment that are both important to salmon and projected to change due to anthropogenic release of greenhouse gases. We describe projections driven by global climate model (GCM) simulations, as well as historical trends and relationships among these environmental conditions. In the second part, we summarize the literature on responses of salmon to these environmental conditions, both projected and retrospective, in freshwater and marine environments.

Physical Changes in Climate and Ocean Conditions

In 2017, global annual temperatures were the third highest on record since 1880 (NOAA 2018). Land and ocean surface temperatures were 0.84°C above the 20th century average, surpassed only by two previous record-setting years in 2015 and 2016 (0.90 and 0.94°C above average, respectively). World oceans were 0.67°C above the average since 1880, while world land surfaces were 1.31°C above average. For 41 consecutive years, the annual temperature has been above this running average, with the six warmest years occurring since 2010. The long-term trend now shows a warming rate of 0.07°C/decade since 1880 and of 0.18°C/decade since 1970.

Annual average temperature for the contiguous United States was the third highest among all 123 years on record in 2017, exceeded only in 2012 and 2016. The 21st consecutive, higher-than-average annual temperature occurred in 2017. In the northwestern United Sates, temperatures were substantially cooler in 2017 than in the record high year of 2015; however, they remained at 0.72°C above average for the 6th year in a row and for the 29th time over the last 32 years.

Global and national climate change

Retrospective

Mallakpour and Villarini (2017) used daily precipitation observations to investigate change in heavy precipitation patterns across the contiguous U.S. during 1948-2012. Results suggest that changes have been stronger in frequency than in magnitude. Specifically, the frequency of heavy precipitation events has increased over much of the contiguous U.S., with the exception of the Pacific Northwest. Thus, while the strongest storms did not appear to have become stronger in the aggregate, they have become more common at the national level. The Pacific Northwest showed many more decreasing trends than increasing trends in both magnitude and frequency of heavy precipitation in all seasons.

While much research has focused on a few summary statistics such as seasonal means, variance, and extreme events, many other aspects of precipitation have changed over the past century. Roque-Malo and Kumar (2017) described the slopes of changes across many different thresholds to better characterize precipitation variability across North America. They reported increases in average precipitation across most of North

America, with exceptions in the Pacific Northwest and parts of the Southeast. They noted significant change in the fraction of wet days and in the average length of consecutive dry periods.

Zhao et al. (2017) described patterns in spring/summer dryness across the USA, as measured by days with no precipitation. They used climate models to assess the influence of Pacific SSTs on interannual variability in spring/summer dryness and found that SST patterns captured by the Pacific Decadal Oscillation were primary drivers. Secondary influences included the West Pacific teleconnection pattern and a wave train over the Pacific-North American sector. Based on observed model biases, they concluded that scientific challenges remain in the generation of reliable projections of hydroclimate variability.

Fountain et al. (2017) inventoried mid-century glaciers and perennial snowfields and evaluated the extent of their change in the American west. Glaciers and snowfields were categorized into two groups, depending on mean air temperature and elevation: Pacific Northwest glaciers typically occurred at low elevations and were influenced by warm, moist air from the Pacific Ocean, whereas those in the interior Rocky and Sierra Nevada Mountains typically occurred at higher elevations under drier, colder conditions.

Based on aerial photographs from 1955 to 1990 and on USGS topographic maps, Fountain et al. (2017) concluded that Pacific Northwest glaciers will be especially vulnerable to climate change because they already occur at marginal winter temperatures. Their inventories suggested that since mid-century, glaciers throughout the western United States may have already decreased by as much as 39%.

Most El Niño events are associated with lower-than-normal precipitation in the Pacific Northwest and higher-than-normal precipitation in California. However, in winter 2015-2016, these observed precipitation anomalies were reversed. Kumar and Chen (2017) explored variability in precipitation patterns during El Niño events utilizing hindcasts (1982-2011) and real-time forecasts (2012-2015) from the NCEP Climate System, version 2 (CFSv2). They concluded that while El Niño events are associated with positive anomalies in California precipitation, there is substantial variability in this association. The probability that El Niño events would coincide with reverse winter precipitation anomalies was estimated to be 40-50% for California and 40% for the Pacific Northwest (Kumar and Chen 2017). Consequently, this analysis suggests that for an individual season, the patterns observed during the 2015-2016 El Niño event were within model expectations.

Projections

Tommasi et al. (2017) provided an overview of global climate prediction systems and their role in forecasting environmental variables important to marine resources. They showed that such predictions can provide opportunities for improved resource management and development in fisheries science. Specifically, they describe climate-sensitive management decisions made at seasonal and decadal time scales that can be informed by such predictions. They then provide case studies where such decisions have been informed by these prediction systems, including decisions on monitoring and fishery closures, annual catch limits, stock rebuilding plans, management of protected areas for marine species resilience and sustainability, and industrial short- and long-term planning. These authors identified scientific priorities for improvement that include strengthening mechanistic ties between climate and marine resources, improving models to better describe such relationships, and developing predictive resolution to the finer regional scales befitting most marine resource decisions.

Huang and Ullrich (2017) predicted the nature of changes in precipitation patterns in the western United States as a consequence of climate change. They utilized the Variable-Resolution Community Earth System Model (VR-CESM) informed with estimated sea surface temperatures, sea ice extents, and greenhouse gas concentrations under the RCP 8.5 scenario. Notable results of their simulations included predicted increases in the number of rainy days in the inter-mountain western and southwestern U.S. and an increase in extreme rain events in the Pacific Northwest.

Rupp et al. (2017b) explored spatial variability in predicted changes of near-surface air temperature in the western U.S. as a consequence of climate change. They utilized high-resolution, large-ensemble climatic simulations to compare predictions from the historical period of 1985-2014 to the future period of 2030-2059 forced by atmospheric conditions from the RCP 4.5 scenario. They concluded that in winter and spring, reductions in snow cover, as measured by albedo effect, explained roughly one-half of the spatial variability in predicted air temperatures. In summer, changes in air temperature in the Pacific Northwest were correlated with patterns of decreasing precipitation.

Roberts et al. (2017) modeled the relationship between air temperature and surface conditions and predicted the effects of climate change for 27 lakes in the southern Rocky Mountains. They predicted future air temperatures using the PSU/OSU GENMOM and MPI ECHAM5 climate models, which they downscaled under the A2 emissions scenario from the IPCC AR4 (most similar to the RCP 8.5 scenario). Results suggest that mean annual lake temperatures will increase by a rate of ~0.25°C per decade through the 2080s. Most strikingly, mean summer temperatures were predicted to increase ~0.47°C per decade with an increase in ice-free days of 5.9 d per decade. They concluded that if realized, these predicted changes will greatly affect the growing season, as well as the structure and function of these mountain lake ecosystems.

Pacific Northwest climate change

Retrospective

Drought has substantial human, economic, and environmental consequences. Changes in drought patterns have been projected to occur as a result of climate change, but the reliability of these projections has not been clear. Abatzoglou and Rupp (2017) presented a precipitation/evapotranspiration framework for evaluating the ability of global climate models to simulate regional drought patterns. Focusing on the northwestern U.S., they compared precipitation and potential evapotranspiration observations to a suite of global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5). In general, models were found to characterize 1) potential evapotranspiration better than precipitation, and 2) seasonal and annual time series better than multi-year time series. However, global climate models tended to underestimate the severity of regional drought.

Ahmadalipour and Moradkhani (2017) analyzed uncertainty in ensemble-based, gridded observations in land surface simulations and drought assessments in the Pacific Northwest. Specifically, they utilized a recently developed 100-member ensemble to simulate hydrologic fluxes under historical conditions using the Variable Infiltration Capacity (VIC) model. They compared the dataset with observations from an earlier ensemble. High disparities in hydrologic fluxes and drought characteristics were found at the monthly timescale, and simulations generally indicated higher temperature, evapotranspiration and lower snowpack and snow water equivalencies than observations. Despite uncertainties, the authors identified a decline in annual snowpack and snow water equivalencies of 3% per decade and a 7% decrease per decade in moisture for southern Idaho agricultural areas.

Brahney et al. (2017b) presented evidence for a climate-driven regime shift in the Canadian Columbia River Basin. They evaluated influences of climate and recent warming on patterns of streamflow in tributary streams. While they identified past strong relationships with oceanographic indicators such as the PDO and ENSO, they found these relationships have become weaker. A comparison of past and present cool phases of the PDO suggests that annual flows have declined. Correlations between summer temperature increases and lower streamflow suggest that historical drivers of streamflow may be shifting as a consequence of climate change.

Brahney et al. (2017a) employed a double mass curve technique for glaciated and non-glaciated streams to estimate changes in runoff due to glacial retreat and the disappearance of perennial snow and ice (cryosphere storage) in the Canadian Columbia River Basin. Estimates of cryosphere storage from this technique were similar to those from direct measurements and mechanistic models. The authors estimated average runoff declines of 26% from 1975 to 2012. Declines in runoff were expected to continue both annually and for the late summer period.

Due to the influence of snow accumulation and ablation on the timing of streamflow in the Columbia River Basin, it is important to monitor snowpack in the region. However, finding sites that represent accumulation and ablation processes can be a challenge. Gleason et al. (2017) used a coupled modeling approach to identify representative snow-monitoring locations in the McKenzie River Basin, Oregon. They utilized a binary regression tree statistical model to classify terrain based on estimates of accumulated snow water equivalent as a consequence of physiographic landscape characteristics. Sites were randomly selected from resulting snow water equivalent categories.

To inform best management practices for agriculture, Malek et al. (2017) developed a platform that congruently captures atmospheric influences on water supply with crop demand. They coupled the VIC hydrologic model with the CropSyst agricultural model to provide simulations of water availability, crop water requirements, and agricultural productivity. Their VIC-CropSyst model can be used in conjunction with socioeconomic models, river system models, and atmospheric models to inform land-atmosphere interactions and the economic influence of different environmental conditions and management decisions.

The Pacific Decadal Oscillation (PDO) has been recognized as a leading index of sea surface temperature variability in the North Pacific Ocean since its introduction in the 1990s. Newman et al. (2016) revisited the PDO and pointed out that it reflects multiple interacting processes working on different time scales. They concluded that researchers should use caution when describing the PDO as a driver of non-oceanic responses in the absence of a convincing physical forcing mechanism, and that rather than a driver of other processes, the PDO may be correlated with them due to a common forcing mechanism. Newman et al. (2016) proffered that climate models may provide the best means to determine causative links between the PDO and non-oceanic processes. However, they noted that present climate models do not realistically capture these interactions.

Reilly et al. (2017) combined Landsat time series data with field measurements of tree mortality to map burn severity as low, moderate, or high in Pacific Northwest forests from 1985 to 2010. They examined temporal trends in relation to environmental conditions and compared results between vegetation zones. Temporal and spatial trends towards larger patches of high-severity fire were found related to drought condition and annual fire extent, affirming previous observations. The authors concluded that concern over increases in high-severity fires in some dry forests is justified. Based on their results, they assert that allowing wild fires to burn during cool, wet conditions may ultimately reduce the number and size of high-severity fires over broader geographic scales.

Projections

Rupp et al. (2017a) utilized an ensemble of CMIP5 global climate models to produce climate change projections for the Columbia River Basin. Under the respective RCP 4.5 and 8.5 emission scenarios, their models projected increases in mean annual air temperature of 2.8 and 5.0°C above a 1979-1990 baseline by the late 21st century. Warming was expected to be more substantial during summer, and annual precipitation was predicted to increase by 5-8% with decreases in summer and increases in winter. However, they observed less certainty in predictions of precipitation compared to temperature. They discuss aspects of the predictions, models, and remaining uncertainties.

Also using downscaled CMIP5 global climate models, Ahmadalipour et al. (2017b) evaluated predicted changes in precipitation, maximum temperature, and minimum temperature for the Columbia River Basin. Reconstructions from a historical period of 1970–2000 were compared to a future period of 2010–2099 using both the RCP 4.5 and RCP 8.5 emissions scenarios. As observed by Rupp et al. (2017a), projections suggested significant increases in annual precipitation and temperature, with the magnitude of changes varying across sub-basins and depending on the representative concentration pathway. While variability across GCMs appeared to be the primary source of prediction uncertainty, downscaling contributed considerably to total uncertainty.

In a more geographically focused study, Ahmadalipour et al. (2017a) utilize downscaled climate predictions combined with hydraulic modeling to investigate predicted changes in spatiotemporal patterns of droughts in the Willamette River Basin, a major tributary of the Columbia River. Streamflow was predicted to increase in wet winter months and decrease in dry summer months. Models also predicted increases in evapotranspiration, reductions in soil moisture, and increases in infiltration and percolation. These changes combined to create more severe hydrological droughts, despite predicted increases in annual precipitation.

Turner et al. (2017) developed a spatially explicit modelling framework utilizing three CMIP5 climate scenarios to predict changes in land cover, land use, and ecophysiology in the Willamette River Basin of Oregon. They simulated change in basin-wide water balance dynamics that account for meteorological influences, as well as change in vegetation cover from 2010 to 2100. Model results suggested warmer, wetter winters with increasing vapor pressure deficits. Upland burned areas were expected to increase. Decline in an index of basin-wide mean leaf area corresponded to a decline in evapotranspiration. Increases in CO_2 were expected to further reduce evapotranspiration by altering stomatal conductance. These cumulative effects were predicted to lead to increases in annual streamflow.

Islam et al. (2017) leveraged CMIP5 climate models to drive the variable infiltration capacity (VIC) hydrographic model in predicting climate-driven changes in snowpack contribution to water supply of the Fraser River watershed in Canada. They compared water supply estimates for a historical baseline period (1980–2009) and a future projection period (2040–2069: 2050s) informed by RCP 4.5 and 8.5 scenarios. Despite a small increase in mean precipitation, the fraction of precipitation falling as snow was projected to decline nearly 50% by the 2050s. As in the Pacific Northwest, models also predicted a decline in snowpack and earlier spring runoff.

Washington State experienced a drought and the most extensive wildfires on record in 2015, in large part due to extremely low snowpack and high temperatures. Marlier et al. (2017) explored whether the 2015 drought was characteristic of future conditions expected to result from climate change. They compared the 2015 snowpack to past conditions (1950-present) and future predicted conditions (mid-21st century). Future climate projections were derived from downscaled output of the CMIP5 under the RCP 4.5 global emissions scenario. Results suggested that the drought in 2015 was directly related to warmer winter temperatures that led to a reduced snowpack.

This finding contrasts with the historical situation, in which low winter precipitation was the predominant driver of drought, a result expected from warmer temperatures in climate change scenarios. The amount of precipitation was normal in 2015, and thus Marlier et al. (2017) concluded that 2015 was an indicator of future consequences of warmer winter temperatures. Their results suggest that temperature-controlled snowpack (rather than precipitation-controlled snowpack) will be the norm by mid-century.

Sproles et al. (2017) compared low snowpack in 2015 in the McKenzie River Basin in Oregon, to predicted snowpack with climate change. They used spatially distributed values for precipitation and snow water equivalence computed with the process-based SnowModel (Liston and Elder 2006) for 1989-2012. They then ran the model with a temperature increase of 2°C. Results suggest that basin-wide snow water storage for the winter 2015 would still be below the average under a 2°C temperature increase scenario. In contrast, the low snowpack year of 2014 (which was less extreme than 2015) would be closer to an average year in a warmer climate.

Stream temperature

Retrospective

Garner et al. (2017) explored the influence of vegetation density, channel orientation, and water velocity on stream temperature in a simulation experiment. They used hemispherical image data representing different uniform canopy density scenarios to parameterize a deterministic net radiation model and simulate radiative fluxes. Higher water velocities had a cooling effect on stream temperatures, while intermediate levels of shade had highly variable effects, depending on channel orientation and the time of day when shading occurred. Results suggest that relatively low levels of shading with strategically placed vegetation could provide substantial reductions in maximum temperatures. These results could be used to implement cost-effective management of riparian restoration.

Forest harvest practices in Oregon during the 1960s led to dramatic increases in stream temperature. New rules were developed to reduce this impact. The rules that apply to state forest lands are stricter than those applied to private land. To assess the effectiveness of these rules, Groom et al. (2017) compared temperature changes pre- and post- harvest on private and state lands. They found that maximum 7-d temperatures increased post-harvest in some private forest sites but not in state forest sites, suggesting that the rules that applied to state-owned forestry activity generally met temperature criteria.

Leach et al. (2017) explored spatial and seasonal variability in stream temperature in headwater streams of western Oregon. They found that temperature in these small headwater streams can vary at small spatial scales, and that the extent of this variability is seasonally dependent. They also compared the NorWest predictions of (Isaak et al. 2017) to monitoring data for these small streams. They noted that while NorWest predictions captured the central distribution of temperatures in these small headwater streams, they did not describe the complex patterns observed.

Laizé et al. (2017) aimed to improve the understanding of large-scale spatial and temporal variability in climate–water temperature relationships, and to assess the influence of basin characteristics on these relationships. Using data from 21 rivers in

Great Britain, the authors fit seasonal and year-round models to predict 3-month average temperatures. Results suggest that atmospheric heat exchanges influence small upland, and/or impermeable (low groundwater influence) basins most, with less influence on larger lowland, permeable basins. They used the study to highlight the importance of accounting for spatial and temporal variability in climate-stream temperature relationships when modeling stream temperature.

Most process-based stream temperature models are not capable of simulating the influence of transient snow cover on thermal regimes in headwater streams of the rain-on-snow zone. To fill this gap, Leach and Moore (2017) developed and evaluated a model that simulates canopy interception, snow accumulation and melt, hillslope through-flow, and stream channel energy exchange processes to predict daily temperature in a forested catchment near Vancouver, Canada. Models generally predicted stream temperature well, though over-predictions were prevalent in the summer low-water period. Their results highlight the importance of lateral advection on stream temperatures in montane headwaters, particularly during the winter wet season.

Variability in stream temperatures has important ecological consequences, and thermal habitat diversity can allow organisms to maximize growth and survival through thermal regulation. Steel et al. (2017) reviewed new information and tools that can help describe patterns in, and influences on, thermal regimes related to ecological and management concerns. They suggest methods of improving management projects and describe opportunities for better management of thermal landscapes in streams.

Projections

Global climate change will alter spatial and temporal patterns in stream temperature. Temperature-sensitive species such as salmonids are likely to be among the most affected by thermal changes that effect habitat suitability for growth and survival. Accordingly, accurate stream temperature modeling is increasingly important to understand thermal regimes and predict changes for salmonid management.

Jones et al. (2017) predicted the response of stream temperatures to climate change in the Rocky Mountains of southern Canada and the northern U.S. They used spatially explicit statistical models to predict mean monthly stream temperatures under RCP 4.5 and 8.5 emission scenarios. Increases in stream temperature were predicted to be similar between scenarios by 2035, but substantially higher in the RCP 8.5 scenario by 2075. Model results suggested that the greatest warming will occur in the shoulder months of winter (April and November) and in glacial-fed streams that lose their source glaciers.

Isaak et al. (2017) collected and organized temperature records from throughout the western U.S. to create the publicly available NorWest temperature database.[3] They utilized the existing database to fit spatial stream-network models that describe mean August temperatures. Models were fit to 40 years of historical data (1976–2015) and used to predict future stream temperatures with climate change. Reconstructions indicated average warming across the region at a rate of ~0.17°C/decade during the historical period. Model predictions suggest that this rate of warming will continue, although the authors note that variation in trends will depend on local climate forcing and stream responsiveness.

Justice et al. (2017) explored the potential for stream and riparian restoration to offset the impacts of climate change on salmon populations. They utilized a deterministic stream temperature model to explore potential benefits of channel and riparian restoration on stream temperatures in the Upper Grande Ronde River and Catherine Creek Basins in Oregon. They focused on streams that had been degraded by intensive land use leading to reduced riparian vegetation and widened channels. Justice et al. (2017) concluded that restoration of such streams could more than make up for expected increases in summer stream temperatures through the 2080s, with substantial benefit to juvenile Chinook salmon.

In a study focused on the Middle Fork John Day River in Oregon, McHugh et al. (2017) leveraged reach-scale habitat models linked to basin-scale life cycle models to evaluate restoration priorities for steelhead *O. mykiss*. Results suggested that in terms of reducing quasi-extinction risk for steelhead, increasing riparian vegetation to reduce limiting stream temperatures was more beneficial than adding woody debris to increase channel complexity.

California Current

Retrospective

Raimonet and Cloern (2017) explored the connection between oceanic and estuarine conditions by comparing monthly time series of temperature and chlorophyll-*a* in San Francisco Bay to those in adjacent waters of the California Current Ecosystem (CCE). Temperature fluctuations were correlated inside and outside the bay, but weakened with distance from the ocean. In contrast, monthly values of chlorophyll-*a* were not correlated between the ocean and estuary; however, on an annual scale, chlorophyll-*a* was correlated with the spring transition index. The authors interpreted

[3] Available at www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html

these results as reflecting estuary-ocean connectivity as a slow and delayed biological process operating via estuary immigration of fish and crustaceans that consume bivalves: increased consumption of bivalves in turn reduces grazing pressure and allows a buildup of phytoplankton biomass.

Messié and Chavez (2017) predicted zooplankton concentrations using a model based on growth/grazing equations coupled with estimates of nitrogen distribution. They apply the model to California, Peru, Northwest Africa, and Benguela. Model results matched well with ship-measured results, with estimated zooplankton concentrations patchy in nature and driven primarily by wind and surface currents. Results highlight the importance of upwelling and surface currents on patterns of plankton concentrations.

Summer upwelling along the U.S. West Coast is driven by prevailing coastal winds. Utilizing satellite data, Flynn et al. (2017) examined patterns in sea-surface temperature response to wind intensification and relaxation cycles. Substantial anomalies related to these cycles were observed to extend far offshore. After re-intensification of winds, SSTs became anomalously cold along central and southern California. These cold SST anomalies persisted, but warmed over the following days. Heat exchange processes during wind relaxations in the Pacific Northwest were found to differ from those in California due to cloud cover.

To determine natural variability and environmental determinants in epipelagic forage communities of the CCE, Santora et al. (2017a) analyzed a 26-year record of oceanographic midwater trawl survey data (1990-2015). Two alternate forage species assemblages were identified based on temperature and upwelling strength. Cool years were associated with increased diversity of juvenile groundfish, while warm years were associated with increased coastal and mesopelagic fishes. Additionally, warm years were characterized by increases in species originating from southern and subtropical waters. Unprecedented biodiversity was observed in the anomalously warm year of 2015. The uniqueness of 2015 was discussed in comparison to other warm years.

In a companion work, Santora et al. (2017b) show that distributions of trophic hotspots in the southern CCE resulted from interaction between strong-upwelling areas and nutrient-retention zones, which concentrated prey and predators across multiple trophic levels. They cautioned that overlap of trophic hotspots with fisheries and shipping routes can increase vulnerability of the ecosystem to forage fish depletion and ship strikes on marine mammals.

Projections

Alexander et al. (2018) used global climate models to assess changes in the mean, variability, and extreme warm and cold sea surface temperatures (SST) in large marine ecosystems of the northern hemisphere. They utilized the RCP 8.5 or "business as usual" emissions scenario to compare predicted trends in SST during the 21st century to those during the historical period of 1976-2005. A substantial increase in mean SSTs was expected during 2070-2099, with temperatures in many regions exceeding those of the warmest years during 1976–2005. They also reported that mean temperature increases were generally larger in summer than in winter because atmospheric heat is integrated over a more shallow mixed layer during summer.

Upwelling along the CCE is regulated by alongshore wind stress and brings nutrient-rich waters to the surface, supporting phytoplankton blooms that form the basis for ecosystem productivity. Brady et al. (2017) investigated potential anthropogenic effects on wind stress and the resulting magnitude of upwelling from 1920-2100. They utilized a model ensemble forced by historical emissions and the RCP 8.5 emissions scenario. Their ensemble had good agreement with the historical period. Results suggest that while anthropogenic effects were obscured by interannual variability during the historical period, these effects will become apparent in the second half of the 21st century. Specifically, the magnitude of upwelling is likely to increase in spring, particularly in the northern CCE, with large reductions in upwelling throughout the summer across the CCE.

"The Blob"

Ocean conditions were anomalously warm in the northeastern Pacific Ocean from 2014-2016, a phenomenon frequently referred to as "The Blob." "The Blob" conditions were unprecedented both in the magnitude of the anomaly and its form, which was distinct from previously described oceanographic patterns such as El Niño or the PDO. Researchers have begun to explore the characteristics of this anomaly, its source, and its effects on biota. Below we summarize research from 2017 describing physical effects of "The Blob" and its consequences on the CCE marine ecosystem.

Gentemann et al. (2017) used satellite-blended reanalysis products and the Bakun Upwelling Index to describe patterns in wind and SST anomalies off the West Coast during 2014-2016. While offshore SST anomalies were stronger in the north, onshore anomalies were larger in the southern CCE with a maximum SST of 6.2°C occurring in September 2015 just south of Point Conception, California. Onshore anomalies were largely persistent through the period, only abating during initiation of the spring upwelling season from May-June each year. Weak wind-driven upwelling seasons, particularly during 2015, contributed to the anomalously high temperatures and associated ecosystem disturbances.

Chao et al. (2017) explored the origins of anomalously warm water temperatures off the coast of central California and within San Francisco Bay from 2014-2016. Observations and model runs suggested that initial coastal warming in 2014 originated from anomalously warm surface conditions offshore (The Blob). This initial warming was subsequently influenced by additional warming from the 2015-2016 El Niño event. They concluded that similar anomalously warm events could potentially be predicted months in advance or earlier because the warming of coastal and San Francisco Bay waters was due to a relatively slow progression of events.

Peterson et al. (2017) examined the physical attributes of Oregon coastal waters and described changes in the phytoplankton and zooplankton communities associated with "The Blob." They found unprecedented changes in the plankton community, characterized by increased species richness in copepod, diatom, and dinoflagellate species. Increased richness resulted from the addition of a number of copepod species that are generally seen only further south. Fourteen species of southern copepods were observed that had never been seen before off the Oregon coast. Despite higher species richness, copepod and euphausiid biomass was reduced, while the abundance of larvaceans, doliolids, and toxic diatom blooms (*Pseudo-nitzschia*) was increased. The authors concluded that low lipid content of the zooplankton community had likely caused cascading trophic effects during "The Blob" period.

Also observed during "The Blob" period were extreme harmful algal blooms caused by plankton diatoms of the genus *Pseudo-nitzschia australis*. Harmful algal blooms affected much of the CCE during 2015 (McCabe et al. 2016). Ryan et al. (2017) attempted to described the extent of toxicity and causality of these blooms in Monterrey Bay, California; they found the highest concentrations of the biotoxin domoic acid ever recorded there. As in other areas of the CCE, initiation of the bloom occurred during the spring upwelling transition, when anomalously warm temperatures were temporarily reduced, leading to good phytoplankton growing conditions.

Ryan et al. (2017) suggest that the extent of toxicity may have been a consequence of the highly anomalous nutrient concentrations that preceded the bloom. Specifically, they found low concentrations of nitrogen and silicate followed by depletion of silicate during the bloom, which may have contributed to the level of toxicity. In laboratory studies, ambient silicate concentrations were been found inversely related to domoic acid production by *Pseudo-nitzschia* (Pan et al. 1996a; Pan et al. 1996b).

Anomalous conditions in the California Current, which co-occurred with “The Blob,” contributed to unusually strong and early dampening of El Niño effects along the central and southern California coast in late 2015. Frischknecht et al. (2017) aimed to determine the causes of this phenomenon. They utilized a suite of hindcast simulations using the Regional Oceanic Modeling System. Their results suggested that the abrupt end of anomalous conditions was a result of the unusual onset of upwelling-favorable winds in fall 2015.

Conditions were also warm in the Bering Sea during the "The Blob" period. Following a cold period of extensive sea ice from 2007 to 2013, the Bering Sea returned to a warm, low sea-ice state in 2014 (Stabeno et al. 2017). Dedicated surveys in 2015 and 2016 produced evidence of reduced spring phytoplankton biomass over the southeastern Bering Sea shelf, lower abundances of large-bodied crustacean zooplankton, and degraded condition of age-0 pollock (Duffy-Anderson et al. 2017).

Advancements in modeling and monitoring

García-Reyes and Sydeman (2017) presented an updated version of the regional Multivariate Ocean Climate Indicator (MOCIv.2) for the California marine ecosystem. Their MOCI version was stratified by season into three indicators for the northern, central, and southern Californian coasts. They simplified the model to include the principle component of a number of established climate indices and physical measurements. The authors demonstrate that MOCIv.2 has strong correlations with regional physical and biological responses.

Autonomous underwater spray gliders provide sustained observation of ocean conditions. Rudnick et al. (2017) described operations and products of the California Underwater Glider Network (CUGN). They interpreted nearly continuous data derived from over 10,000 glider days covering 210,000 km to a depth of 500 m. Gliders surveyed onshore-to-offshore transects, producing continuous measurements including pressure, temperature, salinity, and depth-averaged velocity. Rudnick et al. (2017) present a climatology comprised of rectangular grids using a mean field, an annual cycle, and anomalies from the annual cycle for each variable. They examined these data in the context of interannual climate anomalies during the preceding ten years.

Data from an increasing number of autonomous sensors is improving insights into physical and biological ocean dynamics and global change. The Monterey Bay Aquarium Research Institute has developed a reagent-free, in situ ultraviolet spectrophotometer (ISUS) for measuring dissolved nitrate. The ISUS is designed for deployment on a variety of platforms. Sakamoto et al. (2017) described a 15+ year record of nitrate observations from a mooring buoy in Monterey Bay, California. The resulting dataset describes seasonal and interannual variability, including El Niño and La Niña water-mass anomalies.

Using observations from different types of ocean satellite and in situ observing systems, Moore et al. (2017) evaluated the impact on ocean circulation estimates and forecasts in the California Current over a three-decade time-series (1980-2010). Circulation estimates were computed using a 4-dimensional variational (4DVar) data assimilation system. Results suggest that the observation platforms can influence circulation estimates up to a decade into the future.

Kurapov et al. (2017) performed a six-year (2009-2014) simulation using an ocean circulation model to describe variability in subsurface conditions along the continental slope of the northeastern Pacific coast. Their model captures seasonal cycles in upwelling/downwelling, as well as the timing of summer temperature changes when subarctic waters are replaced by warmer Californian waters. The authors found that modeled seasonal patterns in temperature and upwelling were similar to shipborne and glider-produced measurements.

Ocean acidification and dissolved oxygen

The seasonal upwelling of "acidified" (low pH and carbonate concentrations) and oxygen-depleted waters is a natural phenomenon in the CCE. However, increases in the oceanic uptake of CO_2 as a consequence of climate change have expanded the extent of areas affected by acidification (Feely et al. 2008). Naturally low carbonate concentrations make the CCE sensitive to continued effects from climate change. Consequently, projections of future ocean acidification in the CCE suggest continued temporal and spatial expansion of affected areas in conjunction with increases in temperature and deoxygenation (Gruber et al. 2012). Such expansions pose compounding threats to the rich ecosystem of the region (Bijma et al. 2013).

Due to the threats posed by ocean acidification and deoxygenation in the CCE, Klinger et al. (2017) suggest the importance of incorporating management strategies to maintain and improve resiliency in the ecosystem and dependent fisheries. Identified strategies include designation of marine protected areas that can serve as spatial refugia; management of fisheries in an ecosystem context that can react to variable and changing conditions; and coastal management practices that reduce nutrient pollution and protect aquatic vegetation habitats, such as seagrass and kelp beds, to improve local conditions.

Retrospective

Despite considerable interannual variability, the oxygen content of upwelling waters in the CCE generally increased from the 1950s to 1980 followed by a strong decrease from the 1980s to the 2000s (Koslow et al. 2011). Pozo Buil and Di Lorenzo (2017) utilized a combination of reanalysis products and observations between 1950 and 2010 to investigate the connection between decadal-scale patterns in the oxygen content of CCE upwelling waters and the transport of subsurface water anomalies in the North Pacific Gyre system. They suggest that the North Pacific Current propagates water anomalies downstream into the CCE upwelling system. Thus, by monitoring salinity anomalies (a proxy for oxygen) in the North Pacific Gyre system, trends in the oxygen content of upwelled waters in the CCE may be predictable over a decade in advance. At present, salinity anomalies in the gyre suggest that the CCE will experience low-oxygen anomalies by 2020.

Durski et al. (2017) utilized a regional-scale physical biogeochemical simulation to discern the physical dynamics behind spatial and temporal patterns in dissolved oxygen content and "spiciness" (salinity and temperature) on the West Coast. Results of their model run, simulating years 1981-2006, were able to capture the trend toward lower dissolved oxygen previously described for this period. Model simulations suggest that years with high productivity due to strong nutrient upwelling combined with a robust northward undercurrent along the continental shelf had the lowest anomalies in dissolved oxygen concentration.

The nearshore environment of the CCE contains ecologically productive habitat essential to the recruitment of economically important species. Chan et al. (2017) utilized a network of pH sensors in intertidal habitats throughout the CCE to analyze temporal and spatial patterns of nearshore ocean acidification during the summer upwelling season. They found consistent hotspots that experienced suboptimal conditions for calcifying organisms, while other areas remained less affected. Chan et al. (2017) suggest that heterogeneity in nearshore ocean acidification patterns create opportunities for local adaption and resilience to future increased acidification.

Projections

Long et al. (2016) utilized a global-scale, large-ensemble model under the RCP 8.5 emissions scenario to identify when anthropogenically forced declines in oceanic dissolved oxygen may be statistically detectable from climate variability within the model. Their results suggest that decreases in dissolved oxygen will exceed modeled interannual variability by the 2030s-2040s, after which declines are predicted to be rapid. Declines in dissolved oxygen in the North Pacific Ocean are predicted to be particularly strong, possibly due to poor mixing. Additional declines in DO may further effect the

CCE upwelling system due to previously described current connections in the North Pacific Gyre system (Pozo Buil and Di Lorenzo 2017).

Marshall et al. (2017) utilized an ecosystem model (Atlantis), forced by downscaled climate models and informed by species-specific pH sensitivities, to investigate the effects of ocean acidification on the CCE ecosystem and dependent fisheries. They predicted the pH would decline by 0.2 units from 2013 to 2063. Direct effects of increased acidification were predicted to be substantial for epibenthic invertebrates, including crabs, shrimps, benthic grazers, benthic detritivores, and bivalves. Cascading trophic effects were expected for some species of demersal fish, sharks, and invertebrates that consume pH-sensitive species. Model results suggest that acidification will negatively impact invertebrate fisheries, while impacts for groundfish fisheries will be mixed due to distinct responses by species.

Experiments studying ecological responses to OA

While physiological effects of ocean acidification on marine organisms have been long recognized, the aquaculture industry has been farming fish with minimal reported impacts under CO_2 concentrations beyond those predicted for 21st century. Ellis et al. (2017) attempted to explain this apparent discrepancy. They identify four possible explanations: 1) the use of "control" CO_2 conditions in aquaculture studies that are often much higher than natural marine conditions; 2) the benign aquaculture environment, with abundant food and no predators; 3) aquaculture species that have in part been chosen due to their tolerance of extreme conditions; and 4) aquaculture breeding that generally selects for acidification tolerance. The authors conclude that further integration of aquaculture and climate change sciences could provide useful insights to both fields.

Pteropods, a prey species for Pacific salmon (Aydin et al. 2005; Zavolokin et al. 2014a; Zavolokin et al. 2014b), are highly susceptible to changes in oceanic carbonate chemistry conditions. Thus, Bednarsek et al. (2014) identified pteropods as a bio-indicator for early effects of ocean acidification. They combined field observations, experimental results, and retrospective simulations to explore how pteropods responded to the length and magnitude of exposure to ocean acidification. Exposure history was found to affect shell calcification, growth, and survival. Additionally, they report that pteropods are at or near their physiological tolerance level in the CCE and thus at risk of extinction in coming decades under projected expansion of ocean acidification.

Davis et al. (2017) performed a laboratory study to test the effects of ocean acidification on the common calcifying foraminifer plankton species *Globigerina bulloides*. They found that calcification, oxygen consumption, and the repair of spines important for buoyancy and feeding were all reduced at pH levels between 8.0 and 7.5.

Results suggest that foraminifera will likely be detrimentally affected by future ocean conditions, which may have subsequent effects on the vertical transport of organic and inorganic carbon in oceans due to the role that these species play in this process.

Phenotypic plasticity can allow organisms to respond to changes in their environment. However, the range of responses to varying conditions is not well understood in most species. In a lab experiment, Swezey et al. (2017a) examined the effects of ocean acidification on the colonial bryozoan *Celleporella cornuta* sampled from the northern California coast. The experiment demonstrated plasticity in growth and shell mineral composition under high CO_2 concentrations. Differences between populations in reaction norms for reproductive investment and formation of protective organic covering were also demonstrated.

Climate change is likely to change temperature and other water-mass characteristics congruently with ocean acidification. The response of calcifying organisms to change in multiple oceanographic parameters is not well understood, creating uncertainty in vulnerability assessments of ocean acidification. Swezey et al. (2017b) investigated the interacting effects of CO_2, temperature, and food concentrations in a lab experiment with cultured clones of the bryozoan *Jellyella tuberculate*. They found the combination of high CO_2 and cold temperature led to degeneration of zooids (individuals) in colonies, even though colonies still maintained high growth rates under these conditions. Low-food concentration combined with elevated temperatures led to higher concentrations of magnesium, which was readily dissolved at high CO_2 concentrations. The authors suggest that for species that do not strongly regulate the uptake of skeletal magnesium, skeletal dissolution may be more common than is documented in the literature.

Carbonic anhydrases (CAs) catalyze the reaction of carbonate hydration, making them important to acid-base regulation. Wang et al. (2017) explored the physiological responses of the Pacific oyster *Crassostrea gigas* to high CO_2 exposure. Marked responses in CA activity and mRNA expression were observed. The authors suggest that a mechanism of cytoplasmic CA-based physiological regulation might explain the physiological responses of other marine organisms to ocean acidification.

Salmonid Biological Responses

Phenology

Juvenile migration timing

Weinheimer et al. (2017) investigated how flow and incubation temperature influenced survival and migration timing of juvenile chum salmon in Salmon Creek, Washington between 2008 and 2016. Peak flows during incubation were strongly negatively related to egg survival. Warmer temperatures were also related to early emergence and migration timing. Results suggest that projected future warming may result in a significantly earlier migration, which could lead to lower productivity if marine arrival is desynchronized with spring zooplankton blooms.

Vega et al. (2017) explored variability in marine-entry timing and growth rates of juvenile chum salmon in the Chukchi and northern Bering Seas off Alaska. They analyzed otoliths from juvenile chum salmon caught in surface trawl surveys in the summers of 2007, 2012, and 2013. Results suggest that juvenile chum exhibited consistent marine entry timing and early marine growth rates between years, despite annual environmental differences. This study can be used as a baseline to track future changes in early marine life-history as a consequence of future climate change.

Whether changes in salmonid phenology are a response of phenotypic plasticity or genetic adaption is generally not well understood. As described in previous reviews, one of the few demonstrations of genetic change affecting adult migration timing was provided by (Kovach et al. 2012) for pink salmon in Auke Bay, Alaska. Vega et al. (2017) speculated that the shift in adult run timing reported previously was a byproduct of selection on juvenile migration timing, which had changed concurrently with adult timing.

Manhard et al. (2017) used genetic marker alleles in fry to demonstrate a selection event that changed juvenile migration timing over a single generation. The authors argued that in 1990, late-migrating fry experienced high temperatures and associated poor growth conditions upon entry into saltwater. This late ocean-entry timing led to lower marine survival than in previous years and subsequently a substantially higher proportion of early migrating fish in the population. This change in the genetic composition of the population persisted in subsequent generations. The authors point to their study as a demonstration of how genetic diversity can allow a population to adapt to changing sea surface temperatures.

Adult movements and migration timing

Dempson et al. (2017) explored the influence of climate and abundance on the adult migration timing of Atlantic salmon in Newfoundland and Labrador, Canada. The median date of run timing varied between rivers by up to five weeks. The authors utilized a mixed model analysis incorporating a first-order autoregressive error structure. Results suggest that median run timing has shifted about twelve days earlier from 1978-2012, with some rivers changing more. Earlier runs were associated with warmer climate conditions on the Newfoundland and Labrador Shelf.

Climate change is disproportionately affecting northern latitudes. The ability to predict how migration timing might respond to environmental change depends on understanding how environmental conditions influence migration cues. Carey et al. (2017) described relationships between interannual variability in migration timing (2003-2014) and environmental conditions in a subarctic sockeye salmon population of western Alaska. Run size was found related to a longer migration period and a later midpoint in run timing. Warmer sea surface temperatures were associated with a longer run and the run-timing midpoint was delayed when river temperatures increased earlier in the season.

Shifts in phenology as a consequence of climate change can cause predator-prey mismatches that vary across life stages. Bell et al. (2017) investigated downstream and upstream migration timing of Dolly Varden predators with the migration timing of juvenile pink and other Pacific salmonid prey in the Auke Creek watershed of Alaska. Their results suggest that as a consequence of increased water temperatures, migrations of Dolly Varden have become mismatched with those of abundant juvenile pink salmon. However, as reported previously by Sergeant et al. (2015), Dolly Varden use the upstream adult salmon migration itself as a cue and have successfully maintained close synchrony with returning adults, allowing them to capitalize on salmon eggs.

Few studies connect climate-driven phenological shifts to population abundance. Kuczynski et al. (2017) investigated how temperature and flow, which are known to affect phenological events, influenced the abundance of 21 fish species in French rivers. Utilizing piecewise structural equation models, the authors found that annual variations in abundance were related to interannual variations in temperature that affected migration timing.

Plasticity and adaption

The ability of aquatic animals to adapt to thermal change may be limited by their capacity to supply tissues with sufficient oxygen to meet demand at high temperatures during sensitive life history stages (Pörtner et al. 2017). Accordingly, much research on the ability of salmonids to adapt to climate change focuses on changes in stream temperature, which can reach detrimental levels during both juvenile rearing and adult migration/spawning, thereby limiting population productivity.

Eliason et al. (2017) compared the swimming speeds and cardiac outputs of sockeye parr from distinct populations in Fraser River. Parr that resided in warm and shallow lakes had better swimming performance at higher temperatures than those from deep and cool lakes, providing further evidence that sockeye salmon parr adapted to local environmental conditions.

Sparks et al. (2017) compared developmental rates, survival, and body size at hatching in two populations of sockeye salmon *Oncorhynchus nerka* that have overlapping spawning periods but incubate in distinct thermal regimes. Results did not uncover adaptive differences in developmental rates and survival but did find strong evidence of plasticity in response to temperature, as well as family-specific heritability that could allow for adaptive changes in the two populations.

Waples et al. (2017) explored the hypothesis presented by Williams et al. (2008), that for threatened Snake River fall Chinook salmon, changes to the freshwater rearing environment caused by hydropower development have led to anthropogenically induced evolution in the juvenile life history. Previous observations demonstrated that a substantial proportion of individuals now migrate as yearlings, as opposed to the more traditional fall Chinook subyearling migration behavior.

To explore the potential for such adaptation within this population, Waples et al. (2017) examined data from 2,600 juveniles genetically matched to parents of both natural and hatchery origin. Results suggested that juvenile growth rate was largely heritable, juvenile life history of parents was associated with growth rate, and faster-growing individuals demonstrated increased evidence of earlier migration. These results indicate that the necessary conditions for evolution in migration age do exist in this population.

Ward et al. (2017b) described evidence of plasticity in life-history characteristics of rainbow trout in relation to climate variability and density. The authors used experimentally stocked trout to test predicted life history responses in growth rate, age/size at maturity, and allocation of energy to reproduction. Prematuration growth rates were best explained by climate and density-dependent competition effects. Age-at-maturity and energy allocated to reproduction were then dependent on juvenile growth rates.

Lin et al. (2017) utilized stochastic, individual-based models to simulate the evolutionary and demographic effects of dispersal and selection pressure on sockeye populations. Results suggested that significant demographic and phenotypic consequences could occur on short time scales as a result of factors such as selective fisheries or environmental change.

Jeffrey et al. (2017) characterized changes in body size of Pacific salmon species caught in Canadian waters from 1951 to 2012. Chinook and coho were found to have substantially declined in size during the 1950s and 1960s before recovering to their original size or larger in later decades. In contrast, early declines in the size of pink and chum salmon were found to have halted, and sockeye exhibited no discernable long-term trend. Biomass of competing salmon was found to influence the size of all species, and climate metrics including the Multivariate ENSO and North Pacific Gyre Oscillation were found to influence four species.

Shuntov et al. (2018) provided a critical review of some contemporary views on marine ecology of Pacific salmon during the last century. Their discussion included the influence of sea surface temperature on the distribution of salmon, food shortage and competition for food in winter, pink salmon suppression of other salmon species through interspecific competition, and change in epipelagic communities in ecosystems of the North Pacific Ocean due to chum salmon stock enhancement. They conclude that some prevailing views on these topics have not been confirmed by data from long-term monitoring of the North Pacific Ocean conducted since the 1980s by the Pacific Research Fisheries Center (TINRO Center).

While climate-change vulnerability assessments can be useful in prioritizing management actions, most assessments to date have failed to account for adaptive ability (Thompson et al. 2015). Wade et al. (2017) attempted to account for adaptive capacity in a climate-change vulnerability assessment for steelhead and bull trout in the Columbia River Basin. Estimates of adaptive capacity were based on metrics of habitat quality, demographic condition, and genetic diversity. Both species were found vulnerable to climate change, particularly in the southern and low-elevation parts of their range. However, vulnerability varied greatly depending on the species and specific location.

Population resiliency

Ward et al. (2017a) used time-series methods to explore determinants of population decline in Pacific herring and in some salmon populations during the 1990s following the Valdez oil spill in Alaska. They found support for intraspecific density-dependence in herring, sockeye, and Chinook salmon and a negative effect of pink salmon density on sockeye. However, their evidence did not indicate that the oil spill resulted in the population collapses. Herring productivity was strongly related to changes in environmental conditions effecting freshwater influx to the Gulf of Alaska.

For many salmon populations, climate change is expected to be largely detrimental at the southern extent of the range and to open potential colonization opportunities at the northern end. However, responses in the central range are likely to be complicated and population dependent. Schoen et al. (2017) explored changes in climate, hydrology, land cover, salmon populations, and fisheries over the past 30–70 years in the Kenai River of Alaska, which supports a number of renowned fisheries. Diverse population dynamics of different populations demonstrated the importance of non-climate factors in mediating responses to climate change. Consequently, one cannot assume that northern salmon populations will benefit from climate change.

Glacial recession as a consequence of global warming is opening up new opportunities for salmon colonization. Scribner et al. (2017) explored the importance of stream geomorphology and age on colonization events and gene flow in coho salmon of Glacier Bay National Park, Alaska. They utilized measures of genetic diversity within and among populations, combined with historical information on glacial recession, to inform approximate Bayesian computation model simulations. Results suggest that sustained gene flow from large populations is important to metapopulations recently established in newly available habitat.

Disease susceptibility

Proliferative kidney disease (PKD) is common disease affecting salmonids and stems from an infection by the myxozoa parasite *Tetracapsuloides bryosalmonae.* Bailey et al. (2017a) found that infection prevalence and pathogen load were higher at warmer temperatures in rainbow trout. In a study of wild brown trout, Bruneaux et al. (2017) found that PKD severity was positively correlated with anemia and circulating thrombocytes and negatively correlated with aerobic performance and thermal tolerance. Thus PKD, in addition to other, previously recognized diseases, may become an increasingly severe issue with higher temperatures as a consequence of climate change.

Rainbow trout that survive PKD are reported to not develop the disease again when re-exposed. In an effort to describe the mechanism of immunity, Bailey et al. (2017b) compared disease susceptibility and the immune response of naïve 1+ rainbow trout vs. 1+ rainbow trout re-exposed to *T. bryosalmonae*. Re-exposed fish had no response or mounted a quicker immune response, as demonstrated by a greater number of IgM+ B cells in the blood and by elevated mRNA levels of secretory IgM in the posterior kidney. This response in re-exposed fish minimized both pathogen burden and kidney inflammation, suggesting that rainbow trout have learned immunity to PKD.

Prolonged residence time in waters containing infectious parasites leads to higher risks of infection. Accordingly, different juvenile populations are likely to exhibit distinct parasite infection rates. Mahony et al. (2017) collected Fraser River sockeye in the Strait of Georgia from 2010 to 2012 and screened them for enzootic parasites (*Myxobolus arcticus*, *Parvicapsula minibicornis*, *Ceratonova shasta*) and the bacterium *Renibacterium salmoninarum*. Infection with *P. minibicornis* was more prevalent in salmon caught in the lower Fraser River spawning zone and increased with distance from the river mouth. Infection with *M. arcticus* was more prevalent in salmon from the middle spawning zone. *R. salmoninarum* and *C. shasta* were not detected.

Relevant ecological studies

Freshwater rearing

Understanding the effects of changing stream temperatures as a consequence of climate change on fish populations is necessary for management. Normal fish activities require metabolic consumption of oxygen, and oxygen demands are increased at higher temperatures (Clarke and Johnston 1999). To better define the range of suitable thermal habitat for juvenile Chinook salmon from the Central Valley, California, Poletto et al. (2017) tested the aerobic performance of individuals acclimated at 15 and 19°C to a range of acute temperature changes (12-26°C). Fish consistently demonstrated the ability to maintain aerobic capacities up to 23°C. Similar results have been found in studies of Central Valley steelhead (Verhille et al. 2016). However, the findings of Poletto et al. (2017) contrast with those of other salmonid studies, which have demonstrated a clear peak in aerobic performance at lower temperatures (Eliason et al. 2013; Eliason and Farrell 2016).

Haskell et al. (2017) investigated the feeding ecology of subyearling Chinook salmon in reservoirs of the Columbia River Basin. They explored behavior and growth in relation to the density of *Daphnia* and used bioenergetic models to estimate growth across a range of water temperatures and daily rations of *Daphnia* and American shad.

Results suggest that while shad were a better prey source than *Daphnia*, achieving positive growth as piscivores would require subyearlings to feed at higher consumption rates than empirically observed. Thus, growth in reservoir habitats may be limited, particularly at high temperatures.

Fullerton et al. (2017) explored juvenile Chinook salmon growth in relation to changes in annual thermal regimes as a consequence of climate change. Simulations of a spatially structured, individual-based model indicated that salmon size and smolt date were more sensitive to changes in temperature during spring and summer than during winter. Their results also suggest that network topology may influence the response of fish to changes in the thermal landscape and that spatiotemporal context should be included in discussions of adaptive capacity and long-term viability of populations.

Martin et al. (2017) compared predictions of temperature-related egg mortality in Chinook salmon from a model parameterized by laboratory measurements vs. field data. They found that the laboratory parameterized model measurements greatly underestimated field-derived estimates of thermal mortality. They utilize a mass transfer theory model to show that the discrepancy was a consequence of different water velocities in the lab vs. the field and proffer that flow and temperature-mediated oxygen limitation were the primary mechanisms of thermal tolerance in fish embryos.

In a study of juvenile Snake River steelhead rearing in a small tributary creek, Myrvold and Kennedy (2017) investigated the relationship between growth rate, water temperature, and juvenile size. Results suggest that while larger individuals generally attained higher growth rates, presumably as a consequence of an ability to defend better feeding locations, the advantage of large size diminished at higher temperatures.

As commonly observed in other West Coast rivers, the Sacramento River has been largely disconnected from its extensive floodplains, leading to reduce rearing habitat for juvenile salmonids. Takata et al. (2017) explored relationships between environmental variables and residency time, growth, migration, migratory phenotype, and survival of juvenile Chinook salmon. They utilized flood plain areas of the partially leveed Yolo Bypass, the largest remaining off-channel floodplain of the Sacramento River. Wild juveniles grew more during warmer, inundated years, and flood duration was associated with the achievement of larger size. No significant difference in survival was found between juveniles that used the bypass floodplain and those that did not.

The oxygen- and capacity-limited tolerance (OCLTT) theory suggests that in fish, the capacity of the cardiac-respiratory system to deliver oxygen to tissues is the driver of upper thermal tolerance (Pörtner et al. 2017). Motyka et al. (2017) investigated whether acclimation to hypoxia improved critical thermal tolerance and other associated physiological variables in juvenile steelhead trout. Cardiac output was lower for hypoxia-acclimated fish than for fish under normal oxygen conditions, and no difference in critical thermal tolerance was observed. Nonetheless, hypoxia-acclimated fish consumed more O_2 per volume of blood pumped, which helped compensate for reduced cardiac capacity, indicating that mechanisms other than cardiac output are important for stress tolerance. Motyka et al. (2017) concluded that cardiac function is not the single driver of temperature-induced changes in oxygen consumption as described in the OCLTT theory.

Heterogeneity of available water temperatures within streams may help juvenile salmonids regulate their metabolism to best take advantage of the amount of food available given their developmental stage. For example, in a controlled study, Boltana et al. (2017) reared juvenile Atlantic salmon *Salmo salar* with access to a large range of temperatures within which they could self-regulate. Fish reared in this experimental setting had higher rates of growth, survival, and muscle growth than fish raised in a more restricted range of temperatures.

Juvenile salmon utilize cold-water thermal refugia when temperatures are above optimum. However, within such refuge habitat, food resources may become scarce as fish densities increase. In the Klamath River of California, Brewitt et al. (2017) used temperature-logging radio tags to identify thermal habitat use and conducted isotopic analyses to identify prey sources of Pacific salmonids. They quantified potential food limitation using invertebrate drift samples and fish-density surveys. They found that while fish utilized cold-water refugia at tributary confluences for thermal regulation, the majority of their prey came from the mainstem.

Bellmore et al. (2017) constructed a model that simulates river restoration strategies to determine the most fruitful type of restoration activity for a given stream reach. They applied the model to the Methow River in Washington State and compared responses to riparian vegetation restoration, nutrient augmentation, and side-channel reconnection. Results identified side-channel connection as the best course of action for the study reach, though responses were highly sensitive to the introduction of invasive species. They suggest that assessment of restorations based on food-web structure, as opposed to habitat quality, can improve restoration planning and forecasts of response to restoration.

Wright et al. (2017) explored the effects of hydropower development, acid deposition, and climate change on water chemistry in the River Otra of Norway. They evaluated effects from these multiple stressors on the river and its land-locked and anadromous Atlantic salmon populations. Cessation of acid deposition in the 1980s has allowed pH to increase from ~5 to ~6, resulting in partial recovery of both populations.

A linked set of process-oriented models was used to simulate future climate change conditions in 2100. Minimal improvements in water quality were projected with continued reductions in acid rain, although the model results did not fully consider all effects of climate change. The authors concluded that additional decreases in acid deposition are needed to improve water quality sufficiently for population stability.

In order to properly evaluate water-use tradeoffs between instream and out-of-stream extractions, it is important to understand the nature of ecological responses to changes in stream flow. Rosenfeld (2017) reviewed research on the shape of ecological responses to changes in discharge during summer low flows, when out-of-stream water demand can be the highest. Many physical and ecological responses to flow showed evidence of non-linearity. Non-linear relationships were most common in environments near biological thresholds, such as streams at temperatures near thermal tolerance limits. Non-linear relationships are likely to increase with climate change as a consequence of increased prevalence of stressors related to high temperatures and dissolved oxygen availability.

Juvenile migration

Acoustic telemetry is commonly used to study fish movement, behavior, and survival. However, surgery can lead to higher mortality and altered behavior in tagged fish, potentially introducing bias to results if the tagged population is assumed to be representative. Deng et al. (2017) compared detection probabilities and survival of migrating Snake River subyearling Chinook salmon tagged with new injectable tags to those tagged with surgically implanted acoustic transmitters. Fish were tracked through dams on the Columbia and Snake Rivers. The injectable transmitter was detected at similar rates to surgically implanted transmitters. The injected group had higher survival compared to the surgically implanted group, suggesting that the injected tags have a reduced tag/tagging effect.

Arriaza et al. (2017) documented size-dependent transitions to the smolt stage in Carmel River steelhead, a California population that has declined over two decades despite being the target of restoration. The authors argue that efforts to improve freshwater survival, such as captive-rearing and translocation, may reduce smolt success if they lead to increased densities and thereby reduced growth. They conclude that recovery efforts will likely be most successful if they focus on conditions that promote growth in the river rather than in captivity.

Moore and Berejikian (2017) explored sources of mortality in steelhead juveniles migrating through the Salish Sea using acoustic telemetry. To isolate marine and freshwater effects, they compared survival of steelhead smolts in a reciprocal transplant experiment between a highly urbanized and hatchery-influenced system, the Green River, and a less urbanized system, the Nisqually River. Fish migrating through the Nisqually River had lower survival, which the authors attribute to the extra 64-km migration distance. They did not identify any population-origin effects.

Gosselin and Anderson (2017) investigated carryover effects from the freshwater migration experience of Snake River Chinook salmon smolts. They used a temperature tolerance experiment conducted at 23.5°C to test whether marine survival was affected by river conditions during the downstream migration or during juvenile transport. They found that the recent thermal experience of migrants was negatively correlated with survival: fish that migrated through a warmer river had lower subsequent survival. They also found a negative correlation between seasonal changes in river temperatures and marine survival. Juveniles transported by barge had lower marine survival at the beginning of the season, but substantially higher marine survival by the end. Modeling results suggested that river temperature exposure was the best predictor of marine survival and that increased survival of barged fish later in the migration season could be explained primarily by lower exposure to high temperatures as the juvenile migration season progressed.

Marine rearing

Dale et al. (2017) investigated patterns in diet composition and body condition of subyearling Chinook salmon caught in late-summer surveys off the coasts of Oregon and Washington from 1998-2012. Juvenile salmonids were primarily piscivores, but it was the percentage of invertebrate prey in their diet (14-39%) that best predicted adult returns. Survival to maturation was higher in years with increased invertebrate diets, despite lower average stomach fullness during these years. This may have been a consequence of the higher adult return rates observed for less-fit juveniles that entered the ocean during more favorable marine conditions.

Daly et al. (2017) analyzed the diets of Columbia River Chinook salmon juvenile migrants off the West Coast during May and June. They compared diets during the anomalously warm conditions of 2015 with those during the period of record from 1998 to 2015. While ichthyoplankton biomass was high in 2015, the larval composition of itchyoplankton biomass included abnormal amounts of warm-water species. Also, while Chinook diets contained high proportions of juvenile rockfish in 2015, there was a high percentage of fish with empty stomachs and poor condition. These findings correctly predicted poor adult returns in 2017.

Protected marine mammals have increased in abundance in the northeastern Pacific Ocean since their listing under the ESA during the 1970s. Pinnipeds in particular have increased in number. Chasco et al. (2017) explored competing tradeoffs between increased marine mammal predation and fisheries harvest of Chinook salmon in the northeastern Pacific. They utilized spatio-temporal bioenergetics models to estimate how the magnitude of predation by three species of pinnipeds and killer whales has changed since the 1970s. Chinook salmon biomass consumption was estimated to have increased from 6,100 to 15,200 metric tons. In comparison, Chinook salmon harvest decreased from an estimated 16,400 to 9,600 metric tons. Thus, the authors estimated that total biomass of fish removed from the population has increased since the 1970s.

Debertin et al. (2017) utilized a 39-year scale-growth record to investigate influences on marine growth in a chum salmon population from the Big Qualicum River in British Columbia, Canada. Results suggest that growth is influenced by both density-dependent competition and climate conditions. Specifically, growth was found to decrease with a higher combined biomass of chum, pink, and sockeye in the Gulf of Alaska, and this effect was magnified when North Pacific Gyre Oscillation was positive and Pacific Decadal Oscillation was negative. Additionally, results suggest that when early marine growing conditions are favorable, fewer fish mature late.

Strong correlative evidence exists between copepod species composition and survival of secondary consumers in the Northern California Current. To shed light on potential mechanisms of this relationship, Miller et al. (2017) collected phytoplankton and copepods at an oceanographic station for 19 months and analyzed changes in community composition and lipid profiles for both groups. In both communities, similar seasonal shifts in total lipid content were seen, with higher total lipids in spring and summer compared to fall and winter. Shifts in the composition of primary producers were better reflected by the timing of shifts in copepod fatty acids than by copepod species composition. Results highlighted interactions between copepods and available phytoplankton prey and the effects of these interactions on the nutritional quality of prey available to higher trophic levels such as Pacific salmon.

Yukon River Chinook salmon recently experienced a decline in productivity leading to closures of commercial and subsistence fisheries. Murphy et al. (2017) utilized data on juvenile migrant abundance from summer oceanographic surveys in the Bering Sea to provide insight on future returns of stocks from this Canadian river basin. While survival from survey capture (~September) to adult return was relatively low (5.2%), survey catches were significantly correlated with adult returns. Accordingly, they conclude that a high proportion of what drives productivity occurs in the freshwater or early marine rearing period. Increases in juvenile abundance since 2013 suggest increases in future returns.

Western Alaskan Chinook salmon is believed to spend its entire marine residency primarily in the Bering Sea. The Bering Sea ecosystem demonstrates high interannual variability, largely driven by the annual extent of sea ice, which can be characterized by warm and cool periods. Siegel et al. (2017) used a multidecadal time series of retrospective scale analysis combined with run reconstructions to examine interacting relationships between sea surface temperature, marine growth, productivity, and age at maturation in western Alaskan Chinook tributary stocks. For Chinook stocks at the northern extent of their range, warmer SSTs were correlated with younger age at maturity, largely through the vector of augmented growth. However, results also suggest that warmer SSTs may increase the prevalence of precocious males through reduced growth thresholds for early male maturation. These results suggest that anticipated future warming of the Bering Sea will lead to higher early marine growth rates and a younger average age of maturation of western Alaskan Chinook salmon, particularly in males.

Seabirds may be a reliable indicator of climatic and biotic factors affecting pelagic marine food webs. Sydeman et al. (2017) explored the relationship between seabird indicators, bottom-up climatic forces, and pink salmon competition for resources in the Bering Sea-Aleutian Island ecosystem. Murre and kittiwake breeding success was significantly higher during years with colder winter/spring conditions. The authors interpreted this finding to indicate that colder conditions in the Bering Sea tend to lead to increased productivity at lower trophic levels, producing large, lipid-rich copepods and euphausiids. Productivity increases consequently support higher trophic levels, such as seabirds. Kittiwake breeding success was also reduced during years with high pink salmon abundance, and murres were found to breed later during warm years. Thus, predicted warming in the Bering Sea with reduced sea ice (Wang and Overland 2015; Wang et al. 2012) is likely to affect ecosystem productivity and consequently seabirds in the region.

Phillips et al. (2017) examined density distributions of seabirds and prey fish (including Pacific salmon) in the Columbia River plume to determine if plume size or location effects predator-prey interactions. Murres generally foraged in the center of the plume, while shearwaters occurred in the northern part of the plume, concurrent with the highest densities of prey fish. Densities of both bird species decreased with plume size suggesting that plume size may affect predator-prey dynamics.

Wells et al. (2017) quantified the effect of ecosystem variability in the CCE on common murre predation of Chinook salmon in the Gulf of the Farallones off the central Californian coast. Results suggest that common murres generally forage near their offshore breeding sites. However, in years with low numbers of pelagic young-of-year rockfish (*Sebastes* spp.), murres forage for adult northern anchovies nearshore and incidentally consume more juvenile Chinook salmon migrants, leading to reduced salmon survival. Results demonstrate the significance of top-down impacts on salmon productivity associated with bottom-up ecosystem dynamics.

Auth et al. (2018) explored shifts in the timing and spawning location of several pelagic fish stocks during the anomalously warm conditions of 2015-2016. They describe how several species rapidly changed distribution and spawn timing in response to the warm conditions during 2014-2016. Specifically, larval concentrations in the northern California Current were the highest since annual collections began in 1988 due to increases in northern anchovy and Pacific sardine. Pacific sardines and Pacific hake experienced early spawning and a northward expansion, and northern anchovy experienced an extended spawning period. Results suggest that pelagic species will move poleward and change spawn timing as a consequence of climate change, with unforeseen consequences to food-web structures and fisheries.

Adult migration and spawning

Pre-spawn mortality is an important concern for salmon exposed to high temperatures. Temperature effects can be exacerbated in urban environments, where salmon are likely to encounter higher concentrations of pollutants and more degraded habitat, leading to more stressful conditions. In an effort to quantify these effects for coho salmon in the Puget Sound area, Feist et al. (2017) measured mortality at spawning sites across an urban gradient and compared mortality rates to spatial landscape attributes and climatic variables. They identified road density and traffic intensity as being associated with high-mortality sites. Additionally, high precipitation in summer and fall negatively affected survival, particularly in less-developed areas. They produced a map predicting spawner mortality risk throughout the Puget Sound area.

Berdahl et al. (2017) explored how social interactions may influence migration timing and movement of sockeye salmon. Returning adults tend to migrate in discrete temporal pulses, which help synchronize their arrival on the spawning beds. These movements are generally attributed to environmental stimuli despite weak correlations. The authors describe social interactions as a plausible alternative or additional explanation for observed migration pulses. They present a model that reproduces the observed migratory behavior. The authors hope that their results will inspire further research into the effects of social interactions on migration.

Bond et al. (2016) attempted to disentangle biotic and abiotic factors affecting migration speeds and straying rates of Snake River fall-run Chinook salmon. They utilized 8 years of PIT-tag data from hatchery-reared fish to explore the effects of juvenile barging, rearing location, release location, and environmental conditions during the adult migration. Straying was much more likely for fish barged as juveniles and for adults that migrated at warmer temperatures. Additionally, adult migration speeds were lower for barged fish and for fish reared at two mid-Columbia River hatcheries. The authors suggest that the high straying and slower migration speeds of barged fish indicate that adult migration success could be increased by changing barging process to allow for better imprinting by juveniles.

Modeling migration dynamics is complicated due to individual variability in behavioral response to diverse habitats and environmental conditions. Crozier et al. (2017) utilized a behavior-based simulation model to predict individual adult Snake River spring/summer Chinook salmon migration speeds through discrete reaches of the Columbia and Snake rivers from 2000 to 2013. Utilizing N-dimensional mixture models, they explore potential accounts for why migrant subpopulations behave differently (slow vs. fast migrants). Explanatory variables were time of day, water temperature, and flow at the hour of arrival for individual fish in the study reach. The authors argued that their cumulative travel-time model represents an important step towards effectively utilizing high-resolution behavioral data to better understand the effects of environmental conditions on populations.

Periodic high mortality levels have limited the recovery of spring Chinook salmon in the Willamette River of Oregon. Keefer et al. (2017) investigated the effect of fish condition on adult migration mortality in the mainstem Willamette during 2011-2014. Survival proportions ranged 0.791-0.896. Utilizing generalized linear models, the authors linked reduced survival to the spawning grounds with injuries, including descaling, marine mammal injuries, and head injuries. While some injuries were minor, they may have led to increased mortality through increased susceptibility to pathogens. In contrast, the authors found no relationship between mortality and salmon body size, energetic status, sex, origin (hatchery vs. wild), river discharge, or water temperature.

Sergeant et al. (2017) described monitoring results for dissolved oxygen regimes in relation to salmon density in small streams of southeastern Alaska with high densities of spawning pink and chum salmon. They ran a simulation model linking salmon respiration with dissolved oxygen dynamics to estimate the influence of salmon abundance, discharge, and water temperature on the potential for hypoxia. Hypoxia was observed during high-density spawning events in both monitored streams. Model results suggest that low summertime river discharge is a precursor to density-induced oxygen depletion. Climate models predict that snowfall in winter and rainfall in summer are likely to decrease in southeastern Alaska. Decreases in precipitation would likely lead to decreases in summertime flows, thereby increasing the frequency of hypoxic conditions.

Tillotson and Quinn (2017) performed a similar investigation in a small sockeye spawning stream in the Bristol Bay watershed, Alaska. Specifically, they compared

20 years of biological and environmental data with pre-spawn mortality patterns in a year with particularly high escapement (3 times the previous maximum over a 54-year record). Low dissolved oxygen was identified as a likely driver of mortality, and results from a fish-habitat model suggest that stream flow and spawning density were primarily responsible for decreases in dissolved oxygen. As concluded by Sergeant et al. (2017), these authors suggest that similar events may occur more frequently as climate change is expected to reduce flows and raise temperatures in salmon spawning habitats.

Catch-and-release management strategies have been implemented throughout North America as a conservation strategy for threatened populations while allowing harvest of more plentiful populations. Prystay et al. (2017) investigated the influence of temperature on heart rate and recovery time of sockeye salmon following a simulated interaction with a fishery. Peak heart rate and energy expenditure during recovery increased with temperature. Prystay et al. (2017) suggest that as a consequence of increasing temperatures with climate change, efforts to reduce stress will be needed if catch-and-release strategies are to remain an effective conservation strategy.

Dam management and fishery behaviors

The timing and magnitude of reservoir water releases can have dramatic effects on temperature regimes in managed watersheds. However, the amount of water needed to mitigate temperature depends on characteristics of the watershed interacting with climate. Existing flow management generally focuses on discharge rates and does not typically consider water temperatures due to the complexity of interacting influences on temperature. Using logistic regression models, McGrath et al. (2017) developed a risk-based reservoir-management approach to estimate the probability of exceeding a water temperature threshold of 22°C as a function of discharge and air temperature. Applying the model to streams in the Pacific Northwest, the authors found that minimum recommended discharges to avoid surpassing temperature thresholds were generally higher than observed summer low flows. The authors point out some places where flow management could reduce exposure to high temperatures, and others where flow management is limited in its ability to mitigate temperature threshold exceedance.

A temperature control device was constructed on Shasta Dam in 1997 to manage downstream temperatures for winter-run Chinook salmon spawning in the Sacramento River. However, the effectiveness of this device has not previously been evaluated. Sapin et al. (2017) utilized hydrodynamic models of reservoir operations to explore the ability of the temperature control device to meet downstream temperature objectives. Results suggest that the temperature control device can reduce temperature exceedances compared to more traditional dam operations. However, the authors suggest that effectiveness of the temperature control device is limited in extreme climate conditions and by the complex regulatory environment of the Sacramento-San Joaquín system. The effectiveness of this device is likely to be further limited with climate change.

Burnett et al. (2017) explored the effects of flow management on migration and spawning success in a population of Fraser River sockeye salmon. Gates Creek sockeye, a wild population, migrate roughly 400 km from the mouth of the ocean and must pass a single dam to reach spawning beds. The authors compared two flow conditions: 1) the baseline management condition, in which high attraction flows are released directly adjacent to the fish ladder entrance, and 2) an alternative condition, which attraction flows are released 10 m away from the fishway entrance to reduce flows directly experienced by fish. Adult migrants that passed during the alternative operation spent half the time recovering from dam passage and had ~10% higher survival to the spawning grounds than those that passed during the baseline operation. However, once on the spawning grounds, female spawning success was largely independent of dam passage flows.

Climate change may lead to increased variability in fishery catches. Richerson et al. (2017) utilized data from the West Coast troll fishery during and after a large-scale closure to demonstrate the diversity of response by fishing vessels to change in resource availability. They found that vessels more dependent on salmon fishing were more likely to cease fishing, while vessels with diversified target catch were more likely to continue with participation in other fisheries. However, despite substantial cross-participation, they found limited evidence that increased participation in other fisheries could offset lost revenue.

Literature Cited

Abatzoglou, J. T., and D. E. Rupp. 2017. Evaluating climate model simulations of drought for the northwestern United States. International Journal of Climatology 37:910-920.

Ahmadalipour, A., and H. Moradkhani. 2017. Analyzing the uncertainty of ensemble-based gridded observations in land surface simulations and drought assessment. Journal of Hydrology 555:557-568.

Ahmadalipour, A., H. Moradkhani, and M. C. Demirel. 2017a. A comparative assessment of projected meteorological and hydrological droughts: Elucidating the role of temperature. Journal of Hydrology 553:785-797.

Ahmadalipour, A., H. Moradkhani, and A. Rana. 2017b. Accounting for downscaling and model uncertainty in fine-resolution seasonal climate projections over the Columbia River Basin. Climate Dynamics 50(1-2):717-733.

Alexander, M. A., and coauthors. 2018. Projected sea surface temperatures over the 21st century: Changes in the mean, variability and extremes for large marine ecosystem regions of Northern Oceans. Elementa-Science of the Anthropocene 6.

Arriaza, J. L., D. A. Boughton, K. Urquhart, and M. Mangel. 2017. Size-conditional smolting and the response of Carmel River steelhead to two decades of conservation efforts. PLoS ONE 12(11):e0188971.

Auth, T. D., E. A. Daly, R. D. Brodeur, and J. L. Fisher. 2018. Phenological and distributional shifts in ichthyoplankton associated with recent warming in the northeast Pacific Ocean. Global Change Biology 24(1):259-272.

Aydin, K. Y., G. A. McFarlane, J. R. King, B. A. Megrey, and K. W. Myers. 2005. Linking oceanic food webs to coastal production and growth rates of Pacific salmon (*Oncorhynchus* spp.), using models on three scales. Deep Sea Research Part II: Topical Studies in Oceanography 52(5-6):757-780.

Bailey, C., H. Segner, A. Casanova-Nakayama, and T. Wahli. 2017a. Who needs the hotspot? The effect of temperature on the fish host immune response to Tetracapsuloides bryosalmonae the causative agent of proliferative kidney disease. Fish Shellfish Immunol 63:424-437.

Bailey, C., H. Segner, and T. Wahli. 2017b. What goes around comes around: an investigation of resistance to proliferative kidney disease in rainbow trout *Oncorhynchus mykiss* (Walbaum) following experimental re-exposure. J Fish Dis 40(11):1599-1612.

Bednarsek, N., and coauthors. 2014. Limacina helicina shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem. Proc Biol Sci 281(1785):20140123.

Bednarsek, N., and coauthors. 2017. Exposure history determines pteropod vulnerability to ocean acidification along the US West Coast. Scientific Reports 7(1):4526.

Bell, D. A., R. P. Kovach, S. C. Vulstek, J. E. Joyce, and D. A. Tallmon. 2017. Climate-induced trends in predator–prey synchrony differ across life-history stages of an anadromous salmonid. Canadian Journal of Fisheries and Aquatic Sciences 74(9):1431-1438.

Bellmore, J. R., J. R. Benjamin, M. Newsom, J. A. Bountry, and D. Dombroski. 2017. Incorporating food web dynamics into ecological restoration: a modeling approach for river ecosystems. Ecol Appl 27(3):814-832.

Berdahl, A., P. A. H. Westley, and T. P. Quinn. 2017. Social interactions shape the timing of spawning migrations in an anadromous fish. Animal Behaviour 126:221-229.

Bijma, J., H. O. Portner, C. Yesson, and A. D. Rogers. 2013. Climate change and the oceans--what does the future hold? Mar Pollut Bull 74(2):495-505.

Boltana, S., and coauthors. 2017. Influences of thermal environment on fish growth. Ecol Evol 7(17):6814-6825.

Bond, M. H., and coauthors. 2016. Combined effects of barge transportation, river environment, and rearing location on straying and migration of adult Snake River fall-run Chinook salmon. Transactions of the American Fisheries Society 146(1):60-73.

Brady, R. X., M. A. Alexander, N. S. Lovenduski, and R. R. Rykaczewski. 2017. Emergent anthropogenic trends in California Current upwelling. Geophysical Research Letters 44(10):5044-5052.

Brahney, J., B. Menounos, X. Wei, and P. J. Curtis. 2017a. Determining annual cryosphere storage contributions to streamflow using historical hydrometric records. Hydrological Processes 31(8):1590-1601.

Brahney, J., F. Weber, V. Foord, J. Janmaat, and P. J. Curtis. 2017b. Evidence for a climate-driven hydrologic regime shift in the Canadian Columbia Basin. Canadian Water Resources Journal / Revue canadienne des ressources hydriques 42(2):179-192.

Brewitt, K. S., E. M. Danner, and J. W. Moore. 2017. Hot eats and cool creeks: juvenile Pacific salmonids use mainstem prey while in thermal refuges. Canadian Journal of Fisheries and Aquatic Sciences 74(10):1588-1602.

Bruneaux, M., and coauthors. 2017. Parasite infection and decreased thermal tolerance: impact of proliferative kidney disease on a wild salmonid fish in the context of climate change. Functional Ecology 31(1):216-226.

Burnett, N. J., and coauthors. 2017. Reducing carryover effects on the migration and spawning success of Sockeye salmon through a management experiment of dam flows. River Research and Applications 33(1):3-15.

Carey, M. P., and coauthors. 2017. Migration trends of sockeye salmon at the northern edge of their distribution. Transactions of the American Fisheries Society 146(4):791-802.

Chan, F., and coauthors. 2017. Persistent spatial structuring of coastal ocean acidification in the California Current System. Scientific Reports 7(1):2526.

Chao, Y., and coauthors. 2017. The origins of the anomalous warming in the California coastal ocean and San Francisco Bay during 2014-2016. Journal of Geophysical Research: Oceans 122(9):7537-7557.

Chasco, B. E., and coauthors. 2017. Competing tradeoffs between increasing marine mammal predation and fisheries harvest of Chinook salmon. Scientific Reports 7(1):15439.

Clarke, A., and N. M. Johnston. 1999. Scaling of metabolic rate with body mass and temperature in teleost ®sh. Journal of Animal Ecology 68:893±905.

Crozier, L. G., T. E. Bowerman, B. J. Burke, M. L. Keefer, and C. C. Caudill. 2017. High-stakes steeplechase: a behavior-based model to predict individual travel times through diverse migration segments. Ecosphere 8(10).

Dale, K. E., E. A. Daly, and R. D. Brodeur. 2017. Interannual variability in the feeding and condition of subyearling Chinook salmon off Oregon and Washington in relation to fluctuating ocean conditions. Fisheries Oceanography 26(1):1-16.

Daly, E. A., R. D. Brodeur, and T. D. Auth. 2017. Anomalous ocean conditions in 2015: impacts on spring Chinook salmon and their prey field. Marine Ecology Progress Series 566:169-182.

Davis, C. V., and coauthors. 2017. Ocean acidification compromises a planktic calcifier with implications for global carbon cycling. Scientific Reports 7(1):2225.

Debertin, A. J., J. R. Irvine, C. A. Holt, G. Oka, and M. Trudel. 2017. Marine growth patterns of southern British Columbia chum salmon explained by interactions between density-dependent competition and changing climate. Canadian Journal of Fisheries and Aquatic Sciences 74(7):1077-1087.

Dempson, B., and coauthors. 2017. Influence of climate and abundance on migration timing of adult Atlantic salmon (*Salmo salar*) among rivers in Newfoundland and Labrador. Ecology of Freshwater Fish 26(2):247-259.

Deng, Z. D., and coauthors. 2017. Comparing the survival rate of juvenile Chinook salmon migrating through hydropower systems using injectable and surgical acoustic transmitters. Scientific Reports 7:42999.

Duffy-Anderson, J. T., and coauthors. 2017. Return of warm conditions in the southeastern Bering Sea: Phytoplankton - Fish. PLoS ONE 12(6):e0178955.

Durski, S. M., J. A. Barth, J. C. McWilliams, H. Frenzel, and C. Deutsch. 2017. The influence of variable slope-water characteristics on dissolved oxygen levels in the northern California Current System. Journal of Geophysical Research: Oceans 122(9):7674-7697.

Eliason, E. J., T. D. Clark, S. G. Hinch, and A. P. Farrell. 2013. Cardiorespiratory collapse at high temperature in swimming adult sockeye salmon. Conserv Physiol 1(1):cot008.

Eliason, E. J., and A. P. Farrell. 2016. Oxygen uptake in Pacific salmon *Oncorhynchus* spp.: when ecology and physiology meet. Journal of Fish Biology 88(1):359-388.

Eliason, E. J., M. K. Gale, C. K. Whitney, A. Lotto, and S. G. Hinch. 2017. Intraspecific differences in endurance swim performance and cardiac size in sockeye salmon (*Oncorhynchus nerka*) parr tested at three temperatures. Canadian Journal of Zoology 95(6):425-432.

Ellis, R. P., M. A. Urbina, and R. W. Wilson. 2017. Lessons from two high CO2 worlds - future oceans and intensive aquaculture. Glob Chang Biol 23(6):2141-2148.

Feely, R. A., C. L. Sabine, J. M. Hernandez-Ayon, D. Ianson, and B. Hales. 2008. Evidence for upwelling of corrosive "acidified" water onto the continental shelf. Science 320(5882):1490-1492.

Feist, B. E., and coauthors. 2017. Roads to ruin: conservation threats to a sentinel species across an urban gradient. Ecol Appl 27(8):2382-2396.

Flynn, K. R., M. R. Fewings, C. Gotschalk, and K. Lombardo. 2017. Large-scale anomalies in sea-surface temperature and air-sea fluxes during wind relaxation events off the United States West Coast in summer. Journal of Geophysical Research: Oceans 122(3):2574-2594.

Fountain, A. G., B. Glenn, and H. J. Basagic. 2017. The geography of glaciers and perennial snowfields in the American west. Arctic, Antarctic, and Alpine Research 49(3):391-410.

Frischknecht, M., M. Münnich, and N. Gruber. 2017. Local atmospheric forcing driving an unexpected California Current System response during the 2015-2016 El Niño. Geophysical Research Letters 44(1):304-311.

Fullerton, A. H., and coauthors. 2017. Simulated juvenile salmon growth and phenology respond to altered thermal regimes and stream network shape. Ecosphere 8(12):1-23.

García-Reyes, M., and W. J. Sydeman. 2017. California Multivariate Ocean Climate Indicator (MOCI) and marine ecosystem dynamics. Ecological Indicators 72:521-529.

Garner, G., I. A. Malcolm, J. P. Sadler, and D. M. Hannah. 2017. The role of riparian vegetation density, channel orientation and water velocity in determining river temperature dynamics. Journal of Hydrology 553:471-485.

Gentemann, C. L., M. R. Fewings, and M. García-Reyes. 2017. Satellite sea surface temperatures along the West Coast of the United States during the 2014-2016 northeast Pacific marine heat wave. Geophysical Research Letters 44(1):312-319.

Gleason, K. E., A. W. Nolin, and T. R. Roth. 2017. Developing a representative snow-monitoring network in a forested mountain watershed. Hydrology and Earth System Sciences 21(2):1137-1147.

Gosselin, J. L., and J. J. Anderson. 2017. Combining migration history, river conditions, and fish condition to examine cross-life-stage effects on marine survival in Chinook salmon. Transactions of the American Fisheries Society 146(3):408-421.

Groom, J. D., S. L. Johnson, J. D. Seeds, and G. G. Ice. 2017. Evaluating links between forest harvest and stream temperature threshold exceedances: The value of spatial and temporal data. JAWRA Journal of the American Water Resources Association 53(4):761-773.

Gruber, N., and coauthors. 2012. Rapid progression of ocean acidification in the California Current System. Science 337(6091):220-223.

Haskell, C. A., D. A. Beauchamp, and S. M. Bollens. 2017. Linking functional response and bioenergetics to estimate juvenile salmon growth in a reservoir food web. PLoS ONE 12(10):e0185933.

Huang, X., and P. A. Ullrich. 2017. The changing character of twenty-first-century precipitation over the western United States in the Variable-Resolution CESM. Journal of Climate 30(18):7555-7575.

Isaak, D. J., and coauthors. 2017. The NorWeST summer stream temperature model and scenarios for the western U.S.: a crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. Water Resources Research 53(11):9181-9205.

Islam, S. u., S. J. Déry, and A. T. Werner. 2017. Future climate change impacts on snow and water resources of the Fraser River Basin, British Columbia. Journal of Hydrometeorology 18(2):473-496.

Jeffrey, K. M., I. M. Côté, J. R. Irvine, and J. D. Reynolds. 2017. Changes in body size of Canadian Pacific salmon over six decades. Canadian Journal of Fisheries and Aquatic Sciences 74(2):191-201.

Johnstone, J. A., and N. J. Mantua. 2014. Atmospheric controls on northeast Pacific temperature variability and change, 1900-2012. Proceedings of the National Academy of Sciences of the United States of America 111(40):14360-14365.

Jones, L. A., C. C. Muhlfeld, and L. A. Marshall. 2017. Projected warming portends seasonal shifts of stream temperatures in the Crown of the Continent Ecosystem, USA and Canada. Climatic Change 144(4):641-655.

Justice, C., S. M. White, D. A. McCullough, D. S. Graves, and M. R. Blanchard. 2017. Can stream and riparian restoration offset climate change impacts to salmon populations? J Environ Manage 188:212-227.

Keefer, M. L., and coauthors. 2017. Condition-dependent en route migration mortality of adult Chinook salmon in the Willamette River main stem. North American Journal of Fisheries Management 37(2):370-379.

Klinger, T., and coauthors. 2017. Using integrated, ecosystem-level management to address intensifying ocean acidification and hypoxia in the California Current large marine ecosystem. Elem Sci Anth 5(0).

Koslow, J. A., R. Goericke, A. Lara-Lopez, and W. Watson. 2011. Impact of declining intermediate-water oxygen on deepwater fishes in the California Current. Marine Ecology Progress Series 436:207-218.

Kovach, R. P., A. J. Gharrett, and D. A. Tallmon. 2012. Genetic change for earlier migration timing in a pink salmon population. Proceedings of the Royal Society B-Biological Sciences 279(1743):3870-3878.

Kuczynski, L., M. Chevalier, P. Laffaille, M. Legrand, and G. Grenouillet. 2017. Indirect effect of temperature on fish population abundances through phenological changes. PLoS ONE 12(4):e0175735.

Kumar, A., and M. Chen. 2017. What is the variability in US west coast winter precipitation during strong El Niño events? Climate Dynamics 49(7-8):2789-2802.

Kurapov, A. L., N. A. Pelland, and D. L. Rudnick. 2017. Seasonal and interannual variability in along-slope oceanic properties off the US West Coast: Inferences from a high-resolution regional model. Journal of Geophysical Research: Oceans 122(7):5237-5259.

Laizé, C. L. R., C. Bruna Meredith, M. J. Dunbar, and D. M. Hannah. 2017. Climate and basin drivers of seasonal river water temperature dynamics. Hydrology and Earth System Sciences 21(6):3231-3247.

Leach, J. A., and D. Moore. 2017. Insights on stream temperature processes through development of a coupled hydrologic and stream temperature model for forested coastal headwater catchments. Hydrological Processes 31(18):3160-3177.

Leach, J. A., D. H. Olson, P. D. Anderson, and B. N. I. Eskelson. 2017. Spatial and seasonal variability of forested headwater stream temperatures in western Oregon, USA. Aquatic Sciences 79(2):291-307.

Lin, J. E., J. J. Hard, R. Hilborn, and L. Hauser. 2017. Modeling local adaptation and gene flow in sockeye salmon. Ecosphere 8(12).

Liston, G., and K. Elder. 2006. A distributed snow-evolution modeling system (SnowModel). Journal of Hydrometeorology 7:1259-1276

Long, M. C., C. Deutsch, and T. Ito. 2016. Finding forced trends in oceanic oxygen. Global Biogeochemical Cycles 30(2):381-397.

Mahony, A. M., S. C. Johnson, C. M. Neville, M. E. Thiess, and S. R. M. Jones. 2017. *Myxobolus arcticus* and *Parvicapsula minibicornis* infections in sockeye salmon *Oncorhynchus nerka* following downstream migration in British Columbia. Dis Aquat Organ 126(2):89-98.

Malek, K., and coauthors. 2017. VIC–CropSyst-v2: A regional-scale modeling platform to simulate the nexus of climate, hydrology, cropping systems, and human decisions. Geoscientific Model Development 10(8):3059-3084.

Mallakpour, I., and G. Villarini. 2017. Analysis of changes in the magnitude, frequency, and seasonality of heavy precipitation over the contiguous USA. Theoretical and Applied Climatology 130(1-2):345-363.

Manhard, C. V., J. E. Joyce, and A. J. Gharrett. 2017. Evolution of phenology in a salmonid population: a potential adaptive response to climate change. Canadian Journal of Fisheries and Aquatic Sciences 74(10):1519-1527.

Marlier, M. E., and coauthors. 2017. The 2015 drought in Washington State: a harbinger of things to come? Environmental Research Letters 12(11).

Marshall, K. N., and coauthors. 2017. Risks of ocean acidification in the California Current food web and fisheries: ecosystem model projections. Glob Chang Biol 23(4):1525-1539.

Martin, B. T., and coauthors. 2017. Phenomenological vs. biophysical models of thermal stress in aquatic eggs. Ecol Lett 20(1):50-59.

McCabe, R. M., and coauthors. 2016. An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. Geophys Res Lett 43(19):10366-10376.

McGrath, E. O., N. N. Neumann, and C. F. Nichol. 2017. A statistical model for managing water temperature in streams with anthropogenic influences. River Research and Applications 33(1):123-134.

McHugh, P. A., and coauthors. 2017. Linking models across scales to assess the viability and restoration potential of a threatened population of steelhead (*Oncorhynchus mykiss*) in the Middle Fork John Day River, Oregon, USA. Ecological Modelling 355:24-38.

Messié, M., and F. P. Chavez. 2017. Nutrient supply, surface currents, and plankton dynamics predict zooplankton hotspots in coastal upwelling systems. Geophysical Research Letters 44(17):8979-8986.

Miller, J. A., and coauthors. 2017. Temporal variation in the biochemical ecology of lower trophic levels in the Northern California Current. Progress in Oceanography 155:1-12.

Moore, A. M., and coauthors. 2017. The impact of the ocean observing system on estimates of the California current circulation spanning three decades. Progress in Oceanography 156:41-60.

Moore, M. E., and B. A. Berejikian. 2017. Population, habitat, and marine location effects on early marine survival and behavior of Puget Sound steelhead smolts. Ecosphere 8(5).

Motyka, R., T. Norin, L. H. Petersen, D. B. Huggett, and A. K. Gamperl. 2017. Long-term hypoxia exposure alters the cardiorespiratory physiology of steelhead trout (*Oncorhynchus mykiss*), but does not affect their upper thermal tolerance. J Therm Biol 68(Pt B):149-161.

Murphy, J. M., and coauthors. 2017. Juvenile Chinook Salmon abundance in the northern Bering Sea: Implications for future returns and fisheries in the Yukon River. Deep Sea Research Part II: Topical Studies in Oceanography 135:156-167.

Myers, B. J. E., and coauthors. 2017. Global synthesis of the documented and projected effects of climate change on inland fishes. Reviews in Fish Biology and Fisheries 27(2):339-361.

Myrvold, K. M., and B. P. Kennedy. 2017. Size and growth relationships in juvenile steelhead: The advantage of large relative size diminishes with increasing water temperatures. Environmental Biology of Fishes 100(11):1373-1382.

Newman, M., and coauthors. 2016. The Pacific decadal oscillation, revisited. Journal of Climate 29(12):4399-4427.

NOAA, National Oceanic and Atmospheric Administration,. 2018. Global Climate Report - Annual 2017. State of the Climate Reports. National Centers for Environmental Information, https://www.ncdc.noaa.gov/sotc/global/201713.

Pan, Y., D. V. Subba Rao, K. H. Mann, W. K. W. Li, and W. G. Harrison. 1996a. Effects of silicate limitation on production of domoic acid, a neurotoxin, by the diatom Pseudo-nitzschia multiseries. II. Continuous culture studies. Marine Ecology Progress Series 131:235-243.

Pan, Y., V. Subba Rhao, K. H. Mann, W. K. W. Li, and W. G. Harrison. 1996b. Effects of silicate limitation on production of domoic acid, a neurotoxin, by the diatom Pseudo -nitzschia m ul tiseries. 11. Continuous culture studies. Marine Ecology Progress Series 131:235-243.

Peterson, W. T., and coauthors. 2017. The pelagic ecosystem in the Northern California Current off Oregon during the 2014-2016 warm anomalies within the context of the past 20 years. Journal of Geophysical Research: Oceans 122(9):7267-7290.

Phillips, E. M., J. K. Horne, and J. E. Zamon. 2017. Predator–prey interactions influenced by a dynamic river plume. Canadian Journal of Fisheries and Aquatic Sciences 74(9):1375-1390.

Poletto, J. B., and coauthors. 2017. Unusual aerobic performance at high temperatures in juvenile Chinook salmon, *Oncorhynchus tshawytscha*. Conserv Physiol 5(1):cow067.

Pozo Buil, M., and E. Di Lorenzo. 2017. Decadal dynamics and predictability of oxygen and subsurface tracers in the California Current System. Geophysical Research Letters 44(9):4204-4213.

Prystay, T. S., and coauthors. 2017. The influence of water temperature on sockeye salmon heart rate recovery following simulated fisheries interactions. Conserv Physiol 5(1):cox050.

Pörtner, H. O., C. Bock, and F. C. Mark. 2017. Oxygen- and capacity-limited thermal tolerance: bridging ecology and physiology. J Exp Biol 220(Pt 15):2685-2696.

Raimonet, M., and J. E. Cloern. 2017. Estuary-ocean connectivity: fast physics, slow biology. Glob Chang Biol 23(6):2345-2357.

Reilly, M. J., and coauthors. 2017. Contemporary patterns of fire extent and severity in forests of the Pacific Northwest, USA (1985-2010). Ecosphere 8(3).

Richerson, K., D. S. Holland, and J. Schmidt. 2017. Quantifying and predicting responses to a US West Coast salmon fishery closure. ICES Journal of Marine Science 74(9):2364-2378.

Roberts, J. J., K. D. Fausch, T. S. Schmidt, and D. M. Walters. 2017. Thermal regimes of Rocky Mountain lakes warm with climate change. PLoS ONE 12(7):e0179498.

Roque-Malo, S., and P. Kumar. 2017. Patterns of change in high frequency precipitation variability over North America. Scientific Reports 7(1):10853.

Rosenfeld, J. S. 2017. Developing flow-ecology relationships: Implications of nonlinear biological responses for water management. Freshwater Biology 62(8):1305-1324.

Rudnick, D. L., K. D. Zaba, R. E. Todd, and R. E. Davis. 2017. A climatology of the California Current System from a network of underwater gliders. Progress in Oceanography 154:64-106.

Rupp, D. E., J. T. Abatzoglou, and P. W. Mote. 2017a. Projections of 21st century climate of the Columbia River Basin. Climate Dynamics 49(5-6):1783-1799.

Rupp, D. E., and coauthors. 2017b. Seasonal spatial patterns of projected anthropogenic warming in complex terrain: a modeling study of the western US. Climate Dynamics 48(7-8):2191-2213.

Ryan, J. P., and coauthors. 2017. Causality of an extreme harmful algal bloom in Monterey Bay, California, during the 2014-2016 northeast Pacific warm anomaly. Geophysical Research Letters 44(11):5571-5579.

Sakamoto, C., and coauthors. 2017. Hourly in-situ nitrate on a coastal mooring: A 15-year record and insights into new production. Oceanography 30(4):114-127.

Santora, J. A., and coauthors. 2017a. Impacts of ocean climate variability on biodiversity of pelagic forage species in an upwelling ecosystem. Marine Ecology Progress Series 580:205-220.

Santora, J. A., and coauthors. 2017b. Persistence of trophic hotspots and relation to human impacts within an upwelling marine ecosystem. Ecol Appl 27(2):560-574.

Sapin, J. R., and coauthors. 2017. Demonstration of integrated reservoir operations and extreme hydroclimate modeling of water temperatures for fish sustainability below Shasta Lake. Journal of Water Resources Planning and Management 143(10).

Schoen, E. R., and coauthors. 2017. Future of Pacific salmon in the face of environmental change: Lessons from one of the world's remaining productive salmon regions. Fisheries 42(10):538-553.

Scribner, K. T., and coauthors. 2017. Genetic assessment of the effects of streamscape succession on coho salmon *Oncorhynchus kisutch* colonization in recently deglaciated streams. J Fish Biol 91(1):195-218.

Sergeant, C. J., J. B. Armstrong, and E. J. Ward. 2015. Predator-prey migration phenologies remain synchronised in a warming catchment. Freshwater Biology 60(4):724-732.

Sergeant, C. J., J. R. Bellmore, C. McConnell, and J. W. Moore. 2017. High salmon density and low discharge create periodic hypoxia in coastal rivers. Ecosphere 8(6).

Shuntov, V. P., O. S. Temnykh, and O. A. Ivanov. 2018. On the persistence of stereotypes concerning the marine ecology of Pacific salmon (*Oncorhynchus* spp.). Russian Journal of Marine Biology 43(7):507-534.

Siegel, J. E., M. V. McPhee, and M. D. Adkison. 2017. Evidence that marine temperatures influence growth and maturation of western Alaskan Chinook salmon. Marine and Coastal Fisheries 9(1):441-456.

Sparks, M. M., P. A. H. Westley, J. A. Falke, and T. P. Quinn. 2017. Thermal adaptation and phenotypic plasticity in a warming world: Insights from common garden experiments on Alaskan sockeye salmon. Glob Chang Biol 23(12):5203-5217.

Spence, B. C., and J. D. Hall. 2010. Spatiotemporal patterns in migration timing of coho salmon (*Oncorhynchus kisutch*) smolts in North America. Canadian Journal of Fisheries and Aquatic Sciences 67(8):1316-1334.

Sproles, E. A., T. R. Roth, and A. W. Nolin. 2017. Future snow? A spatial-probabilistic assessment of the extraordinarily low snowpacks of 2014 and 2015 in the Oregon Cascades. The Cryosphere 11(1):331-341.

Stabeno, P. J., and coauthors. 2017. Return of warm conditions in the southeastern Bering Sea: Physics to fluorescence. PLoS ONE 12(9):e0185464.

Steel, E. A., T. J. Beechie, C. E. Torgersen, and A. H. Fullerton. 2017. Envisioning, quantifying, and managing thermal regimes on river networks. Bioscience 67(6):506-522.

Swezey, D. S., and coauthors. 2017a. Plastic responses of bryozoans to ocean acidification. J Exp Biol 220(Pt 23):4399-4409.

Swezey, D. S., and coauthors. 2017b. Interactive effects of temperature, food and skeletal mineralogy mediate biological responses to ocean acidification in a widely distributed bryozoan. Proc Biol Sci 284(1853).

Sydeman, W. J., and coauthors. 2017. Regionalizing indicators for marine ecosystems: Bering Sea–Aleutian Island seabirds, climate, and competitors. Ecological Indicators 78:458-469.

Takata, L., T. R. Sommer, J. Louise Conrad, and B. M. Schreier. 2017. Rearing and migration of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) in a large river floodplain. Environmental Biology of Fishes 100(9):1105-1120.

Thompson, L. M., M. D. Staudinger, and S. L. Carter. 2015. Summarizing components of U.S. Department of the Interior vulnerability assessments to focus climate adaptation planning: U.S. Geological Survey Open-File Report. USGS, 2331-1258, Reston, Virginia.

Tillotson, M. D., and T. P. Quinn. 2017. Climate and conspecific density trigger pre-spawning mortality in sockeye salmon (*Oncorhynchus nerka*). Fisheries Research 188:138-148.

Tommasi, D., and coauthors. 2017. Managing living marine resources in a dynamic environment: The role of seasonal to decadal climate forecasts. Progress in Oceanography 152:15-49.

Turner, D. P., and coauthors. 2017. Assessing mechanisms of climate change impact on the upland forest water balance of the Willamette River Basin, Oregon. Ecohydrology 10(1).

Vega, S. L., T. M. Sutton, and J. M. Murphy. 2017. Marine-entry timing and growth rates of juvenile Chum Salmon in Alaskan waters of the Chukchi and northern Bering seas. Deep Sea Research Part II: Topical Studies in Oceanography 135:137-144.

Verhille, C. E., K. K. English, D. E. Cocherell, A. P. Farrell, and N. A. Fangue. 2016. High thermal tolerance of a rainbow trout population near its southern range limit suggests local thermal adjustment. Conserv Physiol 4(1):cow057.

Wade, A. A., and coauthors. 2017. Accounting for adaptive capacity and uncertainty in assessments of species' climate-change vulnerability. Conserv Biol 31(1):136-149.

Wang, M., and J. E. Overland. 2015. Projected future duration of the sea-ice-free season in the Alaskan Arctic. Progress in Oceanography 136:50-59.

Wang, M., J. E. Overland, and P. Stabeno. 2012. Future climate of the Bering and Chukchi Seas projected by global climate models. Deep Sea Research Part II: Topical Studies in Oceanography 65-70:46-57.

Wang, X., and coauthors. 2017. A carbonic anhydrase serves as an important acid-base Regulator in Pacific Oyster *Crassostrea gigas* exposed to elevated CO2: Implication for physiological responses of mollusk to ocean acidification. Mar Biotechnol (NY) 19(1):22-35.

Waples, R. S., and coauthors. 2017. Human-mediated evolution in a threatened species? Juvenile life-history changes in Snake River salmon. Evol Appl 10(7):667-681.

Ward, E. J., and coauthors. 2017a. Evaluating signals of oil spill impacts, climate, and species interactions in Pacific herring and Pacific salmon populations in Prince William Sound and Copper River, Alaska. PLoS ONE 12(3):e0172898.

Ward, H. G. M., J. R. Post, N. P. Lester, P. J. Askey, and T. Godin. 2017b. Empirical evidence of plasticity in life-history characteristics across climatic and fish density gradients. Canadian Journal of Fisheries and Aquatic Sciences 74(4):464-474.

Weinheimer, J., J. H. Anderson, M. Downen, M. Zimmerman, and T. Johnson. 2017. Monitoring climate impacts: Survival and migration timing of summer chum salmon in Salmon Creek, Washington. Transactions of the American Fisheries Society 146(5):983-995.

Wells, B. K., and coauthors. 2017. Environmental conditions and prey-switching by a seabird predator impact juvenile salmon survival. Journal of Marine Systems 174:54-63.

Williams, J. G., R. W. Zabel, R. S. Waples, J. A. Hutchings, and W. P. Connor. 2008. Potential for anthropogenic disturbances to influence evolutionary change in the life history of a threatened salmonid. Evolutionary Applications 1(2):271-285.

Wright, R. F., and coauthors. 2017. Effects of multiple stresses hydropower, acid deposition and climate change on water chemistry and salmon populations in the River Otra, Norway. Sci Total Environ 574:128-138.

Zavolokin, A. V., V. V. Kulik, and L. O. Zavarina. 2014a. The food supply of the Pacific salmon of the genus *Oncorhynchus* in the northwestern Pacific Ocean. 1. The dynamics of the food spectra and feeding intensity. Russian Journal of Marine Biology 40(2):100-111.

Zavolokin, A. V., V. V. Kulik, and L. O. Zavarina. 2014b. The food supply of the Pacific salmon of the genus *Oncorhynchus* in the northwestern Pacific Ocean. 2. Comparative characterization and general state. Russian Journal of Marine Biology 40(3):199-207.

Zhao, S., Y. Deng, and R. X. Black. 2017. Observed and simulated spring and summer dryness in the United States: The impact of the Pacific sea surface temperature and beyond. Journal of Geophysical Research: Atmospheres.