February 3, 2015

Narrative for Ocean Forum Management Question #1 – What changes have occurred in the estuary, plume and near ocean ecosystem functions, processes and relationships?

1.0 Introduction

The Columbia River is one of the world's great rivers and is the fourth largest river in North America. It originates at Columbia Lake in British Columbia and flows for over 1200 miles before draining into the Pacific Ocean near Astoria, Oregon. The Columbia River Basin drains an area of about 259,000 square miles in seven U.S. states and British Columbia in Canada.

The Columbia River is home to six species of Pacific salmon: Chinook, coho, sockeye, chum, and pink salmon, and steelhead. The basin's salmon and steelhead runs were once among the largest in the world, with an estimated average of between 10-16 million fish returning to the basin annually. The Council's Independent Scientific Advisory Board (ISAB) reanalyzed the limited historical data to better evaluate the potential capacity for salmon and steelhead in the Columbia Basin prior to hydropower development. The ISAB concluded that historical all-species capacity was likely in the range of 5 to 9 million adult fish per year, which is less than previously published estimates (e.g., 7.5 to 16 million adults per year) but still much higher than current abundance levels (~2.3 million fish per year during 2000-2012) (ISAB 2015).

Salmon and steelhead runs, along with other native fish and wildlife in the basin, have declined significantly in the last 150 years. Recent years have seen some improvements in the number of adult salmon and steelhead passing Bonneville Dam; however, many of these are hatchery fish. A wide range of human activities have contributed to this decline, including land and water developments across the region that blocked traditional habitats and dramatically changed natural conditions in rivers where fish evolved (NPCC 2014).

Changes in ocean conditions and marine survival are also considered to be a major contributor to these declines. First, these declines parallel changes in marine survival. Second, poor marine survival has been documented in hatchery-reared fish where freshwater conditions are controlled. Lastly, similar declines have occurred over a broad geographic range from California to British Columbia, and more recently to Alaska, including in relatively pristine watersheds. Ocean conditions may mask, enhance, or even override actions taken in the freshwater habitat to improve salmon returns. For instance, an increase in salmon return after restoring a tributary of the Columbia River during favorable ocean conditions could be due to improved freshwater survival, improve marine conditions, or a combination of both. Hence, in order to evaluate the effectiveness of any mitigation measures, it is essential to evaluate the response of Columbia River salmon to both freshwater and marine environments.

…

1.1 Purpose of this report …[This section needs to be added based on the annotated outline.]

For the purposes of the Ocean Forum, the ocean environments used by anadromous fish can be divided into the following major ecosystems: the Columbia River estuary and plume, the Northern California Current, and the North Pacific Ocean, including the Gulf of Alaska and the Bering Sea.

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1.2 Management questions …

Secondary management question: Have forage fish composition and abundance patterns been altered seasonally, annually, temporally or spatially?)

Secondary management question: Have salmonid predator composition and abundance been altered?

Sub-question: What will be the magnitude of biological change in ocean and plume conditions due to climate change induced acidification and hypoxia

Secondary management question: Have changes occurred in estuarine food webs due to invasive species?

2.0 Physical changes

2.1 The Federal Columbia River Power System

The development of the Federal Columbia River Power System in the Pacific Northwest began in the 1930s under a program of regional cooperation to meet the needs of electric power production, land reclamation, flood control, navigation, recreation, and other river uses. From the beginning, the federal government played a major role in the development of one of the largest multiple-use river systems in the world. Together, the Corps of Engineers and the Bureau of Reclamation have built more than 30 multipurpose hydropower dams throughout the Pacific Northwest.

Congress directed the Bonneville Power Administration, in the Bonneville Project Act of 1937, to build and operate transmission lines to deliver the power generated from dams and to market electricity from federal generating projects on the river. Investor-owned and publicly-owned utilities also built a major system of dams and generating facilities, beginning in the late 1800s. The vast system of dams and reservoirs in the Columbia Basin have provided an important source of energy, irrigation water supply, flood protection, municipal and industrial water supply, as well as maintenance of environmental flows. Some of the major consequences of dam construction and operation include river fragmentation, flow regulation which changes the pattern of flows downstream, and altered water temperatures.

The combined useable storage capacity in U.S. and Canadian reservoirs in the basin is only 42 million acre-feet. This means that the hydrosystem has limited storage in comparison to the mean annual runoff volume and thus has limited capability to reshape river flows to yield energy to better match the seasonal electricity demand or to provide for water supply or ecological needs. Moreover, the construction and operation of these storage projects have had substantial impacts on the ecological integrity of aquatic systems and on the productivity of river systems within the basin (NPCC 2014).

2.1.1 River flow

The Columbia River is a snowmelt-dominated river that fluctuates seasonally in volume, with the highest runoff volumes occurring between April and July and lowest volumes from December to February. Annual runoff at the mouth of the Columbia River was probably about 218 million acre-feet (301,000 cfs) prior to 1900 (Bottom et al, 2005) , but currently averages approximately 192 million acre-feet (roughly 265,200 cubic feet per second) (NPCC 2013). The decrease in annual flow is likely due to both human (flow regulation and water withdrawals) and climatic factors (Bottom et al, 2005).

2.1.2 Spring freshet

Spring freshet timing, strength and duration are thought to be important to downstream juvenile salmon migration (Bottom et al. 2005). The development and operation of the Columbia Basin hydropower system has also altered the timing of the maximum spring freshet flow. Spring runoff properties have been much more highly altered than has the mean flow. For example, average flows during the May through July spring freshet season have decreased by about 43 percent (Bottom et al. 2005). The maximum daily spring freshet flow now typically occurs on or about May 29, whereas in the 19^{th} century maximum flows occurred on about June 12, which is a shift of two weeks earlier (Bottom et al. 2005).

2.1.3 Water temperature

The development and operation of the Columbia Basin hydroelectric power system has also increased river water temperatures by 1-2ºC between 1938 and 2004, and changed the response of temperatures to air temperature forcing. However, a small improvement in water temperatures has occurred since about 1998, possibly due to management of some reservoirs in the system, such as Dworshak, to help reduce summer temperatures (Roegner et al. 2008). Temperature differences between the estuary and ocean has been shown to correlate with the survival of Columbia River Chinook; larger temperature differences were associated with lower survival (Holsman et al. 2012).

2.1.4 Sediments

Sediment transport is a vital river system characteristic for salmonids. The organic component of the fine sediments (silts and clays) helps support a detritus-based food web in the estuary (Simenstad et al. 1990, 1994) and the coarser sediments (sands and gravels) are important to natural habitat construction in the estuary and to maintaining spawning habitat higher in the basin (Bottom et al. 2005).

Sediment transport in the Columbia River is strongly dependent on flow; more so than is the case in other major rivers along the West Coast (Jay and Naik 2002). Consequently, the sediment transport regime of the Columbia River is sensitive to changes in the annual hydrologic cycle and flow regulation. Bottom et al. (2005) estimated that the annual average sediment transport from the eastern portions of the Columbia Basin decreased by roughly 60 percent relative to the 19th century sediment transport due to hydropower development and operation, timber harvest, agriculture and urban development. Decreases in sand transport due to reservoir storage and flow regulation are similarly high, and are now only about 70 percent of the 19th century sand transport (Bottom et al 2005). The largest single factor in the reductions in sediment transport is the reduction in spring freshet flows due to reservoir operations for hydropower generation, flood control and irrigation (Bottom et al. 2005).

2.2 Columbia River Plume

The Columbia River is a major hydrologic and oceanographic feature of the Pacific Northwest. It contributes about 70 percent of the freshwater discharged into the eastern North Pacific Ocean between San Francisco Bay and Juan de Fuca Strait. The areal extent (size, volume and depth) of the Columbia River plume can range from British Columbia to California, and is controlled by a combination of large-scale ocean, atmospheric and hydrologic forcings, all of which vary at scales ranging from tidal to seasonal to inter-annual. In some years, a larger Columbia River plume (characteristics of which can be predicted from a combination of river discharge and winds over the continental shelf) was associated with higher survival of some salmonid stocks.

Plume simulations based on the Virtual Columbia River numerical model suggest that river discharge explains most of the plume variability (>40%), with coastal winds the next most important factor (>20%) (Burla et al. 2010). On a seasonal basis, the largest plume volumes occur during the peak spring runoff. The Columbia River plume extends southward and offshore during a spring and summer dominated by ocean upwelling. Similarly, a northward-extending and coastally attached plume is found in winters dominated by downwelling.

The physical and chemical characteristics of the estuary and plume have also been altered by changes in the Columbia River flow, runoff timing, and sediment transport associated with the construction and flow regulation of multipurpose dams. The downstream effects of these hydrological changes on the 1) estuarine salinity intrusion and stratification, 2) estuarine acifidification and hypoxia intrusion, 3) sediment dynamics, and 4) Columbia River plume area, volume, turbidity and seasonality remain poorly understood and should be considered in future studies (Bottom et al 2005):

Although climate effects on Columbia River hydrology have been and likely will remain smaller than those of human alteration and manipulation, it is vital to consider how climate may constrain future management options in the Columbia River Basin, including efforts to restore depleted salmon populations. Climate projections suggest future changes in temperature and precipitation will alter the snowpack, flow, and water quality in the Columbia Basin with the following anticipated impacts:

- Warmer temperatures during the winter months will result in more precipitation falling as rain rather than snow;
- Snowpack will diminish, particularly in lower-elevation watersheds, and stream flow timing will be altered;
- Peak river flows will likely shift to earlier in the spring; and
- Water temperatures will continue to rise, particularly in the late summer and fall.

Changes in hydrologic flow regimes and warming stream and reservoir temperatures caused by a warming climate will pose significant threats to aquatic ecosystems and are expected to alter key habitat conditions for salmon. Anticipated climate change effects in the Pacific Northwest include specific hydrologic changes such as increased frequency and severity of winter flooding in lower elevation, mixed rain-snow basins. Region-wide increases in winter flows and summer temperatures, combined with lower summer flows, will threaten many freshwater species, particularly salmon and steelhead. Higher winter water temperatures could also accelerate embryo development and cause premature emergence of fry in basin tributaries. Rising temperatures will also increase the occurrence of disease and mortality in several salmon species (NPCC 2014).

2.3 The Ocean

2.3.1 The Northern California Current (NCC)

Columbia River salmon initiate their marine life in the California Current (CC) (Appendix 1), which is an eastern boundary current that flows south on the continental shelf along the coasts of Vancouver Island, Washington, Oregon, and California (need to include a Figure here) and ends off southern Baja California in Mexico. In summer, northerly winds can transport water southward and offshore, generating an “upwelling” condition. It is upwelling that helps make the coastal branch of the CC periodically cool, nutrient-rich, and highly productive (Jacobson et al. 2012). In winter, southerly winds create “downwelling” conditions that result in transport of water northward and shoreward as the Davidson Current.

The ecosystem effects of upwelling are complex and can vary spatially and temporally, depend upon the climate, the length of the upwelling season and the timing of the upwelling (Bograd et al. 2009). In particular, Jacobson et al. (2012) suggested that differences among years in both the source of waters that feed the CC and the volume of water transported in CC among years was controlled by the phase of the Pacific Decadal Oscillation (PDO), a spatial pattern in sea surface temperature which stretches across the entire North Pacific Ocean. During the “cold phase” of the PDO, winds tend to be more northerly and westerly, leading to Ekman pumping of offshore waters, upwelling of coastal waters, and a general cooling of surface waters in the Gulf of Alaska and California Current. During the “warm phase” of the PDO, winds are more southerly or southwesterly, resulting in the transport of warm, subtropical and offshore water towards the coast of North America, and creating downwelling.

When the PDO was first described by Mantua et al. (1997), it was noted the phase of the PDO shifted on decadal time scales (hence the term Pacific Decadal Oscillation). Shifts to a warm phase occurred in 1925 and 1977, while shifts to a cold phase occurred in 1947 and 1998. Since 1998, the phase of the PDO has oscillated with a much higher frequency, with a 5-year cool phase during 1998-2002, and a 5-year warm phase during 2003-2007. More recently the frequency of the oscillation appears to have increased again, with 2-year cool phase from 2008 to 2009 followed by one warm-phase year (mid-2009 to mid-2010) and one cool year (mid-2010 to 2011) (Jacobson et al 2012).

[Add Figure x here showing how hypothesized changes in source waters feed the northern California Current during different phases of the PDO in summer.] (Modified from Hallowed and Wooster, (1992) Figure 4.).

Coastal upwelling can also be disrupted by El Nino events (Hsich et al. 1995), a disruption of the ocean-atmosphere system in the Tropical Pacific Ocean characterized by unusually warm ocean temperatures in the eastern Pacific. El Nino events can result in significant reductions in biological productivity in this region.in higher mortality of many pelagic fishes, salmon and seabirds.

The opposite of El Nino events are La Niñas, which are characterized by unusually cold ocean temperatures in the Eastern Pacific. El Niño conditions generally result in warmer and more nutrient poor ocean waters throughout the eastern Pacific, and are considered 'bad' for salmon in the Pacific Northwest (Peterson et al. 2002; DiLorenzo et al. 2010; McPhayden et al. 2010). La Nina events generally produce cooler, more nutrient-rich water and are generally considered 'good' for Columbia Basin salmon. In recent years, the El Niño's of 1983, 1998 and 2010 have been especially strong, but impacts on salmon are also seen in weaker events such as the prolonged series of events in 1992-1996 and 2003-2006 (Draft NOAA Fisheries Ocean Module, 2014).

2.3.2 The North Pacific Ocean

The North Pacific Ocean is defined as the Pacific Ocean north of approximately 45ºN. This region can be loosely subdivided into the northeastern, north-central and northwestern Pacific Ocean regions and the Gulf of Alaska (GOA). The northern boundaries of each Pacific Ocean region are defined by land, while the southern boundaries are imprecise and may vary with the position of the eastern subarctic current.

Both physical and biological processes in the North Pacific Ocean may be important to salmon survival and operate at multiple scales of space and time. Physical processes in the ocean include climate, winds, stratification, current eddies and large-scale circulation that influence to varying degrees both bottom-up and top-down biological processes. In general, ocean processes operating at larger scales constrain and partially regulate those processes operating at smaller scales, such as upwelling, coastal currents and spring transition (Draft NOAA Fisheries Ocean Module, 2014).

2.4 Biological response to physical changes

Scientific evidence suggests that global climate change is already altering marine ecosystems. Physical changes associated with warming include increases in ocean temperature, increased stratification of the water column, and changes in the intensity and timing of coastal upwelling, as well as increases in ocean acidification and hypoxia events. These changes will alter ocean productivity, the structure of marine communities and, in turn, the growth, productivity, survival and migration patterns of anadromous fish (NPCC 2014).

2.4.1 Growth and survival

Pacific salmon sustain heavy and highly variable losses in the ocean with natural mortality rates often exceeding 90-95% (Bradford 1995; Ocean Research Synthesis report, 2012). Most of this mortality is thought to occur in two critical periods: an early period of predation-based mortality that occurs within the first few weeks or months of ocean entry, and a later period of starvation-based mortality that occurs following the first winter in the ocean (Beamish and Mahnken 2001 (Ocean Research Synthesis report, 2012). Both predation and starvation based mortality are size dependent therefore ocean conditions that lead to slower growth likely increase mortality during these period of ocean life, thus reducing survival and adult returns. For example, temperature can affect growth rates by directly affecting the metabolism of the fish and the quantity and quality of prey available to the salmon (Hinch et al. 1995; Draft NOAA Fisheries Ocean Module, 2014). This will also affect adult size at age and age at maturity, which in turn may have consequences for fecundity, migration ability, and ability to dig spawning redds.

Growth is a key attribute of the ocean ecology of salmon and is often strongly related to survival; high growth rates are usually correlated with high survival or adult return rates. The time period over which growth can influence survival rates can vary as a function of species, stock and life history type.

2.4.2 Productivity

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While the PDO is well known within the context of Pacific salmon trends, the North Pacific Gyre Oscillation (NPGO) is another wind-driven, large scale ocean circulation process. Recent studies suggest it can account for oceanographic variation that is not explained by the PDO, such as low frequency variability in nutrients, chlorophyll and oxygen (DiLorenzo et al. 2008; Peterson et al. 2013).

2.4.3 Zooplankton

In the ocean, large scale shifts in ocean food webs generally occur as a result of shifts between cold and warm phases of the PDO (Peterson and Keister 2004; Keister et al. 2011). During the cold phase of the PDO in the NCC, the amount of cold water transported from the sub-arctic domain relative to warmer waters from the subtropical domain or offshore waters of the central North Pacific Ocean appears to increase. During colder years, more lipid rich zooplankton occur in the NCC ecosystem than during warm years because they are transported south from the sub-arctic (Bi et al. 2011). This means that the food chain leading to salmon has a higher lipid content when “cold ocean conditions” prevail (Hooff and Peterson 2006). This may result in higher quality food, which may be beneficial to the salmon (references; Tucker et al. 2015). When the PDO is in a warm phase, lipid-poor copepod species become dominant in the NCC.

2.4.4 Diet

Diets of Pacific salmon vary in response to a number of factors associated with: 1) the species (diet preferences), 2) the prey (prey size); 3) the fish consumers (predator size); and 4) the environment (temperature). In general, Chinook salmon and steelhead initially feed on zooplankton, macroinvertebrates, and insects in the estuary and NCC, but rapidly switch to forage fish as they get larger. In contrast, sockeye salmon feed primarily on invertebrates throughout their marine life, though may also eat fish in some areas (Farley et al. 20xx). Body size of the salmonid predator is especially important. Generally predators eat larger prey as their body size increases. Another factor affecting diet is prey availability, which is a function of the foraging habitat being used, time of year, year and environmental conditions (Brodeur et al. 2007, Daley et al. 2009; 2014). Shifts in prey availability can occur and longer temporal scales (years to decades) to changing ocean conditions such as temperature and currents. Prey availability can also vary vertically in the water column, between day and night and across the continental shelf (module). Prey availability is an important factor affecting diet and can vary with foraging habitat being used, time of year, year (relative to El Nino and PDO changes), and environmental conditions.

2.4.5 Forage fish

Diet information on yearling Chinook salmon from 19 years of ocean research indicates that during warmer ocean years, juvenile salmon consume 20-29% more food than in the colder ocean years and are in significantly lower body condition (Daly and Brodeur 2014). Research also suggests the biomass of fish prey is reduced during warmer ocean conditions at the same time that the salmon are consuming more food (Daly et al. 2013; Daly and Brodeur 2014). This food stress, along with direct effects of temperature on physiology, can shift competitive responses and increase predation risk for salmonids (Reeves et al. 1987; Marine and Cech 2004). Increasing ocean temperatures will also change food web relationships involving salmon, especially as ranges shift for predators, competitors, and prey (e.g. Murawski 1993; Hays et al. 2005; Cheung et al. 2009). For one, as ocean temperatures warm, the quantity and quality of salmon food will change. Locally, Francis et al. (2012) predict that changes in marine zooplankton community structure will occur as climate changes. In general, when water temperatures are warmer in the NCC (e.g., a warm phase of the PDO), food quantity and quality are diminished and salmon growth declines. Thus, one effect of warming in the NCC could be lower early marine growth of salmon which can in turn reduce survival of some ESUs.

2.4.6 Predation

Top down biological processes that can potentially affect salmon are predation, parasites and disease. There are a wide variety of fish, birds, and mammals that prey on juvenile and adult salmon and numerous pathogens and parasites that can infect salmon. Predation is considered to be a major driver of salmon mortality throughout their entire life cycle. However, relatively little is known about salmon predation in the estuary and the ocean. Predation rates on salmon will depend on characteristics of predators, their prey and the environment they are occupying. Predation may be especially high during certain space/time windows such as during estuarine and early marine life. In the Columbia River estuary, for example, high predation rates by birds (Caspian terns and double-crested cormorants) nesting on islands in the estuary have been documented. Factors such as disease, stress or poor feeding conditions may be the proximate cause of mortality, but most salmon that die, probably end up being eaten by a predator. Faster growing salmon can outgrow their predators more rapidly while larger salmon have a greater chance of outswimming a predator.

Shifts in the PDO can also result in changes to the abundance of fish predators and prey in the NCC. Adult and juvenile Pacific hake (*Merluccius productus*) tend to be more abundant in shelf waters when water temperatures are warmer (Emmett and Brodeur 2000), whereas forage fish tend to be less abundant in warmer ocean condition, resulting in increased predation on juvenile salmon (Emmett and Krutzikowsky, 2008). However, the critical factor here is not necessarily if hake are on the shelf, but when they actually arrive in shelf waters relative to when juvenile salmon enter the ocean. For instance, an early ocean entry of juvenile salmon relative to the northward movement of Pacific hake (eg late-April/early-May vs June) would result in a predator-prey mismatch that would favor salmon. Hence, top down control by this species may be mediated in part by variation in physical conditions in the NCC.

2.4.7 Range expansion of non-native species

Human-induced climate change has the potential to affect predation losses of all populations of salmon through such mechanisms as changes in temperature regimes and currents independent of the PDO. Global climate change models generally predict a northward expansion of warm-water species, including non-native predators (reference Brodeur et al. 2014?). Given that, and an increase in the frequency of warm years associated with climate change and that the northward expansion of non-native predators, predation may become a recurring problem unrelated to the phase of the PDO (Draft NOAA Fisheries Ocean Module, 2014).

The impacts of non-native species on salmon and marine ecosystems are difficult to assess: a concomitant change in salmon survival with the appearance of these unusual species may be indicative that they have a significant effect on salmon; though these results will have to be interpreted carefully. For instance, some have argued the low return of Fraser River sockeye salmon in 2009 may be linked to the high abundance of Humboldt squid on the continental shelf, despite the lack of direct evidence of predation on Humboldt squid on sockeye salmon. This hypothesis is interesting, but fails to explain why the number of Chinook jacks reached a historical high level in the Columbia River for the fall runs in 2009. Predation by Humboldt squid on these fish is expected to be higher, as Columbia River fall Chinook most likely remain on the continental shelf for most of the marine life (Trudel et al., 2009, Tucker et al., 2011), and are therefore expected to interact with Humboldt squid for an extended period of time. They are also smaller than Fraser River sockeye, and potentially more vulnerable to predators (i.e., they have a slower swimming speed).

3.0 Chemical changes

3.1 Ocean Acidification

Ocean acidification (OA) is a progressive increase in the acidity (e.g., lowering of pH) of the ocean over an extended period of time. Average global surface ocean pH has already dropped from a pre-industrial level of 8.2 to 8.1, which corresponds to an increase in acidity of about 30 percent, and is expected to reach values as low as 7.8 to 7.9 by 2100 (reference). The current rate of OA may be unprecedented in Earth's history. The rate of acidification is estimated to be 10 to 100 times faster than any time in the past 50 million years.

A main cause of OA is the absorption of human-generated carbon dioxide released into the earth's atmosphere, primarily by the burning of fossil fuels and deforestation. The discharge of organic wastes and nutrients to marine waters may also contribute locally to AO. In the NCC, upwelling brings colder CO_2 –rich deep water onto the continental shelves, such as along the Pacific Northwest coast. This deeper CO_2 –rich and low pH seawater mixes with the surface layer which carries its own burden of CO_2. The combined effect is an approximate reduction in the carbonate saturation state of about 0.25-0.5 units along the outer coast. The current low carbonate saturation state of the NCC system provides a low buffering capacity to pH and therefore makes it particularly susceptible to OA.

OA is causing changes in seawater chemistry, leading to conditions that are corrosive to organisms using calcium carbonate to make shells, skeletons and other important body parts, such as shellfish, pteropods, and coccolitophore. Changes in pH and carbonate chemistry may affect energy utilization in marine organisms, with more energy spent to regulate their internal chemistry, resulting in less energy available for other biological processes like growth, reproduction, or for coping with other environmental stressors. Elevated CO_2 levels have also been shown to have chemosensory, auditory and neurological effects that impair behavioral activities in non-calcifying animals (Domenici et al. 2012), including predatory and antipredatory behaviors of marine fishes (Ferrari et al. 2010, 2012; Nowicki et al. 2012). Also, larger fishes tended to be less impacted by CO_2-induced changes in predation. Thus juvenile fish may suffer greater climate-related impacts compared to later life stages and larger species (Ferrari et al. 2011).

3.2 Hypoxia

Dead zones are hypoxic (low-oxygen) areas caused by excessive nutrient pollution from human activities that can cause algal blooms which, coupled with other factors, can deplete the oxygen required to support most marine life in bottom and near-bottom water. While not a new phenomenon, oceanographers have begun noting in recent years increased instances of hypoxia in the ocean. These hypoxic areas typically occur in inhabited nearshore coastal areas, where aquatic life is most concentrated. However, unlike the dead zones in estuarine areas which are caused largely by excessive nutrient runoff from land use practices, the Oregon coastal dead zone forms along the open coast where coastal winds drive ocean currents that upwell nutrient-rich but oxygen-poor waters from the deep sea onto the shallow reaches of the continental shelf. This upwelling of nutrients further fuels phytoplankton blooms which eventually sink and decompose to further reduce oxygen levels in the already low oxygen waters along the seafloor. Hypoxic zones along the Oregon coast form seasonally, and can begin in late spring or early summer in response to the onset of upwelling-favorable winds from the North. Hypoxia can persist through the summer months and ultimately recedes for the year during the fall months when winds again shift direction and promote ocean currents that flush the low oxygen water off the continental shelf. Changes in the strength and pattern of upwelling winds and the oxygen and nutrient content of the deep offshore waters thus impacts the likelihood and severity of hypoxia events.

Upwelling-caused dead zones have their greatest impacts on the shallow waters of the continental shelf where extremely low oxygen conditions are not typical. For example, a 2006 dead zone encompassed over 3000 km^2 of the Oregon shelf, an area that exceeds the total combined area of estuaries in the state. This event was unprecedented and was accompanied by massive die-offs of marine organisms. Recent reports have also indicated the novel development of an analogous dead zone along the open coast of Washington state. Since upwelling shelves represent one of the largest fractions of coastal marine waters of the U.S. west coast, uncertainties into the potential for further intensification and expansion of upwelling-driven dead zones represent a major scientific uncertainty and management challenge.

A recent study looking at the impacts of climate change on the world's ocean systems concludes that by the year 2100, about 98 percent of the oceans will be affected by either OA, warming temperatures, low oxygen conditions, or lack of biological productivity, with many areas affected by a combination of these stressors (Thurber 2013). Hypoxia, or low oxygen conditions, could cause mortality in many species and could enhance dominance by other species that are hypoxia-tolerant.

3.3 Biological response to chemical changes

Acidification will likely have little direct effect on salmon, with the exception of some possible biochemical stress (Fabry et al. 2008). However, it may have a dramatic impact on invertebrates which are important in salmon food webs, especially in Alaska (Fabry et al. 2008); the consequences for salmon depend on potentially complex shifts in prey availability and ability of salmon to shift diets. It should be noted, however, that biological effects of climate change, whether in estuarine or ocean environments, are extremely difficult to predict. The rapid expansion of Humboldt squid—a voracious predator-- along the West Coast of North America in recent years and their population explosion in 2009 (Field et al. 2013), remind us that although physical processes are more straightforward to predict, the response of biological systems to physical or chemical changes are much more difficult to predict.

4.0 Biological changes

4.1 Invasive species

Despite that a new introduced species is discovered in the lower Columbia about every five years (Sytsma et al. 2004), the impacts of non-native invertebrate species have not been researched in the Columbia River Basin, and their potential effects on salmonids in the Basin are largely unknown (ISAB, 2011).

Vectors of introduction for non-native invertebrates are more diverse relative to those of fish. In addition to the movement of freshwater organisms from the eastern U.S. (via recreational boats and cargo barges/tugs, intentional or accidental release of bait, and releases from home aquaria), numerous non-native invertebrates have been introduced to the Columbia River estuary via deep-sea shipping vessels. Deep-sea ships can transport non-native invertebrates via ballast water, ballast tank sediment, and hull fouling. Non-native invertebrates can also be moved into the estuary with live seafood and into the river and estuary by releases from home aquaria.

4.2 Hatchery production

… details to be added …

4.3 Biological response to biological changes

4.3.1 Invasive species

There is more information regarding the predatory effects of non-native fish species on native salmonids than there is regarding any other impact, though most predation studies have been performed at relatively small scales, such as individual stream reaches or single reservoirs and that they have often examined the impacts of one non-native species predator.

In addition to predation, non-native species pose a number of other significant impacts to natives species including competition for food and habitat (e.g., larval/juvenile American shad deplete zooplankton species favored by subyearling Chinook); food web alterations (e.g., native resident fish communities in littoral habitats of Columbia River reservoirs are being replaced by non-native species); interbreeding (e.g., genetic introgression between cutthroat trout and brook trout); disease transmission and parasites (e.g., American shad as a carrier of the protozoan parasite of salmon); littoral habitat alterations (e.g., the widespread distribution of Eurasian milfoil in Columbia River reservoirs). Because the cumulative impacts could be enormous, regional scale, multi-species research studies were needed to determine the true impacts of non-natives on native salmonids.

4.3.2 Hatchery production

… details to be added …

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5.0 Management Implications of Physical/Chemical Changes in Ocean

- Monitoring and documenting variability in the North Pacific Ocean will provide a context for better understanding and evaluating salmonid response to all-H recovery actions. Managers may then be better able to decouple the effects of the other Hs from ocean effects on juvenile survival.
- Freshwater management strategies may have conflicting effects on different species or stocks, which may not be manifested until ocean residence. That is, one management

strategy may not fit all ESUs. Need a better understanding of ocean variability and genetic diversity.
- We need to understand and know when ocean conditions and survival will be better or worse than in freshwater. Under poor ocean conditions, delaying smolt releases or movements to the ocean could be beneficial. Ocean conditions may enhance, partially mask, or completely overshadow actions taken in freshwater habitat to improve salmon returns.
- We need a better understanding of ocean carrying capacity, i.e., understand the conditions that could have potential density dependent effects.
- Others?

Management Implications related to biological effects

- Maintain population resilience during favorable ocean conditions when opportunities for life history expression are greatest
- Genetic and life history indices are long term indicators of population resilience (Ocean Research Synthesis report, 2012).
- Risks and uncertainties of future climate change emphasizes the need to monitoring of stock specific ocean life histories and minimize the effects of various stressors (hatchery impacts/density, habitat loss, flow modification, etc) that may limit life-history expression
- There is an apparent relationship between plume characteristics at time of ocean entry and SARs for steelhead. SARs for steelhead increase with size and offshore distance of the plume under favorable large scale ocean conditions but did not change when ocean conditions were poor (Ocean Research Synthesis report, 2012).
- Management actions that can reduce plume residence time may improve yearling Chinook salmon smolt survival for some stocks (Ocean Research Synthesis report, 2012).
- Others?

Critical Uncertainties

- Need to better understand how migration and rearing timing will adapt to changes in the estuarine temperature regime (Draft NOAA Fisheries Ocean Module, 2014).
- Need to better understand the net effect of thermal change on the estuarine food web (Draft NOAA Fisheries Ocean Module, 2014).
- Need to better understand effects of predation. Much of what we know about biological processes affecting salmon in the ocean is related to bottom-up processes or what occurs at the lower trophic levels. We have a very limited understanding of predation during ocean life both in the NCC and beyond (Draft NOAA Fisheries Ocean Module, 2014).
- Need to better understand density dependent growth and survival, especially as it relates to hatchery fish impacts on wild fish (Draft NOAA Fisheries Ocean Module, 2014; Ocean Research Synthesis report, 2012).
- Others?

References

To be added …

Appendix 1. Examples of anadromous fish use in the North Pacific Ocean (Draft NOAA Fisheries Ocean Module, 2014).

Pacific salmon have a complex life cycle that involves both freshwater and marine phases, though it is in the marine environment that they spend the greater part of their lives and gain the bulk of their mass and energy that will subsequently be used for reproduction. Hence, to understand the interactions between salmon and their environment, it is critical to determine where they rear and how much time they spend in different habitats, as it may have a significant effect on their subsequent survival in other habitats (e.g., Weitkamp et al. In Review). The timing of these movements may also affect their survival. For instance, Columbia River basin Chinook salmon and steelhead that enter the ocean early have been shown to perform better than later migrating fish (Scheuerell et al. 2009; Draft NOAA Fisheries Ocean Module, 2014). Below, we give some examples on the migration timing of juvenile salmon through the Columbia River and estuary, and describe their migration in the ocean. These examples were selected to provide an indication of the diversity of the migration strategies used by Columbia River salmon.

Snake River spring/summer Chinook salmon

For Snake River spring/summer Chinook, the average date of estuary entry (as measured at Bonneville Dam with PIT tag data) varies little from year-to-year and occurs in mid-May (reference). Based primarily upon PIT tag data, average residence time of Snake River spring/summer yearling Chinook salmon in the estuary appears to be a week or less and average residence time in the plume also appears to be short and on the order of hours to days. However, there is considerable variation in residence times in different habitats and timing of estuarine and ocean entry among individual fish.

Once yearling Snake River spring/summer Chinook salmon move to the continental shelf in the Northern California Current system (NCC), they can initially disperse in any direction but they quickly begin to migrate along the coast to the north (Trudel et al. 2009; Tucker et al. 2011, 2012; Fisher et al. 2014). Migration to the north appears to be controlled by a combination of environmental and geospatial factors (Burke et al. 2013). As the fish migrate north they distribute over a broad area of the NE Pacific Ocean, including the coastal areas of Washington and British Columbia and Alaska, the continental shelf off Central British Columbia, Central Alaska, Southeast Alaska and the Gulf of Alaska (Trudel et al. 2009; Tucker et al. 2011, 2012; Fisher et al. 2014). Some yearlings from the Snake River ESU move as far north as Kodiak Island by the June-August time period (Trudel et al. 2009; Fisher et al. 2014). Snake River spring/summer Chinook have largely vacated coastal areas of Washington and British Columbia by September. By the end of their first year of ocean life, most fish are in the Gulf of Alaska.

Little is known about the ocean life history of Snake River spring/summer Chinook salmon after they have passed their first year in the ocean until they arrive back in coastal waters of Washington in March and April (Weitkamp 2010; Sharma and Quinn 2012). Returning adult Snake River spring/summer Chinook salmon PIT tagged in the estuary took an average of 18.1 days to reach Bonneville Dam (RM 146) in 2011 and 15.4 days in 2010. Median travel times in 2012 ranged from 40 days for the earliest upstream migrants to about 10 days for the latest migrants, with travel times steadily decreasing throughout the spring. Passage date of adult fish at Bonneville Dam varies with destination of the fish (where the fish ultimately spawn).

Snake River fall Chinook salmon

The Snake River fall Chinook salmon ESU is comprised of both a yearling and sub-yearling component. The estuary and ocean life history of each of these life history types is distinct. Fish from this ESU enter the estuary (based upon passage of PIT tagged fish at Bonneville Dam) in two peaks over a long time period. The peak of the first mode, which are likely the yearlings, is early to mid-May while the peak of the second mode, which is likely the sub-yearlings, has been late June to early July (reference). In the estuary, the two life history types have distinct residence times. On average, the yearlings spend approximately a week in the estuary, which is similar to yearling Snake River spring/summer Chinook salmon. In contrast, some sub-yearlings can rapidly migrate through the estuary while others can rear for an extended period of up to several months in the estuary. Habitat use varies with migrating fish more associated with the mainstem and larger tributaries and rearing subyearlings often associated with shallow water areas such as wetlands and shoreline areas.

Yearling Snake River fall Chinook do not move as far north as yearling Snake River spring/summer Chinook salmon during their first summer at sea (Trudel et al. 2009; Tucker et al. 2011, 2012; Fisher et al. 2014). But by the beginning of their second year at sea they appear to move off the continental shelf and into the Gulf of Alaska (Sharma and Quinn 2012).

The initial dispersal of Snake River subyearling fall Chinook in the NCC is different than yearlings (in general, independent of origin). They first appear in ocean catches in June that are primarily to the north of the Columbia River and some fish have reached the west coast of Vancouver Island (WCVI) by June (Trudel et al. 2009; Tucker et al. 2011, 2012; Fisher et al. 2014). By September, trawl catches show that Snake River fall Chinook sub-yearlings are widely dispersed from central Oregon to the west coast of Vancouver Island. By the end of their first year in the ocean, Snake River fall chinook sub-yearlings have not dispersed much farther to the north than the northern tip of the west coast of Vancouver Island and thus are still in the NCC. Sub-yearlings in general (independent of origin) migrate slower, are found closer to shore in shallower water, and do not disperse as far north as yearlings (Fisher et al. 2007, 2014; Trudel et al. 2009; Tucker et al. 2011, 2012).

Generally, adult fall run fish are found in the lower river in August and September with passage at Bonneville Dam occurring from mid-August to the end of September. Based upon the Interior Columbia River summer/fall group which includes Snake River falls, median date of passage of this reporting group was mid-September from 2004-2007.

Steelhead

Most steelhead migrate very rapidly (< 5 days) through the estuary and into the ocean and are present in the immediate mouth of the river for a very short period (hours to days) (reference). Residence time at the mouth of the river is very short and increases slightly as the season progress. However, there is considerable variation in travel times and timing of estuarine and ocean entry between individual fish. For example, residence time of juvenile steelhead at the mouth of river ranged from 0.1 days to 10.8 days (McMichael et al. 2013). Differences in ocean entry date of days to weeks may not be unimportant and could affect survival of fish in the ocean (Scheuerell et al. 2009; Holsman et al. 2012). Steelhead marine survival appears to be linked to the size of the plume (Burla et al. 2010a). It may be related to moving them quicker through an area of high predation or it may allow them to move off the continental shelf into deeper North Pacific Ocean waters, their preferred marine habitat (Myers et al. 1996).

Once Snake River steelhead leave the estuary they migrate rapidly to the west and leave the NCC off Washington by mid-June. Residence time in the NCC off of Washington appears to be around 10 days on average (Daly et al. 2014?). Steelhead distribute themselves in a broad band across the North Pacific, with most fish found between 40°N and 50°N latitude and from the North American Coast to 165°W (west of the date line) (Myers et al. 1996, 2003; Welch et al. 1998). In general, ocean distribution appears to be highly dependent on temperature (Welch et al. 1998a). There is not much else known about ocean life history of steelhead (but see Atcheson et al. 2012a, 2012b).

Once adult steelhead enter the estuary, their timing of upstream migration at Bonneville Dam varies with age, size and distribution of the fish. Most wild fish pass the dam earlier than hatchery fish. The peak passage of the earlier portion of the returning steelhead has shifted by about 2 weeks from late July to early August, probably in response to warming temperatures and reduced flows in the river.

Snake River sockeye salmon

Snake River sockeye are present in very low abundance levels and so are rarely detected in ocean surveys using any sampling method (Tucker et al. 2009, 2015; Beacham et al. 2014a, 2014b). Based upon PIT tag detections at Bonneville Dam, peak passage of juvenile sockeye from this ESU at Bonneville Dam is generally in late May. Too few sockeye juveniles from the Snake River ESU have been sampled to draw any conclusions about length of estuary residence, although there is relatively little annual variation in migration timing of juveniles (all sockeye stocks combined) through the estuary with peak catches occurring in early June.

Based upon trawl samples, sockeye juveniles from the Columbia River do not disperse south of the Columbia River and have left the NCC by September (Tucker et al. 2009, 2015; Beacham et al. 2014a, 2014b). Juvenile Snake River sockeye enter the Gulf of Alaska/Bering Sea by the end of their first ocean year. Water temperatures may affect the distribution of fish in the GOA with warmer temperatures pushing fish further north, thereby increasing the distance fish migrating south (such as to the Columbia River) have to travel (Welch et al. 1998b; Azumaya et al. 2007; Abul-Aziz et al. 2011). The body size when sockeye salmon begin their return migration can be related to temperatures in the last months of ocean residence with warmer temperatures leading to a smaller body size (reference).

The date when sockeye salmon begin their return migration is apparently a population-specific trait that is independent of where the fish are at sea. Water temperature may play an important role in determining when stocks arrive back to coastal areas near spawning rivers (reference). … return timing to the river and spawning ground …

References

Beacham, T.D., R.J. Beamish, J.R. Candy, C. Wallace, S. Tucker, J.H. Moss, and M. Trudel. 2014a. Stock-specific size of juvenile sockeye salmon in British Columbia waters and in the Gulf of Alaska. *Trans. Am. Fish. Soc.* 143: 876-888.

Beacham, T.D., R.J. Beamish, J.R. Candy, C. Wallace, S. Tucker, J.H. Moss, and M. Trudel. 2014b. Stock-specific migration pathways of juvenile sockeye salmon in British Columbia waters and in the Gulf of Alaska. *Trans. Am. Fish. Soc.* 143: 1386-1403.

Burke, B. J., M.C. Liermann, D.J. Teel, and J.J. Anderson, 2013. Environmental and geospatial factors drive juvenile Chinook salmon distribution during early ocean migration. *Can. J. Fish. Aquat. Sci.* 70: 1167–1177.

Burke, B. J., J.J. Anderson, and A.M. Baptista. 2014. Evidence for multiple navigational sensory capabilities of Chinook salmon. *Aquat. Biol.* 20: 77–90.

Burla, M., A.M. Baptista, E. Casillas, J.G. Williams, and D.M. Marsg. 2010. The influence of the Columbia River plume on the survival of steelhead (*Oncorhynchus mykiss*) and Chinook salmon (*Oncorhynchus tshawytscha*): a numerical exploration. *Can. J. Fish. Aquat. Sci.* 67: 1671-1684.

Ferris, B.E., M. Trudel, and B.R. Beckman. 2014. Assessing marine pelagic ecosystems: regional and inter-annual trends in marine growth rates of juvenile salmon off the British Columbia Coast. *Mar. Ecol. Prog. Ser.* 503: 247-261.

Fisher, J., Trudel, M., Ammann, A., Orsi, J., Piccolo, J., Bucher, C., Harding, J., Casillas, E., MacFarlane, B., Brodeur, R., Morris, J., and Welch, D. 2007. Regional comparisons of distribution and abundance of juvenile salmon along the West Coast of North America. *Am. Fish. Soc. Symp. Ser.* 57: 31-80.

Fisher, J.P., L. Weitkamp, D.J. Teel, S.A. Hinton, J.A. Orsi, E.V. Farley, Jr, J.F.T. Morris, M.E. Thiess, R.M. Sweeting, and M. Trudel. 2014. Early ocean dispersal patterns of Columbia River Chinook and coho salmon. *Trans. Am. Fish. Soc.* 143: 252-272.

Holsman et al. 2012.

Morris, J.F.T., Trudel, M., Thiess, M., Sweeting, R.M., Fisher, J., Hinton, S., Fergusson, E.A., Orsi, J.A., Farley, E.V., Jr., and Welch, D.W. 2007. Stock-specific migrations of juvenile coho salmon derived from coded-wire tag recoveries on the continental shelf of western North America. *Am. Fish. Soc. Symp. Ser.* 57: 81-104.

Myers, K.W., R.V. Walker, R.L. Burgner, and G. Anma. 2001. Distribution, origins, biology, and ecology of juvenile steelhead (*Oncorhynchus mykiss*) in the Gulf of Alaska in summer 1993–2000. *N. Pac. Anadrom. Fish Comm. Tech. Rep.* 2: 30–31.

Scheuerell et al. 2009.

Sharma, R., and T.P. Quinn. 2012. Linkages between life history type and migration pathways in freshwater and marine environments for Chinook salmon, *Oncorhynchus tshawytscha*. *Acta Oecologica*, *41*, 1–13.

Trudel, M., Fisher, J., Orsi, J., Morris, J.F.T., Thiess, M.E., Sweeting, R.M., Hinton, S., Fergusson, E., and Welch, D.W. 2009. Distribution and migration of juvenile Chinook salmon derived from coded-wire tag recoveries along the continental shelf of western North America. *Trans. Am. Fish. Soc.*138: 1369-1391.

Tucker, S., Trudel, M., Welch, D.W., Candy, J.R, Morris, J.F.T., Thiess, M.E., Wallace, C., Teel, D.J., Crawford, W., Farley, E.V. Jr., and Beacham, T.D. 2009. Seasonal stock-specific migrations of juvenile sockeye salmon along the west coast of North America: Implications for growth. *Trans. Am. Fish. Soc.* 138: 1458-1480.

Tucker, S., M. Trudel, D.W. Welch, J.R. Candy, J.F.T. Morris, M.E. Thiess, C. Wallace, and T.D. Beacham. 2011. Life history and seasonal stock-specific ocean migration of juvenile Chinook salmon. *Trans. Am. Fish. Soc.* 140: 1101-1119.

Tucker, S., M. Trudel, D.W. Welch, J.R. Candy, J.F.T. Morris, M.E. Thiess, C. Wallace, and T.D. Beacham. 2012. Annual coastal migration of juvenile Chinook salmon; Static stock-specific patterns in a dynamic ocean. *Mar. Ecol. Prog. Ser.* 449: 245-262.

Tucker, S., M.E. Thiess, J.F.R. Morris, D. Mackas, W.T. Peterson, J.R. Candy, T.D. Beacham, E. Iwamoto, D. Teel, M. Peterson, and M. Trudel. 2015. Coastal distribution and consequent factors influencing production of endangered Snake River Sockeye Salmon. *Trans. Am. Fish. Soc.* 144: 107-123.

Weitkamp, L. 2012. Marine dustributions of coho and Chinook salmon inferred from coded wire tag recoveries. *Am. Fish. Soc. Symp. Ser.* 76: 191-214.

Welch, D. W., Y. Ishida, K. Nagasawa, and J.P. Eveson. 1998a. Thermal limits on the ocean distribution of steelhead trout (*Oncorhynchus mykiss*). N. Pac. Anadrom. Fish Comm. Bull. 1: 396–404

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