5. South-Central California Coast Steelhead and Climate Change

"The West Coast's salmon and steelhead populations have always been sensitive to the variability of the northeast Pacific climate-ocean system . . . So steelhead recovery as a form of human stewardship has to be judged over a broader timeline, with multi-year setbacks in population size considered to be a normal and expected event, and progress judged at the scale of multiple decades and even multiple human generations."

Dr. David A. Boughton, Chair, NOAA Fisheries South-Central/Southern California Steelhead Technical Recovery Team, 2010

5.0 INTRODUCTION

The addition of CO_2 and other greenhouse gasses to the atmosphere over the past two centuries, as a result of industrialization and changes in land use, has substantially altered the radiative balance of the Earth. Less of the energy entering the Earth's atmosphere as sunlight is being re-radiated to space, with the effect that the planet is currently heating up at a pace not seen in human history, and perhaps not for millions of years (Archer and Pierrehumbert 2011, Solomon *et al.* 2009, Archer 2007). The human response to this change will likely be a major theme in the 21st century (Intergovernmental Panel on Climate Change 2012).

The potential physical effects of projected future climate changes are manifold and complex, varying in range and intensity, across various landscape scales and ecosystem types. The biological response is also complex, and with many species, including Pacific anadromous salmonids, uncertain. While SCCCS steelhead have evolved a suite of effective adaptations to a highly variable environment (including multiple paths for completing their life cycle), the rapid rate of projected climate change presents a significant challenge to their long-term persistence. Recent assessments of global climate change and climate change in the United States summarize the general effects on ecosystems (Trenberth, *et al*. 2011, Johnstone and Dawson 2010, Cayan *et al*. 2009, Dettinger *et al*. 2009, Mastrandera *et al*. 2009, Medellin-Azuara *et al*. 2009, Shaw *et al*. 2009, Westerling *et al*. 2009, Backland *et al*. 2008, Bedworth and Hanak 2008, Gutowski *et al*. 2008, Barbour and Kueppers 2008, Hanak and Moreno 2008, Hanak and Lund 2008,

Luers and Mastrandrea 2008, Intergovernmental Panel on Climate Change 2014a, 2014b, 2013, 2007a, 2007b).

These general physical effects include: 1) warmer atmospheric temperatures; 2) rises in sea level due to ice cap melting and thermal expansion of ocean water; 3) acidification of ocean waters; 4) increased droughts (frequency, severity, and duration) coupled with more severe cyclonic storms (intensity and duration); 5) increases in the intensity, frequency and duration of wildland fires; 6) modification of a variety of watershed processes, including run-off, erosion, sedimentation, and a variety of hill-slope processes ranging from ravel to mass-wasting and debris flows; 7) increases in water temperatures in rivers and streams; and 8) alterations in stream morphology (*e.g.*, occurrence and distribution of sediments, pools, riffles, etc.) as a result of changes in the frequency and intensity of high-flow events.

A review of existing studies indicates that regional climate changes would drive ecosystem changes in diverse ways (Dawson *et al*. 2011, Schwing *et al.* 2010). The ability to model and forecast the effects of such changes on steelhead populations is likely to be quite limited due to limitations on the predictability of behavior of non-linear causal networks (Schindler *et al.* 2008). This problem is common to many threatened and endangered species, but is heightened for Pacific salmonids due to their dependence on a succession of different habitats over the course of their life history cycle. However, the environmental changes anticipated for South-Central California Coast steelhead are likely not as profound as other regions of California. For example; (a) in the Central Valley, anadromous fish populations dependent on snowmelt-fed riverine habitats may undergo a conversion to rain-fed habitats, or (b) along the central and north coastal areas where Coho salmon (*O. kisutch*) populations, which have a fixed three year life history strategy, may be less adaptable to environmental changes than steelhead (Moyle *et al.* 2008).

The projected climate changes in South-Central California are expected to mainly intensify patterns that are characteristic of a semi-arid Mediterranean Climate (periodic droughts, intense cyclonic rainstorms, dry, hot summers) to which South-Central Coast populations of steelhead appear to have evolved a flexible, opportunistic survival strategy. An important factor for coastal steelhead populations is the continuing role of the ocean in moderating coastal climates due to its high heat capacity. Coastal steelhead populations at the southern extent of the SCCCS DPS appear to have a more predictable future despite changing climate condition. However, steelhead in the Interior BPG will likely be more vulnerable to climatic changes as a result of increased ambient temperatures and less predictable rainfall patterns (Boughton 2010a). The human response to projected (and actual) climate change introduces an additional uncertainty in the recovery of the SCCCS DPS (Intergovernmental Panel on Climate Change 2012).

5.1 PROJECTED CLIMATE CHANGES

5.1.1 Terrestrial and Freshwater Environment

Geographically, California is situated at the transition between regions of net gain and net loss of water, and predicted future water availability is sensitive to modeling assumptions and emissions scenarios (Hayhoe *et al*. 2004). Climate models appear to make a median prediction of about a 10% loss of precipitation statewide by 2100, under a low emissions scenario (Cayan *et al*.

2009, 2006). However, there is enough variability in the predictions that significantly drier or wetter futures are also reasonable expectations (Trenberth *et al*. 2011, Hayhoe *et al*. 2004, Leung *et al*. 2004, Snyder *et al*. 2002).

For California, the mid-century (2035- 2064) response to global climate change is consistent across scenarios: an annual maximum temperature increase of about +1.9° to +2.3° Celsius (C) for sensitive climate models, and 1° C for the less sensitive model (Shaw *et al.* 2009). The statewide precipitation response is relatively small, ±4 centimeters (cm) across the various scenarios and models, though more precipitation falls as rain rather than snow. Also, the snow melts sooner; and more is evaporated leading to lower soil moisture and streamflows (Null *et al.* 2010, Cayan *et al.* 2008a, Milhous *et al.* 2003). Model simulations suggest that predictability is reasonably good at the 40-year time-scale, perhaps because global climate outcomes at this timescale are dominated not by positive atmospheric feedbacks, but by the inertial effect of the ocean, which limits the pace of climate change (Baker and Roe 2009).

By 2100, the temperature scenarios diverge much more severely, about +2.5° C versus +4.2° C for the lower and middle-upper emission scenarios, respectively. Under the middle-upper emission scenario, the end-of-the-century also marks a period of unprecedented wildfires and significantly more erratic precipitation in the South-Central California watersheds, and the possibility of large decreases in mean precipitation (Shaw *et al.* 2009, Cayan *et al.* 2008a, Milhous *et al.* 2003).

Perhaps more importantly, under the middle-upper emission scenario, the end-of-the-century marks a period of *accelerating* greenhouse gas emissions and climate change, whereas in the lower scenario it is a period of emissions *shrinking* toward zero and global change that is decelerating toward equilibrium (Solomon *et al.* 2009, Cayan *et al.* 2008a). Changes projected under the middle-upper emissions scenario are the prelude for faster changes in the 22nd Century, with no prognosis for stabilizing greenhouse gas concentrations and climate.

Regional climate projections for the South-Central California watersheds suggest a future of longer, hotter summers, with a potentially higher incidence of fog along the immediate coast. These projections also suggest more extreme heat waves and droughts, but with perhaps more intense precipitation events in some areas (Karl *et al.* 2009, 2008, Cayan *et al*. 2008a, Snyder and Sloan, 2005, Snyder *et al.* 2002).

Climate change has the potential to profoundly affect both terrestrial and freshwater ecosystems in California (Maurer *et al.* 2010, Bakke 2008, Barbour and Kueppers 2008, Schindler *et al.* 2008). There are a number of potential negative effects on steelhead and their freshwater and estuarine habitats which are of particular significance. Many of these effects could be exacerbated by the human response to climate change, particularly as a result of the increase competition for limited freshwater supplies. These are summarized below (Schwing *et al.* 2010).

Rainfall and Runoff. Steelhead depend on adequate rainfall and run-off during their migratory seasons to both enter and emigrate from coastal watersheds. In South-Central California adequate stream flow is not only necessary for adults to reach upstream spawning areas and smolts to emigrate to the ocean, but also to breach the sand bar, which seasonally forms at the mouth of most coastal rivers and streams, to allow entrance to and emigration from the watershed to the Pacific Ocean (Jacobs *et al.* 2011, Maurer *et al.* 2006, Quinn 2005).

Rivers and riparian areas (and associated wetland areas) make up less than one percent of the landscape in regions such as South-Central California. These highly productive ecosystems are embedded within upland systems with much lower productivity (Warner and Hendrix 1984). The primary driver of terrestrial hydrologic systems is precipitation. Most of the United States experienced increases in precipitation and stream flow and decreases in drought during the second half of the past century. However, there are indications the severity and duration of droughts have increased in the western and southwestern United States. The full effects of these changes on aquatic organisms such as *O. mykiss* are not well understood (Schwing *et al.* 2010).

Groundwater. Groundwater is an important source of surface flows during dry periods in many South-Central California Coast watersheds. Groundwater contributes to sustaining suitable over-summering juvenile rearing conditions in mainstem and tributary habitats. Surface flows can be maintained as a result of the intersection of a high groundwater table or through the transmission of water through geologic fault systems. The effects of climate change on groundwater systems have not been as extensively studied as have the effects of climate change on surface water systems. One recent investigation in the Santa Ynez Mountains of California suggests that an increase in the biomass of watersheds dominated by chaparral is likely to increase with the increase of atmospheric CO_2 and atmospheric temperature, leading to reductions in summer stream flow (Tague *et al.* 2009). Other Global Climate Models (GCMs) project a decrease in vegetative cover which could lead to an increase in summer stream flow (Boughton 2010a).

Water Temperature. Increased minimum atmospheric temperatures and warmer spring and summer temperatures have led to increased stream temperatures in most of the continental Unites States (Mantua *et al.* 2010). Increased stream temperatures will have direct and indirect adverse impacts on juvenile *O. mykiss.* These impacts include subjecting the species to increased physiological stress, and altering the aquatic environment through modifications such as reduced dissolved oxygen levels or increased growth of algae and rooted aquatic vegetation that can increase the diurnal bio-oxygen demand in a river system.

Elevated stream temperatures can favor the proliferation of non-native warm water species that can compete for living space, food, and also prey on native *O. mykiss*, particularly juveniles. Changes in water temperature are most likely to occur during low-flow periods that coincide with over-summering rearing juvenile *O. mykiss*. Stream temperature increases have already begun to be detected across the United States, though no comprehensive analysis similar to streamflow trends has been conducted. An increase in the incidence of coastal fog could moderate these effects in some coastal areas (Wenger *et al.* 2011, Johnstone and Dawson 2010, Mantua *et al.* 2010, Keefer 2009, Schindler *et al.* 2008, Daufresne and Boet 2007, Battin 2007, Mohseni *et al.* 2003, 1999, Mohseni and Stefan 1999, Eaton and Schaller 1996).

Wildland Fire. Chaparral is the predominant vegetation type within the SCCCS Recovery Planning Area. Wildfires are a natural phenomenon essential for the periodic renewal of chaparral plant communities (Keeley *et al*. 2012, Van de Water 2011, Bendix and Cowell 2010a, 2010b, Sugihara *et al.* 2006, Davis and Borchert 2006). Wildfires can have at least temporary major impacts on freshwater habitats of anadromous and non-anadromous *O. mykiss.* These effects range from increasing the erosion, transportation,

and deposition of massive amounts of fine sediments into watercourses containing coarser-grained spawning gravels to destroying riparian vegetation and facilitating the spread of non-native plant and animal species. The frequency and size of wildfires is expected to increase as a result of increases in atmospheric temperatures (Bell *et al.* 2009, Westerling and Bryant 2008, Westerling *et al.* 2009, Lenihan *et al*. 2006, Miller and Schlegel 2006, Loaiciga *et al.* 2001).

Hot, dry winds (known locally as "Diablo Winds) occur during the summer in the upper Salinas Valley and human-triggered ignitions play important roles in the fire regime of South-Central California chaparral and scrubland forests. These seasonal, hot, dry winds occur primarily during the fall and winter and are driven by large-scale patterns of atmospheric circulation resulting from high pressure over the Great Basin, coupled with low pressure off the coast of South-Central California that drives dry air toward the coast. These winds can spread fires rapidly, sometimes burning many square miles of chaparral and shrub vegetation per day (Keeley *et al.* 2012, Davis and Borchert 2006, Keeley 2006, Keeley *et al.* 1999, Ryan and Burch 1992,). Wildland fire impacts can be compounded by fire-fighting measures to control or extinguish wildland fires (*e.g.*, the use of fire retardants) as well as by post-fire measures to repair damages incurred in fighting wildland fires (Verkaik *et al.* 2012, Capelli 2009, Cooper 2009, National Marine Fisheries Service 2008b, Backer *et al.* 2004, Finger 1997).

5.1.2 Marine Environment

Steelhead adults spend the most of their lives in the marine environment, entering freshwater habitats for brief periods to reproduce. While steelhead are subjected to the same basic ocean conditions (*e.g.*, currents, water temperature, up-welling, abundance of prey base, predator-prey interactions, and water quality) as other anadromous Pacific anadromous salmonids, they may respond and be affected by such conditions differently because of their distinctive behavioral, physiological and other ecological characteristics. Nonetheless, as with other anadromous Pacific salmon, conditions in the marine environment are crucial to the growth, maturation, mortality, and abundance of returning adult steelhead to their freshwater spawning habitats (see Beamish *et al.* 2010 for a comprehensive bibliography of climate impacts on Pacific salmon). .

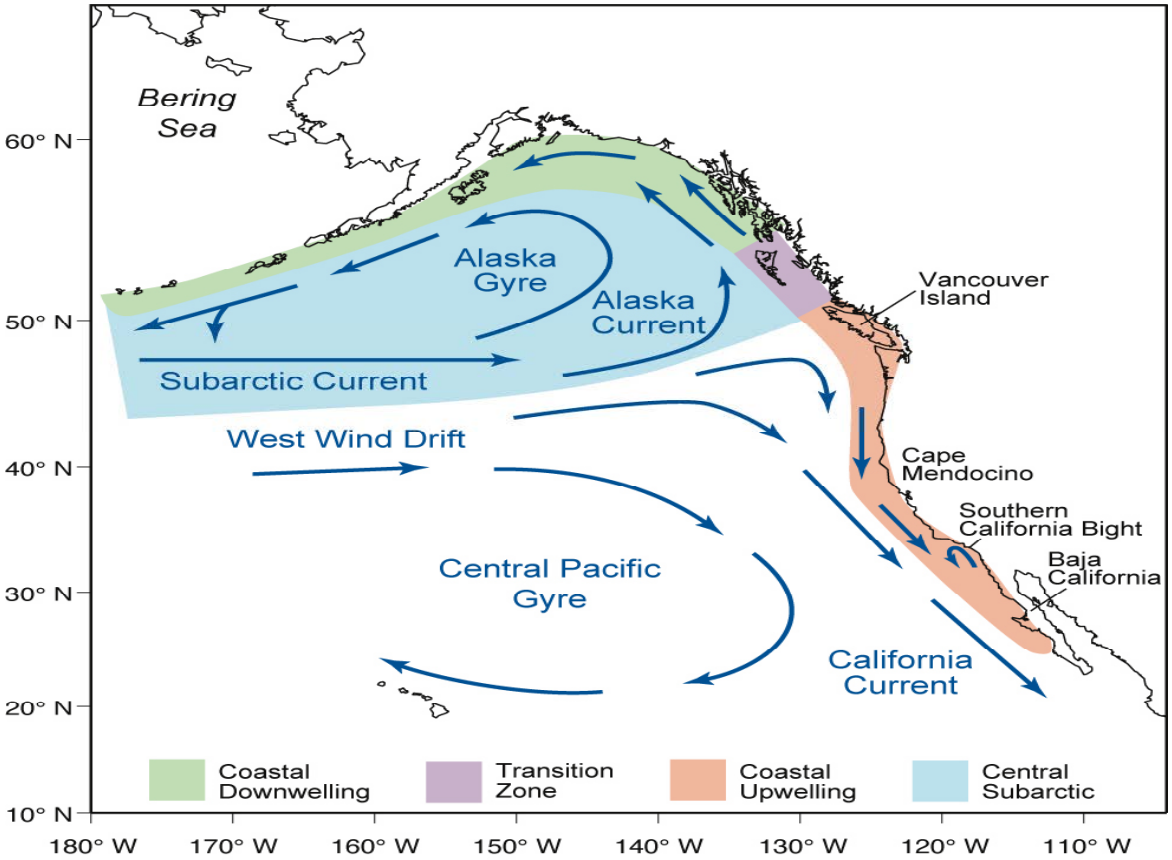

Figure 5-1. Principal Ocean Currents in the North-East Pacific Ocean Affecting Coastal Waters of California (J. A. Barth, Oregon State University

California Current Ecosystem

The California Current Ecosystem (CCE) is one of eight large marine ecosystems within the jurisdiction of the United States. The northern end of the current is dominated by strong seasonal variability in winds, temperature, upwelling, plankton production and the spawning times of many fishes, whereas the southern end of the current has much less seasonal variability. Climate signals in this region are quite strong. During the past 10 years, the North Pacific has seen two El Niño events (1997/98, 2002/03), one La Niña event (1999), a four-year climate regime shift to a cold phase from 1999 until late 2002, followed by a four-year shift to warm phase from 2002 until 2006 (Schwing *et al*. 2010, Peterson and Schwing 2003, Mantua 2011, Mantua *et al.* 1997). Due to the paucity of information on the marine phase of steelhead it is difficult to assess the biological response to projected climate driven changes in the CCE.

Climate-Induced California Current Ecosystem Responses

Numerous climate stressors (*e.g.,* warming, sea level rise, freshwater flow) impact productivity and structure throughout the CCE. The following provides a summary of these issues based upon the analysis developed as part of a NMFS framework for a long-term plan to address climate impacts on living marine resources (Schwing *et al.* 2010, Osgood 2008).

1. Future climate variability in the context of global climate change and a warmer planet

One of the likely consequences of global climate change will be a more volatile climate with greater extreme events on the intra-seasonal to inter-annual scales. For the CCE this will mean more frequent and severe winter storms, with greater wind mixing, higher waves and coastal erosion, and more extreme precipitation events and years, which would impact coastal circulation and stratification. Some global climate models predict a higher frequency of El Niño events and others predict the intensity of these events will be stronger. If true, primary and secondary production will be greatly reduced in the CCE, with negative effects transmitted up the food chain, including to the Pacific anadromous salmonids (Trenberth *et al.* 2011, Mastrandrea *et al.* 2009, Karl *et al*. 2008, Bell and Sloan 2006, Benestad 2006, Bell *et al.* 2004, Trenberth 1999) which will result in decreased ocean survival.

2. The extent and timing of freshwater input and its impact on the nearshore habitat of anadromous fishes

Variability in ocean conditions has substantial impacts on salmon survival and growth, and can be influenced in continental shelf waters by river runoff. Potential changes in rainfall patterns and intensity are likely to increase winter and spring runoff but decrease summer runoff. Climate models project the 21st century will feature greater precipitation in the Pacific Northwest, extreme winter precipitation events in California, and a more rapid spring melt leading to a shorter, more intense spring period of river flow and freshwater discharge. This will greatly alter coastal stratification and mixing, riverine plume formation and evolution, and the timing of transport of anadromous populations to and from the ocean (Maurer *et al*. 2010, 2006, Mantua *et al*. 2010, Poff *et al.* 2010, Barnett 2008, Kim *et al.* 2002).

The situation in South-Central California may be more complex, and difficult to model, because of the uncertainty surrounding the projected climate changes making the likely response of SCCCS steelhead to these climate driven changes more uncertain (Boughton 2010a, Boughton *et al.* 2006, 2007b).

3. The timing and strength of the spring upwelling transition and its effect on production and recruitment of marine populations

Coastal upwelling of cold water carries significant plankton and krill populations into coastal waters. These populations are an important food source for young Pacific anadromous salmonids entering the ocean to begin the marine phase of their life cycle. At present there is some evidence coastal upwelling has become stronger over the past several decades due to greater contrasts between warming of the land (resulting in lower atmospheric pressure over the continent) relative to ocean warming (Bakun 1990). Regional climate models project that not only will upwelling-favorable winds be stronger in summer, but the peak in seasonal upwelling will occur later in the summer (Snyder *et al.* 2003), delaying the availability of an important food source to juvenile salmonids. However, the winds may not be able to mix this light buoyant water or transport it offshore, resulting in the inability of cold nutrient-rich water to be brought to the sea surface.

Figure 5-2 Seasonal Coastal Upwelling Pattern Along the California Coast (Courtesy NOAA)

If this occurs phytoplankton blooms may not be as intense, which may impact organisms up the food chain including salmonids (Roemmich and McGowan, 1995). Given a future warmer climate, the upper ocean will likely be, on average, more stratified. The result will be lower primary productivity everywhere (with the possible exception of the nearshore coastal upwelling zones).

4. Ocean warming, increased stratification and their effect on pelagic habitat

The vertical gradient in ocean temperature off California has intensified over the past several decades (Palacios *et al*. 2004). Areas with enhanced riverine input into the coastal ocean will also see greater vertical stratification. Generally warmer ocean conditions will cause a northward shift in the distribution of most marine species, and possibly the creation of reproductive populations in new regions. Existing faunal boundaries are likely to remain as strong boundaries, but their resiliency to shifts in ocean conditions due to global climate change is not known. The effects of any shift of pelagic species, particularly predator and prey species on Pacific anadromous salmonids, are unclear, but may vary with individual species such as steelhead (Hazen *et al.* 2012, Grebmeier 2012, Shoji *et al.* 2011, Lindley *et al.* 2007, Swartzman and Hickey 2003).

5. Changes in gyre strength, regional transport, and source waters to the California Current and their impact on species distribution and community structure

Observations of the biota of the California Current show pronounced latitudinal differences in species composition of plankton, fish, and benthic communities, ranging from cold water boreal sub-arctic species in the north to warm water subtropical species in the south.

Copepod biodiversity increases in coastal waters due to shoreward movement of offshore waters onto the continental shelf, which is caused by either weakening of southward wind stress in summer or strengthening of northward wind stress in winter.

Regardless of the season, the source waters entering the California Current from the north and offshore can exert some control over the primary phytoplankton and zooplankton species in the current. The occurrence of low

returns of Pacific salmonids when the Pacific Decadal Oscillation (PDO) is in a positive, warm-water phase, and high returns when the PDO is in a negative, cold-water phase suggests a mechanistic link between PDO sign change and the growth and survival of Pacific salmonids. However, for Alaska salmon, the typical positive PDO condition is associated with enhanced streamflows and nearshore ocean mixed-layer conditions favorable to high productivity. Similar, PDO conditions affect steelhead populations with in the South-Central Coast watersheds (Mantua and Hare 2002,

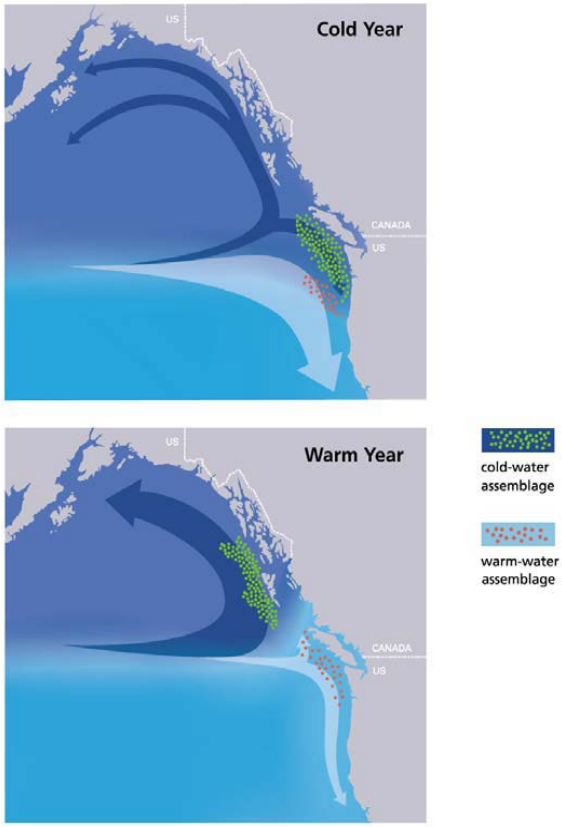

Figure 5-3. Shift in Cold and Warm-Water Faunal Assembles During Pacific Decadal Oscillations and El Niño/La Niña/Southern Oscillations (Osgood 2008)

Mantua *et al*. 1997). Most climate models project roughly the same timing and frequency of decadal variability in the North Pacific under the impacts of global warming. However, combined with a global warming trend, the CCE is likely to experience more years of positive, warm phases (*i.e.*, periods of generally lower productivity).

Two other marine related effects of global climate change are relevant to steelhead as well as other Pacific anadromous salmonids: sea-level rise and ocean acidification.

Sea Level Rise. One of the several life history strategies exhibited by steelhead is the "lagoon-anadromous" strategy where juveniles rear a portion of the year in the estuary of natal rivers or streams. Studies in small coastal estuaries/lagoons seasonally closed off from the ocean by sand bars have shown these habitats can be productive rearing areas for *O. mykiss*. Juveniles rearing in lagoons can grow fast enough to migrate to the ocean after their first year, and generally at a larger size than juveniles rearing in the freshwater portion of the stream system. Fish entering the ocean at a larger size exhibit greater survival rates, and are disproportionately represented in the adult spawning population (Hayes *et al.* 2008, Bond 2006).

Changes in sea level, which have the potential to adversely affect important estuarine habitats, have already been reported and are expected to continue. Researchers have projected by 2035-2064, global sea level rise will range between 6 and 32 cm above 1990 levels, regardless of emission scenarios. Between 2070-2100, the projected range of sea level rise varies between 11-54 cm to 17-72 cm depending on the emission scenario (Cayan *et al*. 2009, 2008b, Pilkey and Young 2009, Raper and Braithwaite, 2006). These more recent estimates suggests a larger rise in sea level than previously projected by Hayhoe *et al*. 2004 and Ewing 1989. A projected 1 meter (m) rise in sea level could lead to the potential inundation of 65 percent of the coastal marshlands and estuaries in the continental United States. In addition to the inundation and displacement of estuaries/lagoons, there would be shifts in the quality of the habitats in affected coastal regions. Prior to being inundated, coastal watersheds would become saline due to

saltwater intrusion into the surface and groundwater (Pilkey and Young 2009). A rise in sea level will most dramatically affect estuaries confined by surrounding development because their inland boundaries are prevented from naturally adjusting in response to ocean inundation. As discussed in Chapter 4 (Current DPS-Level Threats Assessment), estuarine habitat functions and habitat loss may be of particular importance to steelhead, though their role in South-Central California has been the subject of limited investigation.

Ocean Acidification. Another projected effect of climate change on the marine environment is acidification. As a result of increased anthropogenic CO_2 in the oceans since the industrial revolution, the pH of seawater has dropped from 8.2 to 8.1 (on a logarithmic scale, this represents a 26% increase in the concentration of H^+ ions). Estimated future increase in atmospheric CO_2 could result in a decrease in surface water pH of 0.3-0.4 by the end of the century, depending on the emission scenario (Feely *et al.* 2008, 2004). The effects of CO_2 concentration in the marine environment are not uniform, but are expected to vary with water depth, circulation and temperature, and in coastal waters with upwelling and freshwater input and nutrients (National Research Council 2010).

The reaction of CO_2 with seawater reduces the formation of calcium carbonate used in skeleton and shell formation of marine organisms, and can change many biologically important chemical reactions. Effects of ocean acidification will vary among organisms. As an example, ocean acidification has been shown to reduce the abundance of some carbonate forms, such as pteropods (Fabry *et al.* 2008). Because pteropods are an important food source for sockeye (*Oncorhynchus nerka*), pink (*Oncorhynchus gorbuscha*), and chum salmon (*Oncorhynchus keta*, a reduction in pteropods can adversely affect the marine growth of these species. One bioenergetics/food web model predicts a 10% reduction in pteropod production would result in a 20% reduction in the growth of pink salmon (Aydin *et al.* 2005). Because of the lack of information on the marine phase of steelhead, it is unclear if pteropods or other carbonate forming prey constitute a signification portion of their marine diet. The significance of ocean acidification for steelhead and other anadromous salmonids may depend on the change of pH and carbonate equilibrium, its effect on pteropods and pelagic planktonic community structure, and the ability of juvenile and adult salmonids to modify their diets accordingly (Schwing *et al*. 2010). The long-term consequences of ocean acidification on marine ecosystems are poorly understood (National Research Council, 2010). Because the marine life history phase of steelhead is not well understood, as noted above, the long-term consequences of ocean acidification for steelhead are even more uncertain (Nielsen and Ruggerone 2009, Myers *et al*. 2000, 1996).

5.2 CLIMATE INFLUENCES ON STEELHEAD

5.2.1 Steelhead Life Histories and Habitats

The intricate life history of salmonids as well as the complexity of their multiple aquatic habitats means it is rare an isolated environmental factor, or driver, is responsible for variability in a given population. Numerous climate stressors (*e.g.*, warming, sea level rise, freshwater flow) affect population productivity and structure throughout the habitats and life history stages of the various anadromous salmonids. To understand the implications of climate change for salmonids, we established a conceptual framework to organize this complexity (Schwing *et al.* 2010). The framework is reflected in the viability criteria and recovery strategy described in Chapters 6, and 7, which is based on the highly variable climatic conditions characteristic of the SCCCS Recovery Planning Area, and should provide guidance in the adaptive

management of steelhead as the climate continues to change. The criteria and recovery strategy emphasize the need for steelhead population and habitat redundancy and diversity to buffer the SCCCS DPS against current and future extreme weather conditions and associated population fluctuations.

The framework used here organizes complexity into four broad spheres: 1) the multiple life history pathways open to salmonids as a function of their adaptations and ecological tolerances; 2) the environmental opportunities aquatic habitats offer to salmonids at each stage of their life history (Mobrand *et al*. 1997); 3) the suite of habitat-generating processes and stressor-pathways, by which climate (and other drivers) create, destroy, or maintain these aquatic habitats; and 4) the spatial connectivity and timing by which the other domains are knitted into a productive and viable salmonid population. This way of organizing the material allowed a systematic treatment of each life stage, each habitat used by each life stage, and each way climate change potentially impacts each habitat-generating mechanism (Waples *et al.* 2010, 2008a, 2008b, Schindler *et al*. 2008).

5.2.2 Life History Pathways

The life history network described in Chapter 2, Sub-section 2.6 (South-Central California Coast steelhead Freshwater Life Cycle Habitat Use) can be related to the Viable Salmonid Population (VSP) concept of McElhany *et al*. (2000), where viability is measured in terms of four parameters: abundance, productivity, diversity, and spatial structure. Each link in a habitat network involves an interaction between a life history stage and a particular habitat, and has two attributes that emerge from this interaction: survival and capacity. The patterns of survival and capacity across the network translate to abundance and productivity, respectively, for the population as a whole, two of the four VSP parameters (Mobrand *et al*. 1997).

Diversity and spatial structure, the other two VSP parameters, emerge from the parallel linkages in the life history network. Diversity has two broad components: the diversity of pathways offered by the environment (habitat diversity), and the ability of the species to pursue those opportunities (phenotypic plasticity, generalist strategies, and genetic diversity). Spatial structure, the fourth VSP parameter, provides the physical space for parallel linkages to occur in greater numbers and larger capacities, thus increasing the overall resilience of the population.

Because climate is changing, it can be expected steelhead populations will respond in variable ways. In so far as evolution has raised steelhead populations to an adaptive peak, climate change will generally be expected to reduce the fitness of steelhead populations, at least temporarily (Schwing *et al.* 2010).

The interactions between steelhead at distinctive phases in their life history and habitat conditions characteristically associated with those life history phases should be the focus of future research into the effects of projected climate change on steelhead life histories and habitats.

5.2.3 Environmental Opportunities and Habitat Diversity

Environmental opportunities are times and places where physical, chemical and biological conditions support survival, growth, migration and reproduction of anadromous salmonids. Some of these conditions are predictable or discernible, and some are not. Frequently, the relatively predictable components are physical or possibly chemical conditions, traceable to the interaction of climate acting on a geologic template (Buffington *et al*. 2004). In freshwater habitats, these physical components of environmental opportunity are generally functions of variation along three axes: flow, channel morphology or substrate, and water quality - particularly temperature (Beechie *et al*.

2010, Orr *et al*. 2008, Newson and Large 2006, Thorp *et al*. 2006, Stanford *et al*. 1996). In marine habitats, climate-related opportunities tend to be physically structured by water temperature, currents and circulation patterns, chemistry (especially acidification), and for the near-shore domain, sea level rise.

5.2.4 Freshwater Habitat-Forming Processes

The processes that convert climate patterns into spatial and temporal habitat for salmonids are sometimes called habitat-forming processes (Beechie and Bolton 1999). Salmonid habitats are generated by the operation of four broad process domains: watershed (or terrestrial), fluvial, estuarine, and marine domains (Montgomery 1999).

These functional domains can be further subdivided to make meaningful connections between climate processes, spatial and temporal habitat, and salmonid life history pathways. For example, the precipitation pulses from Pacific storm systems drive fluvial processes that tend to produce an ordered sequence of channel types from headwaters to the estuary (Montgomery and Buffington 1997). Some of these, such as step-pools and pool-riffle channels, play specific roles (rearing and spawning, respectively) in salmonid life history.

These broad processes can also be subdivided to indicate differential response to climate change. (Boughton *et al.* 2009, Davy and Lapointe 2007, Buffington *et al*. 2004, Moir *et al*. 2004, Kahler *et al*. 2001; see also, Rivaes *et al.* 2013). For example, the fluvial domain can be divided into a sediment-transport domain and a response, or alluvial, domain downstream (Montgomery and MacDonald 2002). These are expected to have different sensitivities to changes in flow regime and sediment supply. Estuarine domains tend to be small interfaces between the much more extensive fluvial and marine domains and they exhibit a dynamism responsive to alteration of either marine or fluvial dynamics (Jay *et al*. 2000).

As with the life history networks of anadromous salmonids, if multiple ecosystem processes produce the same sort of resource for a salmonid population, resiliency of the population tends to improve. Parallel linkages fall into two general categories: redundant pathways and alternative pathways (Edelman and Gally 2001, Tononi *et al*. 1999).

Redundant pathways are multiple instances of the same process providing the same outcome. For example, if headwater streams provide fish with thermal refugia during the summer, a stream system with multiple tributaries, each providing refugia, is considered highly redundant. Redundancy provides resilience against small-scale disturbances, such as chemical spills (Nielsen *et al*. 2000) or wildfire. But redundant pathways tend to respond in a coordinated fashion to large-scale disturbances, such as droughts or heat waves, and provide little resilience to them because they tend to respond the same way.

Alternative pathways are different processes that produce the same physical conditions. For example, thermal refugia can be generated either in a headwater stream (via the temperature lapse rate), moist shaded conditions (transpiration), or in a coastal lagoon (via proximity to the ocean heat sink). Sparsely shaded higher elevation habitats can also produce warmer water conditions; conversely, lower, shaded habitats can produce cooler conditions. For example, large portions of coastal lagoons can be unshaded, and unless subject to persistent fog, can be warm rather than provide a cool refugia. Wind mixing of the water column (accompanied by elimination of salinity stratification) which allows the lagoon to cool at night, can be a critical factor (Smith 1990).

Due to the large thermal mass of the ocean, coastal thermal refugia would probably be relatively resilient to heat waves, and may even

be enhanced by them through onshore fog movement. Alternative pathways are less likely than redundant pathways to exhibit a consistent response pattern to a large-scale disturbances, and this can promote resiliency even more effectively than redundancy (Levin and Lubchenco 2008). Moreover, alternative pathways appear able to make living systems both more robust and more resilient to sustained directional change – such as climate change - not just disturbances (Whitacre and Bender 2010, Moritz *et al.* 2005, Carlson and Doyle 2002, Tononi *et al*. 1999).

5.2.5 Spatial Connectivity and Timing

The fourth element in this conceptual framework addresses continuity of environmental opportunities for successive life stages of anadromous salmonids. The timing of fish movement from one habitat to another depends on whether environmental conditions in habitats and migration corridors connecting them are suitable, and whether fish are at a suitable stage of development to move between habitats.

Rapidly changing climate may alter such opportunities by creating critical mismatches in development and habitat conditions in areas where anadromous runs are currently adapted. In principle, a river-ocean system could contain the full suite of habitats necessary for all life stages, but if the fish cannot reliably move from one habitat type to the next at the appropriate time in its life cycle, the system is unlikely to support a viable population.

Adult South-Central California Coast steelhead currently enter freshwater in the winter and early spring when flows are high. During these periods of elevated instream flow, adult steelhead migrate to high elevation habitats that are often inaccessible later in the season when flows are lower. The timing of these flows depends on precipitation. Following successful spawning and incubation fry emerge from their redd and enter the water column approximately two months later (emergence time is strongly influenced by water temperature). Growth and development of young fish to the smolt stage is also influenced by water temperature. Smolts typically enter the ocean from late winter to late spring, when ocean feeding conditions are optimal due to seasonal upwelling supporting enhanced primary production. The timing of salmon life cycle stages has been shaped by centuries or millennia of climate conditions, and can be adversely affected by rapid climate change that alters the timing, rate, and spatial location of key physical and biological processes (Thorson *et al*. 2013, Crozier *et al*. 2008).

5.3 RECOVERY PLANNING FOR SOUTH-CENTRAL COAST CALIFORNIA CLIMATE CHANGE

5.3.1 Core Principles

While some physical parameters of climate change are likely predictable, the response of ecosystems and the consequent future conditions of steelhead habitats are less predictable. The inherent difficultly in predicting overall habitat response to climatic changes suggests adoption of a precautionary principle whereby protecting key biological parameters will be necessary to ensure long-term resiliency of the population. This strategy will enhance the resilience of the steelhead metapopulations to respond to ecosystem changes, through forecasting and managing the physical envelope of the species according to a few core principles (see Boughton *et al.* 2010a for a discussion of these principles, also, Kingsford 2011):

- Widen opportunities for fish to be opportunistic (*i.e.,* exploit a variety of habitat types);
- Maximize connectivity of habitats (*i.e.*, within and between habitats);
- Promote the evolutionary potential of populations and metapopulations (*i.e.,* the ability of a population to generate novel

functions, through genetic change and natural selection, that help individuals of a population survive and reproduce) by restoring a natural diversity of habitat types that support a wide diversity of life history expressions; and

- Maintain the capacity to detect and respond sustainably to ecosystem changes as they occur.

The viability criteria outlined in Chapter 6, and the recovery strategy identified in Chapter 7, Steelhead Recovery Strategy reflects these core principles, and provides a basic strategy for dealing with the current variable climate regime, as well as projected future climate regimes.

Because of the potential climate changes and the uncertainties regarding the physical habitats and corresponding biological responses, to these changes, there will likely be a need to extend the analysis of the TRT. The following climate change related questions were identified by the TRT:

- How will climate trends alter the wildfire regime which in turn will alter sediment delivery and hydrologic processes affecting the distribution of steelhead habitat?

- Will different watersheds develop distinctly different wildfire regimes, with implications for habitat dynamics, carrying capacity, and viability?

- What environmental factors maintain suitable water temperatures during the summer, and will they moderate the response of stream temperatures to climate change?

- Are there natural freshwater refugia that sustain *O. mykiss* during droughts longer than the generation time of the fish?

- How are patterns of flow intermittency likely to respond to climate change, and where are suitable flows likely to intersect with suitable water temperatures under scenarios of climate change?