SECTION 6

How is Circulation in Puget Sound Projected to Change?

Circulation in Puget Sound is projected to be affected by declining summer precipitation, increasing sea surface temperatures, shifting streamflow timing, increasing heavy precipitation, and declining snowpack. While these changes are expected to affect mixing between surface and deep waters within Puget Sound, it is unknown how these changes will affect upwelling. Changes in precipitation and streamflow could shift salinity levels in Puget Sound by altering the balance between freshwater inflows and water entering from the North Pacific Ocean. In many areas of Puget Sound, variations in salinity are also the main control on mixing between surface and deep waters. Reduced mixing, due to increased freshwater input at the surface, can reduce phytoplankton growth, impede the supply of nutrients to surface waters, and limit the delivery of dissolved oxygen to deeper waters. Patterns of natural climate variability (e.g., El Niño/La Niña) can also influence Puget Sound circulation via changes in local surface winds, air temperatures, and precipitation.

Drivers of Change

DRIVERS ***Wind patterns, natural climate variability, and projected changes in temperature and precipitation can all affect circulation in Puget Sound.***[A]

- *Observations show a clear warming trend, and all scenarios project continued warming during this century*. Most scenarios project that this warming will be outside of the range of historical variations by mid-century (see Section 2).[1,2] Increasing air temperatures will result in more precipitation falling as rain instead of snow, and snowpack melting earlier in the year. The resulting shift to earlier peak streamflow will result in more freshwater inflows into Puget Sound during winter months, and decreased freshwater inflows during summer (see Section 3).

- *Heavy rain events are projected to become more intense.* Current research is consistent in projecting an increase in the frequency and intensity of heavy rain events.[3] These changes would lead to a further increase in winter streamflow.

- *Most models are consistent in projecting a substantial decline in summer precipitation.* Projected changes in other seasons and for annual precipitation are not consistent

A Throughout this report, the term "Puget Sound" is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term "Puget Sound region" is used to describes the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see "How to Read this Report").

among models, and trends are generally much smaller than natural year-to-year variability.[2] The projected decrease in summer precipitation would accentuate the temperature-driven decrease in summer streamflow.

- *Wind patterns are not projected to change*. There are no projected changes for wind speed or the strength of low pressure systems in the region (see Section 2). Wind patterns affect upwelling, mixing, and currents within Puget Sound.

- *Although long-term changes in climate will likely influence currents and mixing in Puget Sound, natural climate variability is also expected to remain an important driver of regional circulation*. Natural variability in both weather patterns and ocean conditions will continue to affect circulation in Puget Sound. It is not known how variability might change with warming.

Circulation and mixing in Puget Sound

CIRCULATION ***Projected changes in precipitation and streamflow will alter the balance between freshwater inflows and saltwater entering Puget Sound from the North Pacific Ocean.*** North Pacific Ocean water enters Puget Sound through the Strait of Juan de Fuca, mixing with and modifying the water in the Sound. Within Puget Sound, freshwater inflows can impede the mixing between surface and deep waters, a key process for bringing nutrients to the surface and oxygen to depth.

- *The rate of exchange of Puget Sound North Pacific Ocean waters is higher when there is a greater contrast in the density of each.* The exchange occurs in two layers, with relatively warm and fresh water from Puget Sound waters flowing seaward at the surface, and relatively cold and saline Pacific Ocean waters entering the Sound at depth (Figure 6-1). This circulation is driven by differences in density, in which Puget Sound waters become less dense as a result of freshwater inflows. When this density difference is large, the rate of exchange with Pacific Ocean waters is greater. Conversely, when the difference is small the rate of exchange is reduced.[4]

- *Circulation is mediated by the degree of stratification of Puget Sound's marine waters.* Stratification occurs when water density increases with depth, with lower density water at the surface and higher density water below. Water is more dense when it is colder, more saline, and at a greater depth below the surface. Stratification in Puget Sound is weakened when water is mixed by physical mechanisms such as winds and tides. In contrast, stratification is strengthened by solar radiation, freshwater inflows, weak winds and weak circulation, all of which act to decrease the density of surface waters relative to those at greater depths.

- *Mixing of surface and deep waters is of critical importance to biology.* The degree of stratification and seasonal timing of freshwater inputs affects upwelling and the supply of nutrients to surface waters, phytoplankton growth, the delivery of dissolved oxygen to deeper waters, and the effectiveness of pollutant flushing.[5]

Stratification inhibits mixing of deeper, nutrient-rich water, up into the zone where there is enough light for photosynthetic organisms to grow (e.g., algae), and favors the formation of low oxygen zones (hypoxia, see Section 7) at depth. In winter, this is not a major limitation, since the main impediment to biological productivity is a lack of sunlight. During the growing season, in contrast, water column stratification can potentially limit the supply of nutrients to phytoplankton, and the supply of oxygen to deeper waters.[6]

- *Stratification limits the mixing effect of winds.* Greater stratification impedes mixing due to winds. One study, using model simulations of Puget Sound circulation, found that winds can directly influence currents to a depth of about 300 ft. when stratification is weak, whereas strong stratification can limit the influence of winds to the top 100 ft. below the ocean surface.[7] Climate models do not project a change in wind speed or the strength of low pressure systems (see Section 2).

- *Freshwater inflows have a strong effect on the density of marine waters.* In many areas of Puget Sound, variations in salinity are the main control on stratification, and arise as a result of freshwater inflows from rivers.[8,9] Freshwater inflows reduce water density by lowering the salinity of Puget Sound waters. Not surprisingly, density variations are the largest in surface waters near river mouths.[10]

- *Projected changes in air temperature and precipitation will result in greater freshwater inflows in winter, and decreased inflows in summer.* Although total annual streamflow is only projected to change slightly, decreases in winter snow accumulation will drive a shift in the seasonal timing of streamflow, with higher flows in winter and lower flows in summer (see Section 3). This has important implications for Puget Sound circulation, in particular affecting the ability of surface and deep waters to mix.

- *Projected changes in streamflow, could increase the rate of exchange between Pacific Ocean waters and those of Puget Sound in winter, and decrease the rate of exchange in summer.* The reduction in freshwater input during the winter 2000-2001 drought was enough to reduce the exchange through the Strait of Juan de Fuca by −75%.[5] Projected increases in winter streamflow could result in an increase in this exchange rate, whereas projected decreases in summer streamflow could result in a lower rate of exchange. In summer, the resulting increase in flushing time may lead to increased exposure to contaminants and pollutants, and decrease the rate of transport or retention of larvae and plankton.

- *There are no projections of changing stratification in Puget Sound.* Although the effects of surface warming and changing freshwater inputs are well understood, it is not known exactly how important these changes will be. There are other factors that influence stratification, including the temperature and salinity of Pacific Ocean water, ocean currents, wind patterns, and the geographic distribution of precipitation. It is not known how these factors will combine to drive changes in stratification.

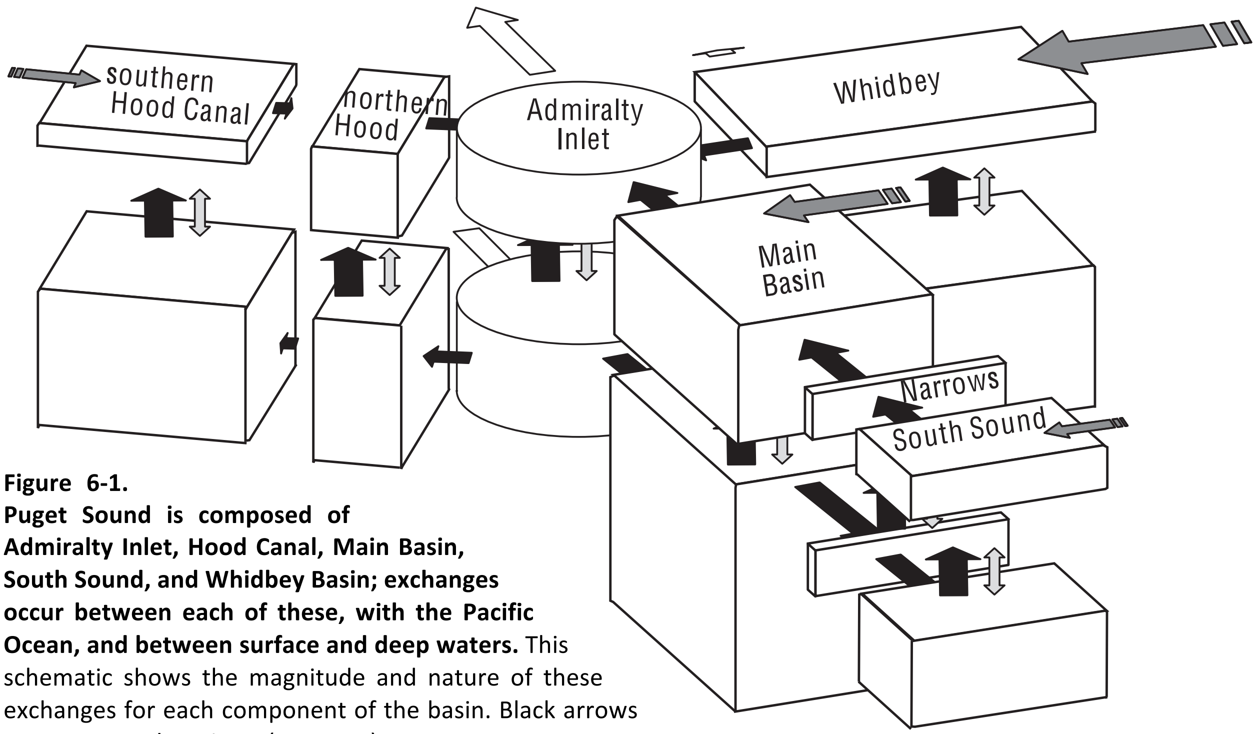

Figure 6-1.
Puget Sound is composed of Admiralty Inlet, Hood Canal, Main Basin, South Sound, and Whidbey Basin; exchanges occur between each of these, with the Pacific Ocean, and between surface and deep waters. This schematic shows the magnitude and nature of these exchanges for each component of the basin. Black arrows represent advection (currents), two-way grey arrows represent mixing, dark grey arrows with dashed ends represent river inputs and white arrows are outlets to the Strait of Juan de Fuca. Boxes have been scaled to show relative volumes. Similarly, arrows have been scaled to show the relative transports with each category. Rivers are proportional on a log scale. The Admiralty Inlet mixing arrow is shown at 50%. *Figure Source: Babson et al. 2006.*[4] *Copyright © La Societe Canadienne de Meterologie et d'Oceanographie reprinted by permission of Taylor & Francis Ltd, www.tandfonline.com on behalf of La Societe Canadienne de Meterologie et d'Oceanographie.*

Coastal Upwelling

UPWELLING ***The effect of climate change on coastal upwelling is currently unknown.*** Upwelling, which occurs along the outer coast of Washington, delivers cold, nutrient-rich water to the ocean surface. These waters affect Puget Sound waters via the exchange through the Strait of Juan de Fuca. Upwelling occurs when northerly winds (from the north) blow along the outer coast of Washington, typically between April and September. These winds push surface water offshore, which is then replaced by deeper water that rises, or "upwells" to the surface. Upwelling affects a wide range of ecological processes, contributing to the productive marine food web of the Pacific Northwest.

- *Upwelling has been hypothesized to increase with warming.* The so-called "Bakun Hypothesis" suggests that upwelling-favorable winds will increase as the climate warms. The idea stems from the fact that land temperatures are expected to warm more rapidly than ocean temperatures. This increasing contrast between land and ocean could drive stronger and more consistent upwelling-favorable winds.[11] This hypothesis is controversial, and may be contradicted by recent projections showing no long-term change in upwelling (see below).

- *Historical increases in upwelling-favorable winds.* One study analyzed 22 observational studies investigating wind trends for records ranging up to 60 years in length. They concluded that studies have consistently found trends in winds that favor increased upwelling along the west coast of North America.[B,12]

- *Warm phases of both ENSO (El Niño) and the Pacific Decadal Oscillatin (PDO) are correlated with a delay and shortening of summer upwelling along the Pacific Northwest coast.* El Niño conditions are also associated with more intense winter downwelling (in which surface waters are driven down to greater depths) along the coast.[13] ENSO and PDO are not projected to change with warming (see Section 2).

- *Projections indicate ongoing variability, but no long-term change in upwelling-favorable winds.* One study evaluated 50-year trends (2000 to 2050) in upwelling favorable winds in the Pacific Northwest, using 23 global climate model projections and a moderate (A1B) greenhouse gas scenario. Model results ranged from a decline of about −40% to an increase of +60%, by 2030-2039 relative to the average for 1980-1989.[C,D,14] Other studies are consistent in finding no evidence for a change in upwelling-favorable winds.[15,16,17] Future trends in upwelling will likely depend on winds, both along the Washington coast and farther south along the U.S. West Coast, and on changes in large-scale atmospheric circulations.[18]

B Many characteristics of Puget Sound's climate and climate vulnerabilities are similar to those of the broader Pacific Northwest region. Results for Puget Sound are expected to generally align with those for western Oregon and Washington, and in some instances the greater Pacific Northwest, with potential for some variation at any specific location.

C Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These are described in the text as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "moderate" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI – descriptors are based on cumulative emissions by 2100 for each scenario. See Section 1 for more details.

D Based on 23 global climate model projections and a moderate (A1b) greenhouse gas scenario.

Additional resources for evaluating and addressing the effects of climate change on circulation in Puget Sound.

The following tools and resources are suggested in addition to the reports and papers cited in this document.

- **NOAA Tides & Currents:** Central resource for information on observed trends in sea level. http://tidesandcurrents.noaa.gov/
- **NOAA Office for Coastal Management:** Provides technical information and support for managing coastal hazards. Tools and products include "Coastal County Snapshots", which allows users to develop customizable PDF fact sheets with information on a county's exposure and resilience to flooding; its dependence on the ocean for a healthy economy; and the benefits received from a county's wetlands. https://csc.noaa.gov/
- **Northwest Association of Networked Ocean Observing Systems:** NANOOS provides Pacific Northwest ocean observations, model estimates ranging from wave heights to ocean properties, forecasts, and a variety of decision-making tools including visualizations of beach erosion rates, tsunami maps, and information on water properties for use by shellfish growers. http://nvs.nanoos.org/
- **West Coast Ocean Data Portal:** A project of the West Coast Governors Alliance, the portal is intended to be a hub for ocean and coastal data, and includes information on Puget Sound. http://portal.westcoastoceans.org/
- **NOAA Climate Prediction Center:** Provides information on seasonal weather predictions and large-scale weather patterns such as El Niño. http://www.cpc.ncep.noaa.gov/
- **Joint Institute for the Study Atmosphere and Ocean PDO website:** Provides a brief overview, along with figures, links, and references on the Pacific Decadal Oscillation (PDO). http://research.jisao.washington.edu/pdo/

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