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# A descriptive analysis of temporal and spatial patterns of variability in Puget Sound oceanographic properties

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ABSTRACT

Temporal and spatial patterns of variability in Puget Sound's oceanographic properties are determined using continuous vertical profile data from two long-term monitoring programs; monthly observations at 16 stations from 1993 to 2002, and biannual observations at 40 stations from 1998 to 2003. Climatological monthly means of temperature, salinity, and density reveal strong seasonal patterns. Water temperatures are generally warmest (coolest) in September (February), with stations in shallow finger inlets away from mixing zones displaying the largest temperature ranges. Salinities and densities are strongly influenced by freshwater inflows from major rivers during winter and spring from precipitation and snowmelt, respectively, and variations are greatest in the surface waters and at stations closest to river mouths. Vertical density gradients are primarily determined by salinity variations in the surface layer, with stations closest to river mouths most frequently displaying the largest buoyancy frequencies at depths of approximately 4–6 m. Strong tidal stirring and reflux over sills at the entrance to Puget Sound generally removes vertical stratification. Mean summer and winter values of oceanographic properties reveal patterns of spatial connectivity in Puget Sound's three main basins; Whidbey Basin, Hood Canal, and Main Basin. Surface waters that are warmed in the summer are vertically mixed over the sill at Admiralty Inlet and advected at depth into Whidbey Basin and Hood Canal. Cooler and fresher surface waters cap these warmer waters during winter, producing temperature inversions.


## 1. Introduction

Puget Sound is a deep, fjord-type estuary covering an area of 2330 km$^2$ in the Pacific Northwest region of the U S (Fig. 1). It is connected to the ocean by the Strait of Juan de Fuca; a turbulent passage with a maximum depth of approximately 200 m, 160 km in length, and 22 km wide at its western end expanding to over 40 km wide at its eastern end (Thomson, 1994). A double sill at the entrance to Puget Sound (i.e., Admiralty Inlet) separates it from the Strait of Juan de Fuca. Whidbey Basin, Main Basin, and Hood Canal are the three main branches of Puget Sound (Fig. 1A). The shallower South Sound is separated by a sill at Tacoma Narrows and is highly branched with numerous finger inlets. The region to the north of Puget Sound (i.e., North Basin) encompasses the San Juan Islands and part of the Strait of Georgia.

Flow within Puget Sound is dominated by tidal currents of up to 1 m s$^{-1}$ at Admiralty Inlet, decreasing to approximately 0.5 m s$^{-1}$ in the Main Basin (Lavelle et al., 1988). The daily difference between high and low tide varies by 2.4 m at the northern/entrance end of Puget Sound to 4.6 m at the southern end. The sub-tidal component of flow reaches approximately 0.1 m s$^{-1}$ and is driven by density gradients arising from the contrast in salty ocean water at Admiralty Inlet and freshwater inputs from streamflow (Lavelle et al., 1988). The total freshwater input to Puget Sound is approximately $3.4 \times 10^6$ m$^3$ day$^{-1}$ with inflow from the Skagit River accounting for the majority (Cannon, 1983). Annual streamflow maxima result from periods of high precipitation and snowmelt. The sub-tidal circulation mostly consists of a two-layered flow in Main Basin, Whidbey Basin, and Hood Canal with fresher water exiting at the surface and saltier water entering at depth (Ebbesmeyer and Cannon, 2001). Intense tidally-driven turbulent mixing at the Tacoma Narrows sill and the absence of major river inflows results in lesser stratified waters in South Sound compared to other basins, but in general surface waters flow north (i.e., out of South Sound)

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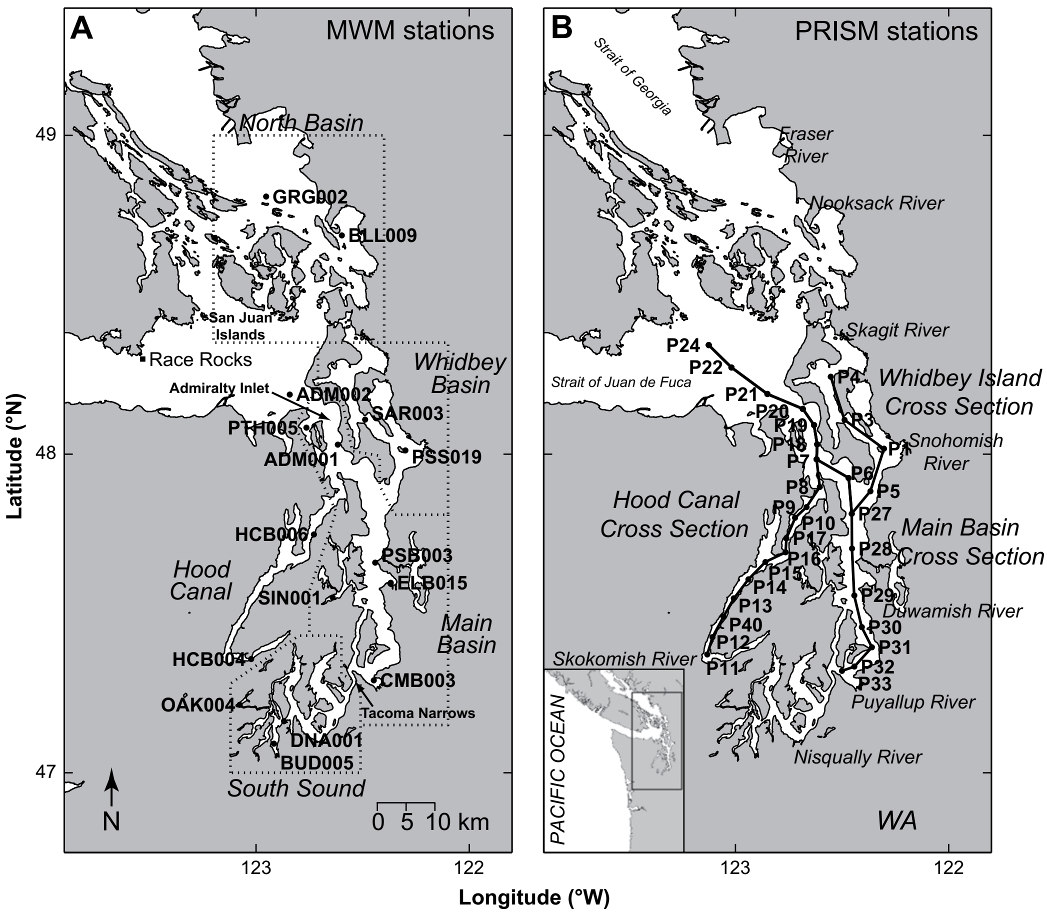


**Fig. 1.** (A) Marine Waters Monitoring Program and (B) Puget Sound Regional Synthesis Model station locations. Only stations examined in this study are shown. The location of Race Rocks lighthouse is shown in (A).

and deeper waters flow south (i.e., into South Sound). Variations to this general pattern of circulation in Puget Sound arise from wind effects which can directly influence currents to a depth of about 100 m when stratification is weak (Matsuura and Cannon, 1997).

Puget Sound has a long history of oceanographic observation that dates back to the early 1930s. These data have been cataloged, tabulated, and presented in graphical form (Collias, 1970; Collias and Lincoln, 1977; Collias et al., 1974; Newton et al., 2002). However, few studies have attempted to condense these observations into a more easily digestible format and examine patterns of variability and spatial connectivity. Additionally, advances in technology have facilitated an increase in the temporal and spatial resolution of observations from more recent monitoring programs. The two datasets reported here, the Marine Waters Monitoring Program (MWM) and the Puget Sound Regional Synthesis Model Program (PRISM), together offer a temporal and spatial resolution useful for this analysis of mean sound-wide patterns over an annual cycle. The MWM data are the only source of ongoing, sound-wide, monthly resolved data, although some of the historical data (i.e., 1950s to 1960s) had brief periods with monthly resolution (Collias et al., 1974). The PRISM data, while collected only twice a year, offer the most comprehensive synoptic view of the entire sound, with data collected over 4-day cruises.

This study provides a descriptive analysis of temporal and spatial patterns of variability in Puget Sound's oceanographic properties using a combination of the MWM and PRISM datasets spanning from 1993 to 2003. MWM data are used to determine climatological patterns and interannual variability in vertical profiles of temperature, salinity, and density and to evaluate the frequency and characteristics of vertical stratification. Spatial connectivity of oceanographic properties in the three major basins of Puget Sound during summer and winter is investigated using PRISM data.

## 2. Methods

### 2.1. Oceanographic data

The MWM program is conducted by the Washington State Department of Ecology in conjunction with the Puget Sound Ambient Monitoring Program. Records at discrete depths date back to 1973, and high quality continuous profile data are available from 1993. The MWM program is ongoing, but we only use profile data to 2002 that had been subjected to our own quality control checks in addition to those of the monitoring departments at the time of publication. Surveys are now conducted monthly using a SeaBird Electronics, Inc. (SBE) 19*plus*® conductivity–temperature–depth instrument (CTD) deployed from seaplane. CTD data were processed using SBE, Inc. SEASOFT© software into 0.5-m bins. More information on parameters sampled and methodologies is documented in Janzen (1992) and Newton et al. (2002). Temperature, salinity, and density observations at 16 core stations from January 1993 to December 2002 are presented here (Fig. 1A).

PRISM surveys are conducted biannually along transects in Main Basin, Whidbey Basin, and Hood Canal by the University of Washington and provide snapshots of summer (June) and winter (November/December) conditions in Puget Sound. Profiles are obtained using a SBE, Inc. 911*plus*® CTD and processed into 0.5-m