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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 × 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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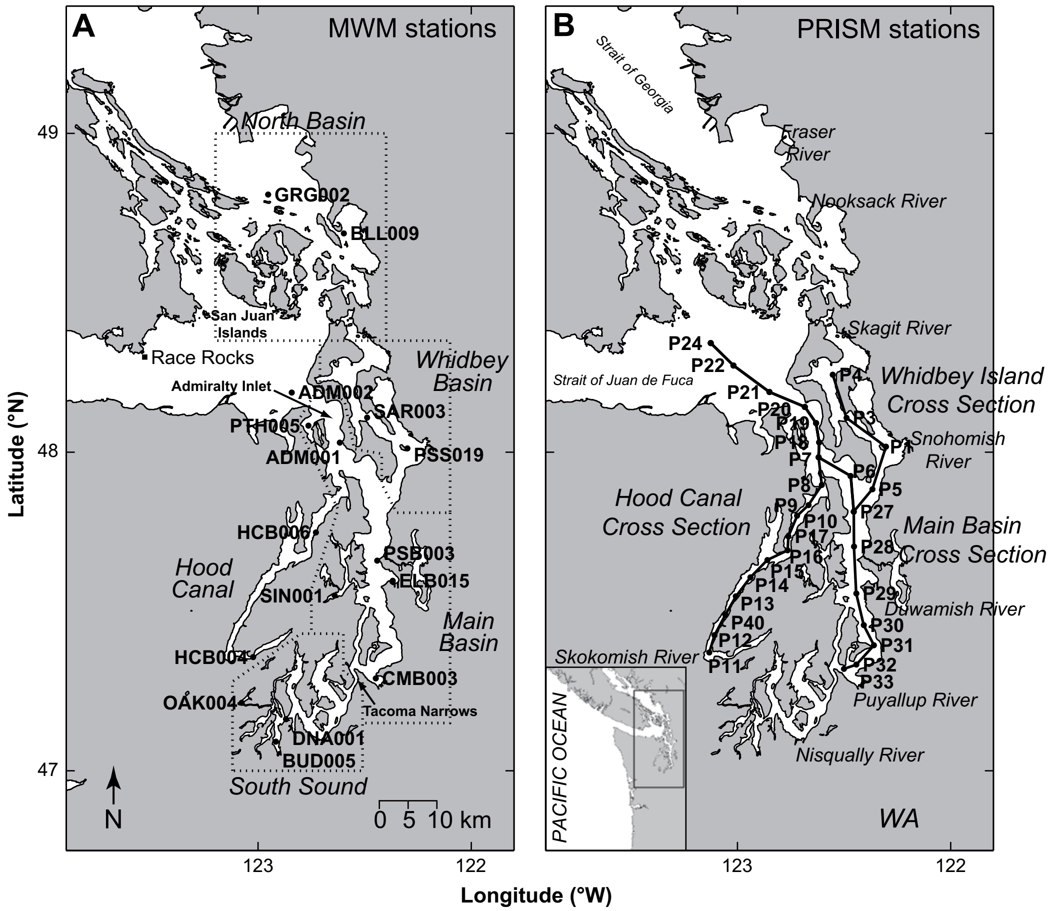

Fig. 1. (A) Marine Waters Monitoring Program and (B) Puget Sound Regional Synthesis Model station locations. Only stations examined in this study are shown. The location of Race Rocks lighthouse is shown in (A).

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 bins. Temperature, salinity, and density observations at 40 stations from 1998 to 2003 are used here (Fig. 1B).

MWM and PRISM data are collected irrespective of tidal stage, yet tides have been shown to significantly influence water quality parameter values at some stations (Janzen et al., 1991; Janzen and Eisner, 1993). The effect of tides is most notable in areas of strong mixing, such as Admiralty Inlet. Further, MWM data are only collected during fair weather when stations can be accessed by seaplane. The possible effects of this meteorological bias on oceanographic properties sampled during MWM flights have not been determined. In spite of these potential limitations, oceanographic processes occurring on seasonal to interannual timescales have been successfully resolved using MWM data (e.g., Bricker et al., 1999; Janzen et al., 1991; Kawase, 2002; Moore et al., 2008; Newton, 1995; Newton et al., 2003). This indicates that high frequency tidal variability in oceanographic properties is generally less than the low frequency variations occurring on seasonal to interannual timescales or longer.

Vertical stratification of the water column was examined using MWM data. Observations <2 m from the surface and bottom were excluded due to noise in the data associated with the CTD equilibrating at the surface and interference from bottom sediments. Vertical density gradients were calculated at 0.5-m intervals and smoothed using a 2.5-m moving average. If the maximum density gradient exceeded 0.1 kg m^{-4}, the water column was said to be stratified. The depth that this occurs is the pycnocline, which marks the boundary layer between the body of less dense water (i.e., fresher) overlying more dense water (i.e., saltier). The stability or strength of the pycnocline is described by the buoyancy frequency (see Turner, 1973), calculated as:

$$N = \sqrt{\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}} \times \frac{3600}{2\pi}$$

where g is the gravitational constant (9.8 m s^{-2}), ρ_0 is a standard constant density (1025 kg m^{-3}) and ρ is density (kg m^{-3}), z is depth (m), and 3600 s $h^{-1}/2\pi$ radians $cycle^{-1}$ converts N from radians s^{-1} to cycles h^{-1}. The buoyancy frequency is the oscillation that occurs when a parcel of water is vertically displaced in a static, density-stratified body of water. The displaced parcel of water will have a density that is different than the surrounding water, and will accelerate back to its initial position. The parcel overshoots its initial position and accelerates back in the other direction, resulting in an oscillation. Higher buoyancy frequencies are associated with

Table 1
Marine Waters Monitoring and Puget Sound Regional Synthesis Model stations, locations, and average profile depths

Survey	Station ID	Water body/station name	Latitude (°N)	Longitude (°W)	Depth (m)
MWM	ADM002	Admiralty Inlet	48.19	122.84	57.2
MWM	PTH005	Port Townsend Harbor	48.08	122.76	21.1
MWM	ADM001	Admiralty Inlet	48.03	122.62	75.1
MWM	PSB003	Puget Sound Main Basin	47.66	122.44	42.6
MWM	ELB015	Elliott Bay	47.60	122.37	68.4
MWM	SIN001	Sinclair Inlet	47.55	122.64	12.7
MWM	CMB003	Commencement Bay	47.29	122.45	106.3
MWM	GRG002	Georgia Strait	48.81	122.95	96.6
MWM	BLL009	Bellingham Bay	48.69	122.60	12.2
MWM	DNA001	Dana Passage	47.16	122.87	34.4
MWM	BUD005	Budd Inlet	47.09	122.92	12.2
MWM	OAK004	Oakland Bay	47.21	123.08	10.4
MWM	HCB006	Hood Canal	47.75	122.73	84.7
MWM	HCB004	Hood Canal	47.36	123.02	45.6
MWM	PSS019	Possession Sound	48.01	122.30	72.3
MWM	SAR003	Saratoga Passage	48.11	122.49	88.9
PRISM	P24	Hein Bank	48.34	123.12	130.3
PRISM	P22	Eastern Bank	48.27	123.02	103.0
PRISM	P21	Buoy SA	48.19	122.85	77.7
PRISM	P20	Admiralty Head	48.14	122.68	59.0
PRISM	P19	Lagoon Point	48.09	122.63	155.2
PRISM	P18	Bush Point	48.03	122.62	125.9
PRISM	P7	Mutiny Bay	47.98	122.62	98.4
PRISM	P8	Hood Head	47.90	122.61	132.1
PRISM	P9	South Point	47.83	122.67	69.7
PRISM	P10	Hood Canal Sill	47.80	122.72	56.0
PRISM	P17	Bangor	47.74	122.76	114.1
PRISM	P16	Hazel Point	47.69	122.77	105.9
PRISM	P15	Dabob Bay	47.66	122.86	136.0
PRISM	P14	Hood Point	47.61	122.94	181.5
PRISM	P13	Eldon	47.55	123.01	148.5
PRISM	P40	Ayock Point	47.49	123.06	160.0
PRISM	P12	Hoodsport	47.43	123.11	130.0
PRISM	P11	The Great Bend	47.37	123.13	88.6
PRISM	P6	Useless Bay	47.92	122.47	118.8
PRISM	P27	Apple Cove Point	47.81	122.46	197.4
PRISM	P28	North of West Point	47.70	122.45	198.8
PRISM	P29	South of Alki Point	47.56	122.44	229.0
PRISM	P30	Three Tree Point	47.46	122.41	226.3
PRISM	P31	Point Robinson	47.39	122.36	217.8
PRISM	P32	Point Piner	47.33	122.44	181.8
PRISM	P33	Dalco Passage	47.32	122.50	153.3
PRISM	P5	Possession Sound	47.88	122.37	221.4
PRISM	P1	Gedney Island	48.02	122.30	107.0
PRISM	P3	Saratoga Passage	48.11	122.49	142.4
PRISM	P4	Skagit Bay	48.24	122.55	80.2

stronger vertical density gradients. Density gradients below 40 m depth were considered to be caused by deep intrusions of oceanic water over the sill at Admiralty Inlet and were not included in the analysis.

2.2. Analyses of temporal and spatial patterns

Climatological monthly means and standard deviations of temperature, salinity, and density were created for MWM data at 0.5-m depth intervals for the period 1993– 2002. Stratification was too infrequent at some MWM stations for a climatological analysis of the depth and strength of the pycnoclines. Instead they are summarized using frequency histograms for each month.

Transects of the mean summer and winter temperature, salinity, and density fields were created for PRISM data in Main Basin, Whidbey Basin and Hood Canal at 0.5-m depth intervals for the period 1998– 2003. PRISM stations cover a greater area of Puget Sound compared to the MWM stations examined here, and allow a better interpretation of the spatial connectivity of oceanographic properties throughout the sound. The names, locations, and average profile depths of MWM and PRISM stations are given in Table 1.

3. Results and discussion

3.1. Climatological patterns and interannual variability

Climatological monthly means of temperature and salinity profiles at MWM stations are shown in Figs. 2 and 3, respectively. Density profiles follow salinity profiles closely, and are shown in Appendix 1. Monthly mean temperatures are generally coolest in February and warmest in September and range from 6.6 to 19.3 °C (Fig. 2). Winter cooling is abrupt and begins around October at all stations. Temperature profiles are uniform during winter months,

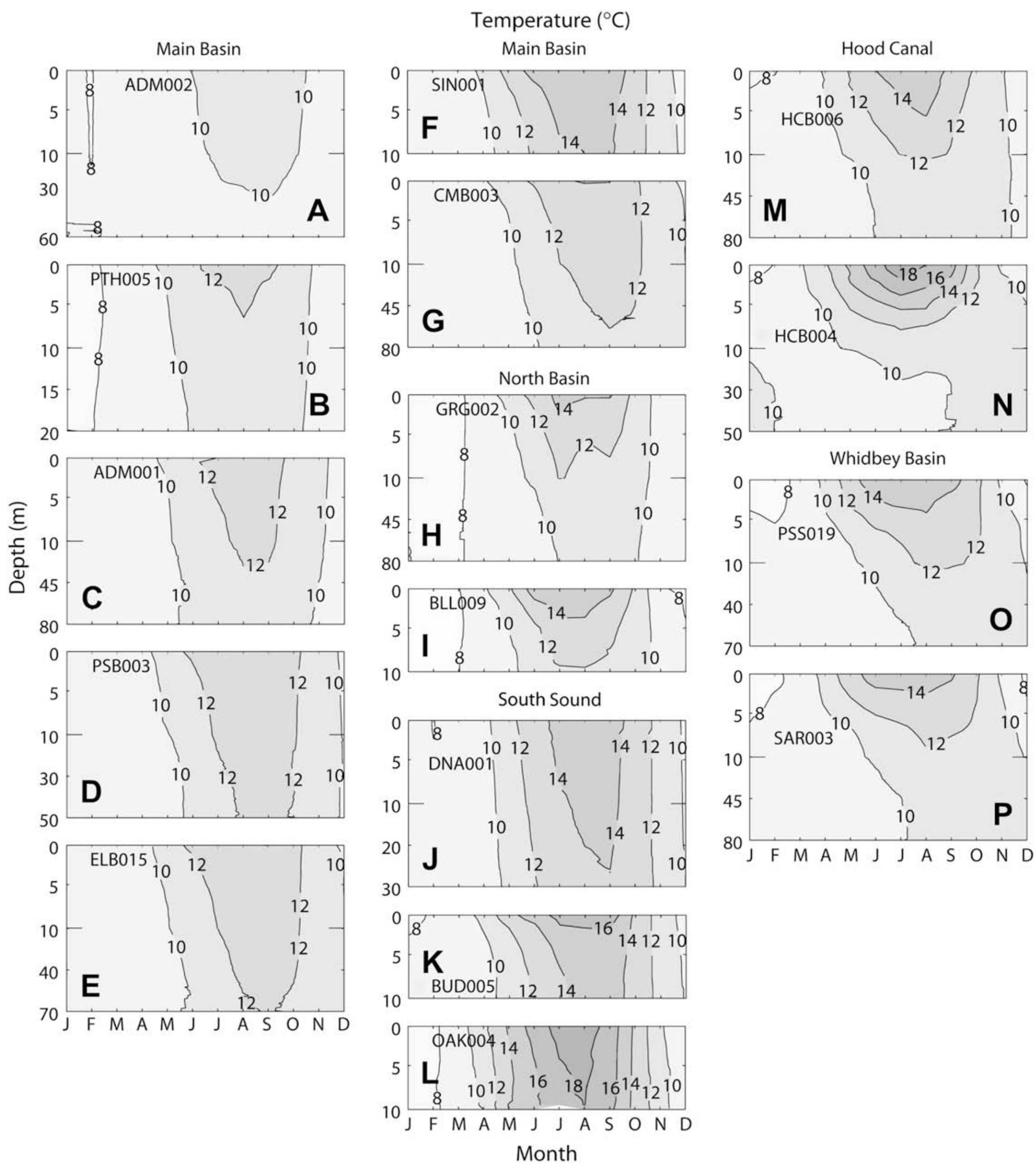

Fig. 2. Climatological monthly means of temperature (°C) at Marine Waters Monitoring stations from 1993 to 2002. Note that the upper 10 m of the water column is plotted on an enlarged depth scale since this is where the greatest variability in oceanographic properties is observed. Depth scaling on the *y*-axis of each subplot is consistent for the upper 10 m, but varies below this depth depending on the station.

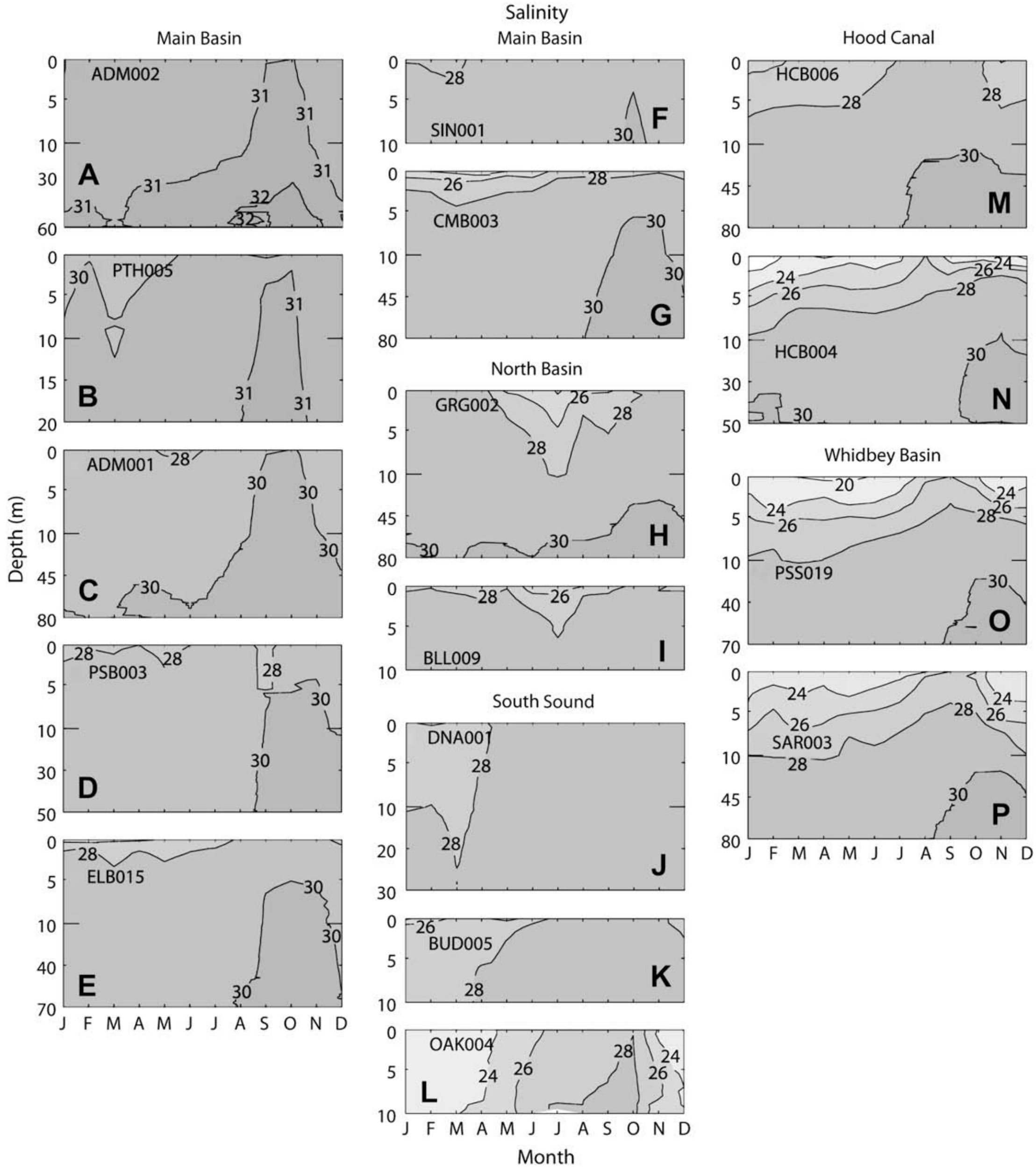

Fig. 3. Climatological monthly means of salinity at Marine Waters Monitoring stations from 1993 to 2002.

with summer warming originating in the surface layer around May. Similar mean annual temperature patterns have previously been documented for the surface waters of Puget Sound and two other estuaries on the Washington coast (i.e., Grays Harbor and Willapa Bay; Newton et al., 2002).

Seasonal temperature ranges are smallest at Admiralty Inlet (i.e., ADM002 and ADM001). Waters at these stations are influenced by those from the Strait of Juan de Fuca and are strongly mixed by tidal stirring over sills. The largest seasonal temperature ranges are observed at stations in the shallow finger inlets of South Sound (i.e., BUD005 and OAK004). Strong vertical temperature gradients of 6– 8 °C per 10 m depth are observed at station HCB004 in Hood Canal in summer, with other stations in Hood Canal, Whidbey Basin, and North Basin also displaying evidence of a warm summer surface layer.

There is a delayed response to summer warming in the deeper waters at stations in Whidbey Basin and Hood Canal by approximately 1 to 4 months. Two possible explanations for this are mixing of warmer surface waters into deeper waters over sills at Admiralty Inlet and at the entrance to Hood Canal and transportation into Whidbey Basin and Hood Canal at depth, or local mixing of surface and deeper waters. While vertical mixing in the North Main Basin of Puget Sound has been found to be significant resulting in mixing distances that represent a significant fraction of the water column (Mickett et al., 2004), approximated vertical eddy diffusivities in Whidbey Basin and Hood Canal are two orders of magnitude less due to strong vertical density gradients (Babson et al., 2006). Longitudinal transport of waters at depth from Admiralty Inlet would require advective velocities of between 0.8 and 1.3 cm s^{-1}. These velocities are approximated by tracking the 10 °C isotherm at ADM002 in Admiralty Inlet and calculating the time taken for it to propagate to stations in Whidbey Basin (i.e., PSS019 and SAR003) and Hood Canal (HCB006 and HCB004) using the climatological monthly mean profiles (Fig. 2). The downward mixing of heat most likely occurs over the sill at the entrance to Hood Canal rather than at Admiralty Inlet, but no MWM stations exist at this location to

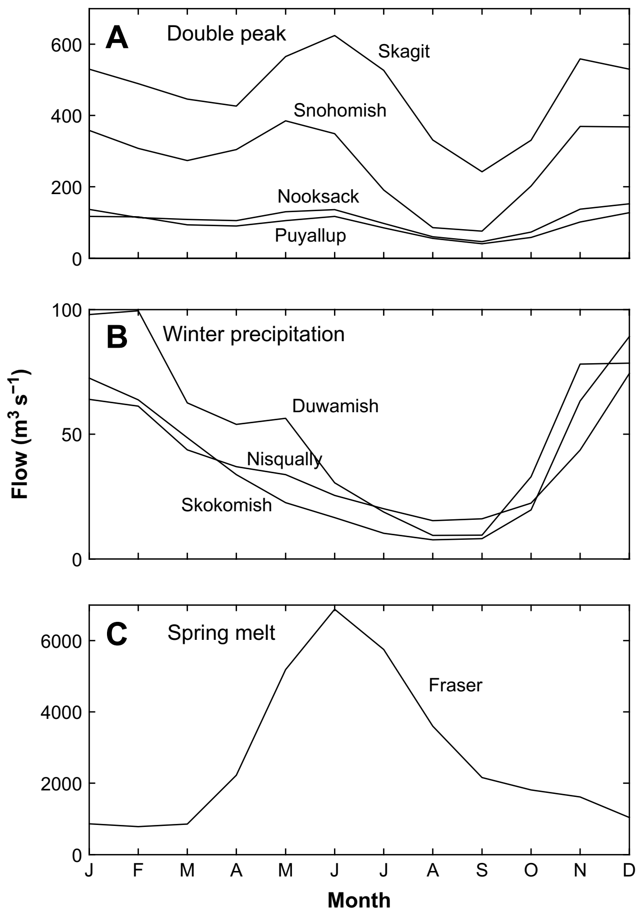

Fig. 4. Climatological monthly mean flow for (A) rivers with a double winter precipitation and spring melt peak (Skagit, Snohomish, Nooksack and Puyallup Rivers), (B) rivers with a single winter precipitation peak (Duwamish, Nisqually and Skokomish Rivers), and (C) the Fraser River with a single spring melt peak in flow from 1993 to 2002. Source: United States Geological Survey and Environment Canada.

track the 10 °C isotherm. Deep waters at ADM002 typically warm to 10 °C by May, but it takes another 2 months for deep waters at PSS019 and SAR003 in Whidbey Basin to reach 10 °C, and another 1 and 4 months for deep waters at HCB006 and HCB004, respectively, in Hood Canal. Dividing the distances from ADM002 to stations in Whidbey Basin and Hood Canal by the time lag for deep waters to reach 10 °C gives the approximate advective velocities. Similarly, tracking the 10 °C from Hansville (near to PRISM station P8) to Hoodsport (P12) in Hood Canal using profiles from a network of automated observing systems (Oceanic Remote Chemical–optical Analyzers, ORCA, http://orca.ocean.washington.edu/index.html; Dunne et al., 2002) gives advective velocities of 1.0– 1.3 cm s^{-1}. The fastest 28-day mean currents entering Whidbey Basin at depth at Possession Sound during a year-long monitoring from 2000 to 2001 were $\leq$2.0 cm s^{-1} (Nairn et al., 2003). Deep currents flowing into Whidbey Basin at Saratoga Passage averaged over 15 days in July 1970 and in Hood Canal averaged over 63 days from February to April 1980 did not exceed 1.0 cm s^{-1} (Cannon, 1983). Therefore, our approximations of longitudinal advection into Whidbey Basin and Hood Canal of between 0.8 and 1.3 cm s^{-1} are realistic. Winter cooling and freshening of the surface waters caps the warm summer signature that is retained at depth in Whidbey Basin and Hood Canal, resulting in a vertical temperature inversion.

Mean seasonal cycles in salinity (and density) are influenced by source waters from the Strait of Juan de Fuca and freshwater inflows from major rivers. Monthly mean salinities and densities range from 16.2 to 33.0 and 12.6 to 25.7 kg m^{-3}, respectively (Fig. 3 and Appendix 1). The saltiest/densest waters are observed at Admiralty Inlet and freshest/lightest waters at station OAK004 in a shallow and narrow finger inlet of South Sound. Fresher/lighter waters are also seen at the surface at stations close to river mouths in Main Basin (i.e., CMB003), Whidbey Basin, Hood Canal (i.e., HCB004), and North Basin.

Highest interannual variability in temperature is seen in the surface layer of stations that stratify during summer (i.e., GRG002 in North Basin, HCB004 in Hood Canal, PSS019 and SAR003 in Whidbey Basin; Appendix 2). For salinity and density, highest interannual variability is seen in the surface layer at stations close to river mouths during winter and spring (i.e., CMB003 in Main Basin, HCB004 in Hood Canal, and PSS019 in Whidbey Basin; Appendix 3 and 4). This variability is directly related to interannual variability in the amount and timing of solar heating and streamflow in Puget Sound (Moore et al., 2008).

Climatological patterns of salinity depend in part on the proximity of stations to river mouths and the elevation of mountains feeding the rivers. Freshwater inflows from the Skagit and Snohomish Rivers peak twice annually from periods of high precipitation in winter and snowmelt in spring and summer (Fig. 4A; Friebertshauser and Duxbury, 1972). As a result, climatological patterns of salinity in Whidbey Basin consist of a fresher surface layer from October until July with saltier and more vertically uniform waters in August and September.

The Duwamish, Nisqually, and Skokomish watersheds collect most of their runoff as rain, with significantly smaller fractions seasonally stored in mountain snowpack. Consequently, freshwater flows peak only once annually in winter due to periods of high precipitation (Fig. 4B). These primarily rain-fed rivers exert the greatest influence on salinity variations at nearby MWM stations from December to April (i.e., at station HCB006 in Hood Canal, and stations DNA001 and OAK004 in South Sound).

In southern Hood Canal, a fresher surface layer is observed year round even though freshwater inflows from the Skokomish River peak only once annually in winter. The slow circulation and low turbulent mixing in Hood Canal (Cannon et al., 1990) may contribute to the maintenance of the fresher surface layer. For example, a model estimate of the residence time in southern Hood Canal is 85.5 days, which is approximately twice as long as the other basins (Babson et al., 2006). Freshwater inputs from smaller rivers entering Hood Canal that have a spring pulse due to snowmelt, such as the Dosewallips River, may also help to maintain a fresher surface layer year round.

The Fraser River strongly influences oceanographic properties in the Strait of Georgia and the Strait of Juan de Fuca (Hickey et al., 1991; Newton, 1995). Peak flows in the Fraser River are approximately 10-times greater than those in the Skagit River. The majority of the Fraser River basin experiences substantially colder winter and spring temperatures than those of Puget Sound watersheds, and its annual runoff is dominated by snowmelt in early spring and early summer (Fig. 4C). As a result, climatological patterns of salinity in North Basin are dominated by the presence of fresher surface layers from June until September.

Salinities in the deep layer of Puget Sound also vary seasonally with saltier water evident at depth during fall and early winter at most stations. This is indicative of deep water intrusions from summer upwelling in the coastal ocean and is an important component of Puget Sound's ventilation (Strickland, 1983).

3.2. Spatial connectivity of oceanographic properties

Mean values of oceanographic properties along PRISM transects in summer and winter show the spatial connectivity of properties and their relationships among basins. During summer, thermal stratification increases with distance up-estuary from Admiralty

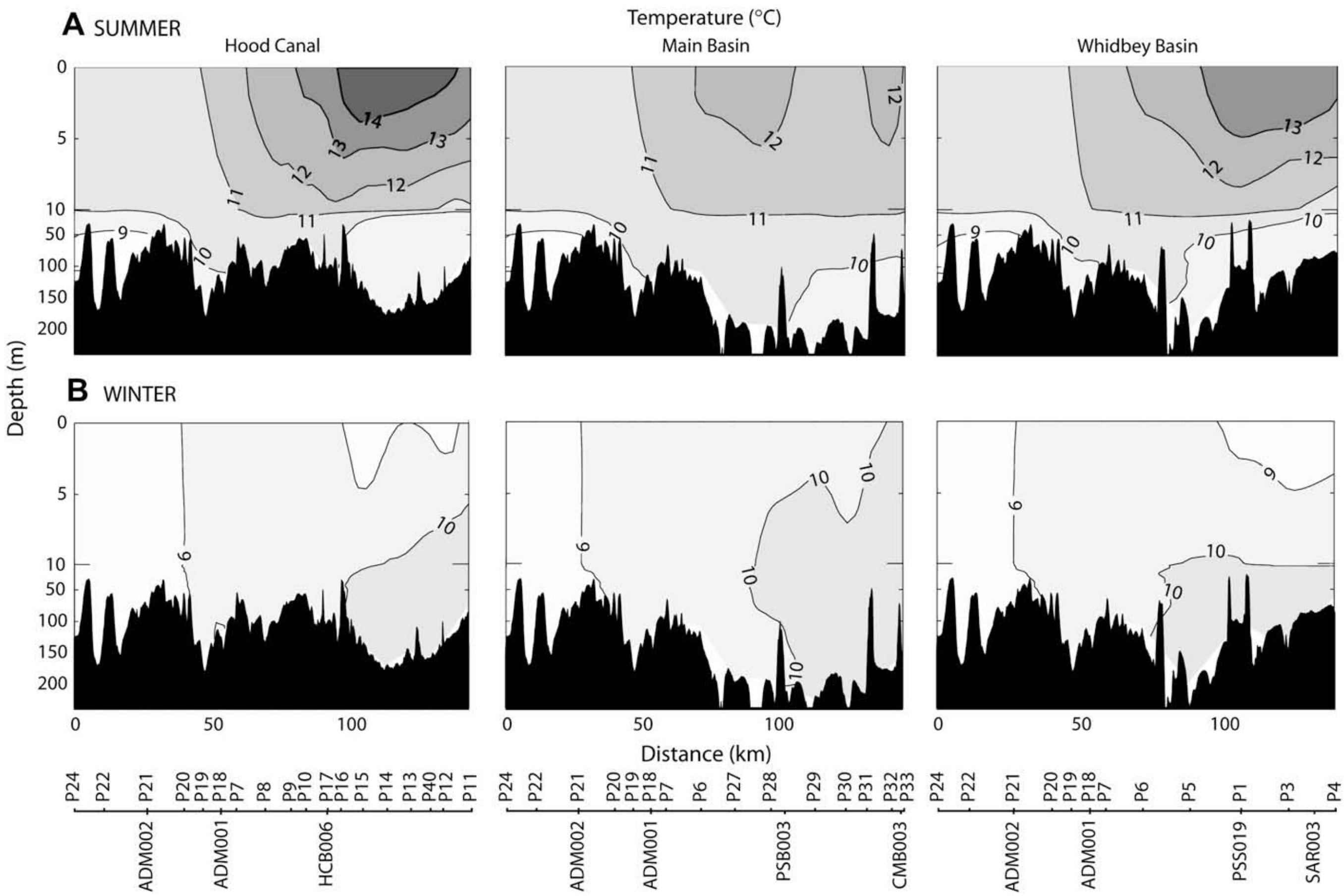

Fig. 5. Mean of summer (panel A) and winter (panel B) temperature (°C) along Puget Sound Regional Synthesis Model transects in Main Basin, Whidbey Basin, and Hood Canal from 1998 to 2003. Note that the upper 10 m of the water column is plotted on an enlarged depth scale.

Inlet into Main Basin, Whidbey Basin, and Hood Canal (Fig. 5; panel A). Thermal stratification in Hood Canal is strongest and most consistent, with a warmer surface layer approximately 10 m deep observed along nearly all of its length (south from station P9). During winter, thermal stratification is considerably eroded in all basins (Fig. 5; panel B). Vertical temperature inversions are observed at stations up-estuary in Main Basin, Whidbey Basin, and Hood Canal with cooler–fresher water overlying warmer–saltier water at depth, consistent with heat being retained in the deep layer from the previous summer and early fall.

Mean patterns of salinity along PRISM transects show evidence of salinity stratification during both summer and winter (Fig. 6), increasing from Admiralty Inlet up-estuary into Main Basin, Whidbey Basin, and Hood Canal. Salinity stratification is evident down to approximately 10 m depth, reflecting the input of freshwater from major rivers. During winter, salty and dense water at depth extends farther up-estuary into all basins (Fig. 6 and Appendix 5). This is shown particularly well by the 30 isohaline and is consistent with climatological patterns of MWM salinity and density.

3.3. Vertical stratification

Climatological patterns of vertical stratification at MWM stations were compromised at some stations by high occurrences of months with no stratification producing highly variable and uninformative results. Stratification of Puget Sound waters is therefore summarized using frequency distributions of the depth and strength of the pycnocline (Fig. 7). Pycnocline depths at each MWM station were binned into either unstratified or 4–6, 6–8, 8–10, 10–20, 20–30, and >30 m categories. Stratification was observed at Admiralty Inlet and at station PTH005 in Main Basin for only 25% of months and was relatively equally likely to occur within all depth categories. At Admiralty Inlet, the detection of a pycnocline mostly resulted from sampling on an ebb tide during periods of high river flow, such that the Skagit River outflow from Whidbey basin is detected. Other Main Basin stations (i.e., PSB003, ELB015 and SIN001) were stratified for 30–50% of months, with the exception of station CMB003 near the mouth of the Puyallup River that was stratified for 70% of months. Pycnoclines at Main Basin stations were mostly at 4–6 m depth. Station DNA001 in South Sound rarely stratified (i.e., 14% of months). Other South Sound stations (i.e., BUD005 and OAK004) stratified for 50–70% of months and mostly at 4–6 m depth. In Hood Canal, station HCB006 stratified for 85% of months with the pycnocline mostly occurring between 4 and 8 m depth, but often at depths between 10 and 20 m. Station HCB004 in Hood Canal was always stratified and 90% of pycnoclines occurred at 4–6 m depth. Whidbey Basin and North Basin stations stratified for nearly 100 and 70% of months, respectively, and mostly at 4–6 m depth.

The strength of pycnoclines is described by the maximum buoyancy frequencies, which were binned into either unstratified or in 20- cycles-h^{-1} intervals ranging from 0 to >100 cycles h^{-1}. When pycnoclines were present at Main Basin and South Sound stations, the maximum buoyancy frequencies were almost always <40 cycles h^{-1}, with the exception of stations CMB003 and OAK004 which stratified strongly at times reaching 70 and 57 cycles h^{-1}, respectively. Station HCB006 in Hood Canal and stations in North Basin also stratified strongly at times, with buoyancy frequencies reaching 63, 66, and 76 cycles h^{-1}, respectively. Station HCB004 in Hood Canal and stations PSS019 and SAR003 in Whidbey Basin

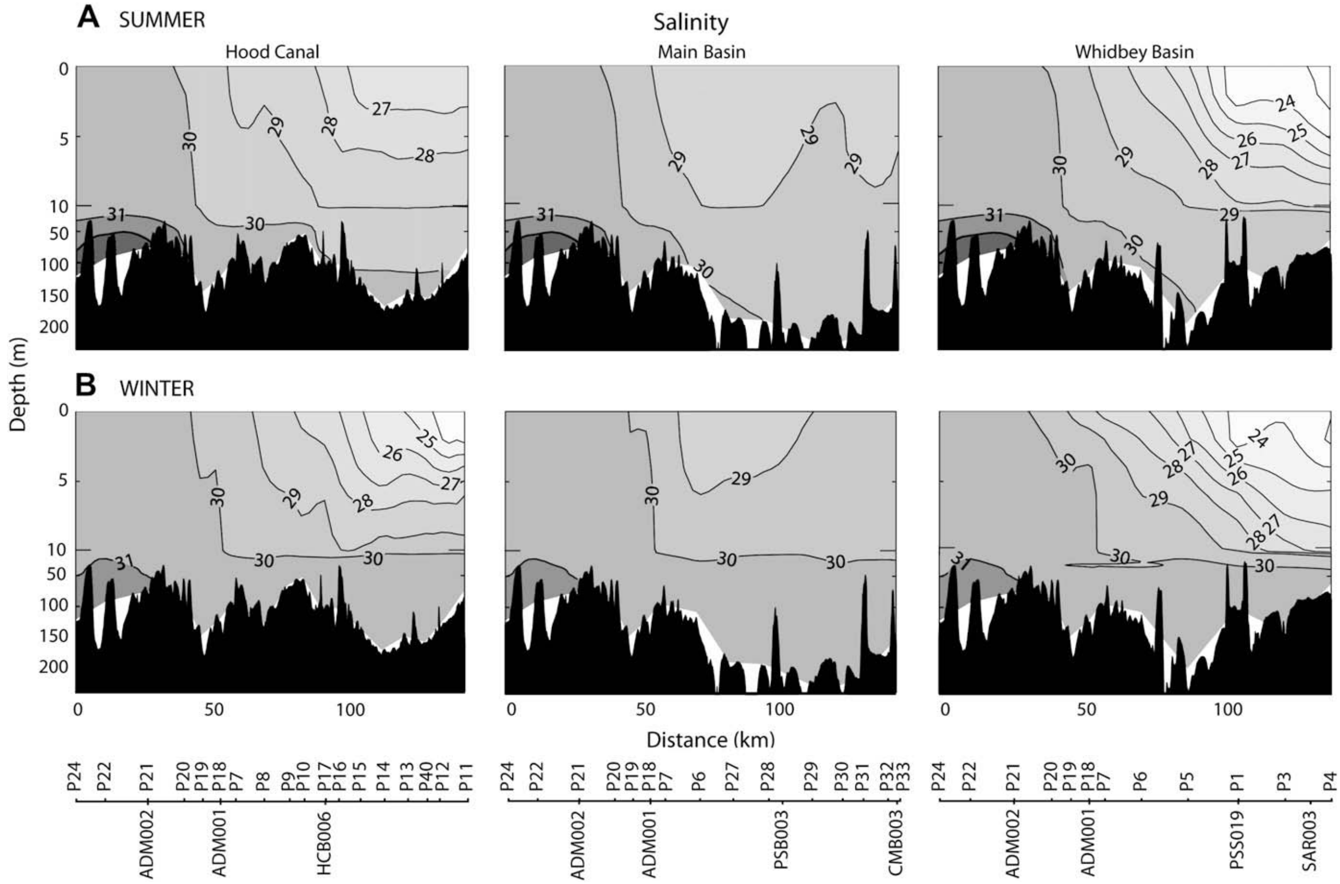

Fig. 6. Mean of summer (panel A) and winter (panel B) salinity along Puget Sound Regional Synthesis Model transects in Main Basin, Whidbey Basin, and Hood Canal from 1998 to 2003.

most frequently had the strongest stratification of all the MWM stations in Puget Sound with maximum buoyancy frequencies usually between 40 and 60 cycles h^{-1}, at times reaching 95, 110, and 94 cycles h^{-1}, respectively.

As reported here and elsewhere (i.e., Matsuura and Cannon, 1997), density distributions in Puget Sound are strongly driven by changes in salinity. Temperature contributes little to vertical density gradients. Therefore, stratification in Puget Sound is mostly influenced by freshwater inflows and mixing over sills. Stations situated close to river mouths and far from sills most frequently develop strong and deep pycnoclines (i.e., stations HCB004, HCB006, PSS019, and SAR003 in Hood Canal and Whidbey Basin). When stratification does occur it is usually between 4 and 10 m depth. This is shallower than previously reported depths of between 10 and 30 m in Main Basin (Matsuura and Cannon, 1997).

3.4. Longer-term context

A recent study found evidence for basin-wide coherence in aspects of Puget Sound's oceanography on interannual timescales (Moore et al., 2008). Single indices were identified that represent over half of the total variability in Puget Sound temperature and salinity at all station–depth combinations using MWM data. These indices were significantly correlated with sea surface temperature and salinity (SST and SSS, respectively) at Race Rocks from 1993 to 2002. Race Rocks has a longer history of observation compared to MWM data, with daily records of SST and SSS available from 1921 and 1937, respectively. Therefore, Race Rocks data can be used to place the MWM observations in a longer -term context. The 10-year period of MWM observations from 1993 to 2002 was substantially warmer and slightly fresher than most years since 1937 (Fig. 8). This should be considered when interpreting the temporal and spatial patterns of variability in Puget Sound's oceanographic properties presented in this study and comparing them to past trends. Furthermore, projections of future climate scenarios for the Pacific Northwest indicate that surface air temperatures could increase by up to 6 °C (Salathé et al., 2007). Given the close correspondence between Puget Sound air and water temperatures (Moore et al., 2008), water temperatures may continue to rise considerably as a result of anthropogenic climate change.

4. Conclusions

We summarize temporal and spatial patterns of variability in Puget Sound's oceanographic properties using continuous profile data spanning 1993–2003 from a network of MWM and PRISM stations. Oceanic source waters, mixing over sills, the depth of the water column, proximity to river mouths, and annual river flow cycles influence the climatological patterns and interannual variability of oceanographic properties. Parts of Puget Sound have strong tidal stirring and reflux over sills and oceanographic properties have small seasonal to interannual variations (e.g., Admiralty Inlet). Shallow finger inlets and areas influenced by large freshwater inflows are often vertically stratified and oceanographic properties are more variable. Near-surface vertical stratification is primarily driven by vertical salinity gradients. Stations that are strongly influenced by freshwater inflows from major rivers often stratify during periods of peak flow. When stratification is observed, pycnoclines are generally shallow at 4– 6 m depth.

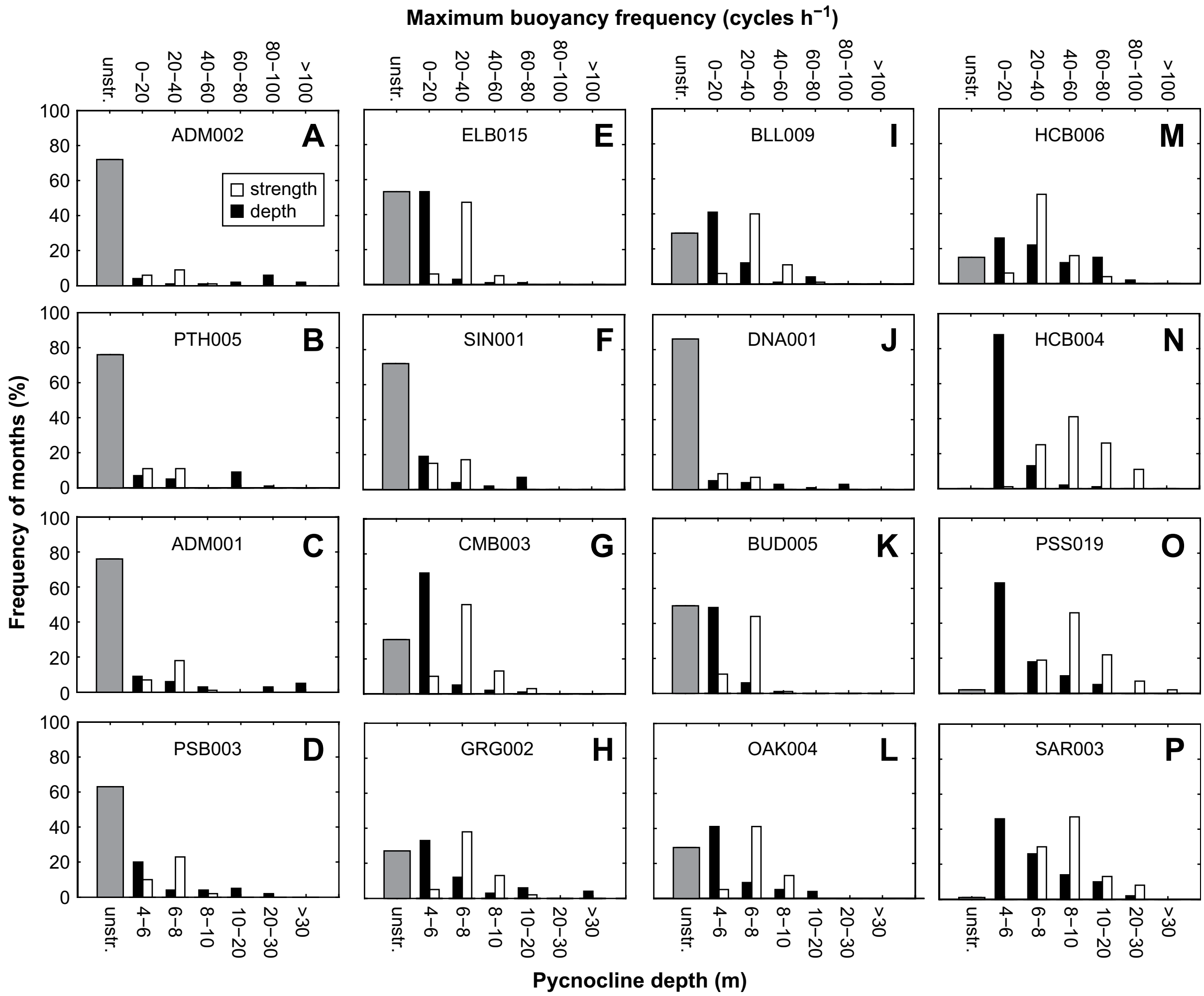

Fig. 7. Frequency distribution of the depth (m) and strength (i.e., maximum buoyancy frequency; cycles h^{-1}) of pycnoclines at Marine Waters Monitoring stations for the time period 1993 – 2002. Gray bars indicate unstratified water column conditions.

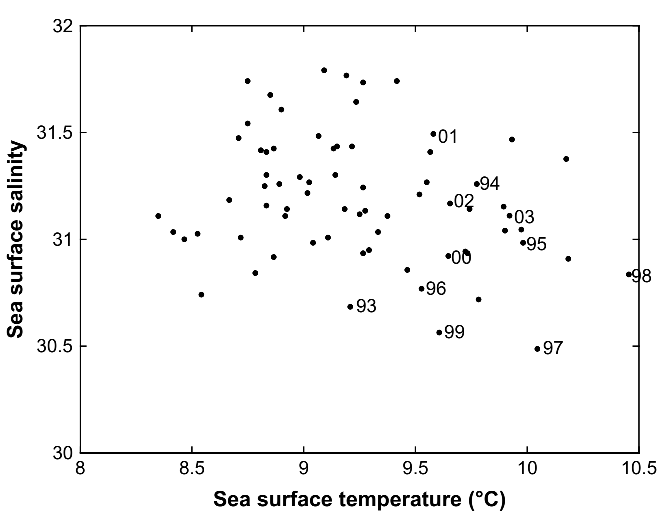

Fig. 8. Annual mean sea surface temperature and salinity at Race Rocks from 1937 to 2002. Values representing the time period examined in this study from 1993 to 2002 are labeled. Figure modified from Moore et al. (2008). Copyright (2008) by the American Society of Limnology and Oceanography, Inc.

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Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecss.2008.09.016.

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