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# Local and large-scale climate forcing of Puget Sound oceanographic properties on seasonal to interdecadal timescales

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*Abstract*

The influence of climate on Puget Sound oceanographic properties is investigated on seasonal to interannual timescales using continuous profile data at 16 stations from 1993 to 2002 and records of sea surface temperature (SST) and sea surface salinity (SSS) from 1951 to 2002. Principal components analyses of profile data identify indices representing 42%, 58%, and 56% of the total variability at depth-station combinations for temperature, salinity, and density, respectively, and 22% for water column stratification. Variability in the leading pattern of Puget Sound water temperature and salinity profiles is well correlated with local surface air temperatures and freshwater inflows to Puget Sound from major river basins, respectively. SST and SSS anomalies are informative proxies for the leading patterns of variations in Puget Sound temperature and salinity profiles. Using this longer time history of observations, we find that SST and SSS anomalies also have significant correlations with Aleutian Low, El Niño-Southern Oscillation, and Pacific Decadal Oscillation variations in winter that can persist for up to three seasons or reemerge the following year. However, correlations with large-scale climate variations are weaker compared to those with local environmental forcing parameters.

Puget Sound is a deep, fjord-type estuary covering an area of 2,330 km$^2$ in the Pacific Northwest region of the United States (Fig. 1). It is connected to the ocean by the Strait of Juan de Fuca, a turbulent passage approximately 160 km in length and 22 km wide at its western end, expanding to over 40 km wide at its eastern end (Thomson 1994). Puget Sound is separated into interconnected basins; Whidbey, Central, Hood Canal, and South (Thomson 1994). The Whidbey, Central, and Hood Canal basins are the three main branches of the Puget Sound estuary and are separated from the Strait of Juan de Fuca by a double sill at Admiralty Inlet. The shallower South basin is separated by a sill at Tacoma Narrows and is highly branched with numerous finger inlets. This study also examines oceanographic properties to the north of Puget Sound (i.e., North basin) in a region encompassing the San Juan Islands and the southern 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, reducing to approximately 0.5 m s$^{-1}$ in Central basin (Lavelle et al. 1988). The daily difference between high and low tide varies by 2.4 m at the northern and entrance end of Puget Sound to 4.6 m at the southern end. The subtidal 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 the entrance and freshwater inputs from stream flow (Lavelle et al. 1988). The total freshwater input to Puget Sound is approximately 3.4 × 10$^6$ m$^3$ d$^{-1}$ with inflow from the Skagit River accounting for the majority (Cannon 1983). Annual stream-flow maxima result from

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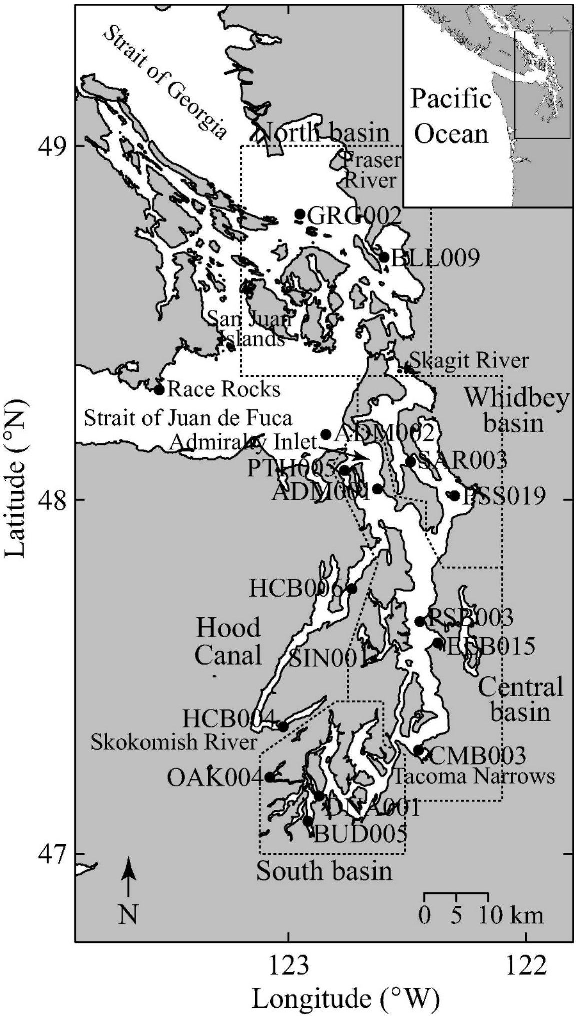

Fig. 1. Puget Sound with the locations of Marine Waters Monitoring Program (MWM) stations and Race Rocks.

periods of high precipitation and snowmelt. The subtidal circulation mostly consists of a two-layered flow in Central, Whidbey, and Hood Canal basins with fresher water exiting at the surface and saltier water entering at depth (Ebbesmeyer and Cannon 2001). Upwelling at the Tacoma Narrows sill and the absence of major river inflow produce lesser stratified waters in South basin compared to other basins, but in general surface waters flow north and deeper waters flow south. Variations to this general pattern of circulation arise from wind effects that can drive a surface current in the same direction as the wind and a baroclinic response in the lower layer to about 100-m depth (Matsuura and Cannon 1997).

While there is a long and extensive history of oceanographic observation in Puget Sound (Collias et al. 1974; Collias and Lincoln 1977), most studies have examined climate forcing of oceanographic properties over relatively short timescales not exceeding a few years (e.g., Janzen et al. 1991; M. Kawase unpubl.; Newton et al. 2003). In general, these studies find that local environmental forcing parameters strongly influence Puget Sound's oceanographic properties. For example, reduced stream flow during the 2000–2001 drought in the Pacific Northwest produced saltier surface waters and decreased salinity and density differences between surface and bottom waters in Puget Sound (Newton et al. 2003). The influence of large-scale climate variations on Puget Sound's oceanographic properties over longer timescales has received less attention.

Large-scale climate variations of the Aleutian Low pressure cell, El Niño-Southern Oscillation (ENSO), and Pacific Decadal Oscillation (PDO) alter local surface winds, air temperatures, and precipitation, thereby potentially influencing Puget Sound's oceanography (e.g., Bos et al. unpubl.; Newton 1995; Newton et al. unpubl.) and biology (e.g., Erickson and Nishitani 1985; Preikshot et al. unpubl.). The Aleutian Low is a semipermanent atmospheric low-pressure cell situated in the North Pacific from late fall to spring. When the Aleutian Low is intense (weak), the coastal ocean is generally warmer (cooler) and more (less) stratified and winter and spring conditions in the Pacific Northwest generally warmer and drier (cooler and wetter) (Trenberth and Hurrell 1994; Latif and Barnett 1996). ENSO and PDO are both patterns of hemispherical climate variability involving sea surface temperature fields, and they produce similar effects in the Pacific Northwest. The main differences between them are that ENSO has its primary signature in the tropics with a secondary signature in the North Pacific, whereas the opposite is true for PDO, and a typical ENSO event persists for 6–18 months, whereas PDO events persist for 20–30 yr (Mantua and Hare 2002). El Niño (La Niña) and warm (cool) phases of the PDO generally produce a warmer (cooler) coastal ocean and warmer and drier (cooler and wetter) winters (e.g., Rasmusson and Wallace 1983; Ropelewski and Halpert 1986; Minobe 1997). These large-scale climate variations are not entirely independent of one another, and the character of the Aleutian Low is strongly influenced by ENSO and PDO variations. In general, an intense (weak) Aleutian Low is more likely during El Niño (La Niña) and warm (cool) phases of the PDO (Trenberth and Hurrell 1994; Mantua et al. 1997; Deser et al. 2004).

At decadal timescales, variations of the Aleutian Low have been found to covary with 5-yr averages of observations of currents and temperature in central Puget Sound spanning from 1934 to 1984 (Ebbesmeyer et al. 1989). This relationship arises because salinity in the Strait of Juan de Fuca increases when the Aleutian Low is intense because of less freshwater entering the Strait of Juan de Fuca from the Fraser River, whereas salinity in Puget Sound remains steady. As a result, the density difference across the entrance sill to Puget Sound at Admiralty Inlet increases, and the inflow of waters from the Strait into Puget Sound from middepth to the bottom is enhanced (Ebbesmeyer et al. 1989). These relationships were determined using current and temperature observations at a single depth from only a few stations in Puget Sound's Central basin. How other basins of Puget Sound respond to variations of the Aleutian Low and the relative influence of ENSO and PDO variations on oceanographic properties is unclear.

Table 1. Percentage of months with data, mean profile depth (± standard deviations) and the depth of profile data used in this study for Marine Waters Monitoring stations from 1993 to 2002.

| Station | Months with data (%) | Mean profile depth (m) | Profile depth used (m) |
|---|---|---|---|
| ADM002 | 74 | 58±12 | 60 |
| PTH005 | 83 | 21±3 | 20 |
| ADM001 | 86 | 76±23 | 80 |
| PSB003 | 84 | 43±21 | 50 |
| ELB015 | 93 | 69±14 | 70 |
| SIN001 | 88 | 13±2 | 12 |
| CMB003 | 91 | 106±19 | 80 |
| DNA001 | 86 | 34±4 | 30 |
| BUD005 | 93 | 12±3 | 12 |
| OAK004 | 90 | 10±5 | 10 |
| HCB006 | 83 | 84±28 | 80 |
| HCB004 | 88 | 46±6 | 50 |
| PSS019 | 83 | 72±25 | 70 |
| SAR003 | 85 | 90±31 | 80 |
| BLL009 | 85 | 12±6 | 12 |
| GRG002 | 70 | 97±28 | 80 |

The scale and types of climate forcing that most influence oceanographic properties will determine the skill and lead times with which certain aspects of Puget Sound oceanography can be predicted. This may have implications for the advanced warning of harmful algal blooms in Puget Sound, some of which are known to flourish when water temperatures are warm and stratification is strong (Nishitani and Chew 1984; Erickson and Nishitani 1985). The aim of this study is to quantify relationships between variability in Puget Sound's oceanographic properties and aspects of the local and large-scale climate and to determine the timescales of response to Aleutian Low, ENSO, and PDO variations. This is achieved using principal components analyses to identify the leading patterns of variability in Puget Sound's oceanographic properties and correlation analyses with selected local and large-scale climate indicators over a 10-yr period. A longer time series of sea surface temperature and salinity is used to evaluate the characteristics of interannual and interdecadal variability and the timescales of response of oceanographic properties to large-scale climate variations. Additionally, a case study of the response of oceanographic properties in the surface and deep layers of Puget Sound during the 1997–1998 El Niño is presented.

## Methods

*Oceanographic data*—This study utilizes oceanographic data from the long-term Marine Waters Monitoring Program (MWM), and the Department of Fisheries and Oceans Canada (DFO). Both monitoring programs are ongoing, but we use data only 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. The MWM is conducted by the Washington State Department of Ecology in conjunction with the Puget Sound Ambient Monitoring Program. Although records at discrete depths date back to 1973, we use continuous profile data at 16 core stations from 1993 (Fig. 1; Table 1). The depth to which observations were consistently made limited the profile data considered here to a maximum depth of 80 m, even though the average water depth of Puget Sound is 108 m (Collias and Lincoln 1977). Surveys are conducted monthly using a SeaBird Electronics Inc. SBE 19*plus*® conductivity-temperature-depth instrument (CTD) deployed from seaplane. CTD data are processed using SeaBird Electronics Inc. SEASOFT© software into 0.5-m bins. More information on the parameters sampled and methodologies is documented in Janzen (1992) and Newton et al. (2002).

MWM data are collected only during fair weather when stations can be safely accessed by seaplane and are known to be tidally aliased (Janzen et al. 1991; Janzen and Eisner 1993). The effect of tide is most notable in areas of strong mixing, such as Admiralty Inlet. 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; M. Kawase unpubl.; Newton et al. 2003). This indicates that variability in oceanographic properties due to tide stage is generally less than that forced by other environmental factors on seasonal to interannual timescales or longer.

The 10-yr time history of MWM data used here is relatively short compared to the frequency of large-scale climate variations such as ENSO and PDO (2–7 and 60–70 yr, respectively). Consequently, we examine DFO observations of sea surface temperature and salinity (SST and SSS, respectively) at Race Rocks in the Strait of Juan de Fuca (Fig. 1) to determine if the period covered by MWM data is typical of a longer time period. Observations at Race Rocks are made daily at or near the daytime high tide. SST data are available from 1921, and SSS data are available from 1937 to present.

*Calculation of vertical stratification*—A modified method of the U.S. Environmental Protection Agency (1982) is used to derive four stratification parameters from the MWM density profiles: the upper pycnocline ($z_m$), lower pycnocline ($z_b$), actual pycnocline ($z_p$), and the maximum Brunt-Väisälä frequency, or buoyancy frequency ($N$). Observations <2 m from the surface and the bottom were excluded because of noise, and density gradients were calculated at 0.5-m intervals and smoothed using a 2.5-m moving average. The upper pycnocline marks the depth boundary of the surface mixed layer and is the first density gradient exceeding 0.1 kg m$^{-4}$ from the surface, provided that the next density gradient below is positive. The lower pycnocline marks the depth boundary of the deep mixed layer and is the first density gradient exceeding 0.2 kg m$^{-4}$ from the bottom, provided that (1) an upper pycnocline exists, (2) the lower pycnocline is ≥2.5 m below the upper pycnocline, (3) there is a bottom mixed layer defined by the first or second density gradients from the bottom (i.e., 2.5 or 3 m from the bottom) being less than 0.2 kg m$^{-4}$, and (4) the next density gradient above is positive. Note that the upper and lower pycnoclines must be ≥4 m from the surface and ≥2.5 m from the bottom, respectively, to ensure that they are not determined by end points outside the smoothing function.

The actual pycnocline marks the depth of the maximum density gradient and must exceed 0.1 kg $m^{-4}$. The strength of the actual pycnocline is indicated by the maximum buoyancy frequency at this depth and is calculated as

$$N = \sqrt{\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}} \times \frac{3{,}600}{2\pi} \tag{1}$$

where $g$ is the gravitational constant (9.8 m $s^{-2}$), $\rho_0$ is density (1,025 kg $m^{-3}$), $z$ is depth (m), and 3,600 s $h^{-1}/2\pi$ radians $cycle^{-1}$ converts $N$ from radians $s^{-1}$ to cycles $h^{-1}$. Density gradients exceeding 0.1 kg $m^{-4}$ that occurred below 40-m depth are considered to be deep intrusions of oceanic water over the sill at Admiralty Inlet and were not considered in the calculation of stratification parameters.

*Temporal and spatial coherence of oceanographic properties*—Principal components analyses of MWM oceanographic properties were used to examine patterns of interannual variability and spatial coherence from 1993 to 2002. Prior to analyses, data were normalized by removing the monthly means and dividing by the monthly standard deviations using the full 10-yr period such that the time series of each property had a mean of 0 and a standard deviation of 1. The number of principal components (PCs) retained was determined by calculating 95% confidence errors in the estimation of eigenvalues following the method of North et al. (1982). Independent PCs with nonoverlapping 95% confidence errors were deemed meaningful and were retained. Time series of the retained PCs were normalized and the loading vectors rescaled to represent the correlation coefficients of the anomalies with the PCs.

*Local and large-scale climate influences*—Correlation analyses were conducted to quantify linear relationships between aspects of the local and large-scale climate and Puget Sound's oceanographic properties. Monthly anomalies of climate indices were calculated using a common base period from 1993 to 2002, matching the time period of MWM observations. Local climate indices examined here are stream flow, air temperature, precipitation, and coastal upwelling. Stream flow (STRM) is approximated by the Skagit River, which accounts for over half the total stream flow to Puget Sound (Cannon 1983) and covaries with freshwater discharge from most major rivers that flow into Puget Sound at seasonal and longer timescales. Data were obtained from the U.S. Geological Survey Water Resources for the Skagit River at Mount Vernon site 12200500. Surface air temperature (AIR) from the U.S. Climate Division data set for the Puget Sound lowlands (climate division 3) was obtained from the National Oceanographic and Atmospheric Administration (NOAA) National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html). The upwelling index (UPWL) at 48°N and 125°W derived from the NOAA Environmental Research Division is used here as an index of wind-driven coastal upwelling of oceanic waters near the west entrance of the Strait of Juan de Fuca. This index is also representative of local wind variability at West Point within Puget Sound (located on the western shore from station PSB003). When the upwelling index is strongly negative (indicating strong poleward alongshore wind stress), wind speed at West Point is high and usually from the south. This usually occurs in the winter and fall. In the spring and summer, the upwelling index is close to 0 or positive (indicating equatorward alongshore wind stress), and winds at West Point are weak and usually to the east (Moore et al. unpubl.).

The Aleutian Low, ENSO, and PDO variations can be tracked by commonly used indices. The North Pacific Index (NPI) indicates the strength of the Aleutian Low and is based on sea-level pressure in the region 30°N–65°N, 160°E–140°W. Low (high) values of the NPI indicate an intense (weak) Aleutian Low. The NPI is provided by the Climate Analysis Section, National Center for Atmospheric Research, Boulder, Colorado, U.S.A. (Trenberth and Hurrell 1994). Following Trenberth (1997), we use SST anomalies in the Niño3.4 region (5°N–5°S, 120°W–170°W) to monitor the behavior of ENSO. Niño3.4 data are provided by the NOAA National Weather Service Climate Prediction Center. The PDO index is defined by the leading PC of SST anomalies in the North Pacific poleward of 20°N using a base period from 1900 to 1993 and is provided by the University of Washington Joint Institute for the Study of the Atmosphere and Ocean (http://jisao.washington.edu/pdo/PDO.latest). Monthly values of the NPI, ENSO, and PDO indices were normalized relative to the common base period from 1993 to 2002.

Local and large-scale climate indices were correlated with the eigenvector time series of the leading PCs of Puget Sound temperature, salinity, density, and stratification parameters from MWM profiles from 1993 to 2002. Correlations were conducted using annual means of PCs and local climate forcings for winter, spring, summer, and fall (i.e., January–March, April–June, July–September, and October–December, respectively) to better evaluate the seasonal dependence of climatic forcing and Puget Sound's oceanographic responses. Annual mean values of the NPI were calculated using October–March 6 month averages because variance in the Aleutian Low peaks in the fall and winter, and annual mean values of the ENSO and PDO indices were calculated using July–June 12 month averages because high autocorrelation of these climate variations rapidly declines from June through July. This reflects the tendency for individual ENSO events and their teleconnections with the PDO pattern to begin in one summer, peak the following winter, and then fade away in the subsequent spring (*see* Newman et al. 2003). SST and SSS at Race Rocks were also included in the correlation analyses to assess relationships with Puget Sound's oceanographic properties. The number of degrees of freedom used to determine probability values of correlation coefficients were adjusted for autocorrelation following Bretherton et al. (1999).

*Lagged response to large-scale climate variations*—Lag correlations were conducted to determine the timescales of

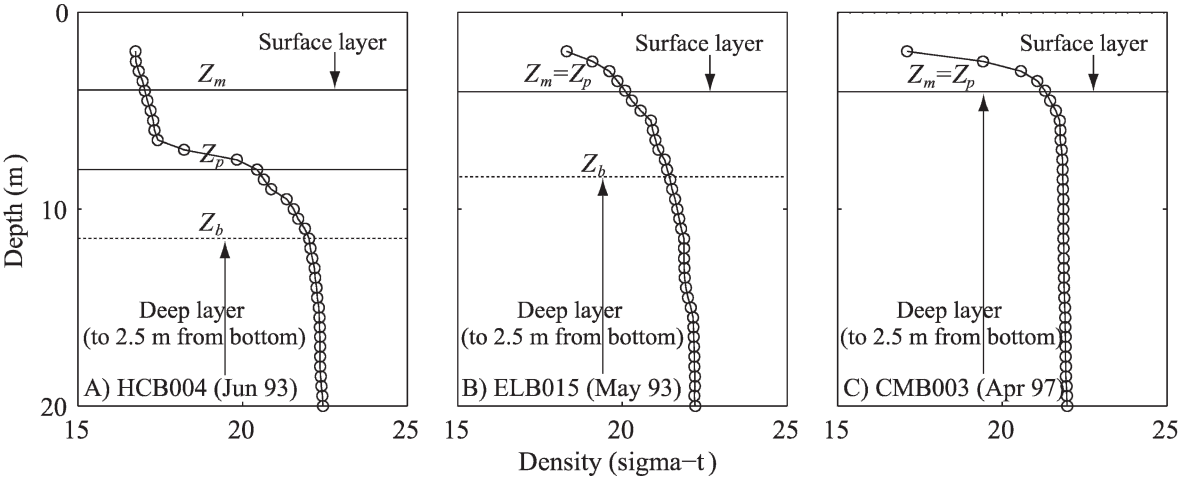

Fig. 2. Examples of density profiles from MWM stations (A) HCB004 during June 1993, (B) ELB015 during May 1993, and (C) CMB003 during April 1997 showing the depth of the upper pycnocline ($z_m$), maximum density gradient ($z_p$), and lower pycnocline ($z_b$). Note that an upper pycnocline can occur at the same depth as the maximum density gradient (B, C) and that a bottom pycnocline can be absent (C) in profiles. The depths over which surface and deep layer water properties are obtained are indicated for each example.

response of oceanographic properties to large-scale climate forcing. Long-term records of SST and SSS at Race Rocks from 1950 to 2002 were used in this analysis because the 10-yr history of MWM observations is not sufficient to capture the low-frequency oscillations of the Aleutian Low, ENSO, and PDO. Annual mean anomalies of SST, SSS, and large-scale climate indices were calculated for winter, spring, summer, and fall using the common base period from 1993 to 2002. Pearson's correlation coefficients were calculated for SST and SSS anomalies with the NPI, ENSO, and PDO indices at lags of zero to eight seasons.

*1997–1998 El Niño*—Oceanographic properties in the surface and deep layers were examined for MWM stations whose depth exceeded 50 m during the 1997–1998 El Niño and 1998–1999 La Niña. The depth ranges of the surface and deep layers were determined using the stratification parameters described previously. If an upper pycnocline was present ($z_m$) or the upper and actual pycnocline were equal ($z_m = z_p$), surface layer temperature and salinity were the mean of values $\geq 2$ m and $\leq z_m$. If a bottom pycnocline was present ($z_b$), deep layer properties were calculated as the mean of values $\geq z_b$ (Fig. 2A,B); otherwise, deep layer properties were calculated as the mean of values $\geq z_p$ (Fig. 2C). If MWM profiles indicated well-mixed water column conditions, surface and deep layer properties were calculated as previously using the mean values of the upper, lower, and actual pycnocline depths determined from months when the water column was stratified at that particular station.

Monthly values of surface and deep layer temperature and salinity at MWM stations were averaged for each basin. Because of the unique mixing environment in Admiralty Inlet, stations ADM002 and ADM001 were considered independently from those in Central basin. Monthly means for each basin were smoothed using a 3-month moving average and qualitatively compared with monthly anomalies of the ENSO index from 1997 to 2002.

## Results and discussion

*Temporal and spatial coherence of oceanographic properties*—Structure in Puget Sound temperature, salinity, density, and maximum buoyancy frequency is well represented by the leading PCs, explaining 42%, 58%, 56%, and 22% of the total variances, respectively, at all depth-station combinations (Fig. 3A–C). The leading PCs for salinity and density profiles are nearly identical, so we show results only for salinity. All other eigenvalues for the remaining PCs have overlapping 95% confidence intervals and therefore hold little meaning. No independent PCs are found to represent structure in the depth of the maximum density gradient. Therefore, variability in Puget Sound temperature, salinity, density, and maximum buoyancy frequency can be adequately described by single PCs (i.e., PC1T, PC1S, PC1D, and PC1N, respectively). This provides evidence for basinwide coherence in Puget Sound's oceanographic properties at all depths on interannual timescales using MWM data. Similar coherence in oceanographic variability has been documented nearby in the Strait of Georgia, with 78% of the total temperature variability at all depths from 1970 to 2005 captured by a single index (Masson and Cummins 2007).

Normalized time series of the leading PCs identify phases when anomalies of oceanographic properties were persistently positive or negative from 1993 to 2002 (Fig. 3E–H). Variations in PC1T indicate that Puget Sound temperatures were warmer than average from mid-1997 to 1999 and cooler than average from 1999 to 2000. Variations in PC1S are largely independent of variations in PC1T on interannual timescales. PC1S identifies a prolonged period when Puget Sound was fresher than average from 1996 to 2000 and saltier than average from 2000 to 2002. The normalized time series of PC1N is less coherent compared to the other leadings PCs but indicates persistent and stronger-than-average stratification from 1997 to 1999 and weaker-than-average stratification from 1999 to 2001.

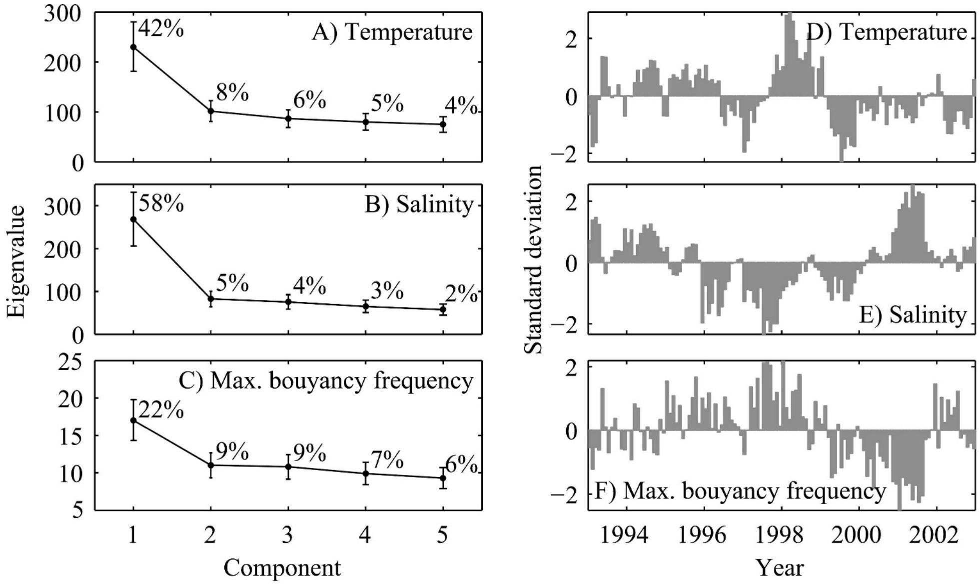

Fig. 3. (A–C) Eigenvalue spectra with 95% confidence error and percent variance explained for the first five principal components and (D–F) normalized time series of the leading principal components for (A, D) temperature, (B, E) salinity, and (C, F) the strength of the pycnocline (i.e., maximum buoyancy frequency).

Examples of how the extreme positive and negative normalized values of the leading PCs translate into measurable units are shown for station CMB003 (Fig. 4). Extreme positive and negative values of PC1T occurred in March 1998 and July 1999, and depth-averaged temperatures at CMB003 were 0.9°C warmer and 0.6°C cooler than average, respectively. Extreme positive and negative values of PC1S occurred in May 2001 and July 1997, and depth-averaged salinity was 1.1 saltier and 0.7 fresher than average, respectively.

Loading vectors for each station-depth combination represent the correlation between variability in Puget Sound's oceanographic properties and the leading PC time series (Fig. 5). In general, loading vectors indicate that variability captured by the leading PCs is greatest at well-mixed stations in Central basin. The least coherence occurs at stations located in shallow finger inlets in South basin and stations influenced by large freshwater inflows from the Skagit and Skokomish rivers in Whidbey basin and Hood Canal, respectively. Coherence is poor below 50-m depth at stations at or near Admiralty Inlet (i.e., ADM002, ADM001, and ELB015). This is likely a result of episodic deep density intrusions from the Strait of Juan de Fuca being mixed over the sill at Admiralty Inlet and flowing into Central basin at depth. Stations that load most strongly on PC1N are those close to river mouths that show persistent salinity stratification. For example, Whidbey basin stations are strongly influenced by the Skagit River, Hood Canal stations by the Skokomish River, and stations ELB015 and CMB003 in Central basin by the Duwamish and Puyallup rivers, respectively. Well-mixed stations that rarely stratify, such as those in Admiralty Inlet, load poorly on PC1N.

*Local and large-scale climate influences*—Monthly values of the indices representing the local and large-scale climate are shown in Fig. 6. Unlike the leading PCs for Puget Sound temperature and salinity, the time series for the climate forcings, particularly those representing the local environment, contain higher-frequency variations at sea-

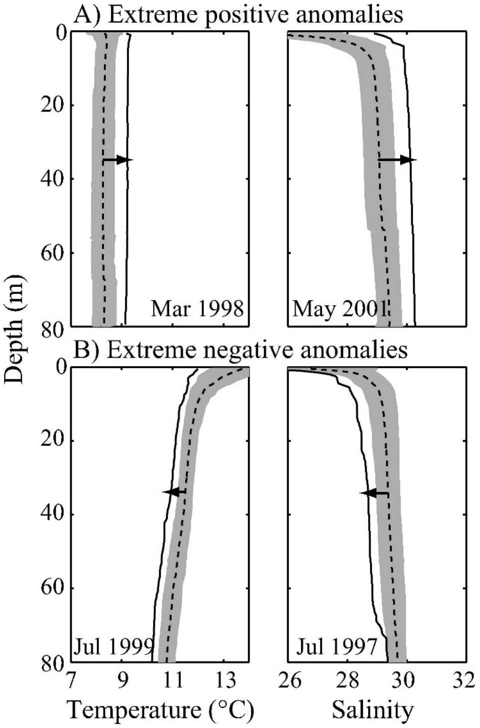

Fig. 4. Vertical profiles of temperature and salinity at station CMB003 for months when PC1T and PC1S, respectively, showed (A) extreme positive and (B) negative anomalies. Climatological monthly means (dotted lines) and standard deviations (shaded areas) are shown for comparison and the directions of change are indicated by arrows.

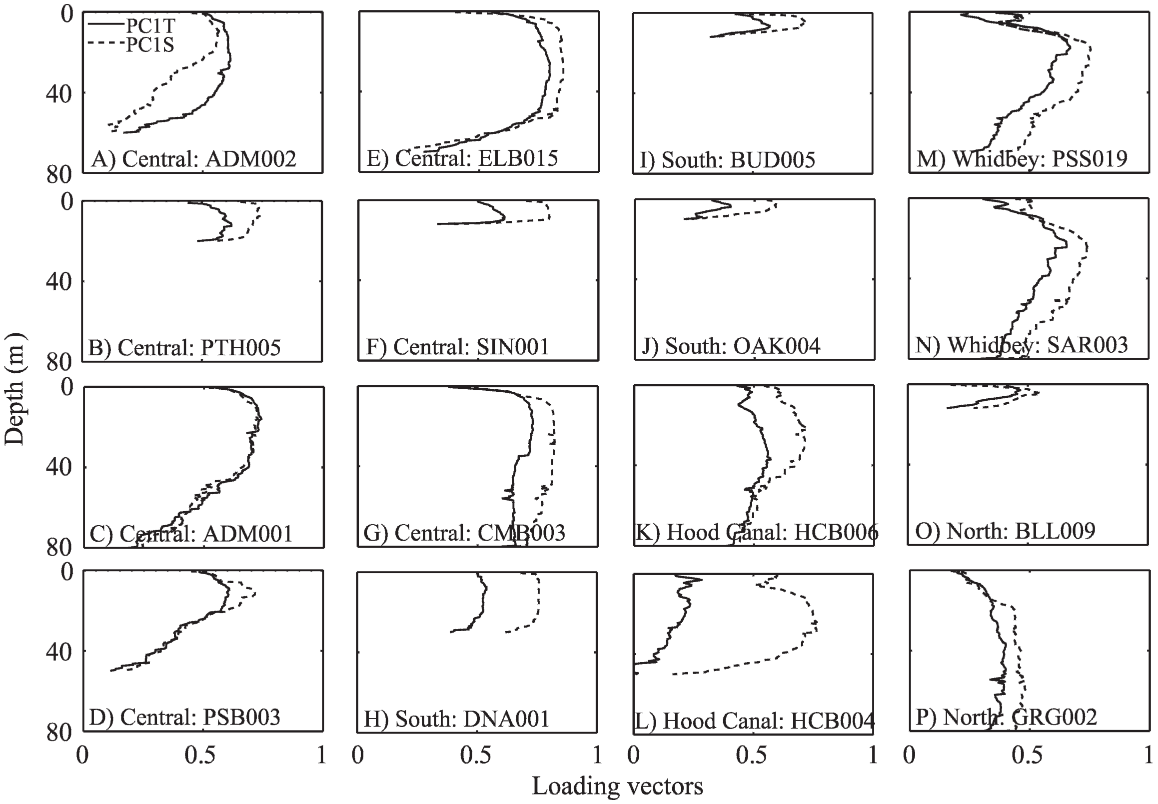

Fig. 5. Loading vectors of the leading principal component for Puget Sound temperature (PC1T) and salinity (PC1S) for each station-depth combination at Marine Waters Monitoring stations. The loading vectors are rescaled such that the $x$-axis can be interpreted as the correlation coefficient for temperature anomalies at each station-depth combination and the time series for PCs from 1993 to 2002. Note that depth scaling on each subplot is consistent, so loading vectors are absent at depth for shallower stations. Central: (A) ADM002, (B) PTH005, (C) ADM001, (D) PSB003, (E) ELB015, (F) SIN001, and (G) CMB003. South: (H) DNA001, (I) BUD005, and (J) OAK004. Hood Canal: (K) HCB006 and (L) HCB004. Whidbey: (M) PSS019 and (N) SAR003. North: (O) BLL009 and (P) GRG002.

sonal timescales. Pearson's correlation coefficients, adjusted degrees of freedom, and probability values for correlations of the leading PCs with climate indices are given in Table 2. There are no statistically significant relationships between PC1T and PC1S, confirming patterns observed in their normalized time series (Fig. 3D,E). As is expected, stratification is stronger in Puget Sound when waters are warmer and fresher. However, salinity variations contribute most to the development of a strong pycnocline rather than temperature gradients. This is indicated by statistically significant correlations of PC1N with PC1S during winter, summer, and fall, whereas the correlations with PC1T are significant during fall only when freshwater inflows to Puget Sound are small. Of the local climate-forcing parameters, AIR is best correlated with PC1T and STRM with PC1S. This was expected from previous studies in Puget Sound and nearby in the Strait of Georgia (Collias et al. 1974; Janzen and Eisner 1993; Masson and Cummins 2007). It follows that increased stream flow and warmer air temperatures are correlated with PC1N (Table 2).

Of the large-scale climate variations, only ENSO covaried significantly with Puget Sound oceanographic properties (Table 2). During El Niño years, Puget Sound temperatures are warmer in spring, summer, and fall, and stratification is stronger during spring. However, the relatively short history of observation (i.e., 10 yr) and high autocorrelation in the PC time series and large-scale climate indices weaken the statistics on interannual timescales or longer. Because PC1T and PC1S covary significantly with SST and SSS variability at Race Rocks, respectively, during most seasons (Table 2), we bridge our analysis using the longer time series from Race Rocks to represent variability in Puget Sound temperature and salinity and examine relationships with local and large-scale climate indices from 1951 to 2002 (Table 3). Results of the longer-term analysis are statistically more powerful because of the increased number of effective degrees of freedom.

As with the analysis of the 1993–2002 profile PCs, the local climate-forcing parameters AIR and STRM correlate most strongly with SST and SSS at Race Rocks, respectively, from 1951 to 2002 (Table 3). The longer-term analysis also reveals a significant negative correlation between UPWL and SST during winter. This reflects interannual and interdecadal variability in the frequency and/or magnitude of winter storms that could not be captured by the shorter-term analysis. Major winter storms can produce anomalously strong southwesterly (downwelling-favorable) winds in the Pacific Northwest and cause reversals of the estuarine flow in the Strait of Juan de Fuca (Cannon 1972; Thomson 1994). When this occurs,

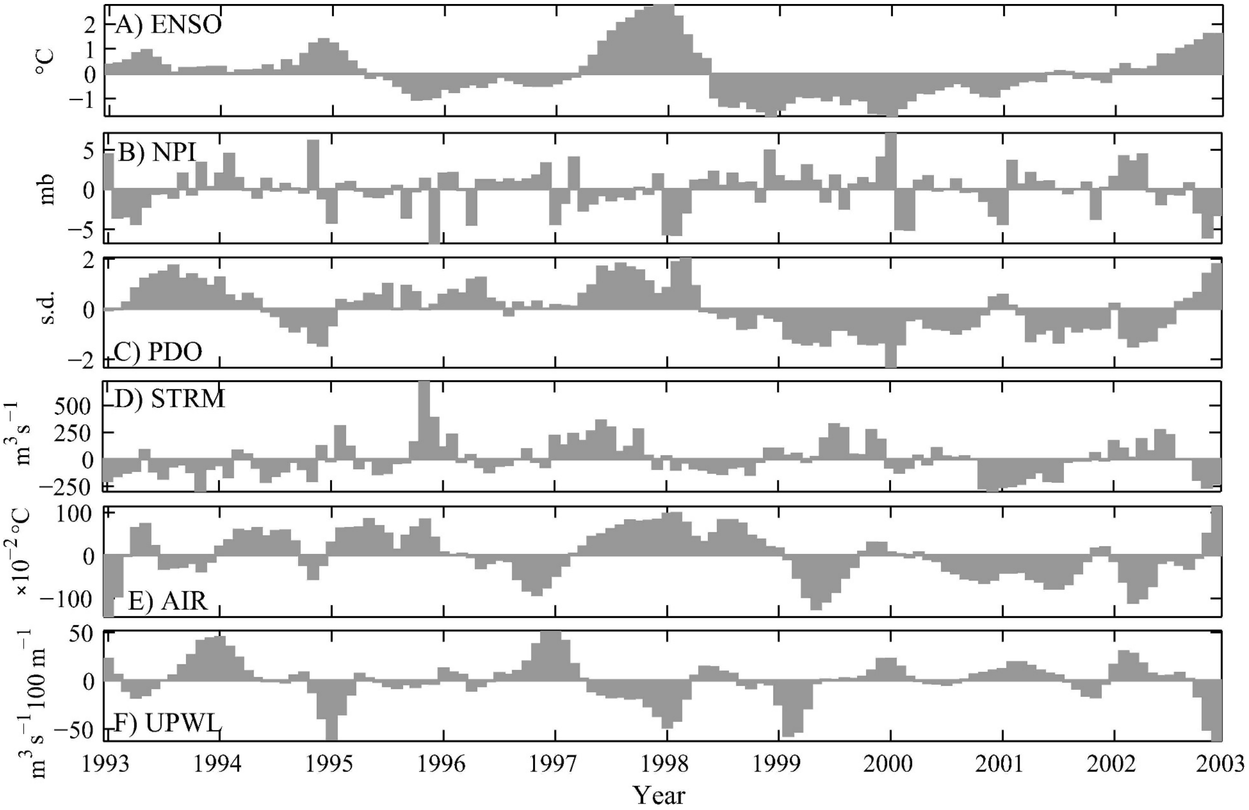

Fig. 6. Monthly values of the indices for the (A) El Niño-Southern Oscillation (ENSO), (B) Aleutian Low (NPI), (C) Pacific Decadal Oscillation (PDO), (D) Skagit River stream flow (STRM), (E) Puget Sound lowland air temperature (AIR), and (F) coastal upwelling (UPWL) from January 1993 to December 2002.

warmer (i.e., 1–3°C), offshore waters intrude eastward into the strait (Holbrook and Halpern 1982).

UPWL is also significantly positively correlated with SSS during spring and may reflect interannual and interdecadal variability in the strength or perhaps the onset of upwelling-favorable winds. Upwelled waters drawn into the Strait of Juan de Fuca are saltier than the surrounding waters, and this signature can be mixed upward into the surface by strong tidal reflux (Thomson 1994). However, we do not see a concomitant significant correlation between UPWL and cooler SSTs during spring.

An intense Aleutian Low (i.e., negative NPI) and warm phases of ENSO and PDO (i.e., positive indices) were significantly correlated with winter SSTs (Table 3). For PDO, this relationship with SST was also marginally significant in spring. Warmer water temperatures are expected when the Aleutian Low is intense or when ENSO and PDO are in the warm phase because southwesterly winds are enhanced, causing downwelling of relatively warm water at the coast, downward displacement of the thermocline, and enhanced poleward advection of coastal water at the surface and within the undercurrent (e.g., Huyer and Smith 1985; Latif and Barnett 1996; Mantua et al. 1997). These local expressions of the large-scale climate variations are supported by significant correlations of winter SSTs with both AIR and UPWL (Table 3).

No significant correlations were found for the large-scale climate indices with SSS. Previous studies have identified relationships between the Aleutian Low, ENSO, and PDO indices and Puget Sound snowpack and stream flow (e.g., Mantua et al. 1997; Mantua and Hare 2002); however, those teleconnections are modest and apparently not large enough to translate into statistically significant correlations for SSS at Race Rocks.

Different climate forcings have seasonally dependent influences on water properties. For example, AIR has the largest correlation with SST in winter and smallest in summer, STRM has the largest correlation with SSS in summer and smallest in fall, and UPWL has the largest correlation with SSS in spring. Most notably, SST has statistically significant correlations with all the local and large-scale climate indices in winter, indicating that winter is the season of greatest coupling between large-scale climate forcings and regional/local-scale forcings in the Puget Sound basin as well as the oceanographic properties at Race Rocks.

*Lagged response to large-scale climate variations*—Lag correlations of large-scale climate indices with SST and SSS at Race Rocks from 1952 to 2002 are shown in Fig. 7. In general, the lag correlations suggest that the influence of ENSO and PDO climate variations on SST is more substantial than Aleutian Low variations. This may be due to the greater persistence in the ENSO and PDO patterns. The lag correlations of the large-scale climate indices with SSS are uniformly weak.

Table 2. Pearson's correlation coefficients for the leading principal components for Puget Sound temperature, salinity, and maximum buoyancy frequency (PC1T, PC1S, and PC1N, respectively) with indices of the local and large-scale climate. Sea surface temperature and salinity anomalies at Race Rocks (SST and SSS, respectively) are also included. Data are from 1993 to 2002. For each table entry, $r_{\mathrm{df}}$, the subscript df indicates the effective degrees of freedom adjusted for autocorrelation. Significance at the 90%, 95%, and 99% confidence levels (i.e., $p \leq 0.10$, 0.05, and 0.01) are indicated by *, **, and ***, respectively.

| | Winter 1993–2002 | | | Spring 1993–2002 | | |
|---|---|---|---|---|---|---|
| | PC1T | PC1S | PC1N | PC1T | PC1S | PC1N |
| PC1T | 1 | | | 1 | | |
| PC1S | $-.40_{3}$ | 1 | | $-.09_{3}$ | 1 | |
| PC1N | $.60_{5}$ | $-.78_{3}$* | 1 | $.56_{6}$ | $-.59_{3}$ | 1 |
| STRM | $.12_{6}$ | $-.81_{3}$* | $.78_{5}$** | $-.52_{8}$ | $-.49_{3}$ | $.31_{6}$ |
| AIR | $.70_{8}$** | $-.30_{3}$ | $.54_{5}$ | $.65_{7}$** | $<.01_{3}$ | $.45_{6}$ |
| UPWL | $-.46_{8}$ | $.18_{3}$ | $-.40_{5}$ | $.08_{8}$ | $.19_{3}$ | $<.01_{6}$ |
| NPI | $-.51_{8}$ | $.02_{3}$ | $-.05_{5}$ | $-.48_{8}$ | $-.01_{3}$ | $-.17_{6}$ |
| ENSO | $.45_{8}$ | $-.01_{3}$ | $.47_{5}$ | $.81_{8}$*** | $-.04_{3}$ | $.74_{6}$** |
| PDO | $.27_{4}$ | $-.11_{3}$ | $.30_{5}$ | $.81_{4}$** | $-.21_{3}$ | $.58_{4}$ |
| SST | $.86_{8}$*** | $-.45_{3}$ | $.65_{5}$ | $.74_{8}$*** | $-.28_{3}$ | $.48_{6}$ |
| SSS | $-.29_{3}$ | $.73_{3}$ | $-.66_{3}$ | $-.20_{6}$ | $.82_{3}$* | $-.48_{6}$ |
| | Summer 1993–2002 | | | Fall 1993–2002 | | |
| PC1T | 1 | | | 1 | | |
| PC1S | $.36_{6}$ | 1 | | $-.40_{8}$ | 1 | |
| PC1N | $.15_{3}$ | $-.71_{3}$ | 1 | $.69_{8}$** | $-.68_{8}$** | 1 |
| STRM | $-.72_{8}$** | $-.75_{6}$*** | $.25_{3}$ | $.31_{8}$ | $-.62_{8}$** | $.76_{8}$*** |
| AIR | $.72_{6}$** | $-.21_{6}$ | $.57_{3}$ | $.33_{8}$ | $-.64_{8}$** | $.58_{8}$* |
| UPWL | $-.20_{8}$ | $.31_{6}$ | $-.44_{3}$ | $-.33_{8}$ | $.19_{8}$ | $-.30_{8}$ |
| NPI | $-.41_{8}$ | $-.16_{6}$ | $.08_{3}$ | $-.32_{8}$ | $-.01_{8}$ | $-.32_{8}$ |
| ENSO | $.83_{8}$*** | $.14_{6}$ | $.33_{3}$ | $.69_{8}$** | $-.03_{8}$ | $.45_{8}$ |
| PDO | $.67_{4}$ | $-.03_{4}$ | $.39_{3}$ | $.47_{4}$ | $-.08_{4}$ | $.33_{4}$ |
| SST | $.45_{6}$ | $-.33_{6}$ | $.30_{3}$ | $.74_{8}$*** | $-.66_{8}$** | $.56_{8}$* |
| SSS | $.57_{8}$* | $.88_{6}$*** | $-.34_{3}$ | $-.30_{7}$ | $.82_{7}$*** | $-.38_{7}$ |

Table 3. As in Table 2 for sea surface temperature and salinity anomalies at Race Rocks (SST and SSS, respectively) from 1951 to 2002.

| | Winter 1951–2002 | | Spring 1951–2002 | |
|---|---|---|---|---|
| | SST | SSS | SST | SSS |
| SST | 1 | | 1 | |
| SSS | $-.31_{28}$* | 1 | $-.28_{7}$ | 1 |
| STRM | $.25_{35}$ | $-.43_{28}$** | $-.31_{7}$ | $-.37_{30}$** |
| AIR | $.88_{35}$*** | $-.30_{28}$ | $.73_{7}$** | $-.31_{22}$ |
| UPWL | $-.55_{35}$*** | $.29_{28}$ | $-.20_{7}$ | $.41_{30}$** |
| NPI | $-.67_{35}$*** | $.13_{28}$ | $-.46_{7}$ | $.02_{30}$ |
| ENSO | $.57_{35}$*** | $-.15_{28}$ | $.43_{7}$ | $-.13_{30}$ |
| PDO | $.58_{16}$*** | $-.08_{16}$ | $.64_{7}$* | $-.02_{16}$ |
| | Summer 1951–2002 | | Fall 1951–2002 | |
| SST | 1 | | 1 | |
| SSS | $-.14_{6}$ | 1 | $-.23_{18}$ | 1 |
| STRM | $-.24_{6}$ | $-.49_{20}$** | $.19_{21}$ | $-.19_{18}$ |
| AIR | $.59_{6}$ | $<.01_{20}$ | $.75_{21}$*** | $<.01_{18}$ |
| UPWL | $.20_{6}$ | $.34_{19}$ | $-.31_{21}$ | $.10_{18}$ |
| NPI | $-.25_{6}$ | $-.20_{20}$ | $-.15_{21}$ | $-.04_{18}$ |
| ENSO | $.22_{6}$ | $.06_{20}$ | $.28_{21}$ | $-.14_{18}$ |
| PDO | $.50_{6}$ | $.26_{16}$ | $.20_{16}$ | $.06_{16}$ |

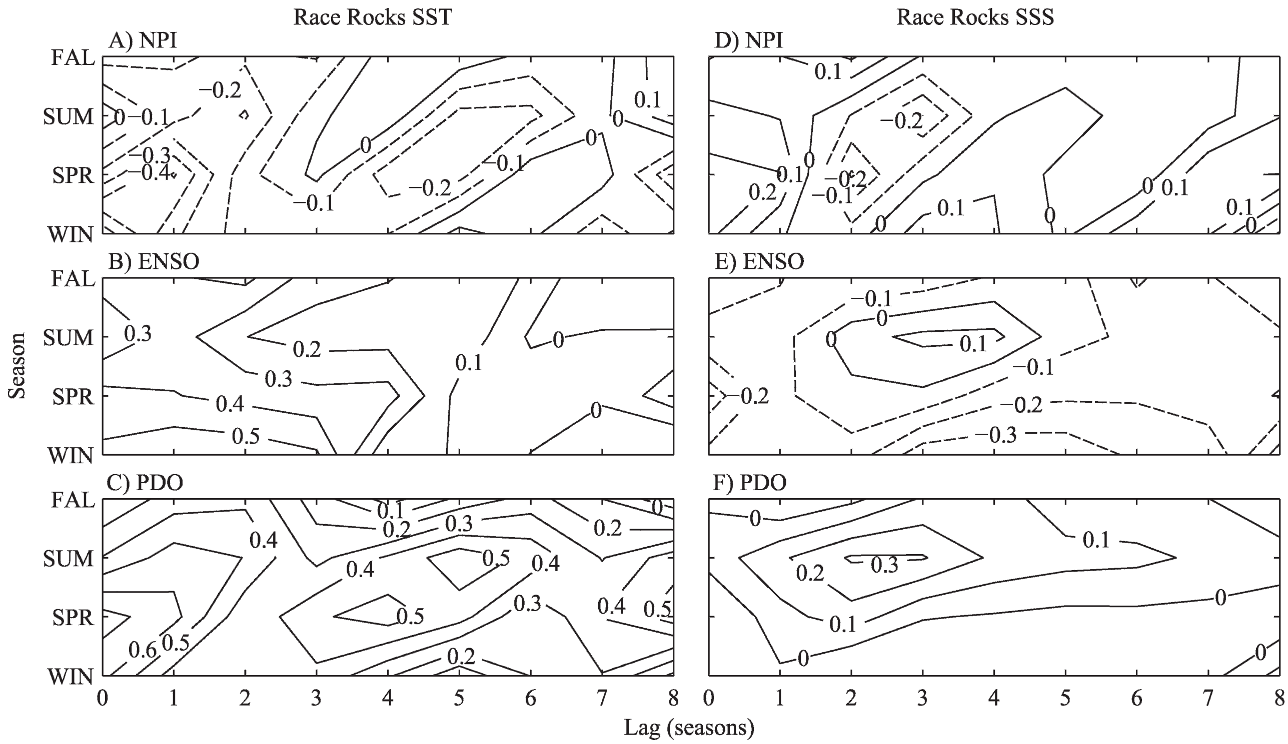

Fig. 7. Correlation coefficients for indices tracking the (A, D) Aleutian Low (NPI), (B, E) ENSO, and (C, F) PDO variations with Race Rocks sea surface temperature (A–C) and salinity anomalies (D–F) lagged at zero to eight seasons for the time period 1952–2002. Positive (negative) correlation coefficients are indicated by solid (dashed) contour lines.

For the Aleutian Low and PDO, correlations with SST are strongest in winter at zero lag, with a secondary signature at a lag of four to five seasons that suggests reemergence of subsurface temperature anomalies the following winter. Memory of winter water temperature anomalies could be provided by persistence in mixed layer properties. The winter climate strongly influences water temperatures via the local atmospheric heat flux. Deep mixing of the water column allows this climate imprint to reach subsurface waters where it can be capped by upper ocean stratification in spring and summer. This deep climate imprint can reemerge at the surface the following winter when deep mixing resumes.

Correlations of ENSO with SST are greatest at lags of zero to three seasons starting with the winter season. The persistence of ENSO-generated winter water temperature anomalies highlights the importance of oceanic teleconnections. Oceanic teleconnections of ENSO exist via the poleward propagation of coastally trapped internal waves along the eastern boundary of the Pacific. These waves take 20–30 d to reach the Pacific Northwest coast from the equatorial Pacific Ocean where they originate (Enfield and Allen 1980; Pares-Sierra and O'Brien 1989; Meyers et al. 1998). The coastally trapped waves displace the oceanic thermocline, creating temperature anomalies at the coast that take another 30–60 d to transit the Strait of Juan de Fuca and influence properties at Race Rocks (Thomson 1994).

An optimal time lag of 10 months was identified for ENSO influences on water temperatures in the Strait of Georgia (Masson and Cummins 2007). We find that SST at Race Rocks responds to ENSO-generated anomalies within the same season (i.e., <4 months). This discrepancy may be due in part to the increased distance that anomalous waters from the coastal ocean must travel to influence temperatures in the Strait of Georgia. The longer lag may also be a result of the index used to represent water temperatures in the Strait of Georgia, which was calculated using observations down to 400-m depth. Temperatures at these depths were found to vary at much lower frequency compared to the surface layer, which is influenced more directly by atmospheric forcing (Masson and Cummins 2007).

The translation of ENSO- and PDO-related changes into observable changes in oceanographic properties can be variable. For example, the mean difference in winter SST at Race Rocks during El Niño and La Niña conditions is similar to the standard deviations of the monthly means (0.61°C compared to 0.61°C and 0.53°C, respectively; Fig. 8A). The mean SST difference between El Niño and La Niña years during summer months is negligible at 0.04°C. A similar response in SST exists for PDO (Fig. 8B). This variable response to changes in the large-scale climate emphasizes the importance of the local climate-forcing parameters. As such, we caution against using large-scale climate indices to make statements about ocean conditions at Race Rocks and in Puget Sound.

*1997–1998 El Niño*—The 1997–1998 El Niño was particularly intense and produced warm temperature anomalies in the surface and deep layers of Puget Sound's

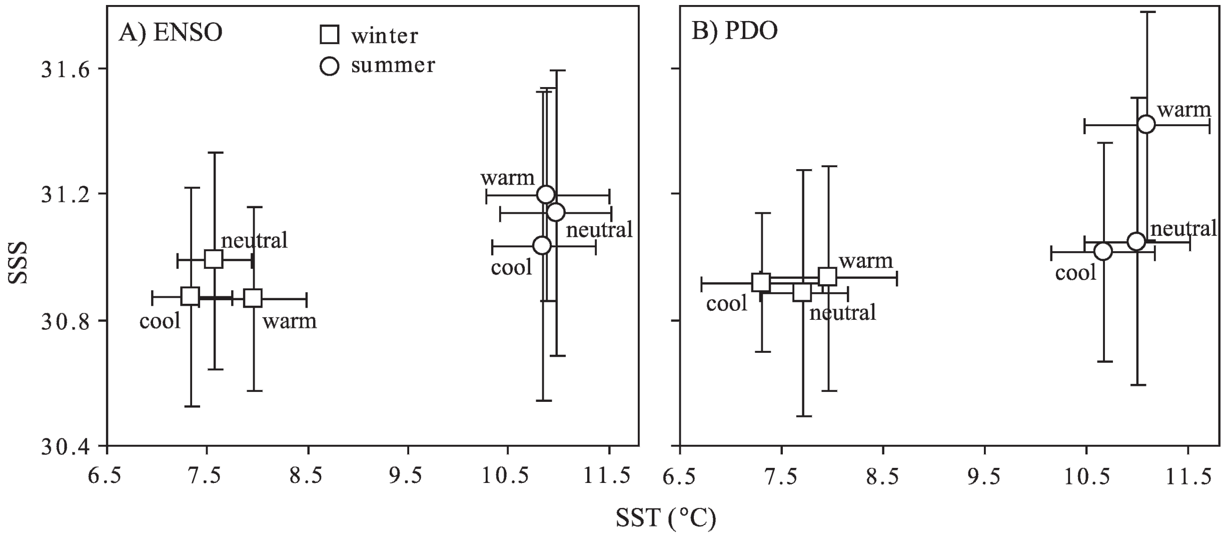

Fig. 8. Mean summer and winter sea surface temperature and salinity at Race Rocks during warm, neutral, and cool phases of the (A) El Niño-Southern Oscillation (ENSO) and (B) Pacific Decadal Oscillation (PDO) from 1937 to 2002.

basins that persisted for up to 8 months (Fig. 9). Mean unsmoothed temperature anomalies peaked at 1.66°C, 1.42°C, 1.62°C, 1.66°C, and 5.78°C above average in Admiralty Inlet and Central, Hood Canal, Whidbey, and North basins, respectively. The large response in North basin is due to a deep (i.e., 6.5-m) and especially warm surface layer at station GRG002 in September 1998. Extreme variability in oceanographic properties has previously been reported at this station and has been attributed to variation in the position of the Fraser River plume (Newton 1995). Excluding September 1998, temperature anomalies in North basin peaked at 2.53°C above average.

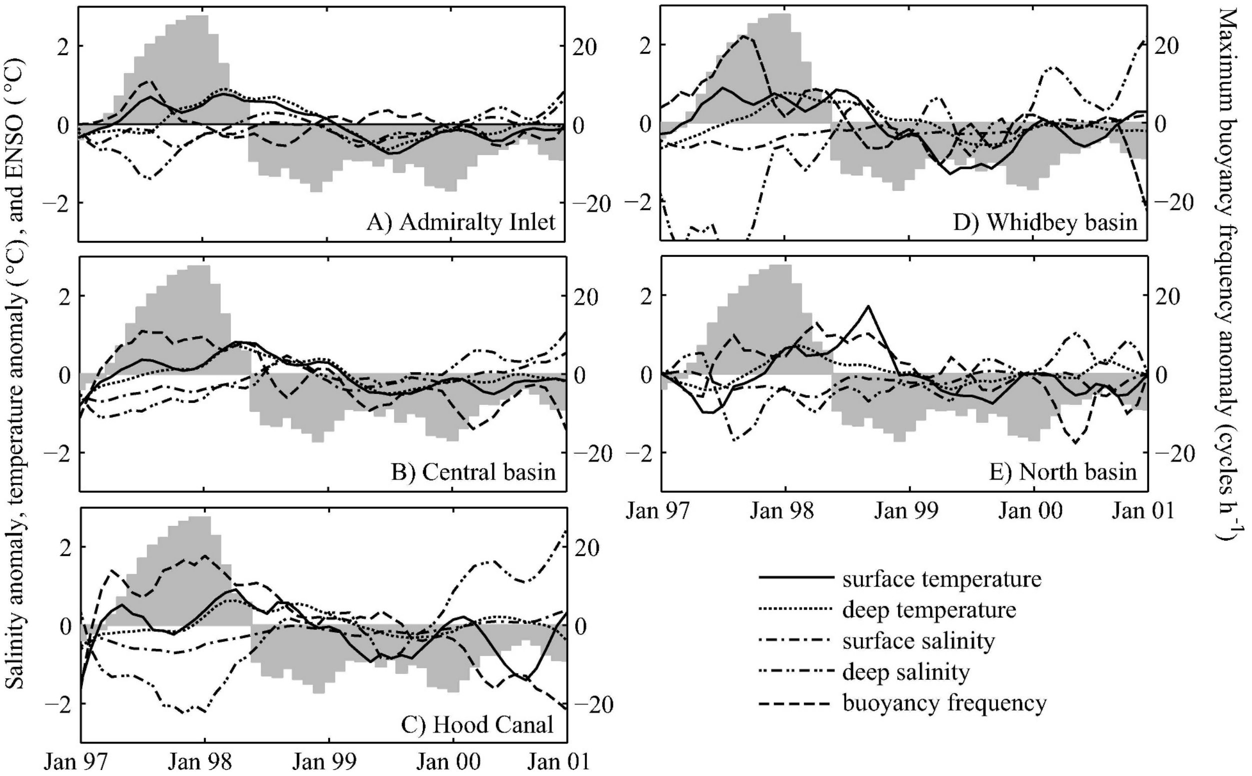

Fig. 9. Mean anomalies of temperature and salinity in surface and deep-water layers and the strength of the pycnocline at Marine Waters Monitoring Stations in (A) Admiralty Inlet and (B) Central, (C) Hood Canal, (D) Whidbey, and (E) North basins of Puget Sound from 1997 to 2000. Mean anomalies of oceanographic properties are smoothed with a 3-month moving average. The Niño3.4 index (ENSO) is shown for comparison.

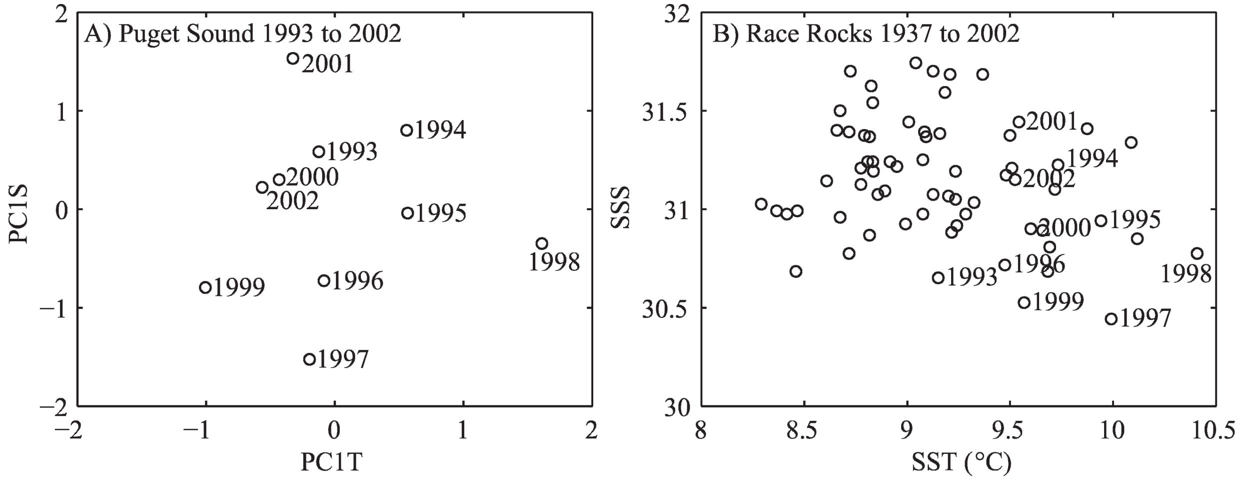

Fig. 10. Mean annual values of (A) the leading principal components of Puget Sound temperature (PC1T) and salinity (PC1S) from 1993 to 2002 and (B) sea surface temperature and salinity at Race Rocks from 1937 to 2002. Values representing the time period examined in this study from 1993 to 2002 are labeled in panel B.

The onset of warm water temperature anomalies in response to the 1997–1998 El Niño differed for Puget Sound's basins (Fig. 9). In Admiralty Inlet and Central and Whidbey basins, rapid warming without lag was observed in the surface layer, but the deep layer did not respond until approximately 4 months later. Warm water temperature anomalies in the surface and deep layers of Hood Canal and North basin lagged the ENSO index by approximately 7 months. The transition to cool water temperature anomalies in response to the 1998–1999 La Niña occurred simultaneously in both the surface and the deep layers in all basins.

Salinities in Puget Sound's basins varied independently from ENSO variations from 1997 to 2000, supporting the results of the correlation analyses and further highlighting the risk associated with generalizing local expressions of the large-scale climate. Drier conditions generally experienced during El Niño winters were expected to increase salinities, but instead stream flow was anomalously high in 1997, and this produced fresher surface layers and stronger stratification in Puget Sound (Fig. 9).

*Longer-term context of MWM history of oceanographic observation*—During the time period from 1993 to 2002, Puget Sound was generally fresher in 1997, warmer in 1998, cooler in 1999, and saltier in 2000 and 2001 (Fig. 10A). Using the Race Rocks records to place this 10-yr period in a longer-term context, we find that it was warmer and slightly fresher than most years dating back to 1937 (Fig. 10B). This should be considered when interpreting temporal patterns of variability in this study.

Indices representing variability in Puget Sound's oceanographic properties are significantly correlated with climate aspects on seasonal to interannual timescales. In general, local climate-forcing parameters are more strongly correlated with oceanographic properties compared to large-scale climate indices. Surface air temperature and streamflow anomalies are the primary forcing parameters that best explain variability in Puget Sound temperature and salinity, respectively. By bridging our analysis using longer-term records at Race Rocks, we determine that large-scale climate variations significantly influence water temperatures during winter but at levels substantially weaker than local climate-forcing parameters. Lag correlations of large-scale climate indices with SST at Race Rocks suggest a persistent and substantial response that typically lingers for up to three seasons (i.e., ENSO) or reemerges a year later (i.e., Aleutian Low and PDO).

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