Oceanographic Changes in Puget Sound and the Strait of Juan de Fuca during the 2000–01 Drought

Jan A. Newton[1,2], Eric Siegel[1] and Skip L. Albertson[1]

ABSTRACT

The recent 2000–2001 drought resulted in substantially reduced river flows that, in turn, markedly affected water properties, as shown by data collected by Washington State's *Puget Sound Ambient Monitoring Program* and the *Joint Effort to Monitor the Strait*. A 'densification' was apparent in the waters throughout Puget Sound, as indicated by a reduction in the density difference between the surface and bottom of the water column. The reduction in the stratification was due to higher salinity surface waters. This observation is notable because stratification regulates numerous biological and physical processes, including the timing of the spring phytoplankton blooms, mixing and flushing. Furthermore, we observed that changes in the density gradient in the Strait of Juan de Fuca led to a marked reduction in the geostrophic exchange velocity (linked to flushing) during the drought year as compared with the higher flow year of 2001–2002. This difference has implications for larval and plankton dispersal/retention and water quality.

RÉSUMÉ

La sécheresse récente de 2000–2001 s'est traduite par des débits fluviaux considérablement réduits qui, en retour, ont influé de façon marquée sur les propriétés de l'eau, comme le révèlent les données recueillies grâce à l'initiative conjointe de surveillance du détroit et grâce au Programme de surveillance du milieu ambiant de Puget Sound de l'État de Washington. Une densification était manifeste dans les eaux dans l'ensemble de la région de Puget Sound, comme l'indique la réduction dans l'écart de densité entre la surface et le fond de la colonne d'eau. La réduction de la stratification était attribuable à la salinité plus élevée des eaux de surface. Cette observation est importante du fait que la stratification régit de nombreux processus biologiques et physiques, y compris le moment du mélange, du lessivage et des efflorescences de phytoplancton au printemps. De plus, nous avons observé que les changements dans le gradient de densité dans le détroit de Juan de Fuca ont entraîné une réduction marquée de la vitesse géostrophique (liée au lessivage) au cours de l'année de sécheresse comparativement à l'année de débit plus élevé en 2001–2002. Cette différence a des retombées pour la dispersion/rétention des larves et du plancton et pour la qualité de l'eau.

---

[1] Washington State Department of Ecology, Olympia, WA

[2] University of Washington, School of Oceanography, Seattle, WA

INTRODUCTION

Variations in air temperature and precipitation have been documented corresponding with dominant phases of natural climate patterns, such as El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). In the U.S. Pacific Northwest, warmer, drier winter conditions are typically associated with El Niño and positive PDO phases, and there is some evidence for cooler, wetter conditions during La Niña and negative PDO (Ropelewski and Halpert, 1986; 1987; Mantua *et al.,* 1997; Hare and Mantua, 2000). Effects from anthropogenic climate change on local weather are only recently being simulated, but some models show alteration of freshwater inflow to estuaries by increased river flows during part of the year and earlier timing of peak flows, with reduced summer and fall flows (EPA, 1997; Hamlet and Lettenmaier, 1999; U.S. National Assessment, 2000; Boesch *et al.,* 2002). Less documented are studies of how these variations may affect marine water properties in the Puget Sound–Georgia Basin (Newton, 1995; Kawase, 2002) and, in turn, what effects on circulation, timing of phytoplankton blooms, and water quality might be anticipated. Lacking is a comprehensive and quantitative understanding of how variation in forcing by rivers, ocean, and local weather affect physical and biological processes, as well as their coupling, in the Puget Sound–Georgia Basin region.

Sustained long–term monitoring of water properties offers an invaluable tool for investigating and recognizing impacts from variations in climate. These databases, if long enough, can be harvested for studies on the correlation of water properties with climate modes. The Marine Waters Monitoring database for Washington State (implemented through the Washington State Department of Ecology and the Puget Sound Ambient Monitoring Program, PSAMP) has been used to address ENSO effects on marine water properties (Newton, 1995; Kawase, 2002). It is also possible to gain insight into atmospherically–driven water property variation by examining event–scale responses to extreme weather conditions. The 2000–2001 drought offers such an opportunity.

The 2000–2001 drought was the second worst in Washington State's recorded history, the driest since 1976–77, and one of five driest events in past 100 years (Hart *et al.,* 2001). The impact on regional river flow was substantial (Figure 1), reducing annual flows of Washington State rivers by 28–72% (Kimbrough *et al.,* 2002). We examine two datasets, one for the greater Puget Sound region and one in the Strait of Juan de Fuca, to investigate the variation of water properties during and following the drought in order to gain insight into how sensitive the region's marine waters are to variations in freshwater inflow. In this analysis, we focus on quantifying the effect of the drought on density–driven stratification throughout Puget Sound and on the density–driven geostrophic exchange velocity through the Strait of Juan de Fuca.

The intensity and persistence of the density stratification of a water column is a key factor with wide–ranging effects (Mann and Lazier, 1991), influencing physical processes such as mixing and circulation that in turn affect diverse biological and chemical processes such as when phytoplankton population growth is strong enough to accumulate as a bloom (Sverdrup's Critical Depth), whether gradients in water quality variables such as oxygen or nutrients will persist (leading to eutrophication

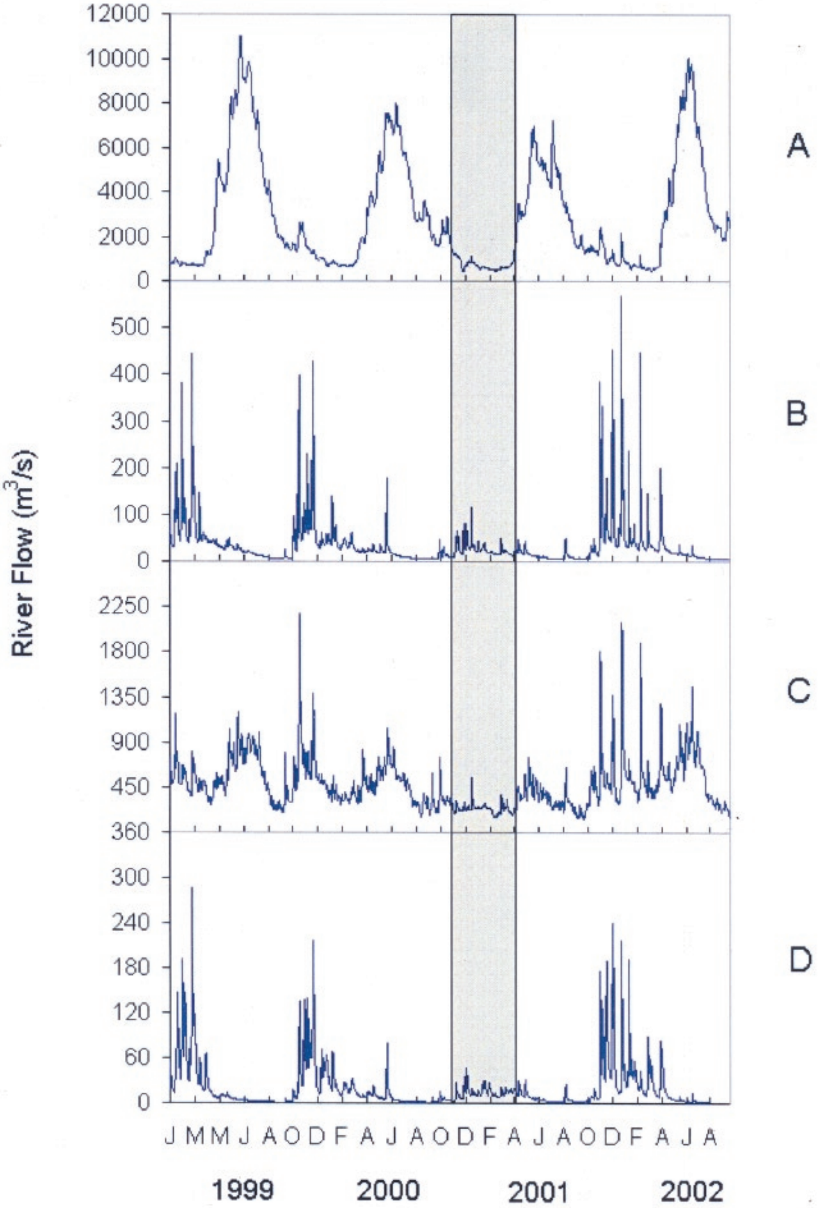

Figure 1. Flow for Three Major Rivers in the Puget Sound –Georgia Basin Area (A. Fraser River, B. Skohomish River, C. Skagit River) and One River on the Outer Washington Coast (D. Willapa River) Showing Reduced Flows Associated with the 2000–2001 Drought (Drought Most Intense November 2000 through April 2001, Shaded Portion). Data Source: USGS and Environment Canada Websites.

sensitivity), and how quickly pollutants will be flushed out or larvae retained. In Washington State marine waters, patterns in stratification persistence and intensity correlate with water quality patterns, affecting properties such as the occurrence of low oxygen concentrations, persistence of nutrient limitation, and prevalence of potentially anthropogenic–sourced constituents such as fecal coliform bacteria and ammonium (Newton *et al.,* 2002).

The Strait of Juan de Fuca is the primary conduit to the Puget Sound–Georgia Basin system from the Pacific Ocean. Flow through this strait typically reflects river–influenced outflow at the surface and ocean–influenced inflow at depth (Thomson, 1994). Thus, variation in water properties due to offshore oceanic variability (e.g., coastal ocean upwelling–downwelling, ENSO) or to watershed variability (e.g., river discharge, air temperature) will be evident.

METHODS

Two databases were utilized for this study: the Washington State Department of Ecology's long–term Marine Waters Monitoring (MWM) database, conducted monthly in conjunction with PSAMP at tens of stations throughout greater Puget Sound; and the Joint Effort to Monitor the Strait (JEMS) time–series from three stations in the Strait of Juan de Fuca, conducted monthly by Ecology through the Marine Ecosystem Health Program. Data access for both is at (http://www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html). Sampling and analytical methods for both programs are the same and are described in Newton *et al.* (2002). Sampling for Washington's MWM program started in 1973; however high quality *in situ* measurements of salinity, temperature, and other oceanographic variables are only available for fall 1989 onwards. Sampling for JEMS started in fall 1999.

We examined the MWM data from 17 stations in greater Puget Sound, as well as 11 stations from Willapa Bay and Grays Harbor on the outer coast of Washington State, where monthly data were available since 1990 (Figure 2). For each of these stations, we took the density data measured as sigma–t (Newton *et al.,* 2002) for the entire water column and calculated the delta sigma–t (maximum − minimum) as an index of stratification. Because water columns are generally stable (density increasing with depth), this is equivalent to the difference between density at the deepest depth minus the surface value. The change in stratification was then calculated as the mean delta sigma–t for the drought year October 2000–September 2001 minus the mean delta sigma–t for the 10–y period October 1991 to September 2001, relative to the 10–y mean delta sigma–t, and expressed as a percent.

We used the density gradient across the Strait of Juan de Fuca measured at the JEMS transect to calculate the geostrophic exchange velocity. The along–channel geostrophic velocity was calculated from the dynamic height or pressure gradient between JEMS Station 0 and Station 2 (Figure 2) for 18 transects, spanning 2 September 1999 to 25 March 2002.

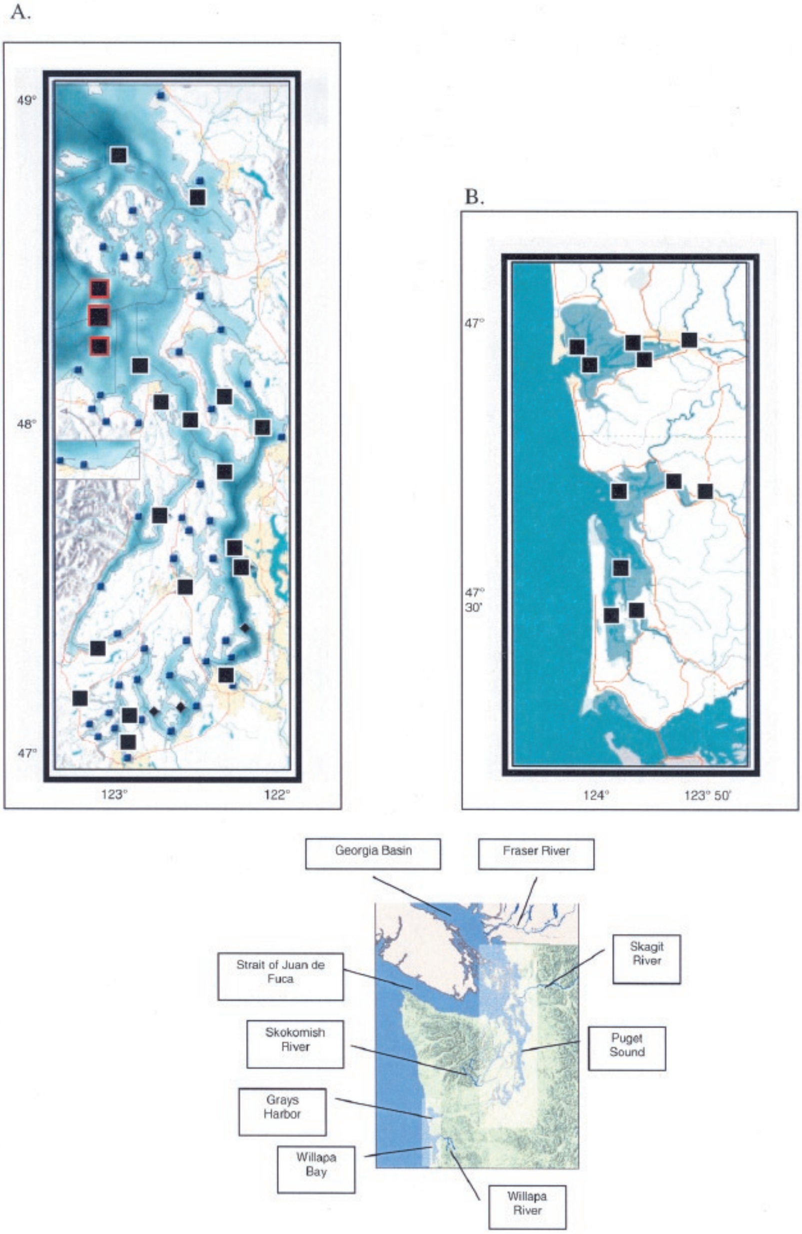

Figure 2. Station Locations for Water–Column Data Used in this Study from the A. Puget Sound–Georgia Basin, and B. Outer Washington Coastal Estuaries Grays Harbor (North) and Willapa Bay (South). MWM Stations Used for the Stratification Analysis are Shown by Black Squares. JEMS Stations Used for Geostrophic Velocity Analysis are Shown by Red–Outlined Black Squares. JEMS Station 0 is to the North, Station 1 Central, and Station 2 South.

The reference layer (depth of no motion) was taken to be 115 m which was the deepest depth common to both stations for all casts. The shallowest common depth was 2 m. The dynamic height was calculated from the reference layer (115 m) to the surface (2.0 m). The dynamic height gradient between Station 0 and Station 2 was used to calculate the balanced across–gradient, along–channel, geostrophic current via the geostrophic equation,

$$u = -\frac{1}{\rho_\circ}\frac{\partial p}{\partial y}\frac{1}{f} \tag{1}$$

where,

$\rho_\circ$ = average seawater density
p = pressure
y = horizontal distance northward
$f = 2\Omega \sin\phi$
$\Omega = 7.29e^{-5}$
ϕ = latitude

The average latitude is 48.3°N and the horizontal distance (dy) between stations is 18,520 m.

In this approach we solve for the classical absolute west–to–east velocity, u, by assuming that there is a deep level–of–no–motion and then calculating velocities at various levels above this. Geostrophy is assumed because the barotropic Rossby radius is on the order of the Strait of Juan de Fuca's width, so that Coriolis should be as important to the flow as the pressure gradient. Strictly speaking the predicted velocities should be tested against the continuity equation, and heat and salt conservation should be checked to see how important friction is to the flow; however we are primarily interested in comparing the relative changes between years. Geostrophic balance has been utilized landward of this location, in Puget Sound near Possession Sound (Chiodi and Eriksen, submitted). Aliasing effects on the data by tides is considered to be minimal, as a 24–h occupation at Station 0 with hourly hydrographic casts revealed a maximum density variation of only about 0.4 kg m^{-3} at a given pressure (M. Warner, UW, pers. comm.).

RESULTS

Water column density stratification strength varies both temporally and spatially in Puget Sound, but at all stations we observed a sharp reduction in stratification intensity during the 2000–2001 time period (Figure 3). To ascertain what was driving this reduction, an increase in the minimum density, a decrease in the maximum, or both, we plotted surface and bottom sigma–t, temperature and salinity. The overwhelming and consistent result was an increase in the surface sigma–t, or 'densification', that was driven by an increase in surface salinity, presumably in direct response to the reduced river flows during the drought period.

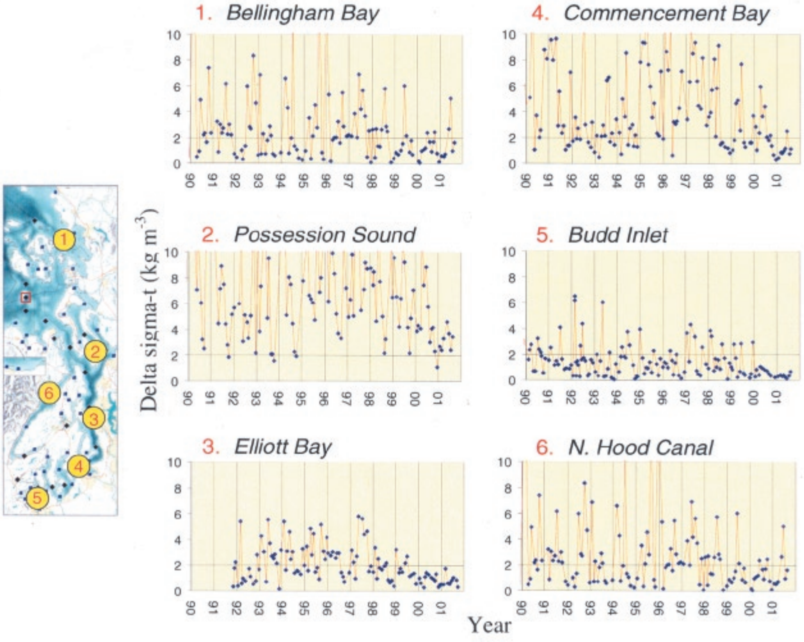

Figure 3. Water–Column Stratification Strength as Indicated by Delta Sigma–t (Maximum – Minimum) Versus Time for Selected MWM Stations in Puget Sound–Georgia Basin. A Line has been Drawn at 2 Sigma–t as a Reference.

The percent change in stratification varied throughout the Puget Sound region, ranging from no effect (~0%) in the well–mixed channels at Admiralty Inlet and Dana Passage to nearly 75% in Budd Inlet and Commencement Bay (Figure 4). The mean reduction in stratification at these stations was 56%. The values for the outer coastal estuaries were similar, with Grays Harbor averaging 52% (0–80% range) and Willapa Bay at 49% (20–60% range).

Water properties in the Strait of Juan de Fuca were consistent with the typically observed water flow (Thomson, 1994), with estuarine waters at the surface indicative of river–influenced outflow, and colder, saltier waters at depth suggesting ocean–influenced inflow. These two water masses can clearly be seen in the JEMS time–series, with the top 50–75 metres warmer and fresher than the deeper waters (Figure 5). Strong seasonal and interannual variation in water column temperature and salinity are also evident. Striking is the lack of low salinity surface water during the 2000–2001 fall–winter season. This signal appears to precede the official drought period (box in Figure 5); however, the Fraser River flow showed reduced flows throughout 2000 (Figure 1) and is the dominant river in the Georgia Basin–Puget Sound system.

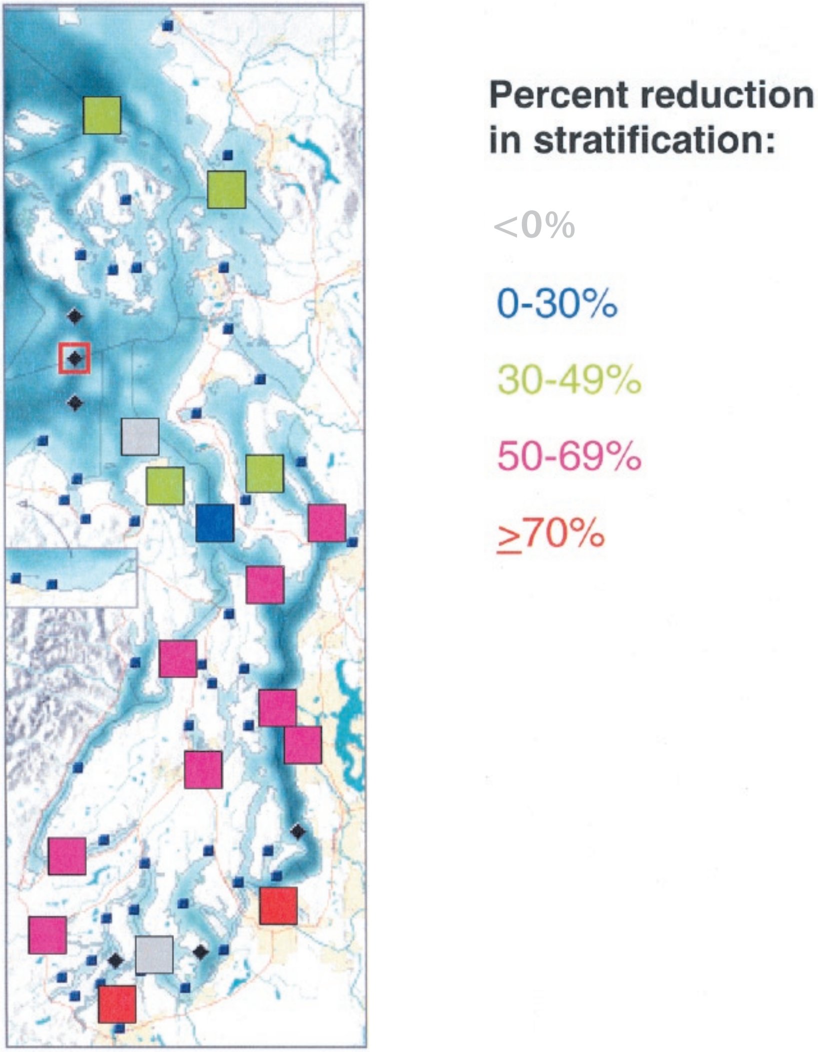

Figure 4. Percent Change in Stratification Intensity [(Oct 00–Sep 01 Mean Delta Sigma–t – 10–y Mean Delta Sigma–t)/10–y Mean Delta Sigma–t)] for Selected MWM Stations in the Puget Sound–Georgia Basin Area. The Mean Change for these Stations was a Reduction in Stratification of 56%.

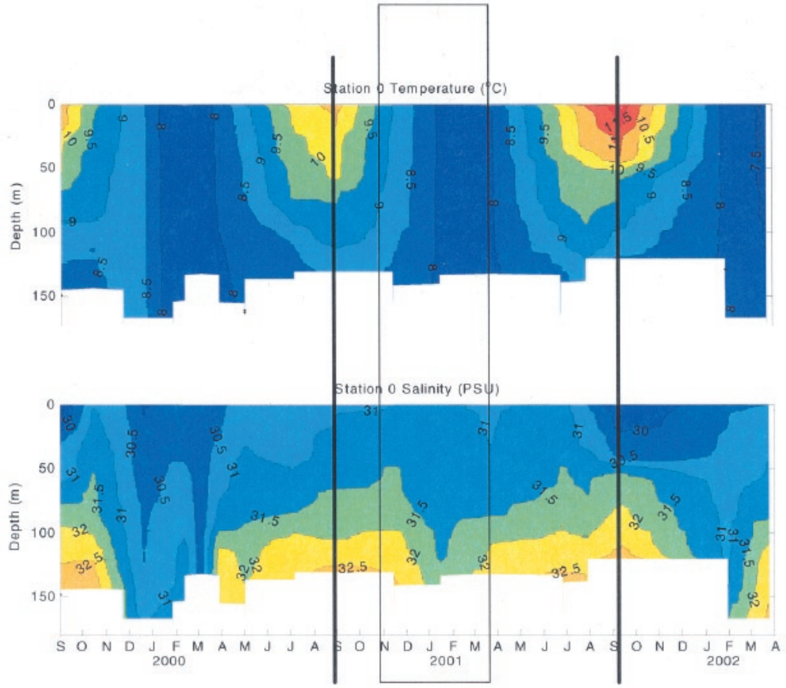

Figure 5. Time–Series Measurements of Temperature and Salinity Versus Depth Measured at the JEMS Monitoring Station 0 in the Strait of Juan de Fuca (Figure 2). The Drought Period is Indicated by the Box and Lines are Drawn to Aid Comparison of September 2000 with September 2001.

The effect of the higher salinity surface water can be seen vividly in comparison of the depth–resolved density gradient across the Strait (Figure 6). The pycnocline shows the expected tilt due to Coriolis forcing (Thomson, 1994) in all months but strong interannual differences associated with the drought period are evident. Comparing the data for September 2, 1999, August 31, 2000 and September 13, 2001 shows a substantially increased surface density in fall 2000 (sigma–t = 24) versus falls 1999 and 2001 (sigma–t = 22). This densification in the Strait of Juan de Fuca during fall 2000 is in agreement with the observations of reduced surface densities from the MWM data in Puget Sound and surrounding regions and occurs during the drought period.

One implication of the weaker density gradient in the Strait of Juan de Fuca is its effect on the along–channel geostrophic exchange velocity of water exiting the Strait. Results of this calculation are shown in Figure 7, where a four–fold difference is seen in the velocity between fall 2000 and fall 2001. This strong difference is resolved by more than one month, increasing our confidence in these calculations. We thus conclude that low river flows into Puget Sound–Georgia Basin lead to a weakened seawater density gradient throughout the estuary, resulting in a decreased outflow velocity through the Strait of Juan de Fuca, which increases the seawater residence time in Puget Sound–Georgia Basin.

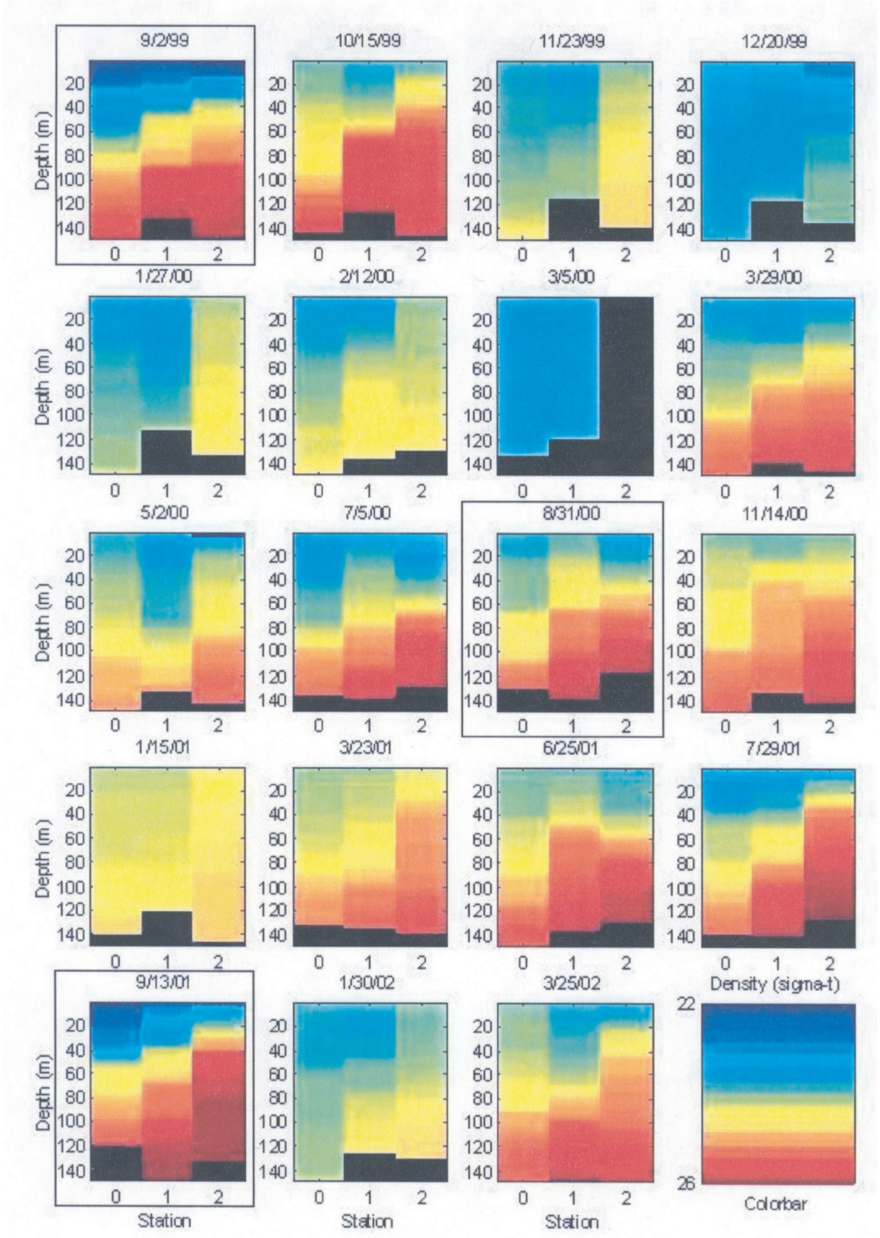

Figure 6. Time–Series of Sigma–t (kg m^{-3}) Versus Depth (m) at the Three JEMS Monitoring Stations across the Strait of Juan de Fuca. Squares Highlight that a Strong Density Gradient was Found in the Fall of Both 1999 and 2001 that was Much Weaker in Fall 2000, When the Drought was Evident. Black Denotes No Data.

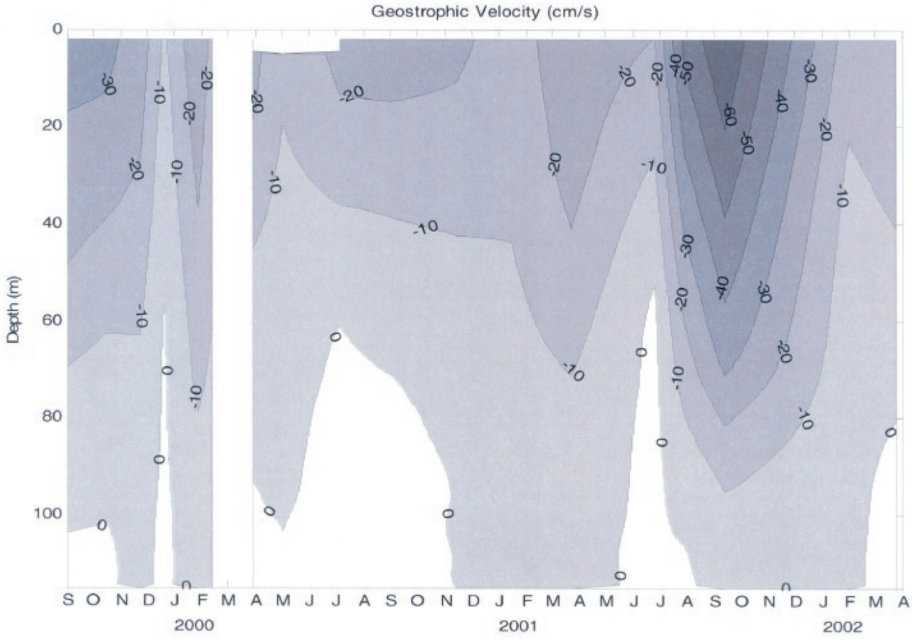

Figure 7. Depth–Resolved Geostrophic Exchange Velocity (cm s^{-1}) Through the JEMS Transect at the Eastern End of the Strait of Juan de Fuca Versus Time.

DISCUSSION

While reduced river input to Puget Sound–Georgia Basin could be hypothesized *a priori* to increase salinity of the receiving marine waters, this analysis has shown that marine water properties are affected by such weather–related forcing on a substantial scale. Our analysis of long–term monitoring data demonstrated that the 2000–2001 drought period and its associated increase of estuarine salinity lead to higher density surface layers and weaker stratification, with a percent reduction in stratification averaging ~50% for Puget Sound–Georgia Basin and the outer Washington coast estuaries. Furthermore, a result of the higher salinity surface waters and weaker vertical density gradient is a decreased outflow velocity through the Strait of Juan de Fuca. This analysis has shown that the flow was affected by a factor of four between drought and normal flow years; the reduced seaward flow presumably translates to longer residence times in the estuary.

Implications of these results could be substantial to ecosystem–level processes. First, marine water quality conditions, such as low dissolved oxygen concentrations, that are maintained by density stratification, could be affected. A reduction in stratification could lead to less probability of low oxygen because of increased mixing (less of a seawater density gradient to overcome). Alternatively, the reduced exchange velocity and an increased water residence time in the estuary could lead to lower oxygen concentrations because of increased time when respiration dominates before exiting the system. Which process dominates is not known for Puget Sound–Georgia Basin but could vary regionally. As opposed to salinity, there are many other factors affecting seawater oxygen concentrations (light and nutrient availability, phytoplankton biomass, river and ocean oxygen conditions, timing and magnitude of ocean intrusions, etc.) and these were not comprehensively investigated for this time–period, partially due to lack of measurement resolution for key variables.

The timing of phytoplankton blooms is also known to be influenced by the depth of the mixed layer relative to where net community photosynthesis is positive. Whether the reduction in stratification during the drought led to changes in bloom timing or intensity cannot be investigated from this monthly–resolved data set. Implications for match or mis–match of phytoplankton blooms with zooplankton and other heterotrophs' emergence could influence biota recruitment success and trophic transfer (Cushing, 1990; Cushing and Horwood, 1994).

Lastly, the fourfold variation in exchange velocity through the Strait of Juan de Fuca potentially has strong implications for the transport or retention of planktonic larvae and ichthyoplankton of valued species (e.g., rockfish, herring, salmon, crab, (Dinnel *et al.*, 1993)) and other planktonic species (especially non–indigenous species or harmful algal species imported from the ocean (Cordell and Morrison, 1996; Trainer *et al.*, 2002)), as well as the flushing time for contaminants or pollutants.

Because marine water properties and flow can be significantly altered by climate–related forcing it is recommended that more effort should be given to quantitative assessments of physical, chemical and biological processes and their linkages in the context of understanding environmental health and natural resource protection.

ACKNOWLEDGEMENTS

Numerous technicians, pilots, boat operators and other staff made the data used in this analysis possible. Notable among these are David Duggins and Alana Hysert of the Friday Harbor Laboratories; Jessica Archer, Julia Bos, Rick Reynolds and Kara Van Voorhis of the Washington Department of Ecology; Kenmore Air, and the University of Washington's Puget Sound Regional Synthesis (PRISM) program. The authors wish to thank Drs. Mitsuhiro Kawase, Mark Warner, Glenn Cannon, Philip Mote and Nate Mantua of the University of Washington for advice and discussions on the application and analysis presented here. JEMS was supported by a grant from the Marine Ecosystem Health Program and the Washington Department of Ecology MWM program is part of the Puget Sound Ambient Monitoring Program.

REFERENCES

Boesch, D.F., J.C. Field and D. Scavia. 2002. *The Potential Consequences of Climate Variability and Change on Coastal Areas and Marine Resources*. NOAA Coastal Ocean Program Decision Analysis Series Number 21. NOAA, Silver Spring, MD.

Chiodi, A.M. and C.C. Eriksen. (Submitted). “Geopstrophic Fjord Exchange Flow Observed with Seaglider Autonomous Vehicles.” *Journal of Physical Oceanography.*

Cordell, J.R. and S.M. Morrison. 1996. “The Invasive Asian Copepod *Pseudodiaptomus inopinus* in Oregon, Washington, and British Columbia Estuaries.” *Estuaries,* 19(3): 629–638.

Cushing, D.H. 1990. “Plankton Production and Year Class Strength in Fish Populations: An Update of the Match/Mis–match Hypothesis.” *Advances in Marine Biology,* 26: 249–294.

Cushing, D.H. and J.W. Horwood. 1994. “The Growth and Death of Fish Larvae.” *Journal of Plankton Research,* 16: 291–300.

Dinnel, P.A., D.A. Armstrong and R.O. McMillan. 1993. “Evidence for Multiple Recruitment–Cohorts of Puget Sound Dungeness Crab, *Cancer magister.*” *Marine Biology,* 115(1): 53–63.

EPA. 1997. *Climate Change and Washington.* EPA 230–F–97–008uu. Office of Policy, Planning, and Evaluation, Washington, DC.

Hamlet, A.F. and D.P. Lettenmaier. 1999. “Effects of Climate Change on Hydrology and Water Resources in the Columbia River Basin.” *American Water Resources Association,* 35(6): 1597–1623.

Hare, S.R. and N.J. Mantua. 2000. “Empirical Evidence for North Pacific Regime Shifts in 1977 and 1989.” *Progress Oceanography,* 47: 103–146.

Hart, C., D. McChesney and J. Stohr. 2001. *2001 Drought Response: Report to the Legislature.* Washington State Department of Ecology, Water Resources Program, Publication #01–11–017, Olympia, WA.

Kawase, M. 2002. “Seasonal Cycle of Deep Water Properties in Puget Sound, Their Interannual Variability and Sensitivity to Climatic Factors.” *In:* Puget Sound Water Quality Action Team, 2002. *Proceedings of the 2001 Puget Sound Research Conference.* T. Droscher, Editor. Puget Sound Water Quality Action Team. Olympia, WA.

Kimbrough, R.A., G.P. Ruppert, W.D. Wiggins, R.R. Smith, S.M. Knowles and V.F. Renslow. 2002. *Water Resources Data, Washington, Water Year 2001.* U.S. Geological Survey Water–Data Report WA–01–1.

Mann, K.H. and J.R.N. Lazier. 1991. *Dynamics of Marine Ecosystems.* Blackwell Scientific Publications, Boston, MA.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace and R.C. Francis. 1997. "A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production." *Bulletin of the American Meteorology Society,* 78: 1069–1079.

Newton, J.A. 1995. "Observations of El Niño Weather Conditions Reflected in the Temperatures and Salinities of Monitoring Stations in Puget Sound." *In: Puget Sound Research '95 Proceedings.* Puget Sound Water Quality Authority, Olympia, WA: 979–991.

Newton, J.A., S.L. Albertson, K. Van Voorhis, C. Maloy and E. Siegel. 2002. *Washington State Marine Water Quality in 1998 through 2000.* Washington State Department of Ecology, Environmental Assessment Program, Publication #02–03–056, Olympia, Washington, USA.

Ropelewski, C.F. and M.S. Halpert. 1986. "Global and Regional Scale Precipitation Patterns Associated with El Niño–Southern Oscillation (ENSO)." *Monthly Weather Review,* 114: 2352–2362.

Ropelewski, C.F. and M.S. Halpert. 1987. "North American Precipitation Patterns Associated with El Niño–Southern Oscillation (ENSO)." *Monthly Weather Review,* 115: 1606–1626.

Thomson, R.E. 1994. "Physical Oceanography of the Strait of Georgia–Puget Sound–Juan de Fuca Strait System." *Canadian Technical Report Fisheries and Aquatic Science,* 1948: 36–98.

Trainer, V.L., B.M. Hickey and R.A. Horner. 2002. "Biological and Physical Dynamics of Domoic Acid Production Off the Washington U.S.A. Coast." *Limnology and Oceanography,* 47: 1438–1446.

U.S. National Assessment. 2000. *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change.* Cambridge University Press, Cambridge, UK.