Seasonal Water Mass Analysis for the Straits of Juan de Fuca and Georgia

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[Original manuscript submitted 7 September 2004; in revised form 6 January 2005]

ABSTRACT *A quantitative analysis of water masses in the coastal waters of southern British Columbia is performed with the Optimum Multiparameter (OMP) analysis method that optimizes the use of a hydrographic dataset by solving an over-determined linear set of mixing equations. The method is applied to a seasonal dataset collected over five years in the Strait of Georgia, a large semi-enclosed coastal basin, as well as in Juan de Fuca Strait, its main connection to the Pacific Ocean. Abundant freshwater discharge into the coastal basin forces an estuarine exchange with oceanic shelf water. Six water characteristics of five source water types are used to obtain mixing proportions over the estuary for each of the four seasons. The model results are found to corroborate known aspects of the local dynamics such as the presence of a deep shelf inflow into Juan de Fuca Strait and of the Columbia River plume in winter at the mouth of the strait. The analysis also quantifies lesser known features of the region, such as the characteristics of the mid-depth intrusions within the Strait of Georgia and the marked effect of remineralization on nutrient distributions in the deep water of the coastal basin.*

RESUMÉ *[Traduit par la rédaction] On effectue une analyse quantitative des masses d'eau dans la zone maritime littorale du sud de la Colombie-Britannique par la méthode de l'analyse multiparamétrique optimale (AMO) qui optimise l'utilisation d'un ensemble de données hydrographiques en résolvant un ensemble linéaire surdéterminé d'équations de mélange. La méthode est appliquée à un ensemble de données saisonnières recueillies sur une période de cinq ans dans le détroit de Georgie, un vaste bassin côtier semi-fermé, ainsi que dans le détroit de Juan de Fuca, son lien principal avec le Pacifique. L'arrivée d'une grande quantité d'eau douce dans le bassin côtier force un échange estuarien avec l'eau océanique de la plate-forme. On utilise six caractéristiques hydriques de cinq types d'eau sources pour obtenir les proportions de mélange dans l'estuaire pour chacune des quatre saisons. On trouve que les résultats du modèle s'accordent avec les caractéristiques connues de la dynamique locale, comme la présence d'un courant profond entrant dans le détroit de Juan de Fuca depuis la plate-forme et la présence du panache du fleuve Columbia en hiver à l'embouchure du détroit. L'analyse quantifie aussi des aspects moins connus de la région, comme les caractéristiques des intrusions à profondeur moyenne dans le détroit de Georgie et les effets prononcés de reminéralisation sur la distribution des nutriants dans les eaux profondes du bassin côtier.*

1 Introduction

The Straits of Georgia and Juan de Fuca are the two main bodies of water separating Vancouver Island and the mainland of the southern coast of British Columbia (Fig. 1). The Strait of Georgia is a semi-enclosed coastal basin that extends about 220 km along the coast, with water depths up to 420 m within its central deep basin. Its main connection with the open ocean is through Juan de Fuca Strait to the south, which is also the outlet for the Puget Sound Basin. Narrow channels between a series of small islands, as well as shallow sills, constrict the flow between the two straits, with most of the water flowing through the deeper western channel comprised of Boundary Pass and Haro Strait. To the west, Juan de Fuca Strait opens up into a more regular channel-like basin of about 20-km width, reaching water depths of 250 m at its mouth. At its northern end, the Strait of Georgia is connected to the open ocean through constricted and shallow channels, with cross-sectional areas much smaller (7%) than those of the southern route (e.g., Waldichuk, 1957).

The three coastal basins form a large estuary in which a complex circulation is shaped by the basin morphology, a large and variable freshwater runoff, strong tidal currents and orographically steered coastal winds. Early descriptions of the physical oceanography of the Strait of Georgia and Juan de Fuca Strait were given by Waldichuk (1957) and Herlinveaux and Tully

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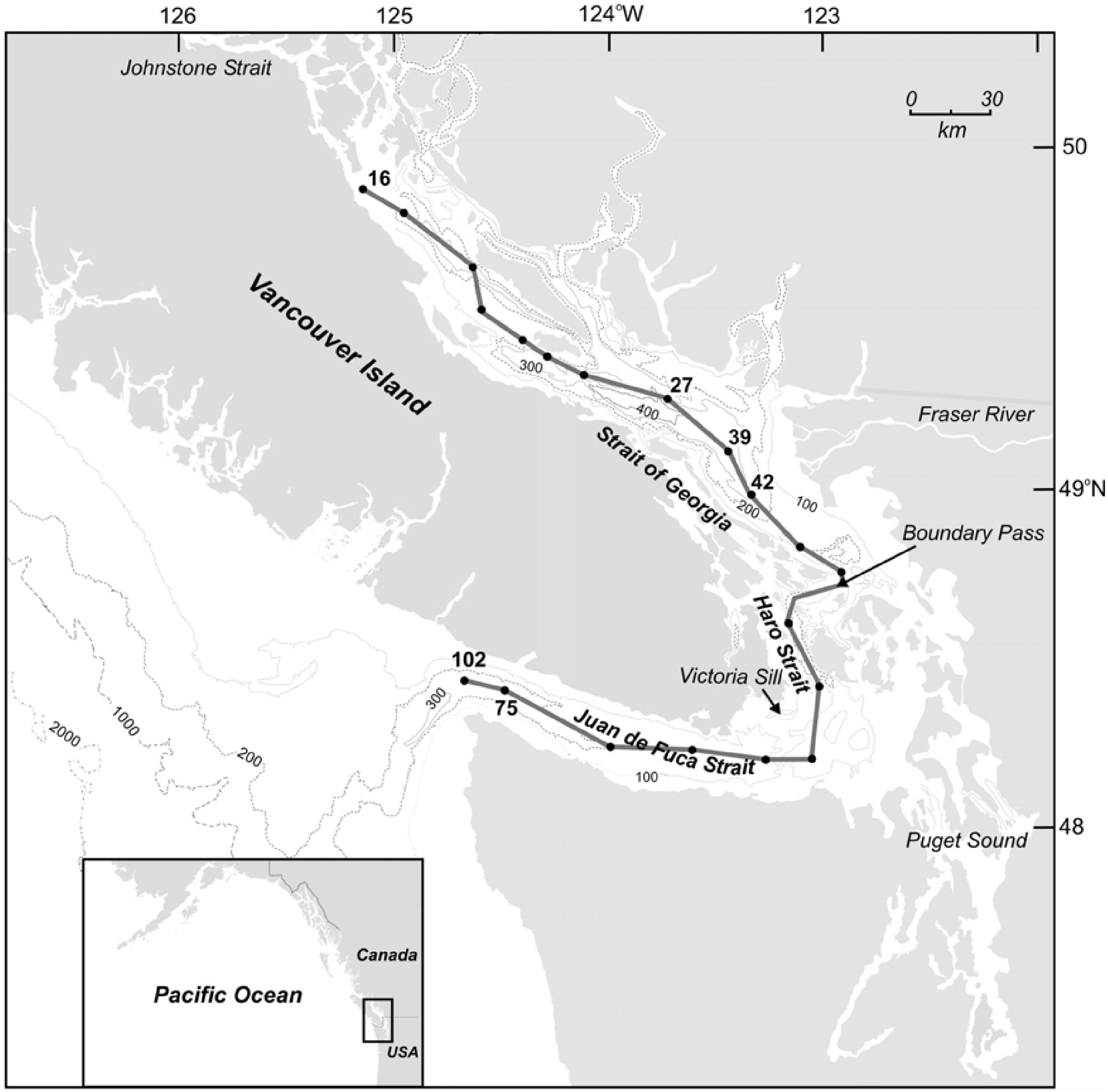

Fig.1 Study area and locations of the sampling station (small circles). The shaded line indicates the position of the along-strait section.

(1961), respectively. Later reviews of the region have been completed by Thomson (1981) and LeBlond (1983).

Rivers and small creeks discharge a significant amount of fresh water into these basins. The most important source of fresh water is the Fraser River. It has pronounced seasonal flow variations with low winter discharge rates and much larger flow during spring freshet (Fig. 2). Tides in the area are mixed, mainly semidiurnal, and strong tidal currents are found in the constricted and shallow passages, producing significant mixing of the water column.

During winter months, strong south-easterly winds predominate while during summer weaker north-westerly winds are common. Associated with the seasonal change in dominant wind direction is a transition from downwelling (winter) to upwelling (summer) conditions over the continental shelf (e.g., Thomson, 1981). As a consequence, the deep estuarine return flow is colder and saltier (denser) during summer. These changes in both freshwater runoff and atmospheric forcing significantly modulate the estuarine circulation of the coastal basin on the seasonal timescale.

In this paper, the Optimum Multiparameter (OMP) analysis is used to estimate the mixture of source water types that best describes the composition of the local water masses. The method has been previously applied to various oceanic regions such as the continental margin off Vancouver Island (Mackas et al., 1987), and the thermocline in the Indian

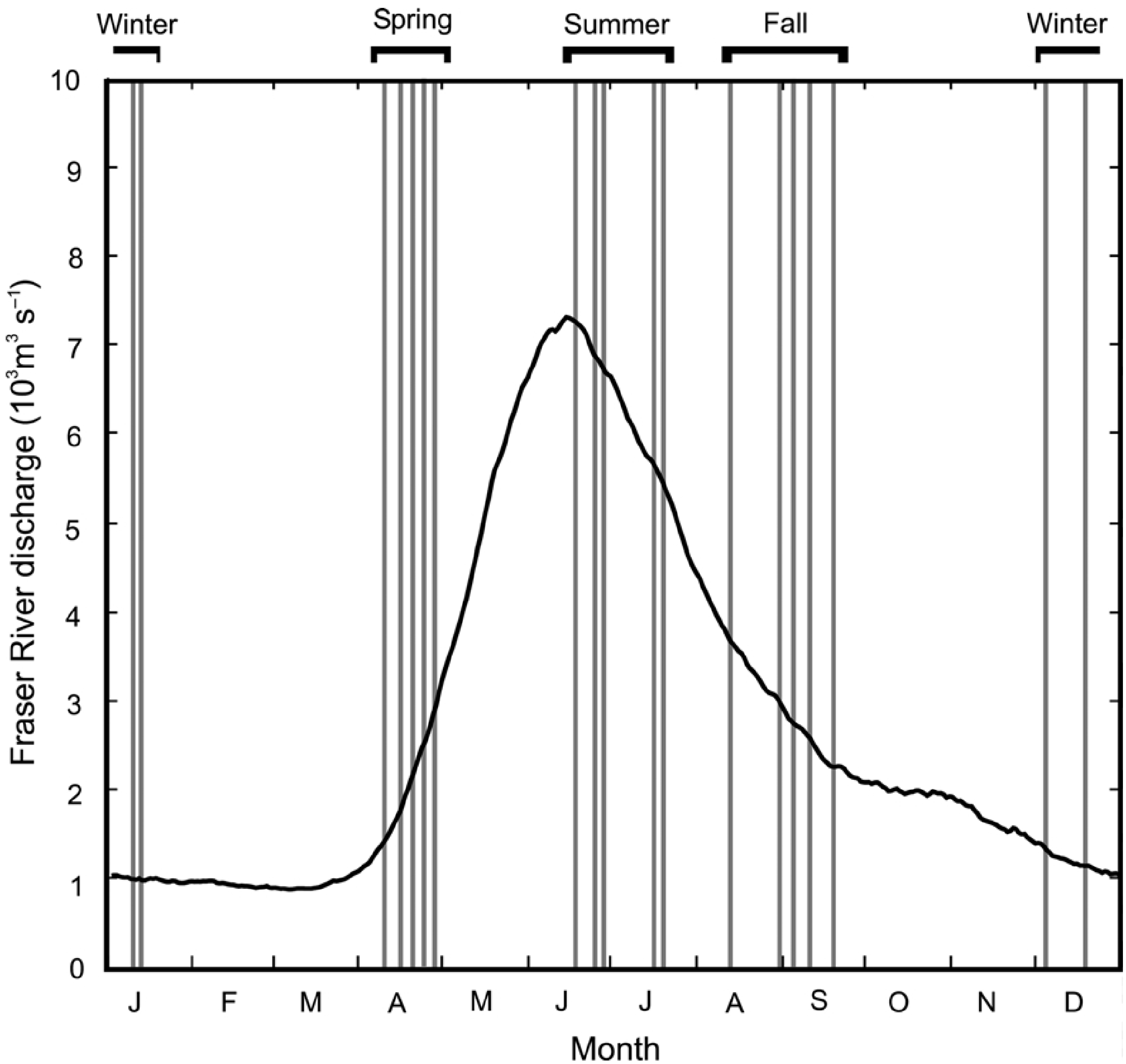

Fig. 2 Mean daily Fraser river discharge measured at Hope, BC, (130 km upstream) and timing of sampling surveys. The mean discharge values were computed over the period 1912–2003.

Ocean (You and Tomczak, 1993). The analysis is performed on a seasonal basis to examine changes in water mass composition during the year. A similar seasonal water mass study for the western South Atlantic Ocean was conducted by Maamaatuaiahutapu et al. (1994) and for the thermocline in the Indian Ocean by You (1997).

In the next section, the dataset used in the analysis is described. A brief description of the method is given in Section 3. The results are described in Section 4, followed by some concluding remarks.

2 Data

In 1999, a field program was established to sample the estuary a few times each year in an attempt to gain a better understanding of the regional circulation and of its seasonal variability. During each survey, CTD profiles and water samples were collected at twenty stations lying along the main axis of the estuary extending from the mouth of Juan de Fuca Strait up to the northern end of the Strait of Georgia (Fig. 1). In addition to temperature and salinity, nutrient salts (nitrate, phosphate and silicate) as well as dissolved oxygen were measured at these stations, near the surface and bottom as well as at depths of 5, 10, 20, 30, 40, 50, 75, 100, 125, 150, 175, 200, 250, 300, 350, and 400 m.

A total of nineteen surveys were conducted over the five-year period from 1999–2003 (Fig. 2). Sampling was carried out seasonally during periods of: (1) early freshet (April), (2) peak freshet (June/July), (3) end of freshet period

(August/September), and (4) low winter discharge (January/December). For the analysis, the dataset has been synoptically divided according to these four seasons (referred to as spring, summer, fall, and winter) and the water mass analysis applied to the resulting four datasets.

3 Method

A linear inverse mixing model, the OMP analysis, is applied to hydrographic, nutrient, and dissolved oxygen data measured seasonally in southern British Columbia (BC) coastal waters. At the location of each data point, and for each season, the model estimates the mixing fractions of predefined source water types. For each data point, the contributions from all water sources are obtained by finding the optimal linear mixing combination in the six-parameter space defined by temperature, salinity, oxygen and nutrients which minimizes the residuals in a non-negative least squares sense. The mass conservation condition adds an additional mixing constraint to the minimization problem.

The problem can be expressed mathematically as the minimization of

$$D^2 = (Ax - b)^T W^{-1} (Ax - b), \tag{1}$$

where A is a matrix containing the tracer values of the source water types, b is a vector containing the observed parameter values for a given sample, x is a vector containing the mixing fractions, and D is a vector containing the residuals. The matrix W contains the weights ascribed to the various parameters to reflect differences in measurement accuracy and environmental variability. In addition, the solution involves two constraints: all source contributions are to be positive,

$$x_i \geq 0, \tag{2}$$

and the fractional contributions from all sources must add up to near unity,

$$\sum x_i = 1 + \varepsilon, \quad \varepsilon << 1. \tag{3}$$

Before solving the optimization problem, both elements of the matrix A and the vector b in Eq. (1) are normalized to make parameters of incommensurable units comparable, as in

$$A'_{ij} = \frac{\left(A_{ij} - A_j\right)}{\sigma_j}, \text{and } b'_j = \frac{\left(b_j - A_j\right)}{\sigma_j}. \tag{4}$$

Here, A_j is the seasonal mean of parameter j for all source water types i, and σ_j the associated standard deviation.

The elements of the weight matrix, W, can de determined by various procedures. Mackas et al. (1987) obtained their weights from the sum of the sample error estimates plus the covariances between tracers of the source water types. Tomczak and Large (1989) used a diagonal weight matrix based on the parameter variability in the source regions. Here, we follow closely the latter, and compute

$$W_j = \frac{\sigma_j^2}{\delta_j}, \tag{5}$$

where σ_j measures the ability of parameter j to resolve differences between water sources and δ_j is the mean of the water type variances for parameter j. The constrained optimization problem is solved by the Generalized Reduced Gradient Method (e.g., Lasdon et al., 1978). Finally, the model results obtained at each measurement point are then interpolated and contoured on the along-strait section of Fig. 1.

4 Results

a *Mean Tracer Distributions*

As for most temperate estuaries, the local water density is mainly controlled by salinity, with temperature acting largely as a passive tracer. The seasonal cycle of salinity in the study area has been recently described and modelled by Masson and Cummins (2004) using data from the same seasonal surveys. Water properties of the coastal basin have been studied in various investigations, such as the early work of Waldichuk (1957), and reviewed by LeBlond (1983). Some aspects of the nutrient cycles and distributions within the estuary have been described by, among others, Tully and Dodimead (1957), Lewis (1978), and Harrison et al. (1991). However, because the present dataset is quite extensive, covering the entire coastal basin over five years, it allows for a description of unprecedented detail of the local climatology for the various water properties.

The five-year mean distributions along the main axis (shaded line in Fig. 1) of the estuary for each of the tracers (temperature, nitrate, phosphate, silicate, and dissolved oxygen) are presented in Fig. 3. The figure also shows density contours, which are indistinguishable from salinity contours, to help delineate known features of the local dynamics. The estuarine circulation draws a mass of dense, cold, nutrient-rich water with low dissolved oxygen at depth into Juan de Fuca Strait from the continental shelf (e.g., Mackas et al., 1987). The mean distribution also shows a fresh and relatively warm surface river plume extending over most of the surface of the Strait of Georgia, with reduced nutrient and high oxygen concentrations associated with high primary production (e.g., Harrison et al., 1991). At both ends of the Strait of Georgia, strong tidal currents are quite effective in mixing the water column and in reducing the local stratification (e.g., Parsons et al., 1981). The deep water mass in the Strait of Georgia, with high nutrient and low oxygen concentrations (e.g., Tully and Dodimead, 1957), is partially isolated from the active estuarine dynamics by the presence of shallow sills. Vigorous mixing in these shallow areas controls water exchange within the estuary and tends to favour recirculation of mixed water in the inner deep strait, limiting direct access of higher salinity shelf water. Hence, vertical gradients of density and temperature in the deep strait are relatively weak.

TABLE 1 Property values for each of the source water types for the four seasons given clockwise from the top left corner as spring, summer, fall, winter.

Source water type	Temp (°C)		Salinity		Oxygen (mL/L)		Nitrate (µM)		Phosphate (µM)		Silicate (µM)	
SW_1: river	9.1	12.5	27.3	25.1	7.5	6.1	10.1	11.1	1.1	1.2	25.0	33.3
	8.1	13.9	27.5	26.2	6.1	6.0	26.3	6.8	2.3	0.9	53.5	30.0
SW_2: deep south	6.8	6.4	33.9	33.9	2.1	1.8	33.4	35.5	2.6	2.7	51.5	57.3
	8.0	6.8	33.2	33.9	3.1	1.6	28.1	34.8	2.4	2.7	43.3	56.1
SW_3: pre-season	9.4	9.1	31.2	31.0	2.9	3.0	28.8	29.4	2.8	2.8	58.1	61.4
	9.2	8.9	31.1	30.9	3.2	3.5	28.4	28.1	2.6	2.6	54.0	56.1
SW_4: surface south	9.7		30.3		6.5		7.3		1.0		17.8	
SW_5 : deep north	8.9	8.7	30.4	30.5	3.9	3.7	28.4	29.2	2.6	2.7	56.8	59.8
	9.0	9.4	30.3	30.3	3.7	3.5	28.4	26.0	2.6	2.6	56.2	54.8

In addition to highlighting known characteristics of the estuary, Fig. 3 also reveals interesting features that have received little attention in the past. For example, the estuarine return flow entering the Strait of Georgia from the south may be discerned as a tongue of relatively low dissolved nutrient and high oxygen concentrations around sill depth. These subsurface intrusions form in the southern strait where vigorous tidal currents flowing through a maze of narrow passages cause partial recirculation of the fresh surface outflow. In the five-year mean fields, the mid-water intrusions are centred at 100-m depth, along the 23.5 density contour, and extend northward across most of the Strait of Georgia (Figs 3b–3e). The water properties of these intrusions do vary during the year (e.g., Masson, 2002) and this aspect of the circulation will be examined more closely in the next section.

Few datasets have been published on phosphate and silicate concentrations in the deep Strait of Georgia. In an early study, Tully and Dodimead (1957) examined samples taken in the upper 150 m only and found high levels of these nutrient salts below the euphotic zone. They attributed the high concentrations of phosphate to the shelf water entering the estuary at depth and the high silicate levels to the Fraser River waters known to be rich in silicate (e.g., Harrison et al., 1991). Figure 3 shows high concentrations of dissolved phosphate (2.75 µM) and silicate (60 µM) in the deep Strait of Georgia. However, these concentrations are clearly higher than in the dense inflow entering from the shelf. The analysis below allows a closer look at the variability of nutrient concentrations at depth within the basin as well as a discussion on the probable sources such as remineralization within the deep basin.

b *Determination of Source Water Types*

The first step in the local application of the OMP analysis is to define the source water types for the study area. The fact that the estuary is a semi-enclosed basin simplifies the problem somewhat relative to typical open ocean applications of the method. The local bathymetry and the estuarine nature of the coastal basin help define the first two water sources for the estuary: surface freshwater inflow in the Fraser River plume (SW_1), as well as deep inflow from the shelf at the mouth of Juan de Fuca Strait (SW_2). A third "virtual" water type is added to the analysis in order to represent water resident in the deep Strait of Georgia which can be, at times, stagnant (SW_3). The latter does not correspond to the typical definition of a source water type where measurement points are considered to be downstream of a number of known water sources. However, it is necessary to represent the contribution to the water masses present in a given season from the water residing in the deep basin during the preceding season. This is consistent with a known flushing time for the basin of about a year (e.g., Li et al., 1999).

A fourth source water type, SW_4, is added for the wintertime analysis to take into account the surface water intrusion into Juan de Fuca Strait of fresh warm water originating from the Columbia River. These surface intrusions are known to enter the strait regularly during winter storms (e.g., Hickey and Banas, 2003), bringing relatively warm, low salinity and low nutrient water northward along the coast. The signature of this water source is clearly identified in the mean distributions (Fig. 3) as a surface lens of warm, fresh and low nutrient water near the southern boundary. The inclusion of the latter source for the winter analysis significantly improves the performance of the mixing model. Finally, in a complementary analysis performed to look at the potential importance of intrusions from the north, a fifth source is identified as the subsurface estuarine inflow through Johnstone Strait (SW_5).

Tracer characteristics for each water source are obtained, for all four seasons, by averaging tracer values measured near the point of origin for that source over the five years of data collection. More specifically, the characteristics of the water sources are obtained from data measured at: stations 39 and 42 above 15 m for SW_1, stations 75 and 102 below 200 m for SW_2, stations 27 and 39 below 200 m for SW_3, stations 75 and 102 above 20 m for SW_4, and at station 16 below 100 m for SW_5 (see Fig. 1 for station locations). Property values for each of the source water types used in the analysis are given in Table 1, with the four seasons given clockwise from the top left corner as spring, summer, fall, winter.

c *Mean Source Water Type Concentrations*

In the first application of the mixing model, all parameters are considered conservative. This is a reasonable first-order assumption considering that, in this very dynamic coastal basin, the effects of advection and turbulent diffusion are generally expected to outweigh local forcing and biogeochemical effects. However, in some of the domain, such as near the surface, this assumption is invalid and may result in large

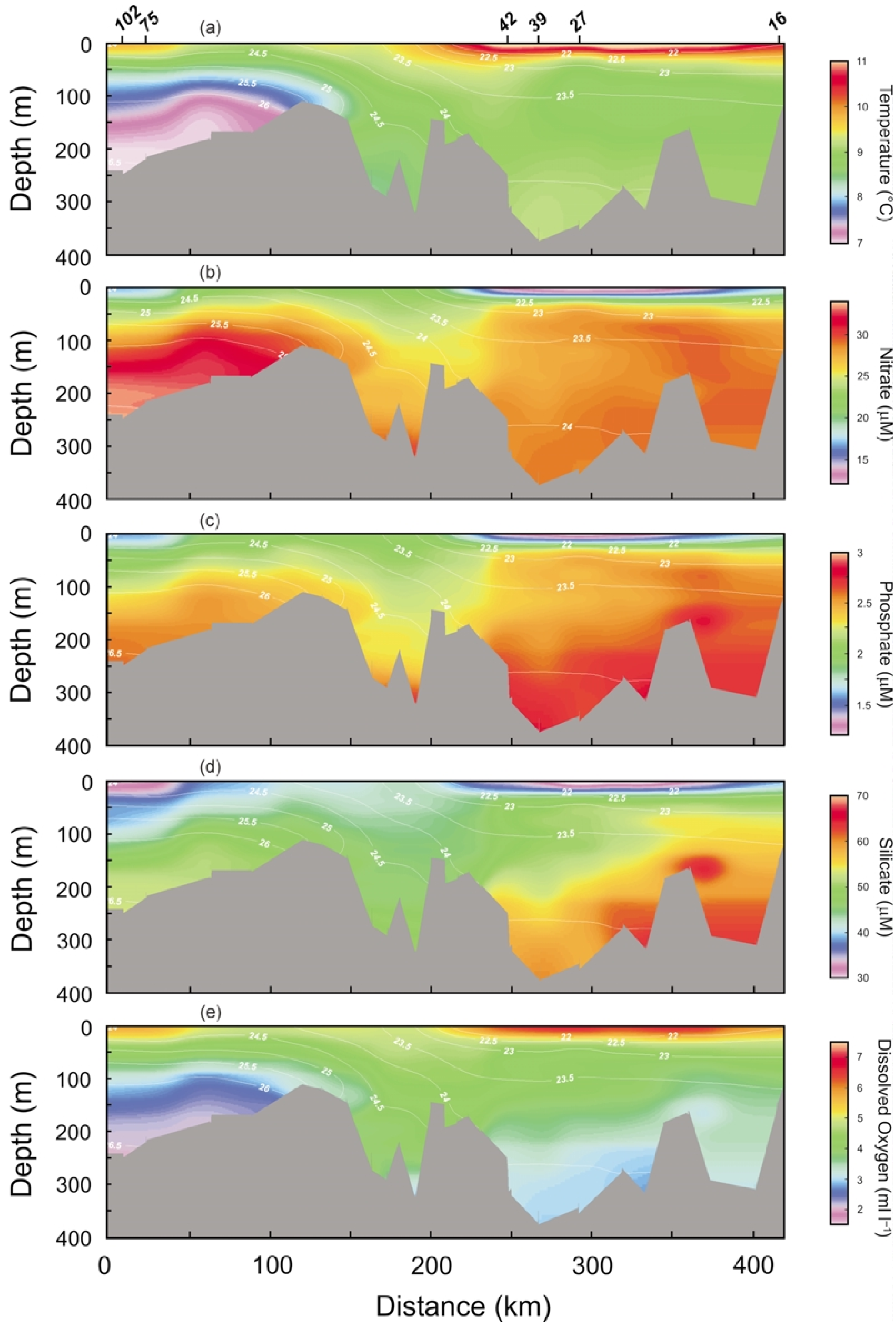

Fig. 3 Five-year mean distributions along the main axis of the strait for (a) temperature, (b) nitrate, (c) phosphate, (d) silicate, and (e) dissolved oxygen. Numbers along the top axis indicate the location of the stations identified in Fig. 1.

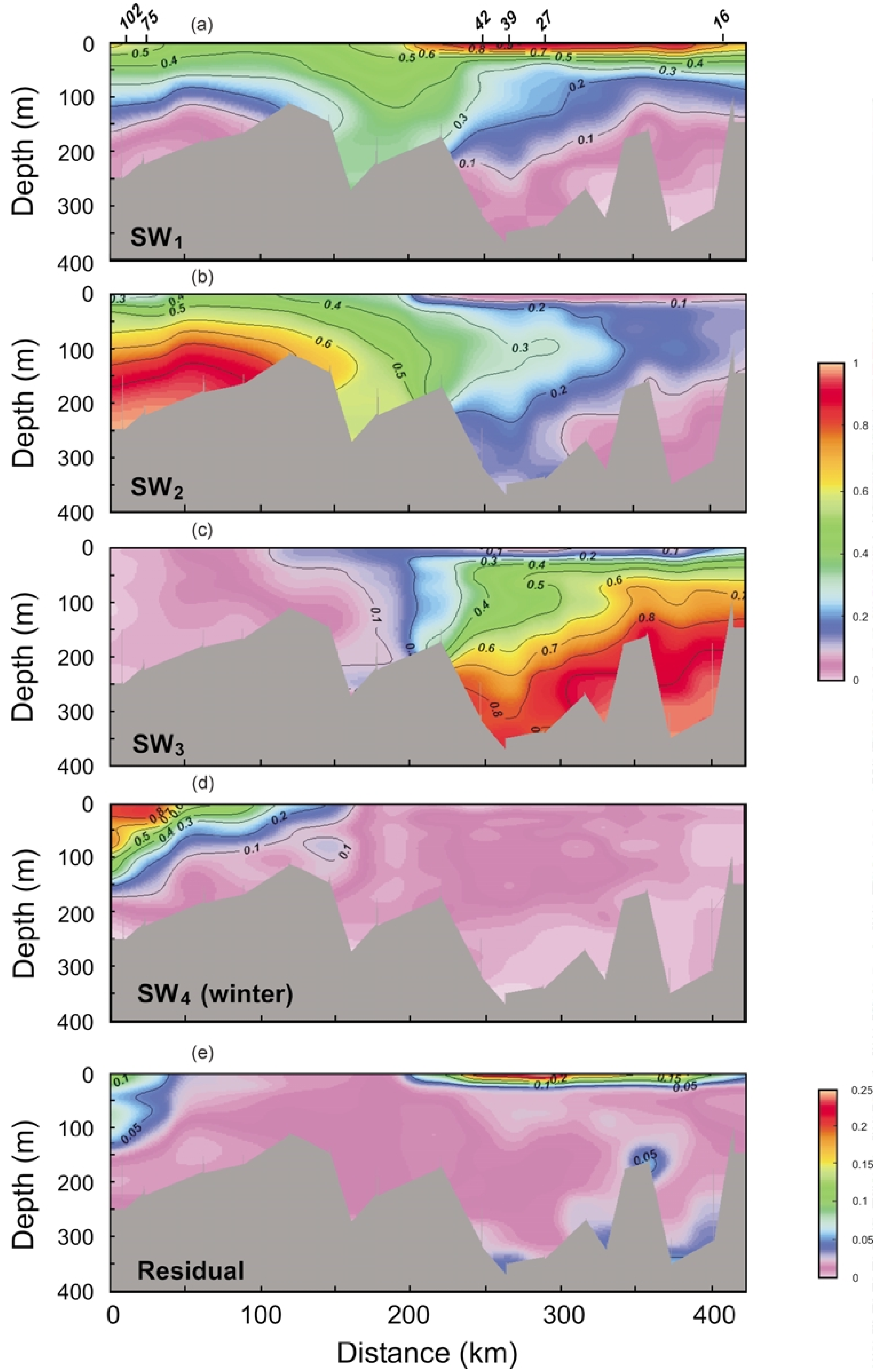

Fig. 4 Mean contributions for the source water type (a) SW_1, (b) SW_2, (c) SW_3, (d) SW_4 and (e) residuals obtained from the seasonal mixing analysis.

residuals, indicating a poor fit to the data. In the next section, an attempt will be made to account for biogeochemical processes by introducing a new column to the water type matrix which represents these changes.

At each measurement location, the analysis is first performed with six parameters and the first three (four in winter) water sources. The resulting mixing coefficients obtained by averaging the results of all seasons are given in Fig. 4, along with residuals (D^2 of Eq. (1)). Many aspects of the distributions so obtained can be associated with known features of the local estuarine circulation, lending credibility to the mixing model. In particular, the dense shelf water inflow (SW_2) and the fresh surface river plume (SW_1) mix in the area of strong tidal currents located between Victoria Sill and Boundary Pass. The resulting mixed water then advects out of Juan de Fuca Strait as a surface outflow, and into the Strait of Georgia as subsurface intrusions. In the deep Strait of Georgia, below sill depth, water can at times be stagnant as indicated by the high fraction of SW_3, particularly evident in the northern half of the basin.

The winter analysis was first performed without the inclusion of SW_4. But, in this case, the mixing model could not achieve a reasonable solution, giving unacceptably high residual values near the surface at the mouth of Juan de Fuca Strait. The winter data were then analysed including an additional source water type (SW_4) representing the surface water influence of the Columbia River plume. This reduced the residuals in this area of the domain considerably and indicated high concentrations of SW_4 at the surface, near the mouth of Juan de Fuca Strait. This water mass does not appear to be present during the rest of the year and, accordingly, the inclusion of SW_4 did not significantly improve the solution for the other three seasons. This is an illustration of how residuals provide a way of assessing the adequacy of the source water type definitions.

Over most of the area, residuals are relatively low for all seasons (Fig. 4e). However, one clear exception occurs near the surface of the Strait of Georgia, within the river plume. This is to be expected given that biological processes and direct heat exchange with the atmosphere are more intense within the more stratified surface plume. But, to a lesser extent, larger residuals are also obtained near the bottom of the deep basin of the Strait of Georgia, indicating the possibility of non-conservative properties. In this case, remineralization and possibly denitrification is expected to affect local nutrient and dissolved oxygen concentrations in the deep basin. Finally, larger residuals in the SW_4 area are due to the intermittent nature of the presence of the Columbia River plume in winter at the surface of the mouth of Juan de Fuca Strait.

d *Seasonal Changes of Mixing Fractions*

Seasonal changes in water mass composition are presented in Figs 5 to 7 for each of the three main source water types. In Fig. 5, the analysis shows that, as expected, the water associated with the Fraser River plume, SW_1, follows the seasonal cycle of the river discharge closely (see Fig. 2) with maximum extent occuring in early summer during freshet. The subsurface recirculation of the fresh water within the Strait of Georgia is also stronger in early summer when the estuarine circulation is at its maximum strength (Fig. 5b). In winter, a less stratified and thicker plume forms as a consequence of increased turbulent mixing during winter storms (Fig. 5d).

The seasonal contribution from the deep estuarine return flow entering Juan de Fuca Strait, SW_2, is contoured in Fig. 6. The penetration of the dense shelf water is maximal in summer when freshwater discharge into the estuary is high and upwelling is prevalent on the coast. This source water type contributes significantly to the mid-depth intrusions penetrating the Strait of Georgia from the south, constituting nearly 50% of the incoming subsurface water mass. The depth of these intrusions varies with season, being restricted to sill depth (around 100 m) in spring and reaching the bottom in summer and fall, during periods of deep water renewal (e.g., Masson, 2002). Finally, in winter, when the estuarine circulation is at its weakest, there is little evidence of these subsurface intrusions entering the Strait of Georgia.

Figure 7 tracks the changes with season of the contribution of the water mass residing in the deep Strait of Georgia during the previous season, SW_3. It indicates that, in winter and spring, the water of the Strait of Georgia below the sill depth (about 100 m) is stagnant, with a large proportion of pre-season water. However, in summer and fall, the analysis indicates that dense intrusions from the south enter the deep basin and displace the ambient deep water mass. This is consistent with the known seasonal cycle of the deep water properties which indicate that the main water renewal events occur in early summer and in the fall (e.g., LeBlond et al., 1991). It is also interesting to note that, for most of the year, sill depth intrusions create, within the Strait of Georgia, a three-layer structure below the surface plume: new intruding water at sill depth becomes intertwined with pre-season deep water. The intruding intermediate layer is characterized by relatively high dissolved oxygen and low nutrient concentrations as well as cold (warm) temperature in the spring (fall), creating subsurface maxima and minima in the vertical profiles of these tracers (see Fig. 3).

e *Sensitivity Analysis*

To verify the robustness of the results relative to uncertainties in the source water type definitions, the analysis was repeated 100 times, varying randomly the seasonal mean characteristics of each of the source water types, A_{ij}, within plus or minus one standard deviation of all measurements contributing to the mean. The average of the results from these 100 simulations was then computed and found to be practically identical to the original results.

In the initial analysis, assumptions were made regarding which water sources contribute significantly to the coastal water mass. Accordingly, four sources were used: the river plume, the deep inflow from the south, the pre-season deep water, as well as surface winter intrusions from the south. This first model, in which possible intrusions from the north were not accounted for, appears to perform generally well, including

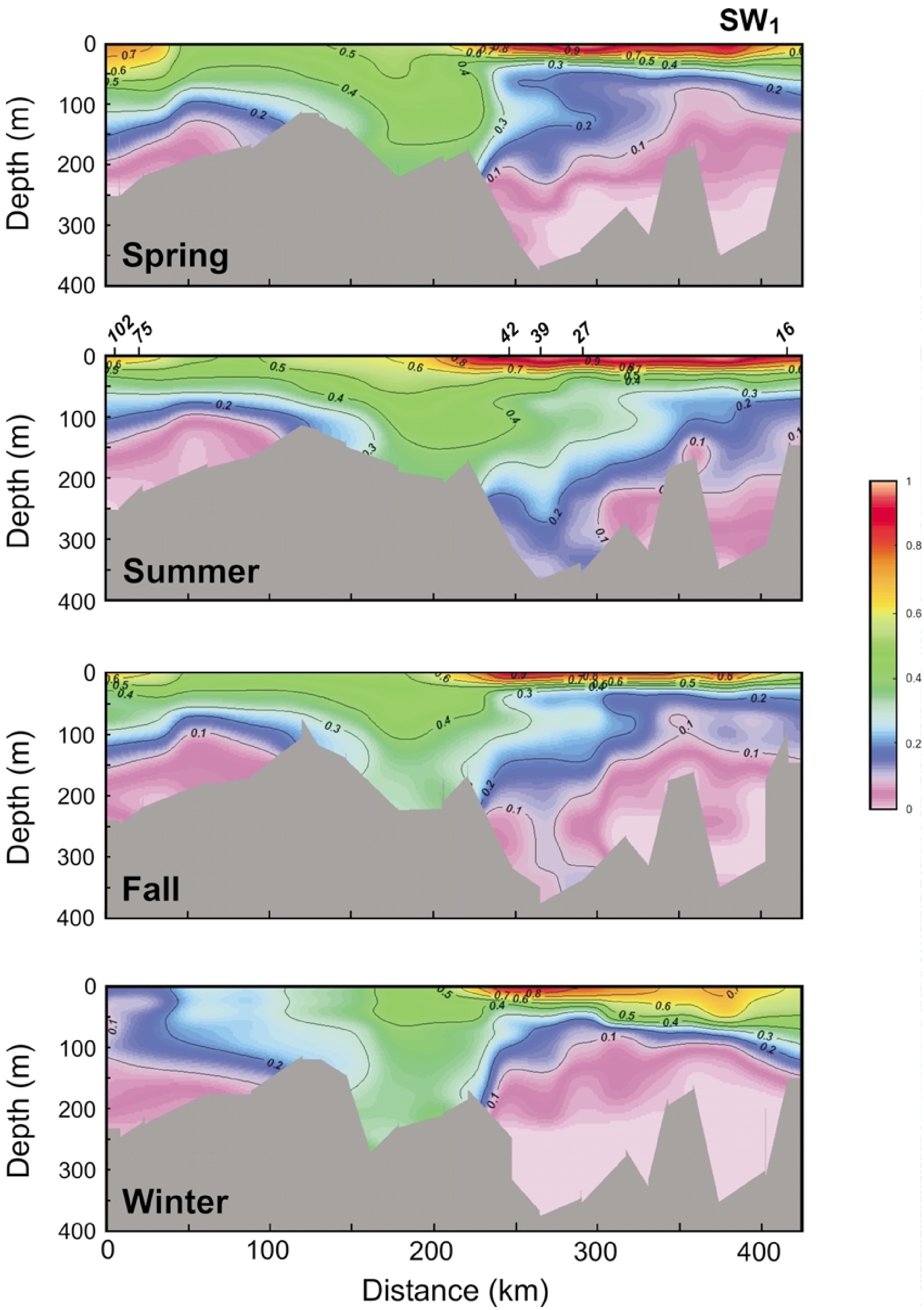

Fig. 5 Contributions from the source water type associated with the Fraser River plume, SW_1, for all four seasons.

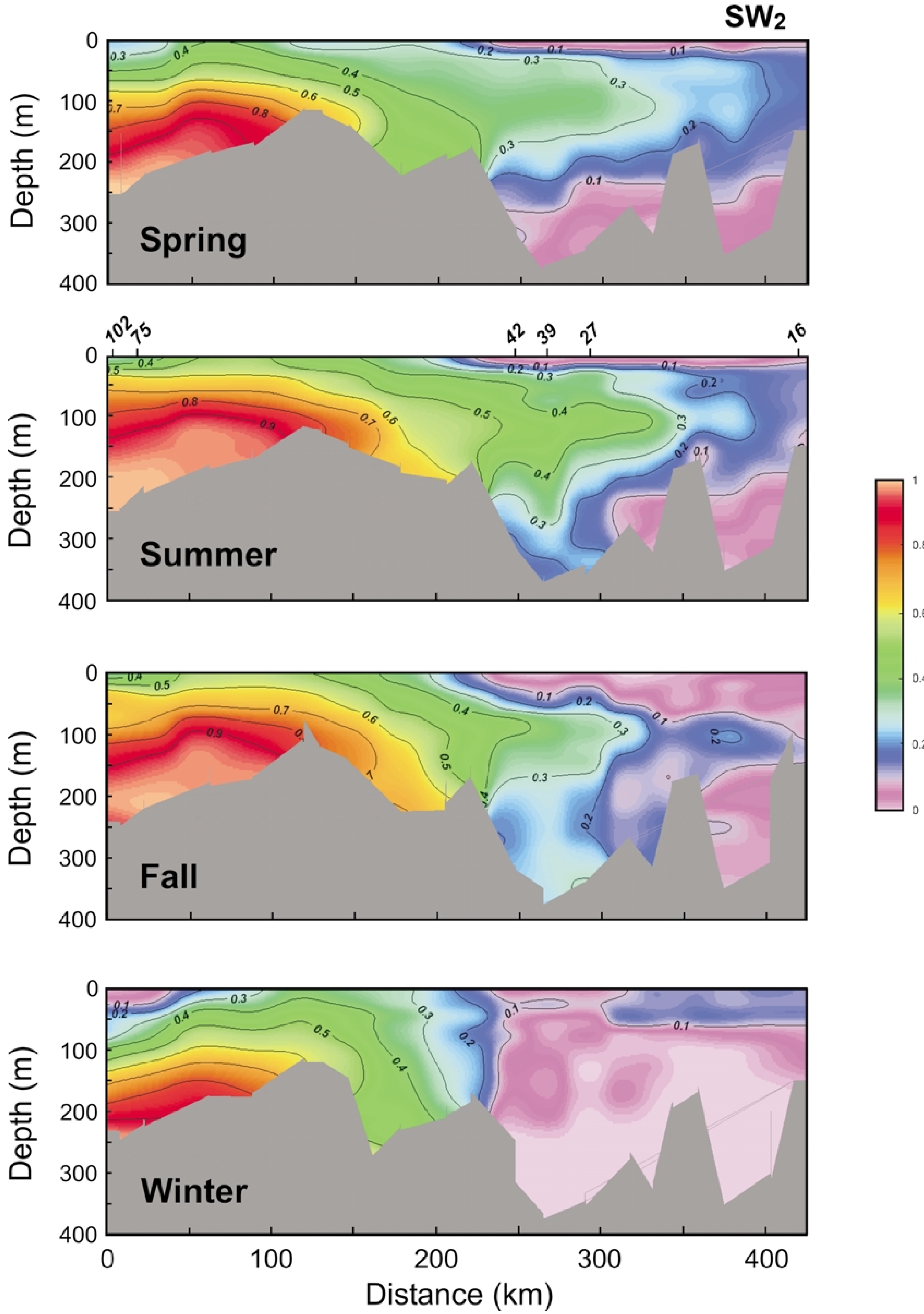

Fig. 6 Contributions from the deep southern inflow, SW_2, for all four seasons.

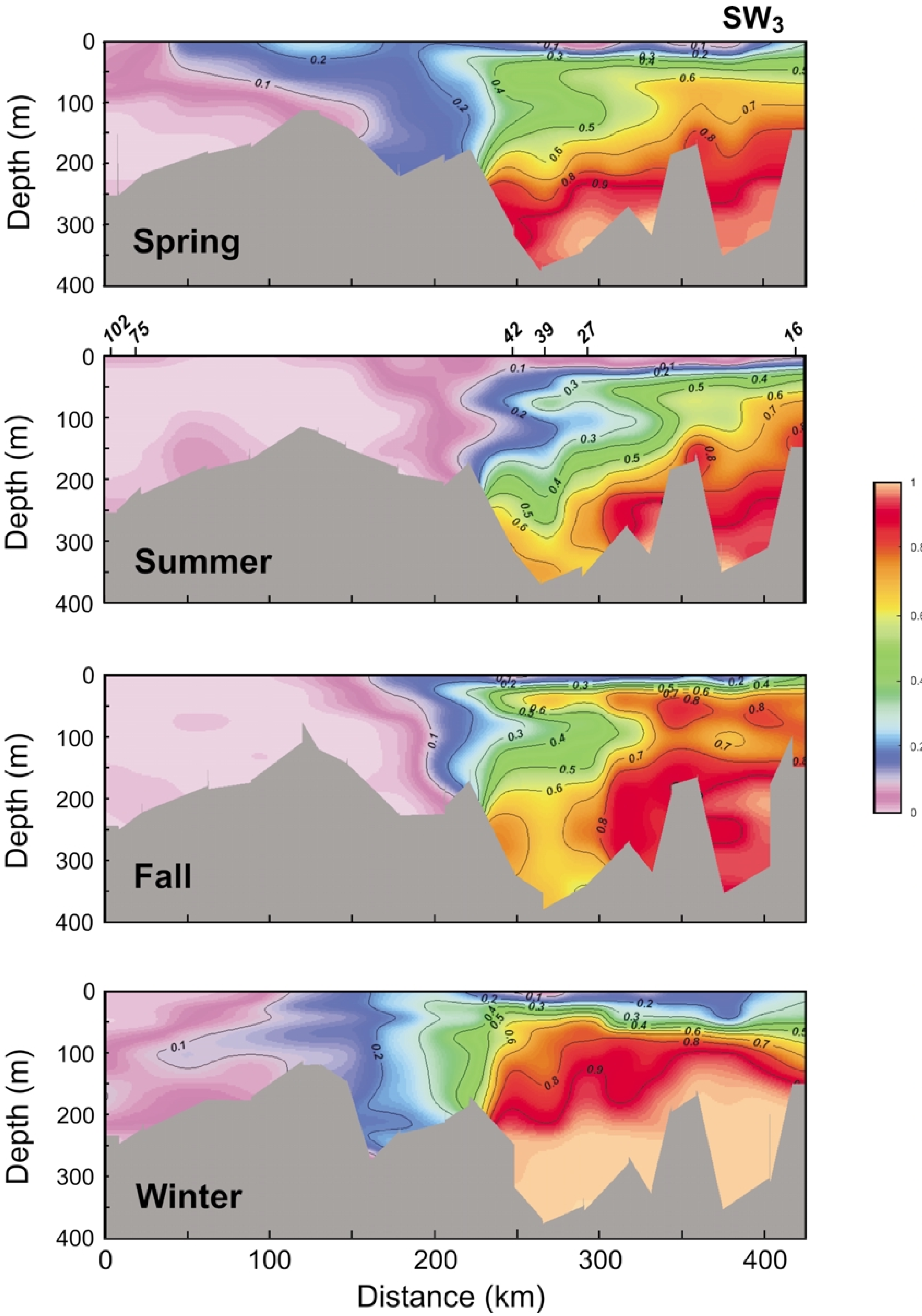

Fig. 7 Contributions from the pre-season water source, SW_3, for all four seasons.

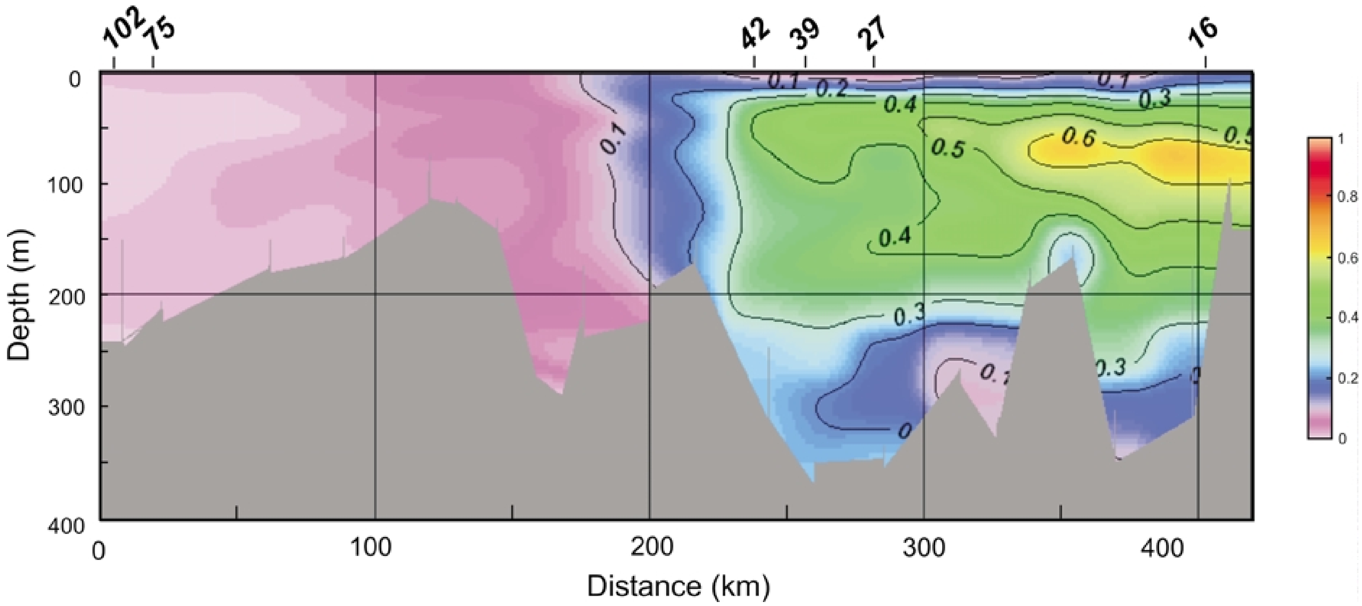

Fig. 8 Contributions from subsurface intrusions from the north, SW_5, averaged over all seasons.

in the northern end of the domain (Fig. 4e). Intrusions from the northern end of the strait have been mentioned in the past (e.g., Waldichuk, 1957; LeBlond, 1983) but have rarely been clearly identified. To examine the impact of such intrusions from the north on the model results, the basic model is now modified by adding a fifth source representing subsurface water originating at the northern end of the Strait of Georgia (SW_5 of Table 1). Figure 8 gives the resulting SW_5 contributions averaged over the four seasons. Contributions from other sources are generally unchanged except for SW_3, the deep pre-season type, which is reduced in the area of high SW_5 values. The contours indicate a distribution of SW_5 consistent with southward advection and mixing of subsurface water from the northern channels at about the sill depth, 80 m. The intrusions are of lesser extent and shallower than the intrusions from the south, owing to the relatively small cross-section of the northern channels, a shallower sill depth and the lower density of the intruding water. The depth of penetration appears to change slightly with season, being shallowest in late summer when the new water type is distributed right under the river plume.

It is legitimate to ask whether or not the addition of the fifth source improves the performance of the mixing model. In order to compare the goodness of fit of the two applications, the sum of residuals was computed in both cases. However, because the variables in Eq. (1) are normalized and the normalization changes with source water type definitions (Eq. (4)), we compute, for each sampling point, a new residual parameter, independent of the normalization:

$$\hat{D}^2 = (Ax - b)^T (Ax - b) \tag{6}$$

Figure 9 presents the value of $\hat{D}^2$ as a function of depth, averaged over the Strait of Georgia, for the analysis with and without SW_5. It shows that adding the fifth water source markedly improves the results around the depth at which the northern intrusions enter the strait. Obviously, the addition of a source water type defined within the domain increases the degrees of freedom of the mixing model and, consequently, locally reduces the residuals. Therefore, although the present results are consistent with the presence of such intrusions, the model is not capable of unequivocally determining their existence.

As noted earlier, the conservation of water properties is an assumption inherent in the mixing model. This is bound to fail in regions where significant biogeochemical changes occur, such as near the ocean surface. A modified version of the method, the so-called extended OMP, combines mixing of predefined source water types with time-integrated biogeochemical changes in oxygen and nutrients due to remineralization (e.g., Karstensen and Tomczak, 1998). The method consists of including an additional column in matrix A of Eq. (1) to represent the increase in nutrients and reduction in dissolved oxygen through the water column due to remineralization. Accordingly, a new unknown, the amount of biogeochemical change in phosphate concentration (ΔP), is added to the problem and estimated by the optimization technique at each sampling location. The extended OMP method is applied to the present dataset but, in contrast to previous applications, we allow here changes in phosphate concentrations (ΔP) to be either positive or negative, in an attempt to account for remineralization as well as primary production. Associated changes in nitrate, and dissolved oxygen are then obtained from the estimated change in phosphate by using the classical Redfield ratios of [16:-138] for [$\Delta N/\Delta P$: $\Delta O_2/\Delta P$] (Redfield et al., 1963).

To complete the model formulation, a $\Delta Si/\Delta P$ ratio is also needed. In contrast to nitrogen and phosphorus, silicon is not part of the organic soft tissue but is an important constituent

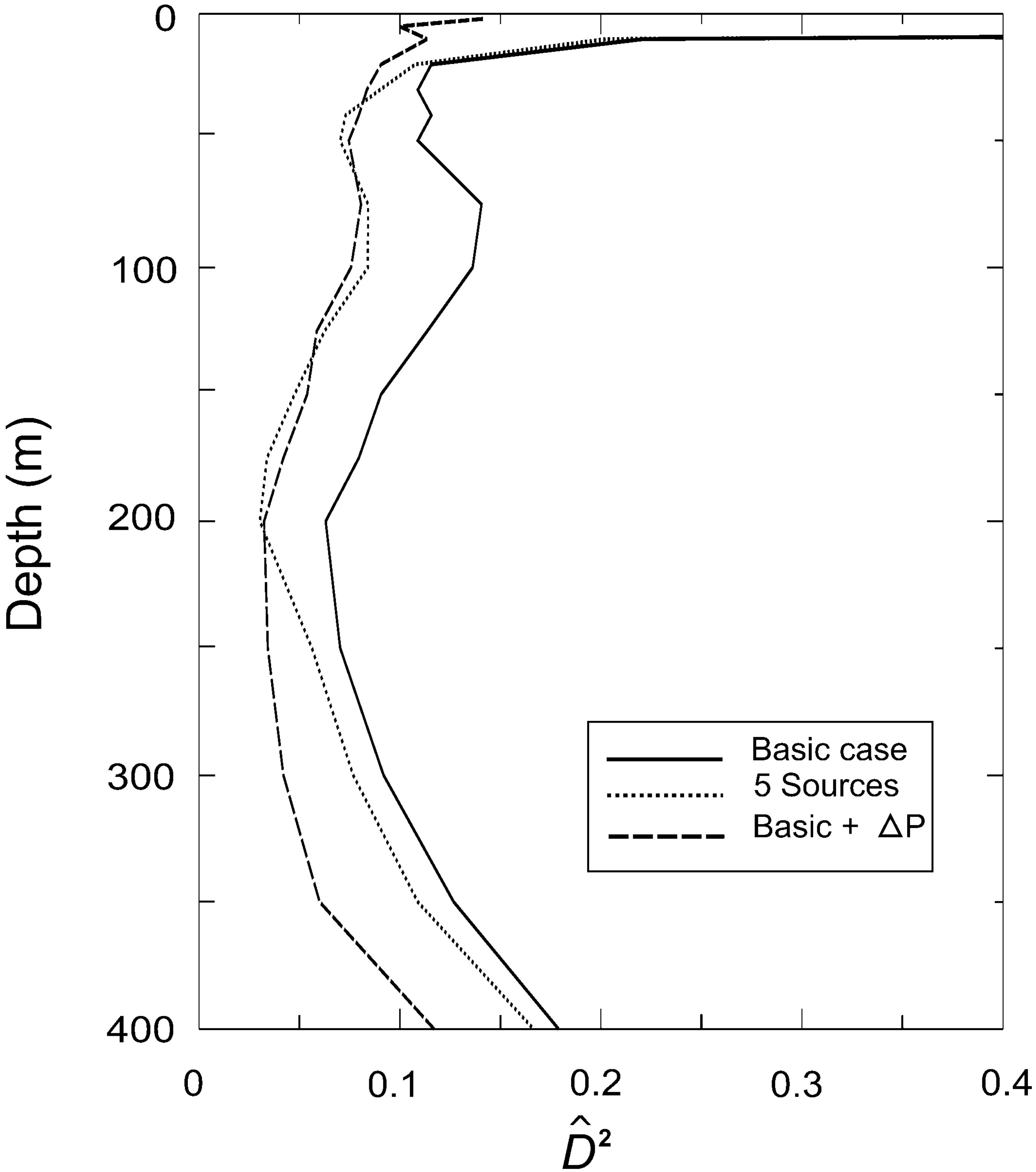

Fig. 9 Residuals, $\hat{D}^2$, as a function of depth , averaged over the Strait of Georgia, for the basic analysis (full line), for the case including a fifth source water type (dotted line), and for the extended OMP case (dashed line).

of silica-shelled phytoplankton such as diatoms. It is transported down the water column by the sinking of these organisms. Because the ratio ΔSi/ΔP varies with species and because the proportion of diatoms to other phytoplankton varies with location (e.g., Redfield et al., 1963), the ratio of dissolved silicate to phosphate also changes significantly. By using a best fit to the measured phosphate-silicate concentrations, we estimated the local ΔSi/ΔP remineralization ratio to

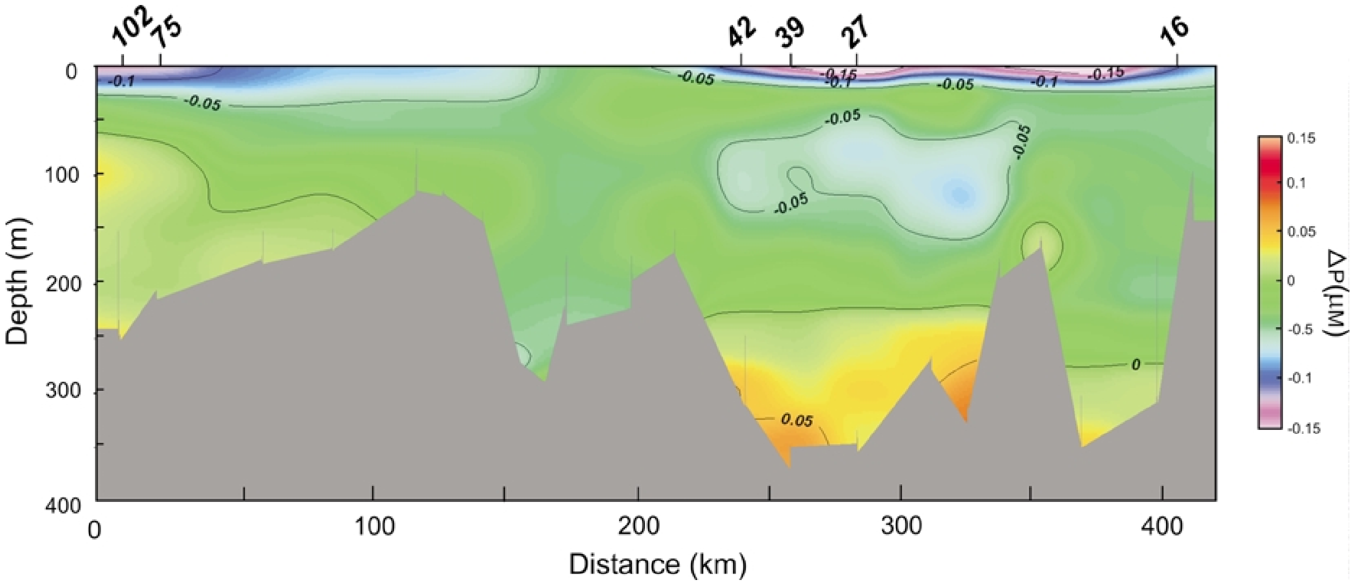

Fig. 10 Mean value for the biogeochemical changes in dissolved phosphate, ΔP, estimated by the extended OMP method.

be 23. This value is consistent with the estimates of Hupe and Karstensen (2000) for the Arabian Sea who found an average ratio of 21 in the upper 2000 m of the water column.

The basic mixing model, with the first four source water types only, is then applied, allowing biogeochemical changes in the oxygen and nutrient concentrations. Overall, mixing fractions of the different source water types are similar to the basic model results. Figure 10 shows the contours of the biogeochemical changes in phosphate, ΔP, estimated by the extended OMP, averaged over the year. As expected, large negative values for ΔP at the surface of the Strait of Georgia indicate a high level of photosynthesis in the euphotic zone. Surface values are largest in April, during the spring bloom. Also, in summer, there are indications of primary production in the surface waters at the mouth of Juan de Fuca Strait. On the other hand, remineralization is evident in the deep Strait of Georgia where ΔP takes larger positive values. This is in agreement with high levels of dissolved nutrient and low dissolved oxygen values measured in the deep Strait of Georgia (see Figs 3b–3e). For the case of silicate, such a high concentration likely contributes to the presence of rare siliceous sponge reefs which have been found at depth in the Strait of Georgia (Conway et al., 2004). The residual parameter D^* (Eq. 6) obtained with the extended OMP is compared in Fig. 9 with the values of the basic case. It is clear that the addition of the biogeochemical changes have improved the overall goodness of fit of the solution, especially near the surface where the large differences between the data and the model estimates have been significantly reduced by the inclusion of the biogeochemical terms.

5 Conclusions

The OMP method is applied to a multi-year dataset of water properties measured in the Straits of Juan de Fuca and Georgia. The analysis is carried out on a seasonal basis with six tracers (temperature, salinity, nitrate, phosphate, silicate, and dissolved oxygen) and three main pre-defined source water types. However, in winter, the analysis indicates that a distinct fourth water source is present at the surface of Juan de Fuca Strait near its mouth. It corresponds to winter intrusions of relatively fresh warm water originating from the Columbia River plume.

The analysis correctly identifies dense shelf water entering at depth in Juan de Fuca Strait and mixing in the area of strong tidal currents in Haro Strait with the fresh surface plume of the Fraser River. The resulting mixed water then advects out of Juan de Fuca Strait as a surface outflow and into the Strait of Georgia as clearly identified subsurface intrusions penetrating the Strait of Georgia at sill water depth (around 100 m). In the deep Strait of Georgia, below sill depth, water appears stagnant in both winter and early spring but is displaced by deep water intrusions in summer and fall.

When a fifth source, representing the subsurface flow originating at the northern end of the Strait of Georgia, is added, model results are consistent with the presence of subsurface intrusions advecting southward from the northern channels at a depth of about 80 m. Given the significantly smaller cross-sectional areas of the northern channels, these intrusions are of much lesser extent than the ones originating from the south. However, although the addition of this water source does improve the local performance of the model, it cannot unequivocally confirm the presence of northern intrusions. Finally, the OMP analysis is extended to include biogeochemical changes due to primary production and remineralization. A large decrease in nutrient concentrations and a concomitant increase in dissolved oxygen in the freshwater plume at the surface of the Strait of Georgia indicate a high level of photosynthetic activity in the euphotic zone. This process is at a maximum in April during the intense spring bloom. On the other hand, the mixing model indicates a marked increase in nutrient and oxygen concentrations in the deep Strait of Georgia associated with remineralization.

Acknowledgements

Comments from Sophia Johannessen and Patrick Cummins on an early draft of the manuscript are appreciated. Thanks go to Lizette Beauchemin for the preparation of the figures. Some figures were prepared with the help of the Ocean Data View software (Schlitzer, 2002). Thanks also go to the various crew members of the CCGS *Vector*.

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