Water Properties in the Straits of Georgia and Juan de Fuca

(British Columbia, Canada)

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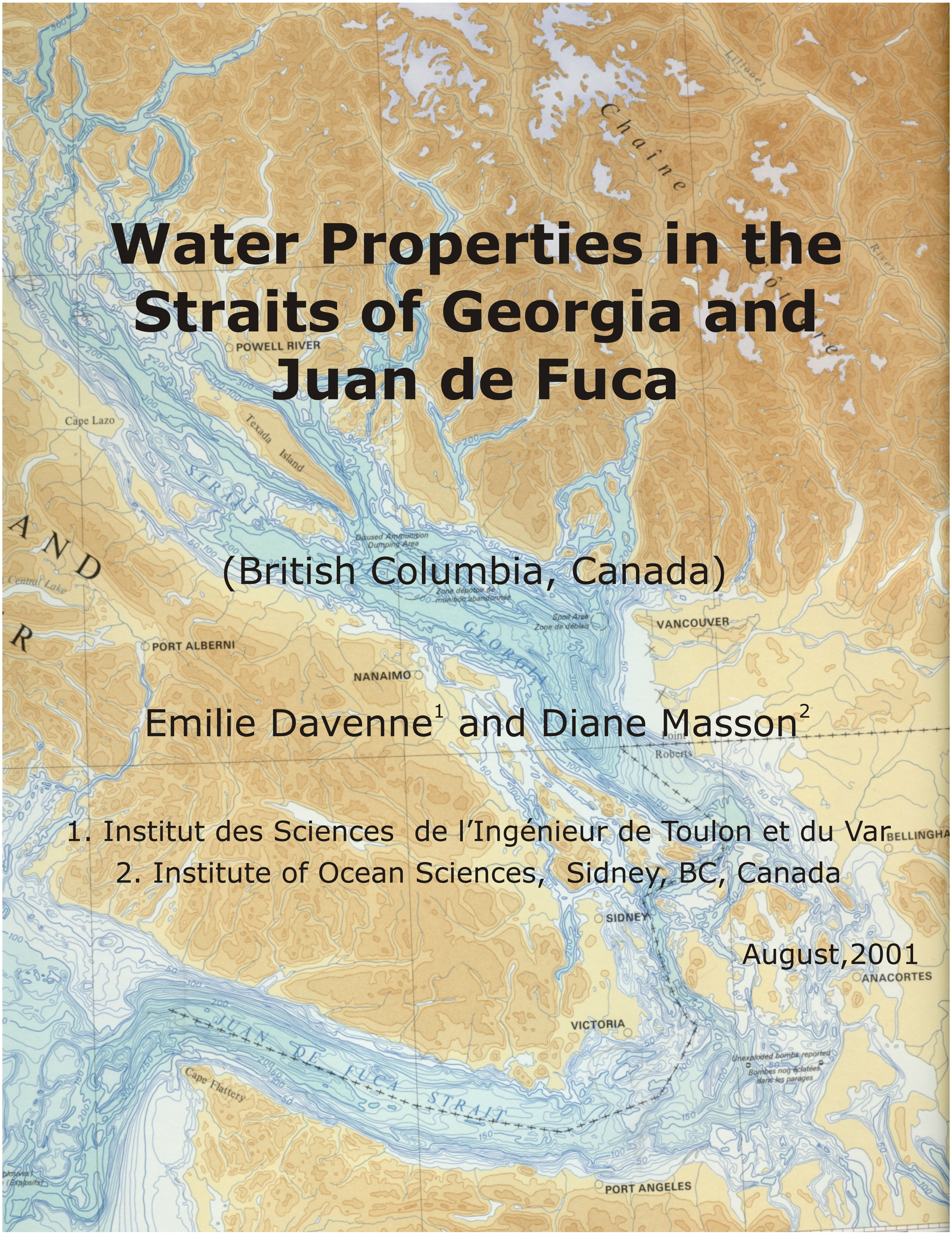

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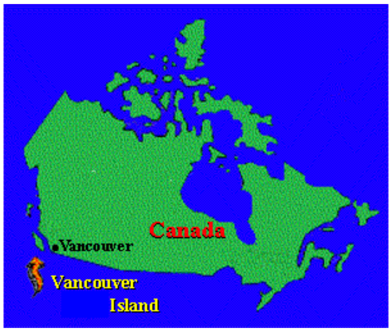
Introduction



The Institute of Ocean Sciences (IOS), on Vancouver Island is part of Fisheries and Oceans Canada. Its mission is to improve the knowledge and understanding of ocean events in the Pacific region. The Bedford Institute, based in Halifax, Nova Scotia is the eastern counterpart of IOS.

The research activities at IOS cover a wide range of subjects such as sedimentology, remote sensing, biology, modelling, hydrography, etc., to further the understanding of the oceans.

I worked for 2 months in the physical oceanography division of IOS, under the supervision of Dr. Diane Masson. My task was to synthesise the data acquired in the Straits of Georgia and Juan de Fuca, which separate Vancouver Island from the mainland.

The in-depth study of this area started in 1999 and its goal is to highlight the mechanisms of water circulation and its variations from year to year, by repeatedly observing the waters of the straits in the same seasons. This will result in a better understanding of the ocean climate of this coastal region, which will help improve fisheries management and the evaluation of human impacts on the ecosystem.

My work consisted of recovering all the available data since 1999, processing and displaying this data set and building a database to provide easy access to and to facilitate the selection of parameters. I used already existing software. This database is a practical tool and a base for future studies. I participated in a field trip at sea for a week, which made me aware of the difficulties and the hazards involved in acquiring the data. Finally, by using previous studies and the sensible advice of Diane Masson, I was able to highlight some interesting processes.

To understand the study area, I first discuss some external forces which influence the circulation of the water: climate, tides, currents, fresh water supply, etc. I then identify the types of data collected, their location, their acquisition and processing. Finally, certain physical processes are highlighted in an attempt to better understand the oceanography of the region.

-II-

Regional oceanography

II.1 - Geography and bathymetry

This study focuses on the straits separating Vancouver Island from the mainland. Juan de Fuca Strait is located on the border between the USA and Canada. Haro Strait connects it to the Strait of Georgia, to the north.

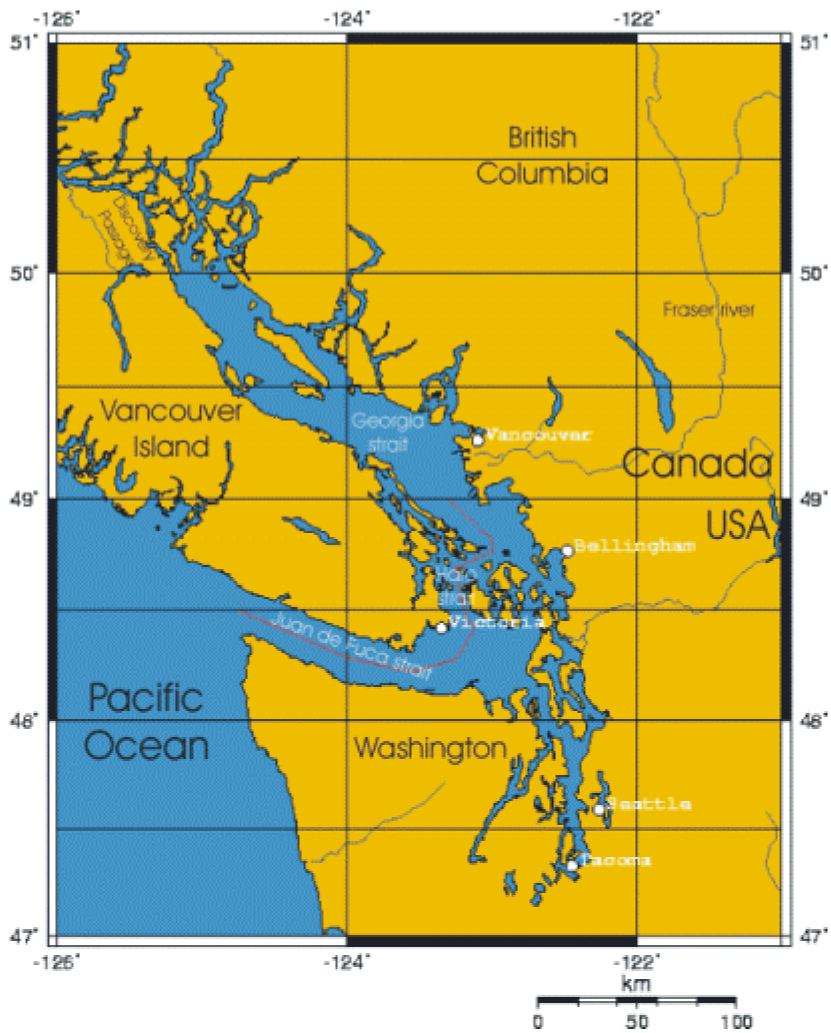


Figure 1 – Study area

The Strait of Georgia has 2 openings to the ocean: one to the south through Juan de Fuca Strait and one to the north, which consisting of long and narrow channels like Discovery Passage

Two sills separate the area into three main basins:

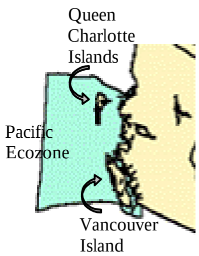
- The Victoria sill located south of the city of Victoria, which has a depth of 55 to 100 m,
- The sill at Boundary Pass, within the Gulf Islands, which has a depth of 150 m to 175 m.

Three basins are defined by these sills:

- The Strait of Juan de Fuca is about 100 kilometres long and 25 km wide and has depths ranging from 180m to 250m on the pacific coast and 55m at the sill,
- Haro Strait is 50km long and 5km wide and has a maximum depth of about 300m,
- The Strait of Georgia is more than 200 km long and about 28 km wide. It has a mean depth of 155 m and maximum depths greater than 400 m in the central part of the basin to the south of Texada Island.

Figure 2 – Bathymetry of the study area

II.2 - Climate



The coastal area that extends from Vancouver Island to the Queen Charlotte Islands is an 'ecozone' which has a unique climate, wildlife, relief and vegetation. This ecozone has one of the warmest and most humid climates in Canada. The climate is maritime but the precipitation levels are only 600 mm per year at the south of the Strait of Georgia. The regions to the north are generally more humid, getting up to 3,000 mm of precipitation per year. Compared to the rest of Canada, there is little variation in the monthly temperatures. In July, the mean temperature is between 12 and 18 °C and, in January, it is between 4 and 6 °C. There is generally no sea ice. The terrestrial barrier imposed by the Alaskan peninsula prevents a large portion of the cold arctic currents from reaching the south along the west coast. Within the Canadian boundary of the ecozone, from north to south, the temperature of the ocean surface does not vary by more than about 3 °C at any given time. The seasonal variation of the ocean temperature is within a very limited range of 7 °C, which is a sharp contrast to the east coast where variations in the ocean temperature are in the range of 20 °C. This area constitutes a mid-latitude transition, between the polar seas of the Arctic and the temperate waters of the Pacific Ocean.

The dominant winds are from the Northwest in the summer (associated with the anticyclone centered west of California) and from the Southeast in winter (associated with the depression in southern Alaska).

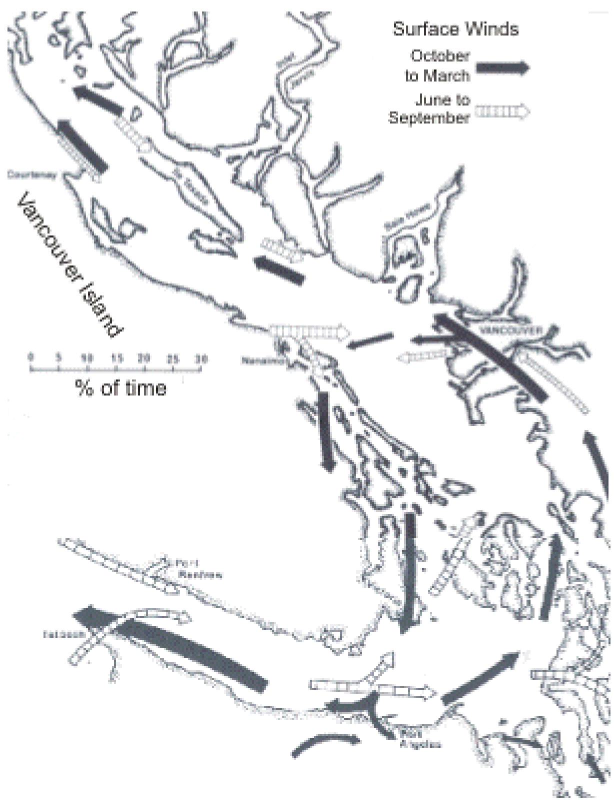


Figure 3 – Winds

II.3 - Tides

The study area is mixed tidal system: the diurnal and semi-diurnal components are combined differently in different areas. When the semi-diurnal component is dominant, there are 2 high tides and 2 low tides of equal importance per day while there is only 1 high tide and 1 low tide per day when the diurnal component is dominant.

The offshore area near the city of Victoria is an amphidrome for the semi-diurnal tide. Only the tidal range resulting from the diurnal tide exists.

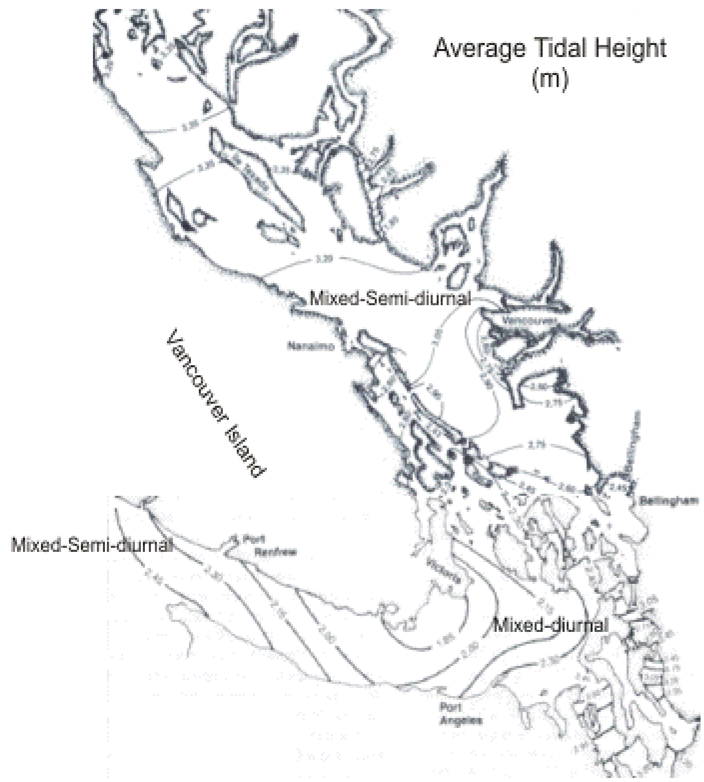


Figure 4 – Mean Tidal Height

II.4 - Fresh water inflow

Many rivers flow into the straits of Georgia and Juan de Fuca. Among these, the Fraser river, which meets the ocean at Vancouver, has the largest discharge and has a major influence on the surface water properties. It has a large annual variation in the discharge rate with its maximum discharge at the beginning of summer (May-June), corresponding to the maximum snowmelt, and a minimum during winter (December-March). Also, the river discharge rate has large interannual variations.

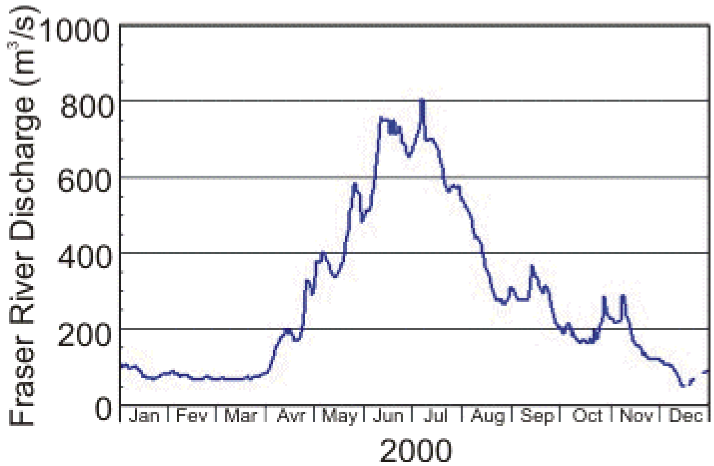


Figure 5 – Seasonal variations of the Fraser River discharge (2000)

Unlike the open ocean, an estuary has its density almost completely determined by the salinity with the temperature playing a minimal role.

II.5 - Currents

II.5.1 - Tidal currents

Tidal currents are very strong in the narrow passages and the associated mixing plays an important role in controlling the water mass exchange between basins.

In the Strait of Georgia, the tidal currents have the characteristics of a stationary wave that produces a maximum inflow and outflow 3h before high tide and 3h before low tide, respectively. They are generally weak, except in the passes and narrows. In surface waters the tidal currents are strongly modified by currents forced by the wind and the Fraser River runoff. The main direction of the inflow is towards the Northwest, more or less parallel to the coast and slightly pushed to the right by the Coriolis force. The flow is faster on the mainland side than on the Vancouver Island side.

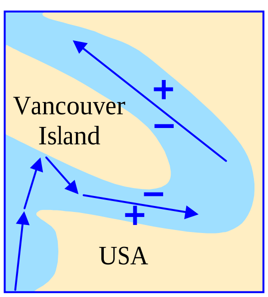


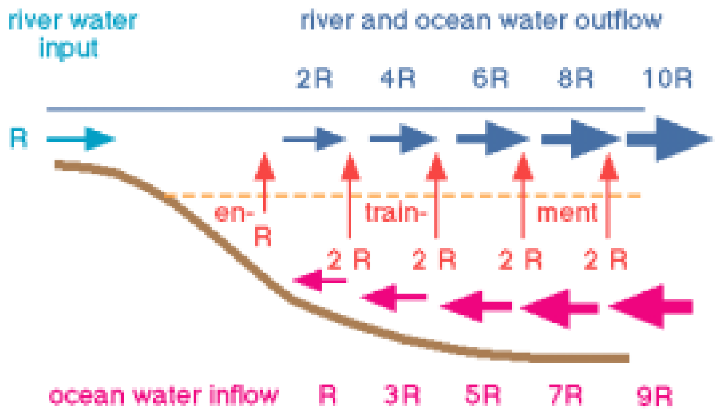
Figure 6 –.Tidal currents in the Straits of Georgia and Juan de Fuca

The tidal current enters Juan de Fuca Strait from the south, following the coast of Washington State and turning toward Vancouver Island. It then follows the Southeast direction, along the main axis of the strait. The wave is a combination of a stationary and a progressive wave varying with distance from the entrance to the strait. A slight acceleration of the current due to the Coriolis force is noticeable along the American coast. Speeds of 75 to 130 cm/s are attained during spring tides. These speeds are often surpassed when the runoff is constrained in the narrow channels.

The tidal currents in Haro Strait are always strong and mixed.

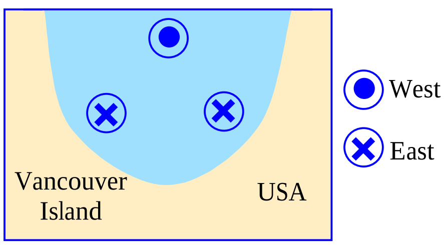
II.5.2 - Residual currents

The circulation produced by residual currents follows the same path in the 2 straits: the Fraser River brings a large amount of fresh water which induces a flow of surface water towards the west in Juan de Fuca Strait and towards the Southeast in the Strait of Georgia. This forces a reverse current in deep water.



As the diagram shows, the circulation of water forced by a river is characterised by an increasingly strong surface outflow and by a deep inflow that weakens as it approaches the mouth of the river. Turbulent mixing, whose rate varies according to the strength of the flow, occurs between the 2 opposing water transports.

Figure 7 – Principle of estuarine circulation



In Juan de Fuca Strait, the currents are essentially parallel to the axis of the channel. Near the surface, the residual current has a speed of 10 to 20 cm/s (40 cm/s at the start of summer) toward the west, concentrated in the middle of the channel. In deep water, the residual current is stronger on the sides of the channel, flows toward the east and has a typical speed of 10 cm/s.

Figure 8 – Diagram of the residual currents in Juan de Fuca Strait

The residual circulation follows the same path in the Strait of Georgia, but in a less obvious way than in Juan de Fuca Strait because there are more influences, such as a complex bathymetry or strong tidal currents, which affect it. It develops more or less according to the relative strength of these factors.

II.5.3 - Ocean currents

The waters west off Vancouver Island are affected in the summer by the California Current which flows east then south, at a speed of about 20 cm/s. Near the start of winter, the California Current is shifted offshore by the Davidson current, which flows northward until the start of spring.

There is also the California Undercurrent, a northward subsurface flow that originates off California. It attains a maximum speed of 10 cm/s and is centered at a depth of 200 to 300 m over the inner portion of the continental slope.

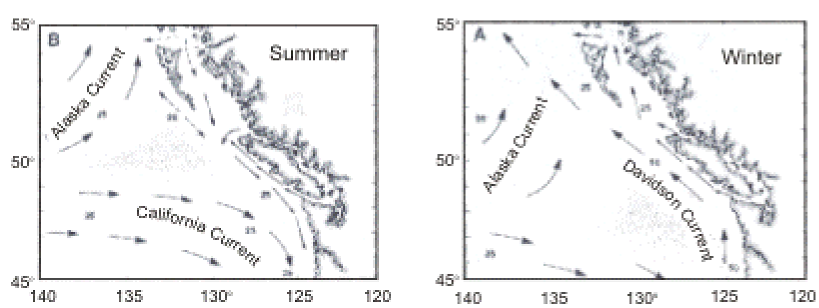


Figure 9 – Ocean Currents offshore Vancouver Island

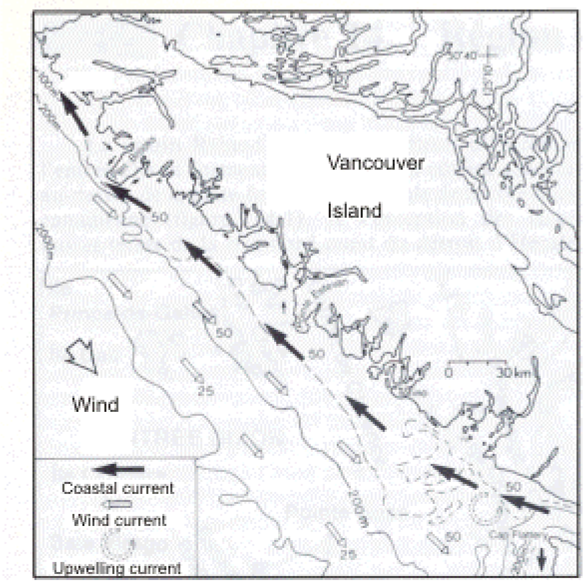
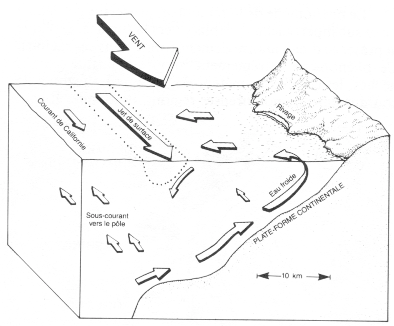


Figure 10 – Vancouver Island current

In addition, a persistent nearshore current flows to the Northwest all year long (the Vancouver Island Coastal Current). In summer, this current is confined to within 15 to 20 km of the shore and extends all along the west coast of Vancouver Island, attaining speeds of 50 cm/s near the surface and 15 cm/s near the bottom. In summer, the coastal current flows against the prevailing winds while, in winter, the coastal current merges with the wind-driven current. The coastal current is forced by the fresh water flowing out of Juan de Fuca Strait.

II.6 - Upwelling



In summer, the northwesterlies blow along the coast of Vancouver Island, moving the coastal waters offshore and resulting in a lowering of the sea level. As a result, the deep cold, nutrient rich water is upwelled, forming summer upwelling. In winter, the wind blows in the opposite direction, moving water onshore and causing the sea level to rise; downwelling occurs to restore equilibrium.

This annual cycle plays a very important role in determining the properties of the water entering the Strait of Juan de Fuca.

Figure 11 – How coastal upwelling works

II.7 - El Niño

During an El Nino, there is a general breakdown of the trade winds system over the equatorial Pacific Ocean. This leads to a decline in upwelling of cold water and, thence, a warming of coastal waters. This phenomenon is stronger in the equatorial regions, but it can have an influence around Vancouver Island. Its main consequence is the global warming of water due to warmer water flowing from the South, or to a change in the winds which modifies the characteristics of the water which enters the Strait of Juan de Fuca.

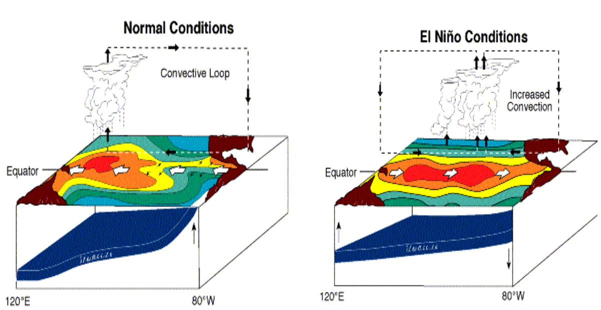


Figure 12 – El Niño driven conditions

-III-

DATA COLLECTION PROGRAM

III.1 - Types of data collected

Several parameters are measured in order to characterise the masses of water and determine their origin and progression. Temperature and salinity are two important properties because they determine the water density. In the present study, these two classic oceanographic parameters have been measured.

Due to its geography, the study area offers other possibilities for characterising the water mass. The circulation in the 2 straits is very fast and properties like the concentration of nutrients or the volume of dissolved oxygen can be useful tracers because the biology does not modify their concentration quickly enough.

Therefore, during this study, we measure:

- temperature in ºC,
- salinity in psu (practical salinity units),
- volume of dissolved oxygen in ml/l,
- nitrates (NO_3),
- silicates (Si),
- phosphates (PO_4) in μmol/l.

The systematic collection of data from the Straits of Juan de Fuca and Georgia was initiated in 1999. A grid of about 75 stations is visited during each mission.

Data is available for 9 cruises: 3 per year for each year (1999, 2000, and 2001). The dates of the measurements were chosen in relation with the Fraser River discharge. The missions are in spring (April) before the Fraser freshet, in June or July during the freshet, and at the end of the summer (August, September) when the river discharge has significantly decreased. In addition, a field mission is now scheduled for January (2001, 2002).

Each mission organised at IOS is assigned a number. Here are the field missions which will be used in this study:

	1999	2000	2001
Spring	April : 1999-09	April : 2000-07	April : 2001-10
Summer	June : 1999-16	July : 2000-17	June : 2001-19
Fall	August : 1999-20	August : 2000-27	
Winter			January : 2001-01

Figure 13 – Field Missions

The measured parameters are not the same at all the stations: along the main axis of the 2 straits all 6 parameters are sampled ('rosette' stations), while only temperature and salinity are sampled at the other stations ('CTD' stations). About 75 stations are predefined:

Figure 14 – Location of the sampling stations

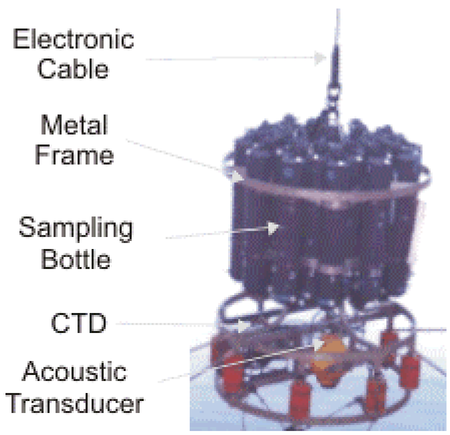
III.2 - Data acquisition

IOS has the opportunity to use several oceanographic vessels: the Tully is dedicated to offshore missions; the Vector, a smaller vessel, is used for coastal work in protected water. These ships are part of the fleet of the Canadian Coast Guard. These vessels are also used for search and rescue.

Most of the data used in this study have been collected with the CCGS Vector.

Figure 15 – The CCGS Vector

The instrumentation used for the field missions:



- A CTD probe for measuring real-time temperature and salinity via digital recording on a PC,

- A rosette with 25 bottles to sample water at fixed depths.

Figure 16 – Rosette and CTD

All the instruments are installed on a metal frame and are lowered into the water at the same time. The pressure sensor of the CTD probe transmits its depth as it is lowered. An electronic cable links the probe to the surface. The depth sounder allows us to compare the position of the system relative to the bottom using a transducer installed on the metal frame. The temperature and salinity are recorded during the descent down to about 5m off the bottom. The rosette is then brought back up, either in a continuous fashion or stopping at pre-defined depths to obtain water samples by closing a bottle using a signal from the electronic cable. The bottles are triggered at every 50m up to 200m, then at every 25m up to 50 m and finally at every 10 m.

The files containing the depth, temperature and salinity data are stored and 2 types of samples are taken from each bottle. A water sample is analysed for dissolved oxygen on the boat and 2 samples for nutrient analysis are frozen, to be analysed later in the laboratory.

The acquired data is saved in the standard IOS header format. The files contain all the information pertaining to the data: date, hour, station name, latitude and longitude. These files are then archived in a shared directory. There are 2 types of files available: those having the .ctd extension contain temperature and salinity data and those with the .che extension contain dissolved oxygen and nutrient data. The nutrient data are available only as Excel files that contain depth values and the concentration of the 3 elements (NO_3, Si, PO_4) in mol/l.

III.3 - Data processing

The goal is to display the data in a simple manner in order to highlight the processes important to the circulation of the water masses in the straits of Juan de Fuca and Georgia.

For this purpose, I used a software package written by a German scientist, Reiner Schlitzer, which is tailored to oceanographic data and has specific modules for analysis and display, Ocean Data View (ODV). It works like a geographic information system (GIS). It is possible to plot the data on a map and produce various graphics. ODV has a module to select the data by criteria (location, date and data interval) that is very useful.

The different types of data are available in separate files and the sampling depths for different parameters are not always the same. For example, there is much more temperature and salinity data than oxygen or nutrient data. The first task was to construct files with a format that was accepted by ODV and that synthesised all the data for each depth. Many different file formats can be imported into ODV but the difficulty was in assembling all the data (temperature, salinity, dissolved oxygen and nutrients) in the same file so that the software could make a spatial correspondence between the different types of data.

The first part of my term was thus devoted to writing an IDL program that would reformat the data so that it could be analysed using ODV.

I chose the text (.txt) format as output format because it is the simplest to work with. ODV reformats the data in column order: mission, station, latitude, longitude, depth and other specific data (in our case temperature, salinity, and σ_t which is calculated from the temperature and salinity using the equation of state, dissolved oxygen, NO_3, Si and PO_4).

The program reads the .ctd, .che and nutrient files and writes to a .txt file all the existing data for each depth. The difficulty was to match the data for dissolved oxygen and nutrients to the temperature and salinity data so that ODV could create graphs with all of the parameters. In effect, if the data for a certain depth was not written in the same line in the .txt file, ODV could not establish a correspondence between the different data and the complete analysis of the data was impossible

The program outputs 1 file for each station and each mission. Once all the stations for a mission are processed, it is possible, using another program, to combine all the stations for a mission into a single file. These files can then be imported into ODV.

-IV-

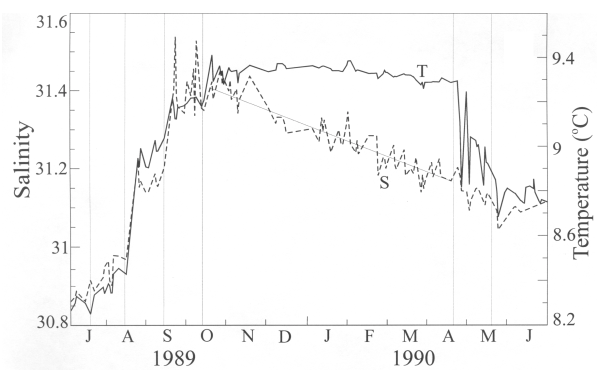
Oceanographic processes of interest

The movement of the various water masses in the Straits of Juan de Fuca and Georgia is governed by many factors resulting from the particular geography of this area. The Fraser River runoff follows a very strong annual cycle that has effects all year round and constitutes an important forcing for the circulation in the surface layer. Tidal currents and winds also influence the flow. The presence of the sills of Victoria and Boundary Pass hamper the circulation of the water. The objective of this study is not to understand the complete circulation in the two straits but to highlight certain clearly defined processes. This will lead to further study of the general mechanisms which govern the circulation of the water mass.

IV.1 - Deep water renewal in the Strait of Georgia

The deep water mass comprises water deeper than 300 m, well below the depth of the sill at Boundary Pass. It is formed by the intrusion of dense water that flows over the sill, generating a gravity current that flows along the bottom and penetrates to the deep basin of the strait, changing its properties. This subject has been the subject of several studies in the past and there are different data sets of the deep water area.

IV.1.1 - Existing Theory: comparison with recent data



In Masson (2002), variations in temperature and salinity of the bottom water for a complete year (July 1989-June 1990) are given for a sampling station offshore of Nanaimo, where the maximum depth is about 400m.

Figure 17 – Temperature and salinity of the deep water in the Strait of Georgia from June 1989 to July 1990.

In conjunction with the dissolved oxygen and nutrient data, this figure makes the following conclusions possible:

- 2 seasons of deep water renewal are identified:

  - The end of summer brings water that is warm, salty, rich in nutrients and poor in dissolved oxygen: the temperature and salinity reaches a maximum in October,

  - The spring (April-May) brings colder, nutrient poor and oxygen-rich water.

- The temperature varies in steps (sudden increase in fall and a severe decline in spring), while the salinity increases sharply at the end of the summer and then decreases gradually.

- Most of the water enters the basin during the two deep water renewal seasons (spring and fall). During the rest of the year, deep water diffuses slowly with the water above.

Station 39 is the deepest station that also has dissolved oxygen and nutrient data. The measurements here can be as deep as 380 m.

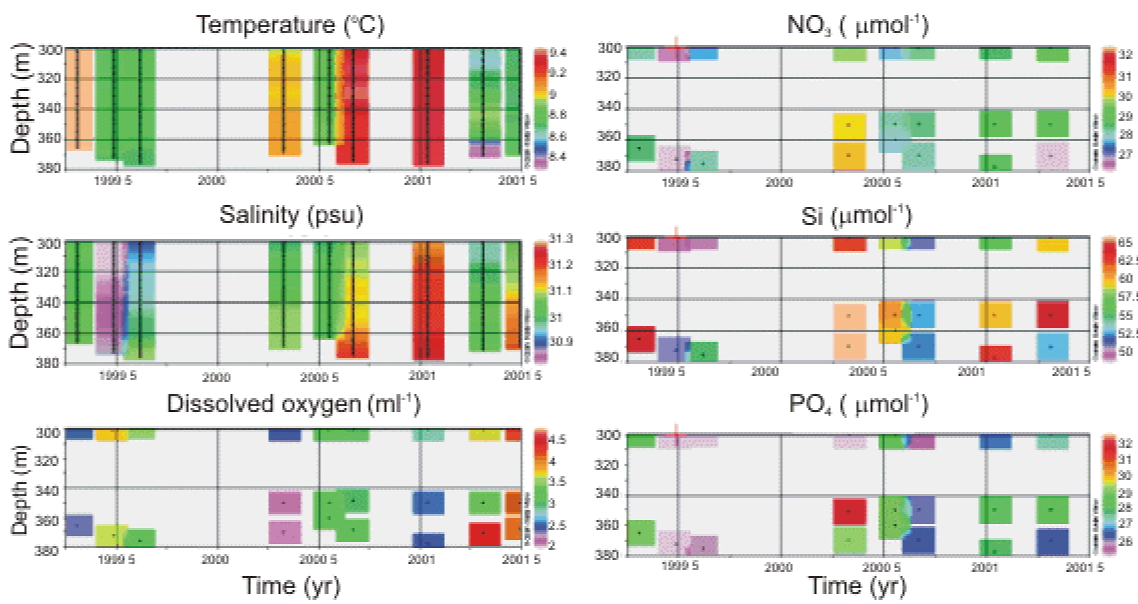


Figure 18 – Bottom water properties of the Strait of Georgia (station 39)

The figure above displays the data available at station 39 from 300 m to the bottom: each vertical bar represents a mission. There are only 2 or 3 deep water measurements for dissolved oxygen and nutrients because these parameters are sampled less often.

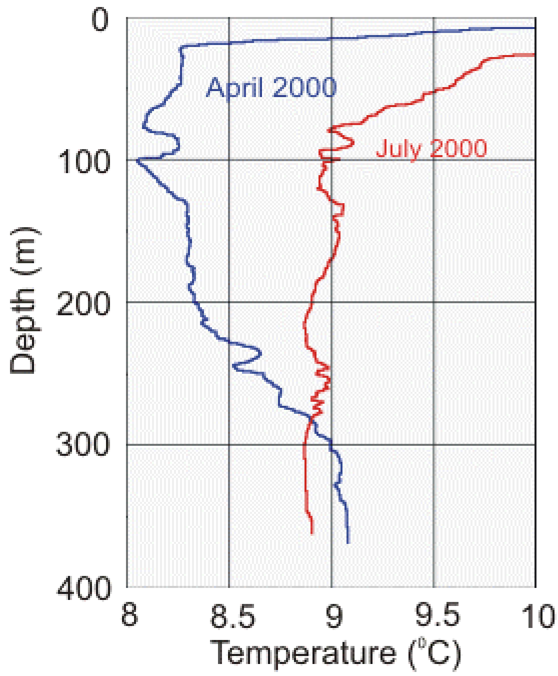
The resolution of this data does not give us access to details such as the dates and the exact duration of the process but allows us to see the variations of the different parameters over several years

Several events are interesting:

Between April and June 1999-2000:

A mass of colder water has entered the deep basin between April and June or July for the years 1999 and 2000. The difference in temperature between the months of April and June is much more pronounced in 1999: 1.1°C in 1999 compared to only 0.3°C in 2000. The very strong warm anomaly present in 1999 is the result of the El Niño of 1998, the strongest event ever recorded in this part of the Canadian coast, affecting the coastal water temperatures. The temperature difference observed in 2000 is weaker but is more typical of the normal variations observed.

The plot of the complete temperature profile for station 39 highlights the presence of a warmer water mass at the bottom in April 2000.



It is clear that a mass of warmer water is present in April at the bottom of the Strait of Georgia below about 300m. This water mass has disappeared in July, replaced by colder water: The profile is quasi rectilinear below 100m.

The difference in the bottom water temperature between the 2 measurements is quite small compared to differences measured in the rest of the water column, but the behaviour of the temperature profile verifies the existence of a deep cold water intrusion.

Figure 19 – Temperature profile for April and July 2000, station 39.

The cold water mass is also richer in dissolved oxygen and poorer in nutrients.

Between January and April 2001:

The cold water intrusion does not happen between April and June as it does in 2000, but is already present in April 2001. A layer of colder water is clearly obvious from 360 m. This indicates that for the year 2001, the intrusion of water in the spring occurs earlier than in the previous year.

Between August 2000 and January 2001:

Warmer, saltier water arriving at the end of the summer (October), that is described in previous studies, is evident in January 2001.

IV.1.2 - Bottom water from 1999 to 2001

The field missions of 1999 to 2001 allow us to have a more complete understanding of seasonal cycle of the deep water in the Strait of Georgia. Fig. 20 shows the mean temperature and salinity of the water below 300 m in the Strait of Georgia. The standard deviation of the data is also given.

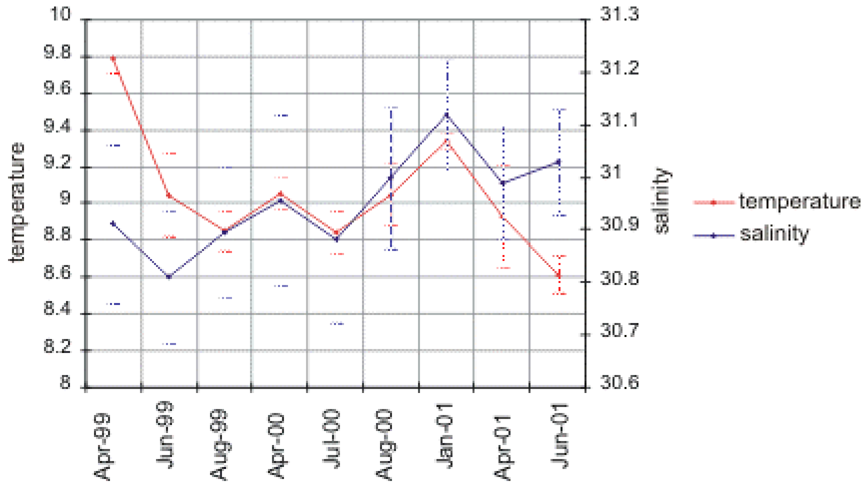


Figure 20 – Mean temperature and salinity at the bottom of the Strait of Georgia

Some interesting points:

- The drop in temperature is much more evident between April and June 1999 than it is for 2000 as was noticed for station 39; but the drop in salinity is almost the same for both years.

- The differences in temperature and salinity for the 'normal' years (2000 and 2001) are much more noticeable between the winter and the spring than between the spring and the summer.

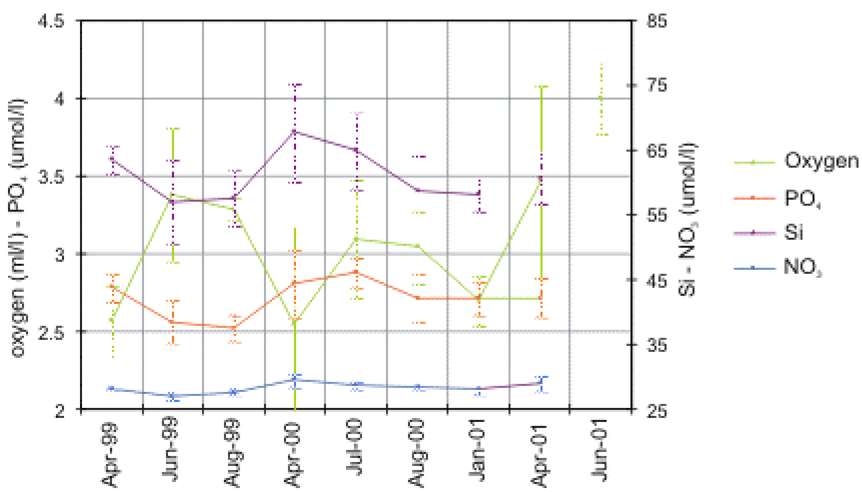


Figure 21 – Mean dissolved oxygen and nutrients at the bottom of the Strait of Georgia

The 3 nutrients evolve in a similar manner. They show a well-defined minimum for the spring of 1999. This is not as evident for the spring of 2000 where only a tendency to be lower is observable. The oxygen however has maximum values in June or July 1999 and 2000, showing the arrival of spring renewal intrusions with water rich in O_2. The increase in dissolved oxygen between April and June 2001 is unexpected, as dissolved oxygen tends to decrease slightly from June or July to August 1999 and 2000. If the intrusions happened later in 2001**,** oxygen should then decrease between April and June 2001. Maybe we can put forward the following hypotheses: in 2001, the intrusion started earlier than usual and lasted longer?

The evidence of the deep water renewal in the Strait of Georgia can be characterised by showing the state of the bottom water at different seasons. An image of the complete strait helps to understand the extent of the process of renewal.

The following figures display the parameters that indicate most clearly the presence of the new water mass: temperature and dissolved oxygen. The data used is from the area displayed on the left. The colour scales are the same for all figures to make comparison easier.

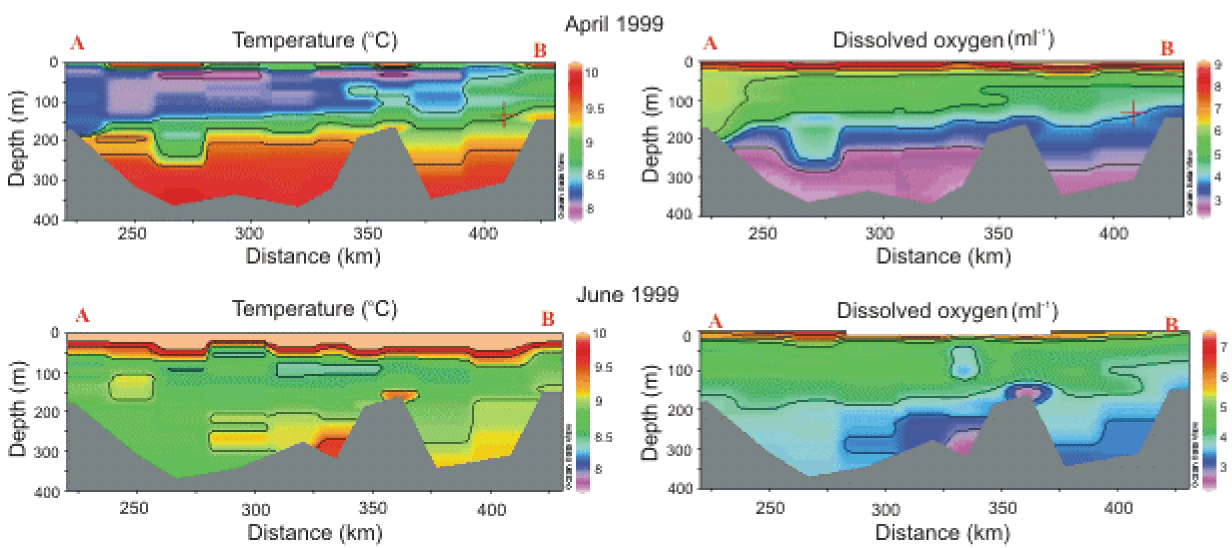


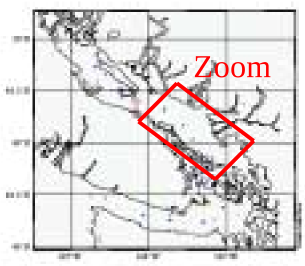
Figure 22 – Deep water renewal, spring 1999

It is clear that, at the bottom of the Strait of Georgia, warm, oxygen poor water apparent in April 1999 has disappeared by June 1999 to be replaced by cold, oxygen rich water.

IV.2 - Mid-depth intrusions in the Strait of Georgia

The measured physical and chemical properties of the water mass in the Strait of Georgia show that, at mid-depth (typically between 50 and 250 m) past the Boundary Pass sill, small and localised water masses have different characteristics from the water that surrounds them, suggesting that water of contrasting properties have penetrated the strait at mid-depth.

IV.2.1 - Highlights



The following diagrams zoom in on the area where the intrusions are detected: 100 km from Boundary Pass between 50m and 350m depth. Only the properties that demonstrate clearly the process are displayed: the temperature, dissolved oxygen and one of the 3 nutrients. The salinity observations do not show the intrusions clearly. The intrusive water masses have a tendency to adjust their position in the water column according to their density. Because the density is mostly determined by salinity, they intruding water will not show a contrast in salinity with the ambient water. However, the intrusions will show a contrast in temperature for most of the intrusions, as well as the dissolved oxygen and the nutrients

The intrusions are visible during several periods of the year, but they seem to appear more frequently during certain seasons; in fact, they are clearly evident in spring (April) and absent or weak during June, July or August. We also observe mid-depth intrusions in the only winter data set available.

Spring 1999-2000-2001:

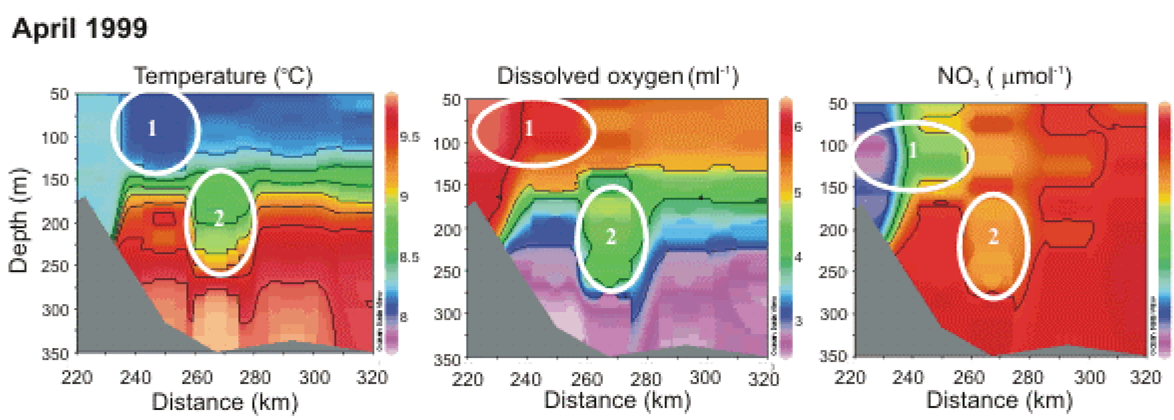
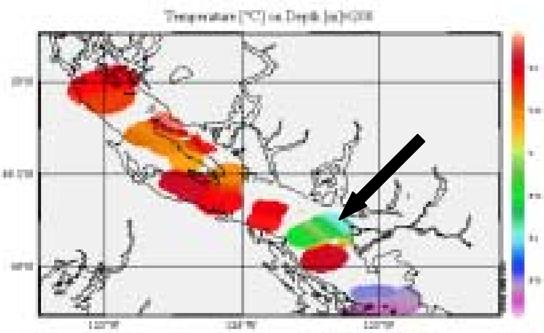


Figure 23 – Mid-depth intrusions, spring 1999

Two distinct intrusions are identifiable. A water mass advancing toward the north end of the strait is the first one. The temperature signal is not very clear but the dissolved oxygen and nutrient levels identify this water mass. The water is slightly colder, richer in dissolved O_2 and poorer in nutrients than the surrounding water. This intrusion is at the same depth as the sill. But the second identifiable intrusion, clearly visible in the 3 parameters, is deeper, indicating that this second intrusion has a higher density than the first one. It has adjusted its depth with the ambient water mass to have a uniform density.



This figure shows the status of the temperature in April 1999 at a depth of 200m. It is evident that the second intrusion observed in the previous figure occupies the whole width of the strait: the temperature difference is striking.

Figure 24 – Sectional view at 200 m, spring 1999

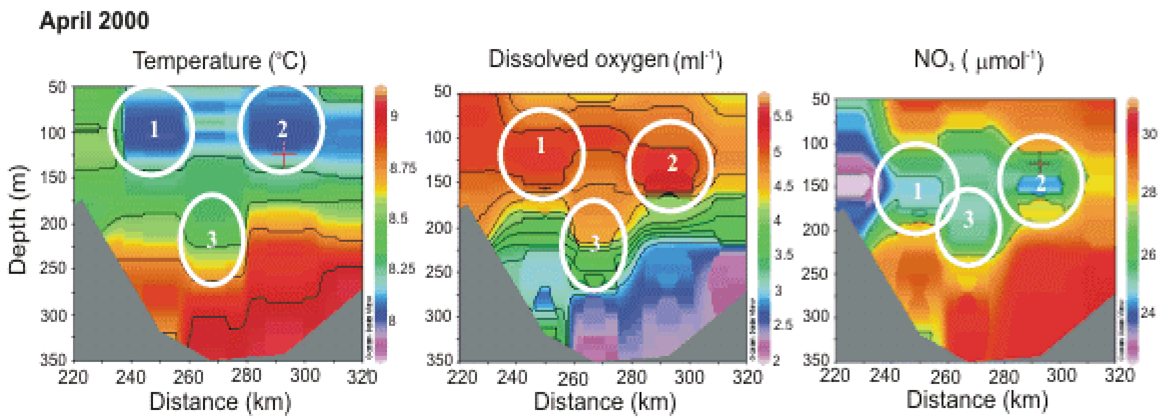


Figure 25 – Mid-depth intrusions, spring 2000

The signs of intrusion for April 2000 are much stronger than for the preceding spring: the observed differences for the 3 parameters are more obvious. Intrusions at different depths are observable as before; but here there exists 2 intrusions at shallower depth (1 and 2). The second intrusion is located in the northern strait. We see clearly that the third intrusion is between the first and second intrusion. This would indicate that the chronological order of the intrusions would have been 2, 3, then 1. 1 and 2 would have stayed at their initial depth and 3 would have sunk to be in equilibrium with the rest of the water mass.

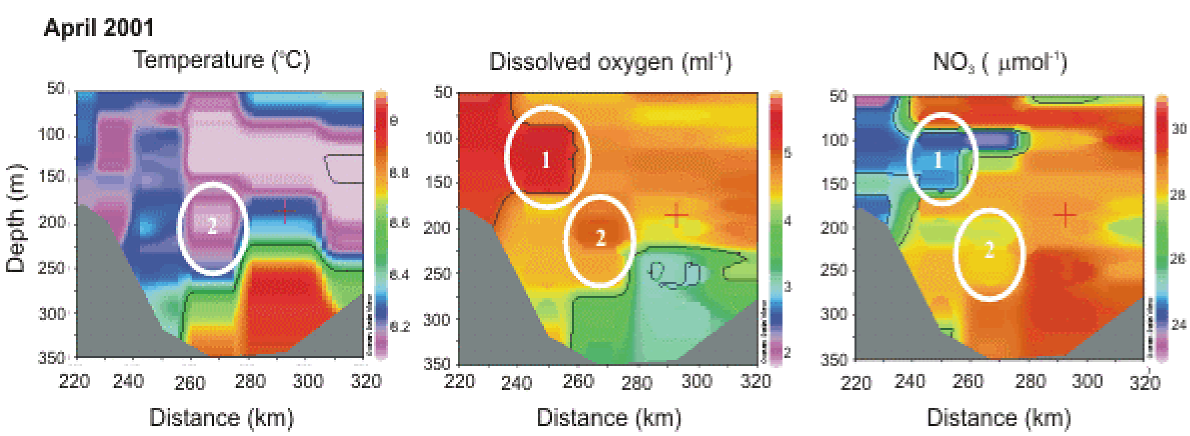


Figure 26 – Mid-depth intrusions, spring 2001

Several intrusions at different depths are visible. The first intrusion does not have a strong temperature signal, but we can observe that a water mass rich in dissolved O_2 and poor in nutrients is advancing into the strait. The second intrusion is less obvious but its presence is confirmed by the 3 parameters.

Finally, spring intrusions bring colder water containing more dissolved oxygen and fewer nutrients then the surrounding water mass. These characteristics correspond to those associated with the spring deep water renewal in the Strait of Georgia described earlier. The water flowing over Boundary Pass will penetrate at a depth determined by its density: along the bottom for the denser water, at about 200m depth for less dense water, and finally at sill depth (about 120m) for the lighter water. The intrusions have properties that are independent of the water column and are determined by the mixing of upper and lower water mass during their transport.

Summer 1999:

While intrusions are observed in the every spring, an intrusion is also observed in the summer of 1999. The dissolved oxygen is not a clear indicator of this but temperature and nutrient values clearly indicate its presence. Contrary to the characteristics of the spring intrusions, the water is warmer than that of the surrounding water (and always poorer in nutrients).

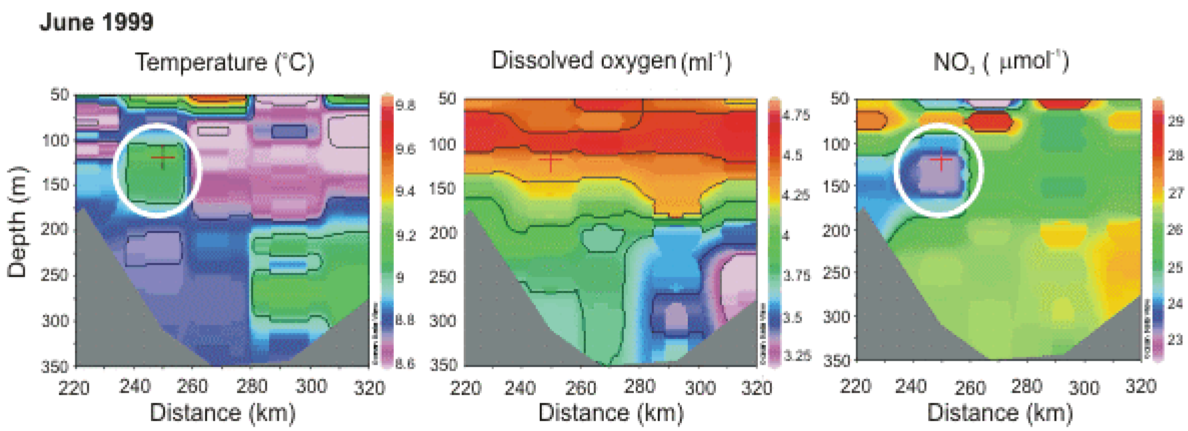


Figure 27 – Mid-depth intrusions, summer 1999

Winter 2001:

The mid-depth intrusions are better defined in the winter than in the spring. This is undoubtedly due to the fact that in winter, the deeper water in the Strait of Georgia is relatively warm (from 50m to the bottom) and very poor in dissolved O_2. Therefore, the observed differences in the intrusive water seem larger, but this does not necessarily indicate that intrusions are more important in terms of the volume of water involved.

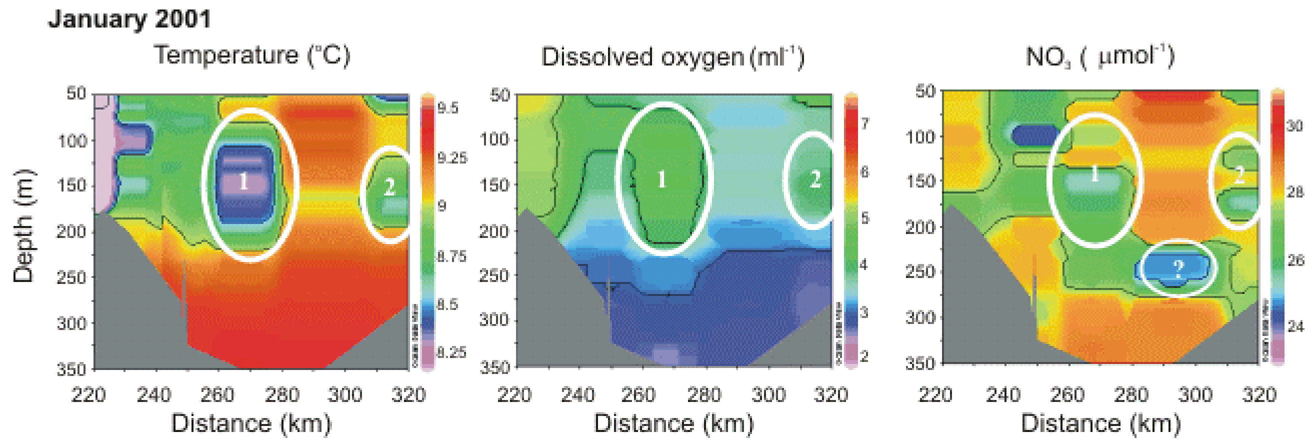
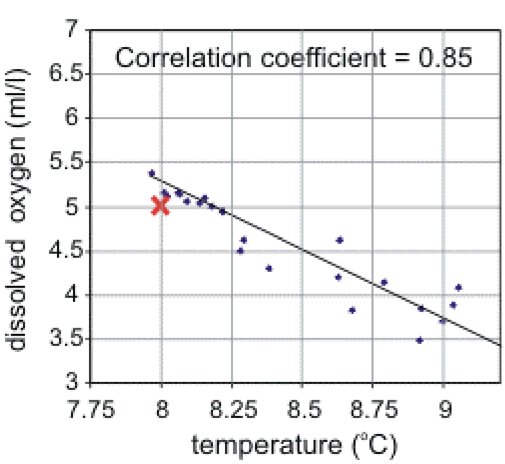


Figure 28 – Mid-depth intrusions, winter 2000

Two intrusions are identifiable at about the same depth. However, the nutrient signal is less well defined than that of the temperature or the oxygen. It nevertheless indicates the presence of nutrient poor water at a depth of about 250m**.** This is not observed in the temperature and the oxygen. Does this indicate the presence of an intrusion that has lost its characteristics of temperature and oxygen but has retained those of the nutrients? Or is it that the water properties of the intrusion only present a contrast for the nutrients?

It is realistic to think that the intrusions occur through the year, as past of the estuarine circulation. They are more or less visible depending on the contrast between their properties and those of the surrounding water. According to the seasons, the characteristics of the water in the Strait of Georgia change with upwelling, El Niño, wind, etc., and the water properties of the intrusions change more or less accordingly. The intrusions may an essential role in the ecosystem because of their importance in regulating the water exchange between the Strait of Georgia and the open ocean.

Path of an intrusion:



Considering the intrusion 1 of January 2001, the initial water temperature at the level of the sill is typically 8°C and the initial oxygen level is 5 ml/l. If we display the temperature-oxygen data (which are the 2 most prominent characteristics for this intrusion), for water between 50 and 200 m in depth, from the Boundary Pass sill up to station 39, the data points are strongly correlated, with the 2 parameters therefore evolving in the same way. This is consistent with the concept that after passing the sill, the intrusion propagates to the north of the Strait of Georgia while mixing progressively with the surrounding water mass.

Figure 29 – Temperature–dissolved oxygen diagram of intrusion 1 of January 2001

IV.2.2 - Relationship with the tidal cycle

Flow control at Boundary Pass:

The tidal currents are very strong at Boundary Pass, especially during the spring tides. These currents cause vigorous mixing of the water column. During weaker neap tides, the currents are much weaker and a stronger stratification is possible. Weaker neap tidal currents could then allow the dense water from Juan de Fuca Strait to pass the Boundary Pass sill and to continue into the Strait of Georgia without much mixing. The sill then functions as a gate, letting the water from Juan de Fuca Strait in during neap tides when mixing is at a minimum.

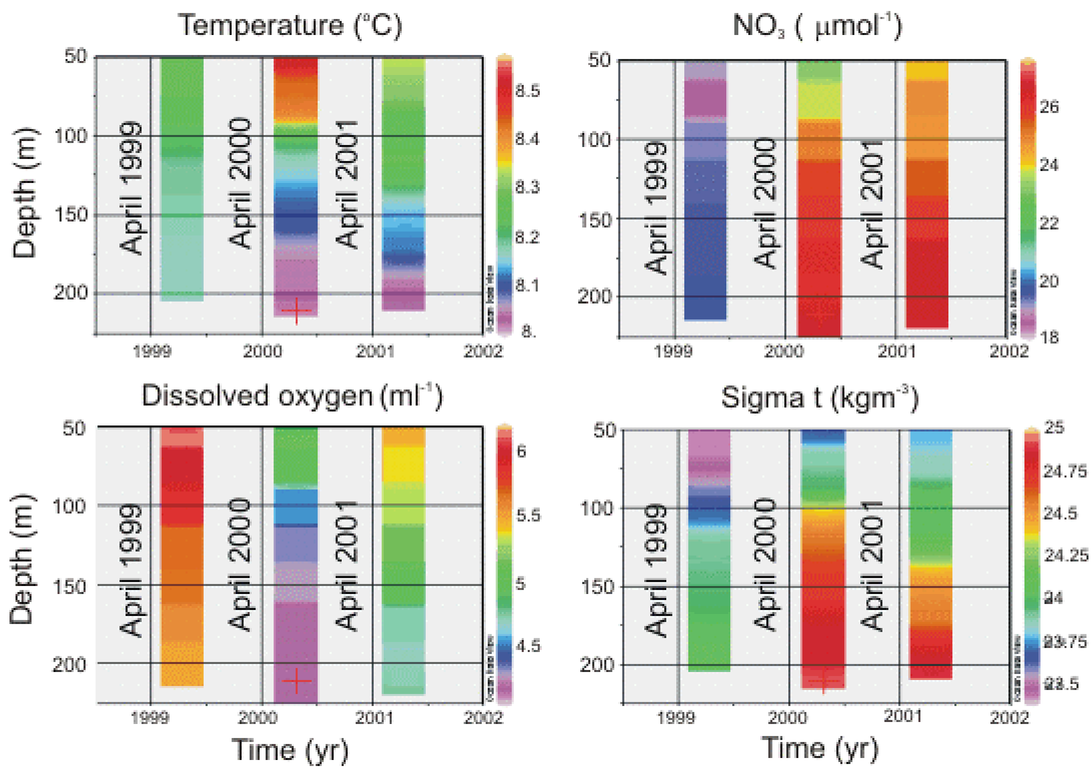


Figure 30 – Stratification at the Boundary Pass sill

The stratification over the sill during neap tides is illustrated in the figure above. Different parameters measured in April at station 56 are shown during 2 tidal stages: spring tide in 1999 and neap tide in 2000 and 2001.

It is evident that the water column is more homogeneous for April 1999 than for 2000 and 2001. It is also noticeable that during neap tides, the water near the bottom of the sill is denser than during the spring tide. Masson (2002) suggests that the intrusions are possible during neap tides when dense enough water is available at the bottom of the sill.

Advection velocities of the intrusions:

The fortnightly tidal cycle is typically 15 days: the time lapse between 2 neap or 2 spring tides. Assuming that the intrusions appear during neap tides, it is possible to estimate the advection velocity of the intrusions when 2 consecutive events are observed. Intrusions have previously been identified during 4 missions: April 1999, 2000 and 2001 and January 2001.

It is possible to determine the time separating the 2 neap tides by consulting the tide tables. By measuring the distance separating the 2 intrusions, the speed at which the water mass is displaced can be determined.

Mission	**Dates of the minimum tidal heights of the neap tides**	**Time interval between 2 consecutive neap tides**	**Distance between 2 consecutive intrusions**	**Advection speed**
April 1999	01/04 – 13/04	12 days	35 km	3.4 cm/s
April 2000	23/03 – 05/04 – 17/04	13 days – 12 days	45 km – 35 km	4 cm/s – 3.4 cm/s
January 2001	05/12 – 19/12 – 03/01	14 days – 15 days	30 km – 25 km	2.5 cm/s – 1.9 cm/s
April 2001	25/03 – 08/04	14 days	30 km	2.5 cm/s

The speed at which the intrusions are displaced northward is about 3 cm/s. This is similar to the currents measured in the Strait of Georgia in the area of the intrusions (Chang et al., 1976). The average speed over a long period is 3.56 cm/s., toward the north of the strait, near stations 39 and 40 at a depth of 200m.

Relationship between density and tidal cycle:

Why do certain intrusions remain at sill depth and others have a higher density that causes them to sink down the water column? Intrusions are formed during neap tides due to minimum mixing of the water column. It is the dense bottom water that passes the sill that forms the mid-depth intrusions. The weaker the tides, the stronger the stratification in the sill area, which could allow denser water to come into the Strait of Georgia.

The following method was used in an attempt to establish a link between the tidal amplitude that induces mixing of the water column and the observed intrusions:

- Find the dates for the minimum tidal heights during neap tides (same number as the observed intrusions),
- Calculate the maximum tidal height during neap tide (with the tidal height data 3 days before and after the minimum neap tide), and the maximum tidal height during spring tide (with data from 15 days before the mission),
- Establish a classification (A) of 1 to 9 for the missions having decreasing tidal amplitude and a classification (B) of 1 to 15 of the intrusions having decreasing tidal amplitude.

The higher the classification in A and B, the denser the water entering the Strait of Georgia and the deeper the intrusion will likely be.

Missions	Number of intrusions observed	Dates of the minimum tidal heights of the neap tides	Maximum tidal height of the neap tides (in m)	Maximum tidal height of the spring tides (in m)	Classification	
					A	B
April 1999	2	1/04 - 13/04	3.021 – 2.734	3.301	6	7-13
June 1999	1	22/06	2.893	3.966	4	9
August 1999	0	4/08	2.962	2.962	8	8
April 2000	3	23/03 – 5/04 – 17/04	2.7 – 3.078 – 2.955	2.955	9	14-4-10
July 2000	0	9/07	3.17	4.003	3	3
August 2000	0	21/08	2.771	3.546	5	12
January 2001	3	5/12 – 19/12 – 03/01	2.865 – 3.934 – 3.068	4.121	1	11-1-6
April 2001	2	25/03 – 8/04	2.671 – 3.196	3.196	7	15-2
June 2001	0	15/06	3.069	4.073	2	5

The table shows that:

- July 2000 and June 2001 have high tidal levels (A and B are small) and no intrusions are observed.

- There does not seem to be a direct relationship between the tidal amplitude at the time of the intrusions and the depth at which they were observed: intrusions 3 and 2 of April 2000 and 2001 have stronger tidal conditions that the intrusions observed at lesser depths.

- In January 2001, when the strongest tidal conditions were observed, intrusions were clearly identified.

The test, which has been developed to explain the existence of intrusions at mid-depths in the Strait of Georgia, is not conclusive. Obviously, other parameters have an effect on the formation of dense water that passes the Boundary Pass sill and reducing this process to tidal height only is too simplistic.

The intrusions must appear continuously during the year at each neap tide, as part of the deep return flow of the estuarine circulation. Their characteristics will not be determined uniquely by the level of tidally induced mixing, but also by the properties of the water masses being mixed at the sill relative to the properties of the water inside the strait.

IV.3 - Deep water in Juan de Fuca Strait

General characteristics:

The deep water mass in the Juan de Fuca Strait extends to a depth of about 100m at the Pacific end of the strait. Its thickness diminishes along the strait to just a few meters at the Victoria sill**.** It constitutes the deep water return current of the estuarine circulation forced by the freshwater discharge from the Fraser.

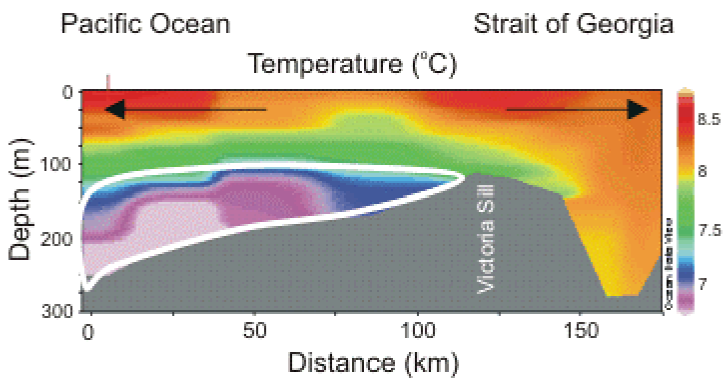


Figure 31 – Typical position of the deep water mass in Juan de Fuca Strait (April 1999)

The annual cycle of the deep water is influenced by the events that happen on the west coast of Vancouver Island and which have repercussions in the strait. The shift in wind direction, which causes upwelling during the summer and downwelling in the winter, produces a well marked annual cycle of water properties: upwelling brings relatively cold, salty, nutrient rich and oxygen poor water.

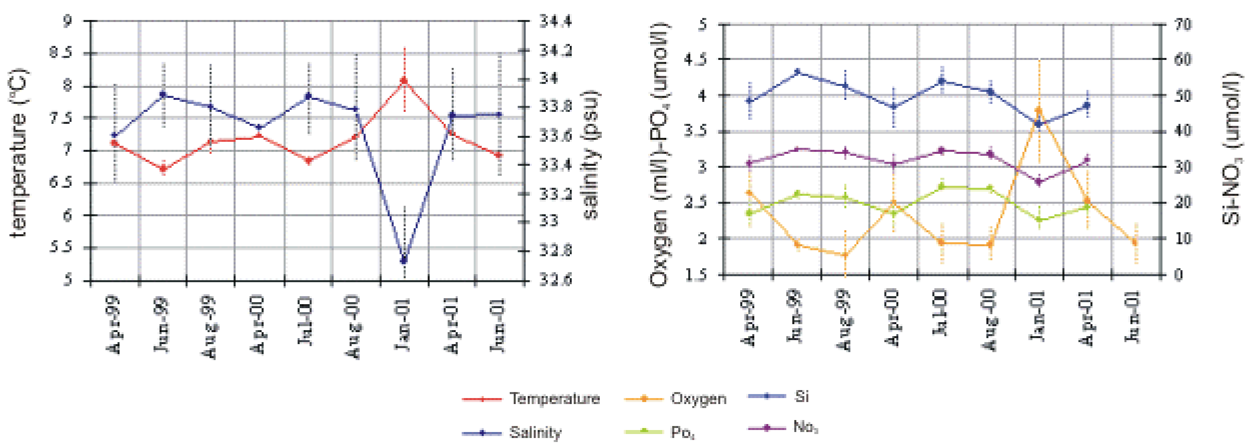


Figure 32 – Mean water properties of deep water in Juan de Fuca Strait (1999-2001)

The means are calculated from data measured at a depth of 100m to the bottom.

The 6 parameters behave in the same way and the periods of inversions are similar. Warm, salty water is observed in winter (January 2001). Upwelling has stopped and the cold nutrient rich water brought to the coast by upwelling has been replaced by warmer, less salty, oxygen rich and nutrient poor water. The arrival of upwelling, around June or July, is well defined in summer by a minimum in temperature and dissolved oxygen and a maximum in salinity and nutrients.

There are no abnormally high temperatures in 1999 as there were for the bottom water of the Strait of Georgia. The mean temperatures are the same for the 3 years for the same periods. The effects of the El Niño of 1998 have already disappeared in the Juan de Fuca Strait. The circulation in the Juan de Fuca Strait, much more open to the ocean, allows for faster exchanges.

The variability of the properties of the deep water in Juan de Fuca Strait is less than for the surface water. However it is strong for a deep water mass. The seasonal cycle is well defined but it is difficult to clearly identify the different seasons on the TS diagram below.

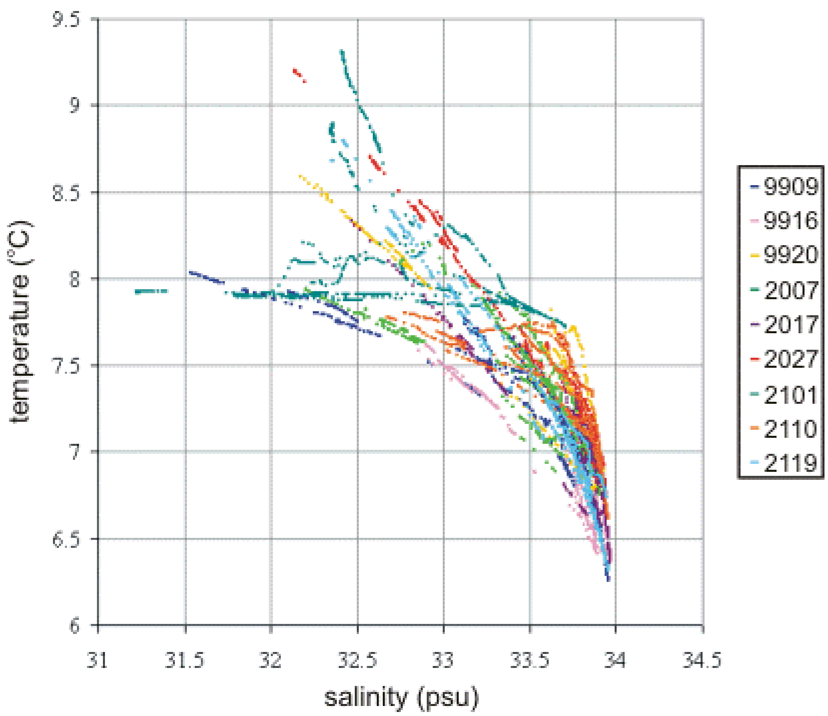
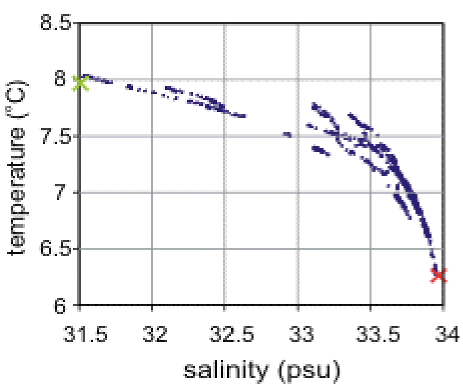


Figure 33 – TS diagram of the deep water in Juan de Fuca Strait (9 missions)

Propagation from the ocean to the Victoria sill:



The data of April 1999 is a useful to illustrate the evolution of the water properties in its progression along the strait.

The TS diagram for the deep water in Juan de Fuca Strait (April 1999, from 100m to the bottom) illustrates the mixing which happens along the strait starting with the initial water mass at the mouth of the strait. The basic characteristics of the water mass can be determined: about 34 psu and 6.25°C. The initial water mass is indicated with a red cross.

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Figure 34 – TS diagram of the deepwater in the Strait of Georgia (April 1999)

It is possible, using the method called the 'core method', to represent the concentration, in percent of the initial water mass, of the deep water mass along the strait. The core is the region where the water properties are at their minimum (or maximum) along an increasing (or decreasing) distribution. The core weakens gradually along its progression, due to mixing with the surrounding water. The concentration scales are as follows: 100% for the core characteristics (here 6.25 and 34 psu) and 0% for the end state at Victoria sill (8°C and 31.5 psu, indicated with a green cross on the previous figure). By converting the temperature and salinity data into percentages, the position of a point on the TS diagram determines the proportion of the initial water mass left from the starting point.

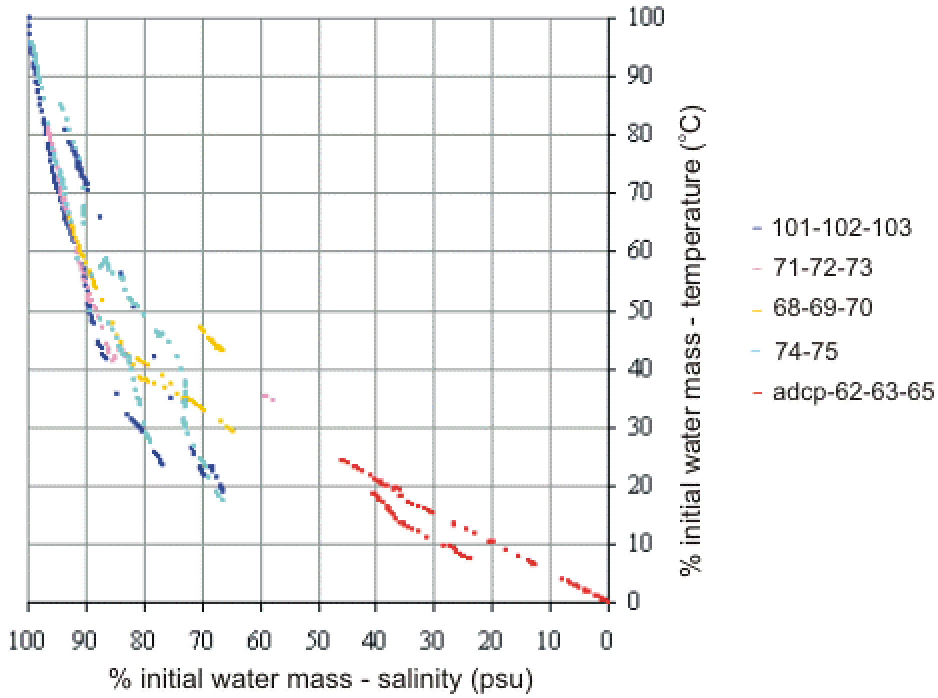


Figure 35 – Mixing of deep water in Juan de Fuca Strait (April 1999)

The lines transverse to the strait, which are made of 2 to 4 stations, are represented by different colours to visualise the progressive mixing along the strait.

Station Group	Position / entrance to the strait	Range of %	
		Temperature	Salinity
101-102-103	0 km	100-20%	100-65%
71-72-73	20 km	100-35%	100-55%
71-72-73	60 km	80-40%	95-85%
68-69-70	85 km	65-30%	90-65%
ADCP-62-63-65	130 km	25-0%	50-0%

The group 101-102-103 represents the source at the ocean boundary and, therefore, the initial core (the concentration is 100%). The group 74-75 shows no major differences: but the decrease in the properties of the water mass along its course is evident in the next 3 groups of stations.

The dissolved oxygen and nutrient diagrams confirm that the deep water in Juan de Fuca Strait originates from the ocean and moves toward the Victoria sill.

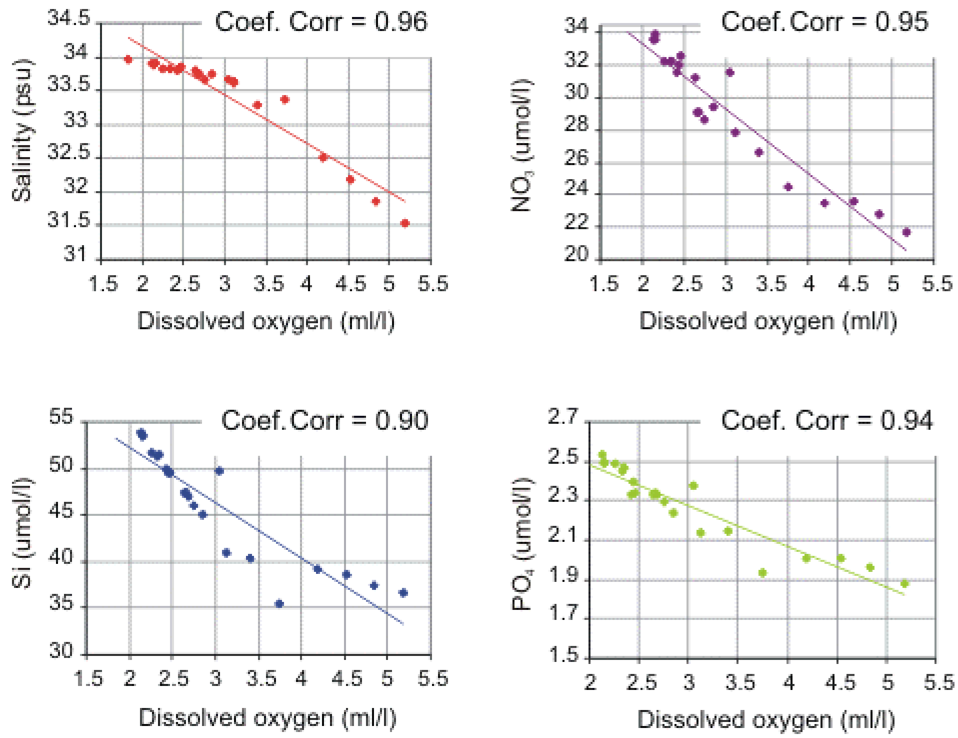


Figure 36 – Oxygen-nutrient diagrams of deep water in Juan de Fuca Strait (April 1999)

These parameters evolve in the same way (the correlation coefficients are high). This is consistent with the idea that they originate from the same water mass and are dissipated at the same rate. It is assumed that changes in concentration are mainly caused by mixing with the surrounding water and that local biological activity only plays a minor role in changing the measured properties

IV.4 - Fraser River plume

The Fraser River discharges into the Strait of Georgia near the city of Vancouver. The fresh water flows through 2 main arms of the river, with 87% of the flow in the south arm.

Its discharge follows a strong seasonal cycle, with maximum flow in early summer during snowmelt. The freshet period lasts for about 3 months. There is also significant year to year variability to the flow. In the following figure, the flow in 1999 is significantly larger than in 2000.

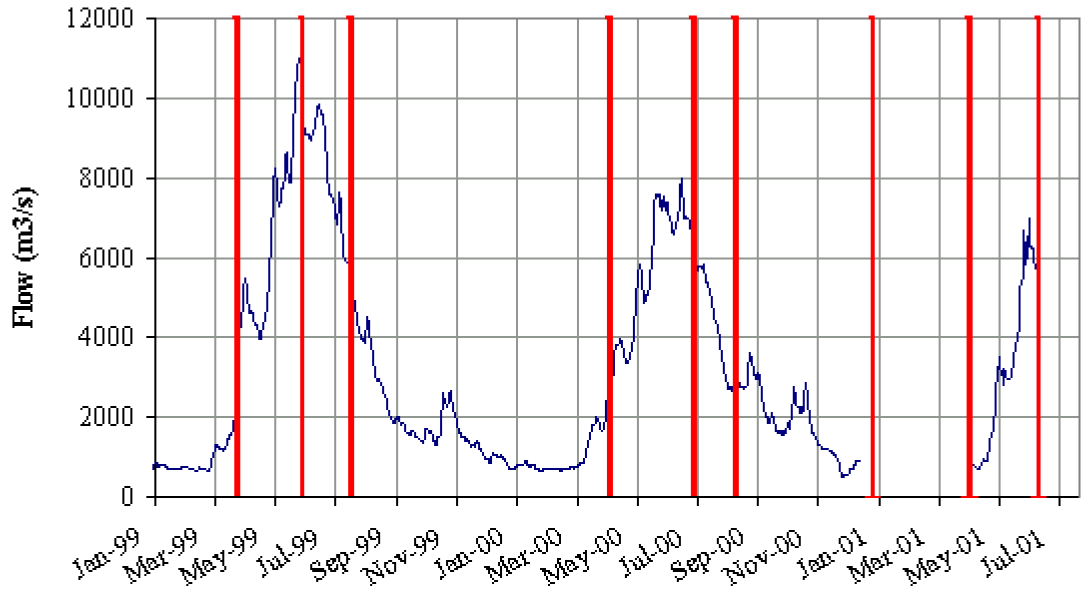


Figure 37 – Fraser River discharge (1999-2001)

The dates of the missions are marked in red.

There was no data collected between December 2000 and April 2001.

The missions were planned to collect information at the beginning, during and after the freshet. In addition, data was collected in January 2001 when the Fraser River discharge is at its lowest.

General characteristics:

Mean values were computed for the top 10 meters of the water column at stations near the Fraser River (37 to 46).

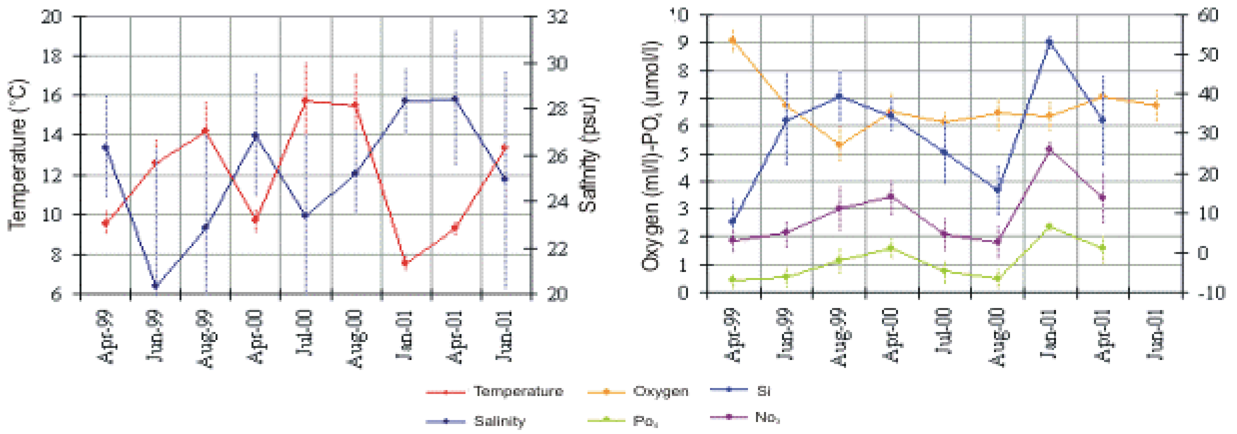


Figure 38 – Mean values of the water properties of the Fraser River plume (1999-2001)

The different parameters vary within a larger range than in the case of the other water masses studied (over 8ºC for temperature and 8 psu for salinity), leading to larger standard deviations. This is due to the fact that the surface water is more strongly affected by the wind, heat from the sun, fresh water, etc. This causes a sampling problem for this area because of the stronger horizontal and vertical gradients of the water properties. The position of the plume changes quickly due to winds and tides which makes it difficult to accurately measure the characteristics of the plume. This problem is a source of variability in the data.

Obviously, the temperature is higher in the summer, reaching a maximum in August. The salinity varies inversely with a minimum in summer associated with the maximum freshwater discharge. The salinity reached lower values in the summer of 1999 when the freshet was stronger. The nutrients vary accordingly, but with larger year-to-year variability as is seen in the summer of 1999 and 2000. In January 2001, the nutrients reached a maximum because of the reduced biological activity in winter. The summers of 1999 and 2000 show different characteristics: larger values in 1999 than in 2000. The oxygen reaches its maximum in April of the 3 years

It is difficult to separate the effects of the biology from the effect of advection of water into the region because the biology is very active near the surface. Station 42 (located close to the river mouth) illustrates this limitation. The water properties measured at 40m are displayed to show the contrast between the water of the river plume and the water of the strait.

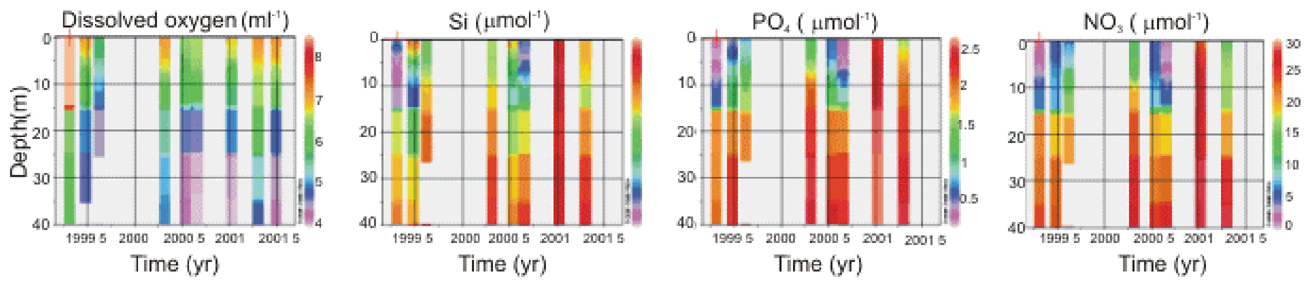


Figure 39 – Dissolved oxygen and nutrients (station 42)

The Fraser River plume always has large dissolved oxygen and low nutrient values inside the strait.

In the TS diagram, the properties of the plume are more dispersed than for the deep Juan de Fuca Strait but the water properties are well grouped according to the seasons.

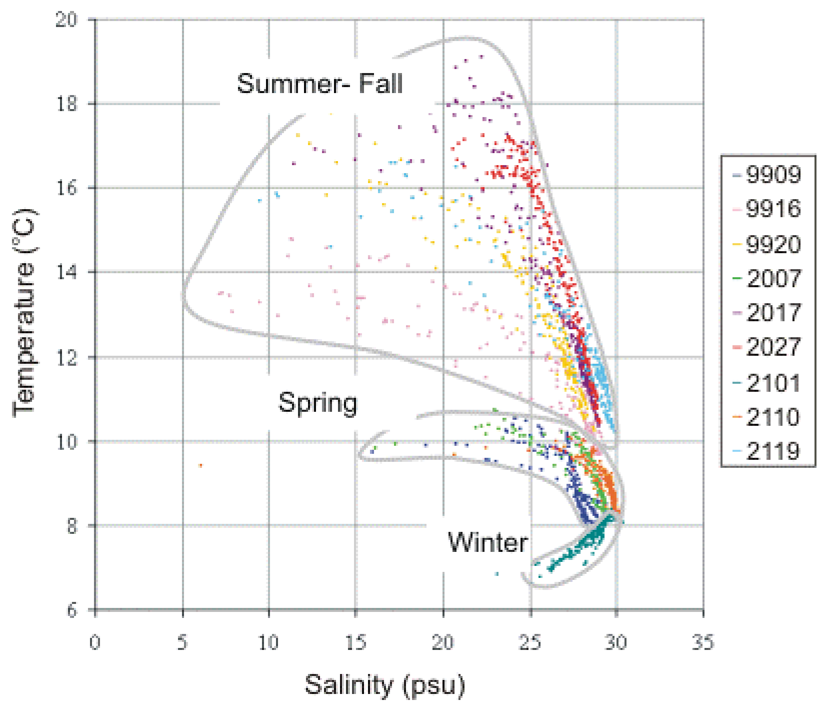
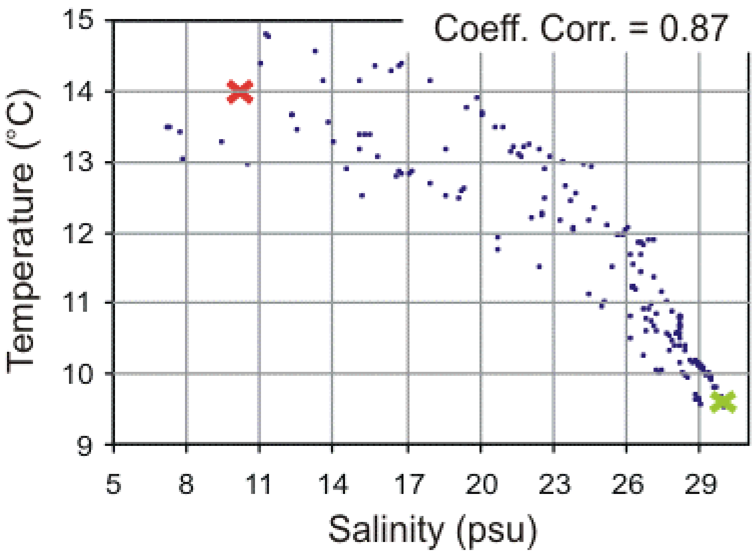


Figure 40 – TS diagram of the Fraser River plume (1999-2001)

Path of the river water:

The water flowing from the river into the strait can be displayed in the same way as was done for the deep water in Juan de Fuca Strait.



The summer of 1999 (June) was the strongest freshet of the Fraser River and this data set is used here. The TS diagram shows a linear distribution with a high correlation coefficient. The initial water mass flowing from the river (red cross) has scattered characteristics with temperature of about 14ºC and salinity 10 psu. The end point is chosen as station 61 in Haro Strait where the water is at 9.5ºC and 30 psu (green cross).

Figure 41 – TS diagram of the Fraser River plume (June 1999)

The temperature and salinity data are then converted into percentages of initial water mass.

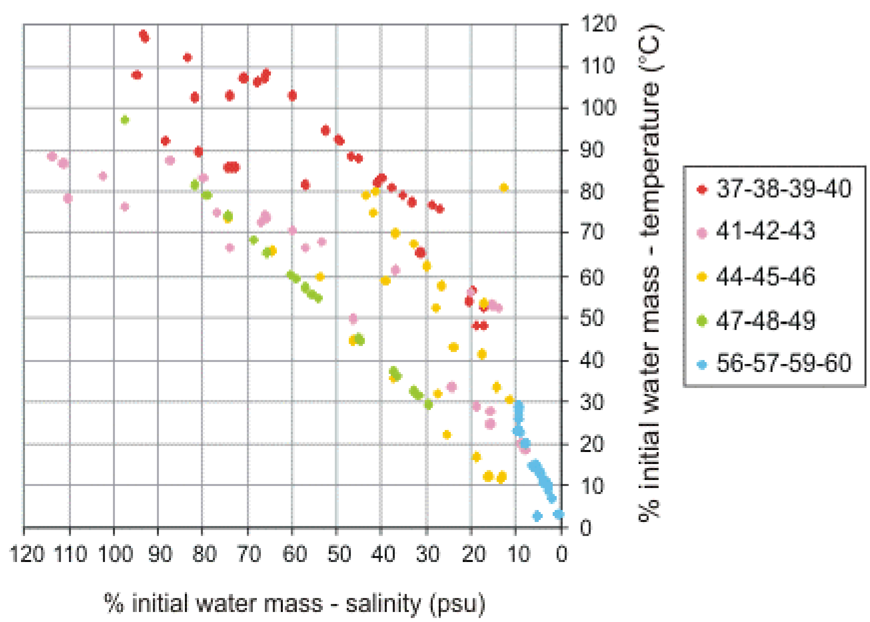


Figure 42 – Mixing rate of river water (June 1999)

The percentages reach values larger than 100, because the characteristics of the initial water mass were taken as average values.

The results are less conclusive than those obtained for the deep water in Juan de Fuca Strait:

Group of stations	Position / estuary (north arm)	Range of %	
		Temperature	Salinity
37-38-39-40	10-40 km	120-50 %	100-20 %
41-42-43	25-40 km	90-20 %	115-10 %
44-45-46	40-50 km	80-10 %	65-15 %
47-48-49	60 km	100-30 %	100-30 %
56-57-59-61	70-110 km	30-0 %	10-0 %

The results are scattered but so are the positions of the stations relative to the Fraser River mouth. The values decrease moving away from the mouth. The temperature and salinity decrease in the same way.

Very little oxygen and nutrient data is available, as the stations here are sparse and not very deep. But the diagrams show clearly that the parameters vary consistently. It indicates that the water mass originates from the river mouth and is progressively diluted as it flows seaward into Juan de Fuca Strait. An anomaly exists for the silicates; is it the biology in this case that modifies it or is it a consequence of the spatial gradient of the plume?

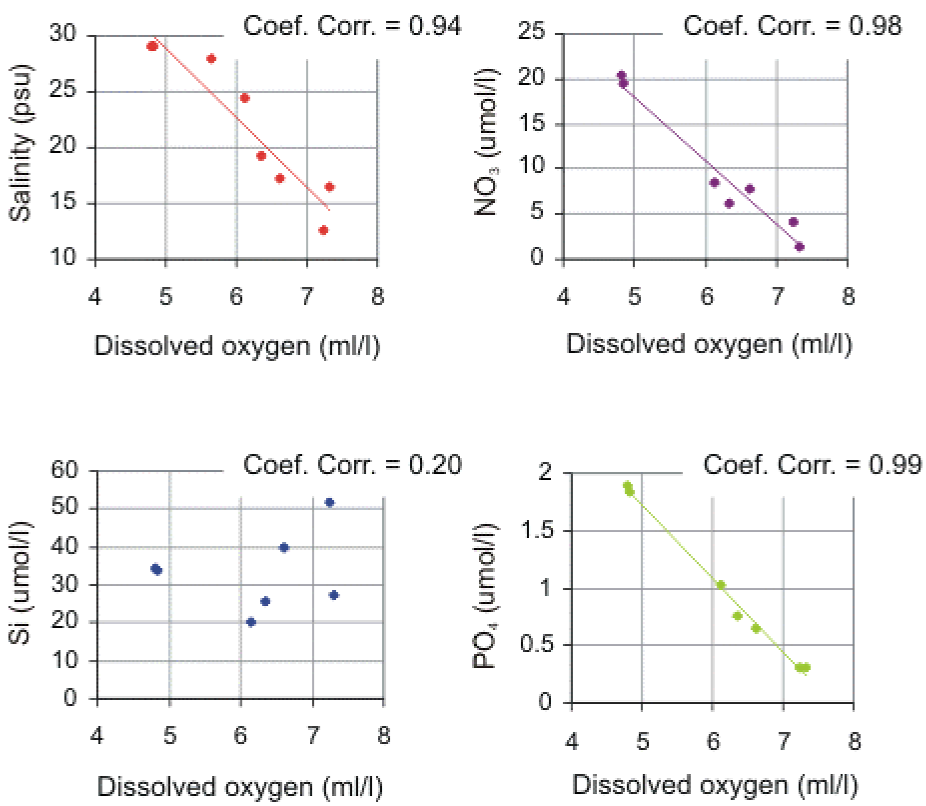


Figure 43 – Oxygen-Salinity and Oxygen-Nutrient diagrams, Fraser River plume (June 1999)

IV.5 – Surface and deep water mass

The study of the various water masses has highlighted the fact that the seasonal cycle of the water temperature at the bottom and at the surface is reversed. The deep water reaches its maximum in winter when the surface water is at its coldest. It is interesting to determine at what depth the tendencies change.

Summer and winter are represented by July 2000 and January 2001, respectively. The means are calculated in slices of 25m for the 2 seasons, over the whole area and separately for the 2 straits.

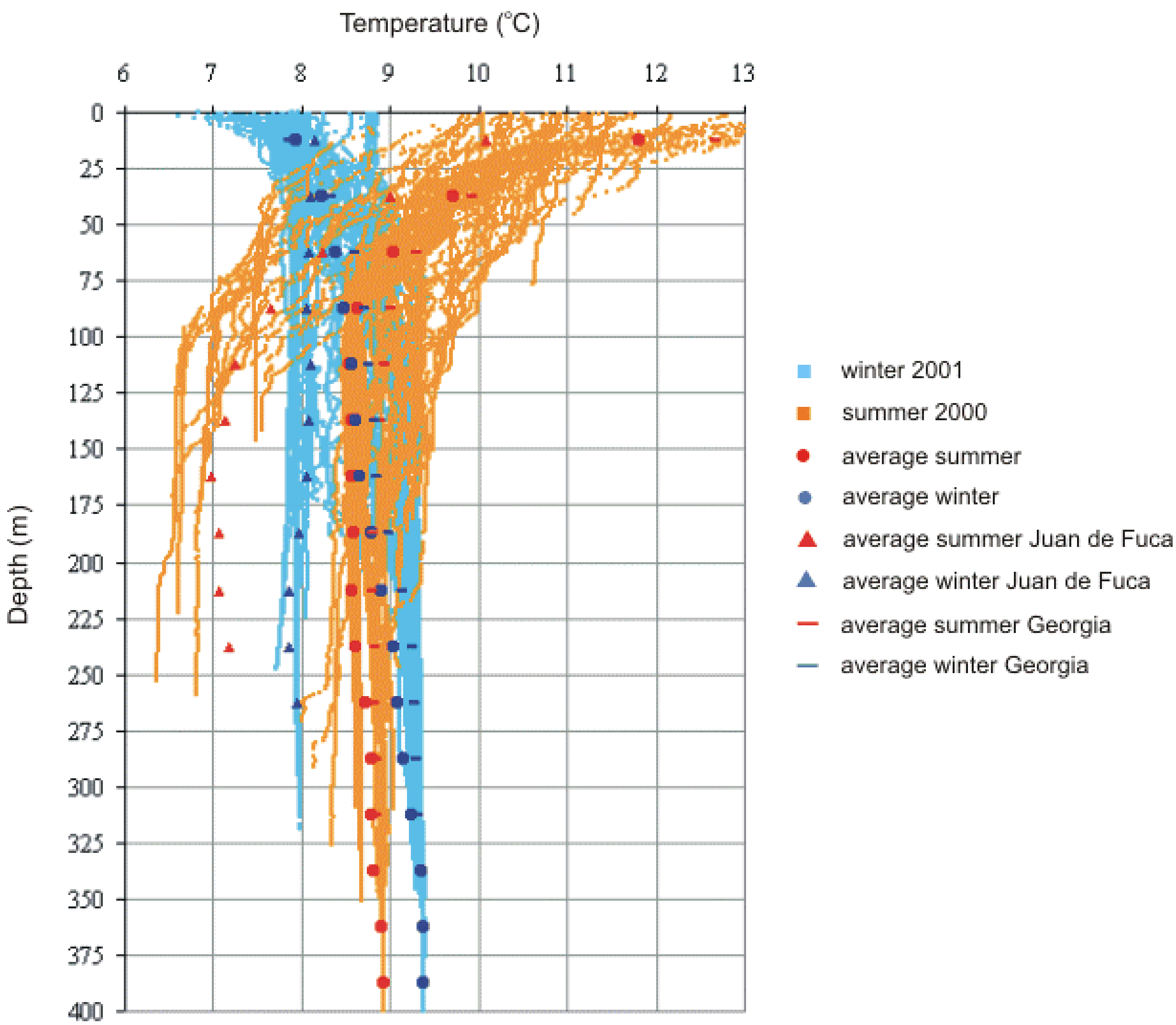


Figure 44 – Temperature averages in the Juan de Fuca and Georgia Straits (July 2000, January 2001)

The depth at which the change between surface and deep regime occurs is at the intersection of the mean temperature curves of the winter and summer.

The 0-75m layer is warmer in summer than in winter for the 2 straits. In the Strait of Georgia an intermediate layer, extending from about 125 to 200 m, has a mean temperature that is similar for the 2 seasons; it is a transition zone. Finally, the water below 200 m is considerably warmer in winter than in summer.

In Juan de Fuca Strait, there is no intermediate zone. The water mass goes from a surface to a deep regime starting at a depth of about 75m. On the other hand, the intermediate layer in the Strait of Georgia extends from 125 m to 200m. Above this, the water is warmer in the summer than in the winter and inversely below it.

There doesn’t appear to be such a transition zone in the Juan de Fuca Strait. The intermediate layer in the Strait of Georgia may be a result of the mid-depth intrusions entering the strait from the sill area. The water mass forming these pulses are determined by mixing at the sills and have characteristics distinct from both the surface and bottom water. Such intrusions do not occur in Juan de Fuca Strait.

-V-

Conclusion

This project has the advantage of involving several different aspects of oceanography. I have succeeded in addressing all the aspects of the problem. The fieldwork taught me about all the difficulties of collecting data. During the data processing, I learned to use both IDL and ODV in order to construct a small database. Finally, I was able to do some data interpretation and identify some interesting processes. All aspects of this work were stimulating. The data is recent and it was rewarding to process data I had acquired. Above all, the main satisfaction came from being able to identify certain mechanisms and linking those to what had been published before in the scientific literature. Especially gratifying was the identification of the mid-depth intrusions.

I was able to develop simple techniques to examine the progressive mixing of the deep water mass of Juan de Fuca with the surface waters of Strait of Georgia. Comments and encouragement from Diane Masson were a great help during my work term

I was able to learn about Vancouver Island from not only a scientific point of view but also its natural beauty. I lived for 2 months in Canada; conscious that the environment and the oceans are essential and it is imperative to improve our knowledge so they can be better protected.

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