EFFECTS OF COASTAL CURRENTS ON PACIFIC SALMON MIGRATION
INFERRED FROM A FINE-RESOLUTION NUMERICAL MODEL

By

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Abstract

Experiments performed using a numerical model of salmon homing migration show that coastal currents can significantly affect sockeye salmon (*Oncorhynchus nerka*) returning on the northern coast of British Columbia. The numerical model combines results from a fine-resolution hydrodynamic model of the waters off northern British Columbia with a spatially-explicit individual-based model of salmon migration. Results suggest that coastal tidal currents affect the return timing by causing the number of returning salmon to vary at a cycle corresponding to the dominant tidal period of 12.4 h. Such variations are associated with patchiness in the salmon distribution due to spatial variations of the tidal field. Moreover, results showed that wind-driven currents can cause the number of returning salmon to vary at storm periods of 3 to 18 days. Therefore, the salmon interactions with the coastal currents could provide an explanation for some of the variability seen in data of returning salmon. Simulations of continuous salmon diversion for 1992 to 1994 suggest that currents alone cannot produce a large interannual variability for these years. However, these simulations showed a large variability at storm period within the summer, which could have influenced the calculation of the Northern Diversion Rate. The findings of this thesis can then help to design appropriate sampling strategies, such that aliasing problems due to coastal currents are minimized.
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Fisheries scientists are turning their interest towards the interaction between fish and their environment. The variability seen in fisheries abundance could be caused by fishing, but it could also be caused by large variabilities in the environment such as climate changes (Beamish, 1995). The ocean conditions can also have an effect on salmon migration at shorter time scales. For example, a study found that currents can alter the return timing of migrating Sockeye salmon (Thomson et al., 1994) and recent sampling reveal that salmon tend to avoid areas of warm sea surface temperature (Welch et al., 1995).

With many variables that can influence salmon migration, it is a difficult problem to isolate the effect of each component and understand how the ocean conditions interact with salmon life history. Bio-physical modeling is being currently used to describe these complex ecosystems because of their flexibility in focusing on chosen behaviour mechanisms and physical environment variables. Simple scenarios can be simulated to understand the bio-physical interactions separately before proceeding to more complex models. An understanding of the relationship between salmon and their physical environment could be useful in the design of appropriate sampling strategies and could help explain some of the variability seen in salmon data.

The goal of this thesis is to understand how the coastal currents affect the spatial distribution and return timing of migrating salmon returning through Queen Charlotte
Chapter 1. Introduction

Sound area. Ocean currents could significantly affect salmon migration where the magnitude of the current is close to salmon’s swimming speed, such as in the coastal ocean. Close to the northern coast of British Columbia, tidal currents are of the order of 0.5 m s\(^{-1}\) and wind-driven currents are of the order 0.1 m s\(^{-1}\). These values are comparable to the salmon’s swimming speed of one body-length per second. The tidal currents in the area vary over diurnal to semi-diurnal period, while the wind-driven currents change at periods associated with weather systems passing over the Northeast Pacific. These two components of the currents should affect the salmon at different time scales and it is worthwhile to study them separately.

A possible modelling strategy would be to simulate the physical environment from a coupled atmosphere-ocean model of the North Pacific, which would include coastal areas and estuaries. A weather prediction model could be used to derive atmospheric pressure, temperature fields and winds. These fields would then force a hydrodynamic model to simulate large scale ocean circulation associated with atmospheric pressure systems, along with the circulation associated with perturbations due to storms, tides and changes in water density.

Salmon could then be simulated for their whole ocean phase from the time they enter the estuaries until they return. The simulations would include feeding strategies, where food sources could be simulated from an ecosystem model coupled with the hydrodynamic model. Based on food intake and potential interactions with predators, the model could also simulate salmon growth and mortality. Behaviours of temperature preference and changes in swim speed and orientation could also be included.

The modelling strategy used in this study, however, focus on salmon returning to the coastal environment since previous numerical studies (Kolody and Healey, 1998) indicate that open ocean processes cannot explain the variability observed in coastal migration route and that coastal processes might be more important than offshore. Coastal currents
on the coast of Northern British Columbia are mainly forced by tides, wind and buoyancy forcing. The bathymetry and stratification also play an important role in the coastal circulation, mainly in tidal currents. Therefore, these forcing should be included in the coastal currents simulations. Studies indicate that salmon homing migration is direct and that they do not feed during their return home. An ecosystem model simulating food ability is therefore not necessary in this study and changes in swim speed and orientation due to feeding are also not included.

The modelling strategy used here does not intent to simulate migrating salmon which are feeding, avoiding predators, having temperature preference and following the scent of their rivers. It does simulate, however, salmon swimming directly towards Vancouver Island, at one body-length s\(^{-1}\), and being advected by tidal and wind-driven currents. Some randomness in orientation is also included to account for other possible behaviours.

In order to perform numerical experiments of salmon migration subject to tidal and wind-driven currents, a spatially-explicit individual-based model of salmon migration was developed. The numerical model combines a physical and a biological component. The physical component is a hydrodynamic model of the northern coast of British Columbia that predicts the coastal currents at a fine scale both in space (5 km) and in time (1 h). The biological component simulates salmon swimming at one body-length per second towards Vancouver Island; their positions are tracked individually.

Since the numerical model is computationally consuming in time and space, a regression method is used to predict ocean currents from wind data for the years 1992 to 1995. The results obtained from these predictions are used in an interannual variability study of the effects of coastal currents on salmon migration.

Chapter 2 outlines the life history of sockeye salmon, describes the physical oceanography of the British Columbia coast and discusses various bio-physical modeling efforts. The individual-based model of salmon migration is described in chapter 3 where both
model components, physical and biological, are discussed. The model results assessing the effects of tidal currents and wind-driven currents are presented in chapters 4 and 5 respectively. A study of interannual variability, including the currents predicted from a regression method, is presented in chapter 6. The discussion, which includes a comparison with data, is found in chapter 7. The conclusions, in chapter 8, emphasize the main findings of this work.
The effects of the physical environment on sockeye salmon (*Oncorhynchus nerka*) return timing and spatial distribution are poorly known, particularly while the salmon are in their oceanic phase, and the mechanisms proposed for their homing migration are also still controversial despite many studies done on the subject. This chapter outlines the life history of salmon and the current thinking on the effects of ocean conditions on their migration. The physical oceanography of the northern coast of British Columbia is described and various ecosystem models are discussed.

### 2.1 Sockeye salmon

#### Sockeye salmon life history

Sockeye salmon typically start their migration towards the ocean in July, after spending approximately one year in fresh water (Healey and Groot, 1987; Pearcy, 1992). To reach the ocean from the Strait of Georgia and the Fraser River, juvenile salmon have the choice between two routes (figure 2.1): south through Juan de Fuca or north through Johnstone Strait. The latter route seems to be preferred (Healey and Groot, 1987). They then proceed northward along the coast towards the open ocean for a period of three months. In November, for their first winter at sea, salmon migrate south-west into the open water of the Gulf of Alaska. They remain in their oceanic feeding grounds for nearly two years (Pearcy, 1992). Fish tagging experiments indicate that, after their
ocean phase, salmon migrate rapidly from the open Gulf of Alaska directly to their home stream in the spring. They return to spawn in their natal stream from the coastal ocean either through Juan de Fuca Strait or Johnstone Strait. The choice of either route varies from year to year and the ratio of salmon returning through Juan de Fuca Strait versus Johnstone Strait is referred to as the “Northern Diversion Rate”.

The mechanisms involved in the migration of sockeye salmon from the open ocean feeding areas to their natal streams are not yet fully understood. Their observed direct and rapid migration caused a proposed theory of random or nearly-random drift (Saila and Shappy, 1963) to be discarded (Groot and Quinn, 1987; Healey and Groot, 1987). More information is needed about their orientation mechanisms, their swimming speed and the interaction with their environment, such as ocean currents, temperature and salinity.

**Sockeye salmon orientation**

Sockeye salmon seem to possess an ability to orient themselves precisely. It is still unclear whether salmon possess abilities of compass orientation, bi-coordinate navigation, or a combination of both (Quinn, 1990). Compass orientation indicates the ability to move in a particular compass direction (e.g. south-east), even in an unfamiliar territory (Healey and Groot, 1987). A proposed explanation is that salmon may be sensitive to the magnetic field of the earth (Leggett, 1977). Bi-coordinates navigation, or goal orientation, implies that the animals have the ability to navigate towards a specific geographic goal from an unfamiliar territory (Healey and Groot, 1987).

**Sockeye salmon swimming speed**

Various experiments in ultrasonic tracking (Groot *et al.*, 1974 ; Stasko *et al.*, 1976; Madison *et al.*, 1972) report adult salmon ground speeds (a sum of ocean currents and
Figure 2.1: Schematic diagram showing the two possible return migration routes of the Fraser River Sockeye salmon: either through Juan de Fuca or Johnstone Strait (after Hsieh et al., 1991)
active swimming) of $0.44 \text{ m s}^{-1}$ to $0.51 \text{ m s}^{-1}$, or about one body-length per second, but these estimates are highly variable. For example, daily variations were observed by Stasko et al. (1976) where some salmon were purely passive (i.e. drifting with the current) during the night. Daily variations in speed were also observed by Groot et al. (1974). Tracking experiments showed that salmon were influenced by tidal currents and tended to be passive during ebb tides. Moreover, various physiological studies indicate that the swimming speed of a fish can depend on such factors as its size and the temperature of the surrounding waters.

**Effects of water circulation on sockeye salmon**

In regions where the currents are comparable in magnitude to the fish swimming speed, such as in the coastal environment and the open ocean for adult salmon, or when the currents act for a sufficiently long time scale, salmon migration paths are likely to be deflected by the currents. Various simulations (Dat et al., 1995; Thomson et al., 1994; Peterman et al., 1994; Hamilton et al., 1985) included the effects of ocean currents in the calculations of migrating salmon trajectories and showed that surface ocean currents can affect the migratory route of salmon. The temporal and spatial ranges of variability that would affect salmon migration paths are not yet well known. For example, tidal currents of order of $0.5 \text{ m s}^{-1}$ and wind-driven currents of the order of $0.1 \text{ m s}^{-1}$ could be large enough compared to the salmon swimming speed to deflect salmon migration path and to affect the salmon return timing and the distribution of a salmon run.

**Effects of temperature and salinity on sockeye salmon**

Sockeye salmon migration might also be affected by their surrounding water temperature. Blackbourn (1987) found that salmon return timing was affected by sea surface temperature. In warm winters, salmon were found further north in the Northern Pacific
and therefore returning late compared to cold winters. Welch et al. (1995) found that salmon have preferred temperature limits in the spring and summer. Moreover, proposed theories on salmon migration (Leggett, 1977) include the possibility of salmon following the fresh water signature, or some other trace property, of their natal stream to return home.

2.2 Oceanography of the British Columbia coast

The current in the open ocean is mainly composed of two components: the tidal currents and the non-tidal currents (Thomson, 1981). The latter includes all processes other than astronomically driven tidal forces. The non-tidal current are large scale systems driven by the prevailing surface winds and by horizontal density gradients set up by differential heating of the ocean. These non-tidal current tend to dominate in the open ocean while tidal currents are more important on the coast.

The currents of the outer shelf of the northern coast of British Columbia are associated with the quasi-steady oceanic gyres of the North Pacific as well as with local winds and buoyancy sources (figure 2.2). The eastward North Pacific Drift and Subartic Current split into two flows as they reach the eastern North Pacific coast: the northward Alaska current and the southward California current (Thomson, 1981). The Alaska current is part of the cyclonic gyre flowing around the Gulf of Alaska and the California current is part of the sub-tropical gyre. The current flow increases in the winter when the Aleutian Low in stronger and the circulation is reduced in summer.

The main channels around the Queen Charlotte Islands are Dixon Entrance at the north of the Islands, Hecate Strait at the east of the Islands and Queen Charlotte Sound between the Queen Charlotte and Vancouver Island. Dixon Entrance is 170 km in length and is composed of two 400 m deep channels separated by Learmont Bank, a shallow
**Figure 2.2:** Prevailing currents in the North Pacific Ocean. Double arrows are intense boundary currents (speeds typically 1-2 m s$^{-1}$). Current speeds are less than 0.25-0.5 m s$^{-1}$ over most regions. The broken arrows correspond to a winter current off the Oregon-Washington coast (after Thomson, 1981).
ridge of 35 m depth. Hecate Strait is a 220 km long valley with a depth of nearly 50 m at the north and near 300 m at the south. Queen Charlotte Sound is composed of shallow banks and three broad troughs (figure 2.3).

The coastal circulation is mainly forced by tides, winds, atmospheric pressure gradients and river runoff (Thomson, 1989). Offshore, the vertical structure of the water column is a two-layer system with the pycnocline near a depth of 200 m. The top layer is stratified with surface warming and dilution from river runoff in the spring. The bottom layer is well-mixed. The water over the shallow banks in Queen Charlotte Sound tends to be continuously mixed by tides. The salinity at the entrance of Johnstone Strait tends to be fairly constant throughout the year and the change in stratification is due to the surface warming in summer (see Appendix A).

The tide propagates northward along the coast of North America, where one branch enters Hecate Strait and the other enters Dixon entrance. They meet at the northern end of Hecate Strait (Crawford et al., 1988; Crawford et al., 1990). It is a predominantly mixed semi-diurnal tide. The main components are the principal lunar component, $M_2$, and the mixed diurnal component, $K_1$. Their typical peak tidal currents are about 0.3 and 0.1 m s$^{-1}$ respectively (Crawford et al., 1985). The tidal heights range from 3 to 5 m.

The winds along the northern coast of British Columbia are controlled by two semi-permanent atmospheric pressure systems. In winter, the Aleutian Low brings strong south-southeasterly winds. Along the outer coast, these winds generate a net Ekman transport towards the coast within the top 100 m of the water column. When this transport is blocked by the coast, the sea level on the coast rises, which creates geostrophically balanced northward coastal current in the upper layer. If the wind dies, this current disappears. At the entrance of Queen Charlotte Sound there is no coastal barrier and the surface waters are directed northward into the sound and into Hecate Strait as a well
Figure 2.3: Bathymetry of the Queen Charlotte Islands region; depth is in meters (after Thomson, 1989).
defined relatively warm current. Typical speeds of this current are $3\%$ of the wind speed (Thomson, 1989). In summer, the North Pacific High moves north and brings north-northwesterly winds to the northern coast of British Columbia. These winds generate a net Ekman transport away from the coast which promotes coastal upwelling along the west coast of Vancouver Island (Ikeda and Emery, 1984) and the Queen Charlotte Islands. Strong inertial-period currents have also been observed in Queen Charlotte Sound (Thomson and Huggett, 1984). Near Cape St-James, at the tip of the Queen Charlotte Islands, a persistent outflow was found (Crawford et al., 1995). A intermittent surface outflow was also observed across the mouth of Queen Charlotte Sound. The summer wind-driven currents in the area were found to be of the order of $0.1\, \text{m s}^{-1}$ (Crawford et al., 1985).

In winter, the overall salinity is uniform at 50 and 200 m depth. At the surface, minimum salinity usually occurs in late fall and can arise through heavy precipitations. In summer, it has an east-west gradient with the low salinity near the coast. Some upwelling can be seen in the summer on the west coast of the Queen Charlotte Islands, which brings cool, high salinity water up to a depth of 200 m. The sea surface temperature is dominated by the annual heating cycle, with a maximum of 10 to $13^\circ\text{C}$ in August and a minimum of 4 to $8^\circ\text{C}$ in winter.

The effects of strong El Niño-Southern Oscillation (ENSO) events appear to affect the oceanography of the North Pacific (Emery and Hamilton, 1985). During times of strong ENSO events (e.g. 1940-41; 1957-58; 1982-83 and 1997-98), anomalously warm water with surface temperatures of 1 to $2^\circ\text{C}$ above normal appears along the outer coast of British Columbia. These anomalies are more pronounced between October and June and are generally associated with an intensification of the Aleutian Low and an accompanying tendency for stronger and more persistent southeast coastal winds. This leads to northwestwards flowing surface currents along the coast (Thomson, 1989).
2.3 Ocean circulation models in fisheries

Because systematic observations of currents and biological sampling are not readily available, many ecosystem numerical models have been developed to study the interaction between the physical environment and biological processes. The modeling strategies used in this study combine a ocean circulation model that can predict currents, salinity and temperature with a model simulating biological processes. The examples mentioned here include studies on the transport of phytoplankton and zooplankton, eggs, larvae, and fish.

Examples of the modeling of zooplankton and transport of primary producers

Hofmann et al. (1991) produced simulated drifter trajectories off the coast of California from a three-dimensional velocity field obtained from a circulation model developed by Haidvogel et al. (1991) and found that the simulated tracks compared well with observed drifter trajectories. Their results helped to explain the variability found in zooplankton distribution.

St-John et al. (1993) used flow fields inferred from a Strait of Georgia (JF8) circulation model (Crean et al., 1981) to investigate the influence of physical processes on nutrients and phytoplankton distribution.

Examples of ecosystem modeling of eggs and larval transport

Page and Smith (1989) combined a tidal model of the southwest coast of Nova Scotia (Greenberg and Petrie, 1988) with a wind-driven model of the same region (Wright et al., 1986) to yield surface currents. These currents were then used in a simulation of particle dispersion in the surface layer. They found that constant winds have an important effect on particle trajectories while periodic winds have little effect.
Bartsch et al. (1989) investigated larval transport processes in the North Sea by combining a three-dimensional circulation model (Backhaus and Hainbucher, 1987) with a model of larval advection and vertical migration. Their results suggested that a better understanding of ecosystems could be achieved from environmental modeling.

Helbig et al. (1992) examined environmental influences on the recruitment of Newfoundland/Labrador Cod by simulating the drift of particles and identifying nursery grounds. The currents were derived from a mean current field model developed by Greenberg and Petrie (1988) combined with a mixed layer model developed by Pollard and Millard, (1970). They were able to predict the distribution of cod eggs and larvae.

Kasai et al. (1992) modeled the advection and diffusion of sardines eggs in the West Pacific to investigate the effects of the Kuroshio current on Japanese sardines. They used a depth-averaged model to resolve the circulation field. Their results indicate that the circulation associated with the winter monsoon has a significant effect on the survival of the Japanese sardine.

Walters et al. (1992) simulated the effects of physical transport processes on fish larvae in Queen Charlotte Sound area. The ocean circulation model yielding currents was developed by Hannah et al. (1991). This model was intended to be used as an exploratory tool to study the life history of fish in the waters off the northern coast of British Columbia.

Cod and haddock larval transport on Georges Bank was studied by Werner et al. (1993). They simulated larvae that were either passive or migrating vertically. The currents were inferred from a three-dimensional circulation model of Georges Bank. They found that physical advection was important in the distribution of larvae.

Similarly, Bartsch and Knust (1994) simulated vertically migrating sprat larvae in the German Bight. They used two ocean circulation models (Backhaus, 1985; Backhaus and Hainbucher, 1987) to yield a three-dimensional current field which was used in a
larval transport model. Their modeling effort showed the importance of including larval vertical migration in their larval transport model.

An advection-diffusion model was developed by DeYoung et al. (1994) to explore the effects of ocean conditions on the residence time of capelin larvae in Conception Bay, Newfoundland. The three-dimensional velocity field was inferred from a diagnostic model of the circulation in Conception Bay (DeYoung et al., 1993).

Bernsten et al. (1994) simulated transport of particles in the North Sea with the aim of applying the study to larvae. Their circulation model was the Princeton Ocean Model developed by Blumberg and Mellor (1987) and yields three-dimensional velocity fields. They found a great year-to-year variability in larval drift patterns related to the water circulation.

Davidson and DeYoung (1995) used a diagnostic model that calculated the ocean circulation from a density field (DeYoung et al., 1993) to model the advection of cod eggs and larvae on the Newfoundland Shelf.

Hinckley et al. (1996) combined an eddy-resolving, semi-spectral primitive equation model (SPEM) adapted for Shelikov Strait and the Gulf of Alaska (Hermann and Stabeno, 1996) to an individual-based model of fish in their early stage to investigate the early life history of marine fish. The same bio-physical model was used to assess interannual variability of the early life history of walleye pollock (Hermann et al., 1996).

Examples of ecosystem modeling of fish migration

Hsieh et al. (1991) studied the interannual variability of sockeye salmon migration (Northern Diversion Rate, return timing and marine survival) by comparing it to large-scale atmosphere-ocean variability. They derived their upper level currents and temperature from a modified version of the Brian-Cox model (Cox, 1984) applied in the North Pacific (Hsieh and Lee, 1989). They found that the correlations between the physical
environment and the sockeye variables were highest in the first and final months of the sockeye's marine life.

Thomson et al. (1992) examined the influence of interannual variability of the northeast Pacific currents on the latitude of land-fall for returning sockeye salmon. They combined a salmon migration model with daily surface currents; the currents were obtained from an Ocean Surface Current Simulation (OSCURS) model of the North Pacific (Ingraham and Miyahara, 1988). In a similar study, Thomson et al. (1994) used currents derived from the OSCURS model to examine the effect of the North Pacific surface current on Fraser River sockeye salmon return time. They found that currents in the open ocean affected return timing by deflecting the salmon in different oceanic domains along the coast of British Columbia.

Felchhelm et al. (1994) simulated the dispersal of least cisco along the western Beaufort Sea coast in Alaska. Their numerical model was one-dimensional and combined advection of fish with an empirical physical model; in this physical model, surface currents equaled a fraction of the wind speed in the same direction. Model results compared well with data of fish arrival over 12 years.

Peterman et al. (1994) investigated the influence of surface currents on migrating juvenile salmon. They used surface currents provided by a circulation model of the Strait of Georgia driven by surface winds, tides and Fraser River discharge. They found that the surface wind-driven currents were large enough to deflect Chilko Lake juvenile salmon migrating downstream into the Strait of Georgia.

Dat et al. (1995) used daily surface currents from the OSCURS model (Ingraham and Miyahara, 1988) to test the influence of currents on returning sockeye salmon. They found that surface currents increased the speed of homeward migrating salmon and that compass orientation alone was a sufficient orientation mechanism to explain their migration.
Chapter 2. Background

The results from these modeling studies showed that the strategy of combining a physical and a biological numerical model would aid to understand the effect of the physical environment on biological processes. In most cases, the environment was found to have an important effect on fish life history.

Modeling strategies to simulate migrating salmon

Most of the previous examples combined a spatially varying field of the physical environment with an individually-based model (IBM) of fish or larval biology. IBMs simulate populations in which individuals can differ in their foraging, growth and mortality rates and follow these individuals through one or more critical stages in their life cycle (Tyler and Rose, 1994). A spatially-explicit IBM is a model that also includes the spatial locations of the individuals.

Studies described above by Thomson et al. (1992), Thomson et al. (1994) and Peterman et al. (1994) all used spatially-explicit IBMs to simulate particular stages of the life history of migrating salmon. In these models, each individual salmon was influenced by the ocean currents at their specific positions. In Thomson et al. (1992) and Thomson et al. (1994), the current field was provided by an empirical model of the northeast Pacific circulation, OSCURS (Ingraham and Miyahara, 1988), that poorly resolves coastal currents. Peterman et al. (1994) used a current field provided by a hydrodynamic model of the Strait of Georgia (Crean et al., 1981) which was more refined than the OSCURS model (Ingraham and Miyahara, 1988) since it included tidal, wind and buoyancy forcing. The use of a refined hydrodynamic model might not always be necessary and will depend on the biological processes that are being studied. Peterman et al. (1994) studied migrating juveniles out of the Strait of Georgia where tidal currents and small eddies might be important, hence they chose a hydrodynamic model capable of resolving these features.
The modeling strategy used in this study follows the example above by combining a physical numerical model with a biological model to investigate the effects of the coastal currents on returning salmon spatial distribution and return timing. Therefore, a hydrodynamic model of the northern coast of British Columbia is combined with a spatially-explicit individual-based model of salmon migration. The hydrodynamic model has a fine resolution in time and space and includes tidal and wind forcing. The model framework enables the study of the effects of currents at various time scales. The salmon migration model follows each salmon individually in order to study each salmon track and study the distribution of salmon at a specific time. The salmon behaviour is kept simple to provide a clearer interpretation of the results.
Chapter 3

Numerical model

The goal of this thesis is to obtain a better understanding of how the physical environment affects the spatial distribution and return timing of migrating salmon returning through the Queen Charlotte Sound area. A spatially-explicit individual-based model (IBM) was developed to help address these questions. In the model, each individual salmon is subject to its physical environment, which varies with location and time. Moreover, each salmon can have its own behaviour of swimming speed and orientation. Groups of salmon are tracked to examine the salmon distribution and return timing (time series of the number of salmon returning each day) and therefore to infer the effects of the physical environment on returning salmon at different spatial and temporal scales.

The numerical model of salmon migration combines a physical and a biological model. The former is a hydrodynamic model of the waters off northern British Columbia (Cummins and Oey, 1997) predicting ocean currents, temperature and salinity at a fine horizontal scale (5 km) and varying in time. The second model is a spatially-explicit IBM of salmon migration using the field of physical variables obtained by the hydrodynamic model. Each salmon is advected by the currents but also moves according to a pre-determined set of behaviours such as swimming speed and chosen orientation. This pre-determined set of behaviours can be varied to yield different possible scenarios of migration.

The two models could be blended following two different strategies. A possible approach would be to run the two models simultaneously in time. The hydrodynamic model
would be run for one iteration, yielding a field of physical variables. The salmon positions would then be calculated with a subroutine embedded in the hydrodynamic model. The hydrodynamic model would again be run for its next iteration and calculate new salmon positions, and so on until the full salmon trajectories are inferred. Obviously, this technique is extremely time and space consuming. Because salmon do not influence currents, a second approach, which is used in this study, is to run the two models separately. The hydrodynamic model is run once for the whole series of iterations. This yields a series of coastal current fields for a range of times specific to returning salmon (i.e. from June to September) and at a certain desired time interval (hourly in this study). Once this time-varying field of currents is stored, the IBM of salmon migration can be run by reading a new field of coastal currents at each time interval. This will produce trajectories of individual salmon, salmon distributions and time series of return timing of salmon.

3.1 Ocean circulation model

The Princeton Ocean Model

The Princeton Ocean model (Blumberg and Mellor, 1987) solves the primitive hydrodynamic equations in three dimensions. These equations include the equations (Gill, 1982) for conservation of mass, momentum, temperature and salinity coupled by an equation of state. A turbulent closure sub-model is also solved (Mellor and Yamada, 1982) to provide vertical mixing coefficients. The important simplifications being made are the hydrostatic assumption, the f-plane approximation and the Boussinesq approximation with respect to density variations. The terrain-following \( \sigma \)-coordinate system used in the vertical permits a good resolution of the surface and bottom flows over irregular bathymetry.

In order to implement this model for a specific region, the user specifies the initial
and boundary conditions, the spatial resolution, the time steps and the forcing. The latter may include the tides, surface heat flux, wind stress, precipitation and river runoff at the coastal boundaries. This model has been implemented for various coastal regions, for example in the South Atlantic Bight (Blumberg and Mellor, 1983) and the North Atlantic Shelves (Oey and Chen, 1992).

Model of the northern coast of British Columbia

The domain of the model discussed in Cummins and Oey (1997) covers an area of 450 x 800 km$^2$ (figure 3.4). The spatial resolution is 5 km in both horizontal coordinates and there are 21 $\sigma$-levels in the vertical. A realistic representation of the bottom topography is included. Tidal forcing consists of sea-surface elevation and velocities due to tides applied at the open boundaries for the leading semi-diurnal ($M_2$, $S_2$) and diurnal ($K_1$, $O_1$) tidal components. The elevations at the boundaries are obtained from a global tidal model. The model was initialized with a temperature and salinity vertical profile representative of the summer stratification in Queen Charlotte Sound. This allows the model to support internal tidal motions. In order to include the wind-driven effects, the model is also forced with inputs of daily winds. The daily winds are obtained from moored buoys (see figure 3.5) deployed by the Marine Weather Programs, Environment Canada (Cherniawsky and Crawford, 1996). These data are available for the years following 1989. The outputs of the hydrodynamic model are three-dimensional fields of time-varying salinity, temperature and coastal currents.

The hydrodynamic model was first run without the wind-stress to investigate the tidal currents in the area. Tidal ellipses of the main tidal components ($M_2$ and $K_1$) in the area obtained from the hydrodynamic model are shown in figure 3.6. The maximum tidal currents are 0.75 m s$^{-1}$ and 0.45 m s$^{-1}$ for the $M_2$ and $K_1$ tidal components respectively. The largest tidal currents are seen in the shallow water at the tip of the Queen Charlotte
Figure 3.4: Model domain of the numerical model developed by Cummins and Oey (1997). The model coordinates were rotated by 30° clockwise from true North.
Figure 3.5: Map of the coast of British Columbia showing the location of the wind buoys that provided data to force the hydrodynamic model (after Cherniawsky and Crawford, 1996)
Chapter 3. Numerical model

Islands, in Queen Charlotte Sound and in Hecate Strait. Comparison of the model results with tide gauge measurements indicates that the average relative rms difference between observations and the model surface elevation are less than 5 % for the largest tidal constituents. The model results including either only tidal forcing and both tidal and wind forcing also compare well with drifter observations (Crawford et al. (1998); Crawford et al. (1999)). The model results from the hydrodynamic model including wind forcing produces wind-driven currents that are weaker offshore and of the order of 0.1 m s$^{-1}$. The wind-driven current closer to shore are much stronger, and can be as large as 0.3 m s$^{-1}$.

3.2 Numerical model of salmon migration

The salmon migration model is essentially a particle tracking model where the particles have prescribed behaviours. The passive-tracking part uses the near-surface current fields obtained from the hydrodynamic model. The input current fields change hourly and are distributed on a 5 km grid. At every time-step, the particle tracking model calculates new positions of each individual particle due to the advection of currents.

The particle tracking scheme follows an algorithm developed by Bennett and Clites (1987) which includes current shears as well as currents. This method, which avoids the trapping of particles on land, is as follows: by doing a Taylor series expansion about a particle position at time $t$, the following expression is derived to predict particle positions at time $t + \Delta t$:

$$\frac{x^{t+\Delta t} - x^t}{\Delta t} = u(x^t, y^t) + \frac{1}{2} \left( \frac{\partial u}{\partial x} (x^{t+\Delta t} - x^t) + \frac{\partial u}{\partial y} (y^{t+\Delta t} - y^t) \right)$$

$$\frac{y^{t+\Delta t} - y^t}{\Delta t} = v(x^t, y^t) + \frac{1}{2} \left( \frac{\partial v}{\partial x} (x^{t+\Delta t} - x^t) + \frac{\partial v}{\partial y} (y^{t+\Delta t} - y^t) \right).$$

Rewriting the current shears as $u_x$, $v_x$, $u_y$ and $v_y$ for simplicity, the above equations can
Figure 3.6: Results from the hydrodynamical model: ellipses for the $M_2$ component of the tidal currents (left) and the $K_1$ component of the tidal currents (right) (after Cummins and Oey, 1997)
Chapter 3. Numerical model

be written:

\[ x^{t+\Delta t} = x^t + \frac{1}{A} \left[ \left( 1 - \frac{\Delta t v_y}{2} \right) \Delta tu + \frac{\Delta t^2 u v}{2} \right] \]  
(3)

\[ y^{t+\Delta t} = y^t + \frac{1}{A} \left[ \left( 1 - \left( \frac{\Delta t u_x}{2} \right) \right) \Delta tv + \frac{\Delta t^2 v_x u}{2} \right] \]  
(4)

where

\[ A = \left[ \left( 1 - \frac{\Delta t u_x}{2} \right) \left( 1 - \frac{\Delta t v_y}{2} \right) \right] - \left( \frac{\Delta t^2 v_x u y}{4} \right). \]  
(5)

Equations 3 to 5 yield the position of a particle at time \( t + \Delta t \) from its position at time \( t \), the currents and current shears at that position at time \( t \). This scheme helps preventing the trapping of particle on land because the shear of the currents are also included, thus taking into account the currents at more than one grid-point. The particle is then allowed to turn if it is close to be trapped on the coast.

A simpler method to track particles would be to use the following approximation, which does not include current shears:

\[ x^{t+1} = x^t + \Delta t u(x^t, y^t) \]  
(6)

\[ y^{t+1} = y^t + \Delta t v(x^t, y^t). \]  
(7)

A comparison between the two numerical tracking scheme (figure 3.7) shows that the Bennett and Clites scheme helps prevent particles from being trapped along the coast and is thus preferable.

Sensitivity tests were done to determine the proper time-step \( \Delta t \) (see equation 3 to 5) that should be used in the salmon migration model. A time-step that is too large might yield inaccurate results. The model was run with time steps of 1, 10, 30 and 60 min for 5 different trajectories. The flow field used as an input for the migration model represented tidal forcing only. The flow field changed hourly over 14 days. The aim of this sensitivity test was to decrease the time step until the trajectories obtained from the model became
Figure 3.7: Comparison of two particle tracking numerical schemes. The left panel shows the results from a Bennett and Clites scheme and the right panel shows the results from a simple numerical scheme as in equations 6 and 7.
Figure 3.8: Results of a sensitivity test done to determine the proper $\Delta t$ to be used in the migration model. Experiments were done with time-steps of 1, 10, 30 and 60 min. The tidal currents used in the simulation were hourly.
identical for different time steps. The trajectories from runs with time-steps of 30, 10 and 1 min are similar (figure 3.8). A time-step of 10 min was then chosen to maintain numerical stability and accuracy.

The motion due to salmon behaviour is calculated separately. Each individual salmon can have its own behaviour. For simplicity, the behavioural components included here were salmon swim speed and compass-orientation. The model calculates the new position of a salmon by vector addition of the following: (1) the horizontal displacement vector due to advection by currents alone as calculated by the particle tracking scheme, and (2) the horizontal displacement vector due to behaviour alone. This procedure is done for each salmon, and repeated at each time step.

The numerical model of salmon migration, as described above, was run first with the tidal currents only and then with currents including both tidal and wind forcing. Various experiments were done to assess the influence of coastal currents on the return migration of salmon at two different time scales. First, the effects of tidal currents, of period 12.4 to 24 h, were studied using the results of the hydrodynamic model without wind forcing. Then, the effects of wind-driven currents, with a period of 3 to 15 days, were studied using the results of the hydrodynamic model that included wind forcing.
Chapter 4

Model results: effects of tidal currents

Model results for a study on the effects of tidal currents on salmon returning migration are presented here. These results are also discussed in Bourque et al., (1999).

Surface tidal currents in the northern coast of British Columbia are dominated by the $M_2$ semi-diurnal tide (figure 3.5), with contributions from both the surface and internal tide. The internal tide is most evident in deep waters offshore where it dominates the barotropic tides. A mean residual current is also generated. The largest tidal currents can be seen in the shallower waters, more specifically over the banks found near the tip of Vancouver Island and within Queen Charlotte Sound (figure 3.5). Sockeye salmon swimming through these areas are affected by currents of the order of 0.5 m s$^{-1}$, which are similar to their swim speed.

Results from various simulations of the salmon migration model are presented here. The effects of tidal currents on the return timing of salmon and on their spatial distribution are described first. A simulation of a returning sockeye salmon run is then shown.

4.1 Salmon return timing

The model started 3200 simulated salmon southwest of Queen Charlotte Island (figure 4.9). The imposed salmon behaviour was kept simple: the swim speed was 0.5 m s$^{-1}$ ($\sim$ one body-length per second) and the compass orientation was 110° with respect to true North (all salmon were swimming parallel to each other). The simulated salmon were
Figure 4.9: Position of the salmon at the start of the experiment and after six days. Their swim speed was 0.5 m s\(^{-1}\) and their compass orientation was towards the tip of Vancouver Island (110° with respect to true North).
evenly distributed in space, each being separated by 2 km. The model was run for 30 days following the procedure described in chapter 3. After about six days, the salmon reach the tip of Vancouver Island (figure 4.9). The sinuosity of their trajectory during that time results from the variability of tidal flows (figure 4.10).

A time series of return timing at the northern tip of Vancouver Island was created by summing the number of salmon found at any instant between the 125 and 135 km y-coordinate of the model (i.e. near the tip of Vancouver Island). A time series of the number of salmon arriving every hour was then reconstructed from the arrival time of each salmon with a histogram (bin size = 1 h) (figure 4.11). The simulated salmon begin arriving near Vancouver Island after 3 days from the start of the calculation and it took 7.25 days for all of them to reach the island. This time series shows an oscillation with a period of 12.4 h (approximately 2 peaks per day), which corresponds to the period of the principal semi-diurnal (M2) tidal component.

The sensitivity of return timing to variations in salmon starting time, starting position and swim speed was examined (see appendix B). In each case, return timing times series showed an oscillation at the semi-diurnal period (12.4 h).

4.2 Salmon spatial distribution

Six days from the start of the calculation, the distribution is no longer uniform (figure 4.9). Two major features can be discerned: a long east-west band (100 x 10 km^2) with a relatively high concentration of salmon, and various smaller bands (20 x 10 km^2) of high concentration, separated by areas of similar size where no salmon are present. The sensitivity of the spatial distribution to salmon starting time, starting position and swim speed was examined (see appendix B). In all cases, the spatial distribution showed alternating empty patches and areas of high concentration of salmon. The shape and size
Figure 4.10: Trajectory of five salmon for the experiment shown in figure 4.9: their swim speed is 0.5 m s$^{-1}$ and their compass orientation is 110° with respect to true North.
Figure 4.11: Time series of return timing defined as the number of salmon arriving near the tip of Vancouver Island (passing between the position of 125 and 135 km on the y-axis axis). The time scale corresponding to a full $M_2$ tidal cycle is shown.
of these areas are not affected by the starting time of the calculation, but some differences were apparent for varying swimming speeds and migrations paths.

The sensitivity of the model to spatial resolution was also tested (see appendix C). Tidal currents resolved for a finer horizontal resolution (2.5 km) were used for a simulation of the salmon model. This change in resolution did not affect significantly the results. Similar features were seen in the spatial distribution and return timing at both 2.5 and 5 km resolutions.

4.3 Simulation of a sockeye salmon run

To simulate the return of a sockeye salmon run, different initial conditions were considered. Successive rows of salmon, one every 4 hours, entered the coastal domain; for each row, the salmon were evenly distributed along the 350 km y-coordinate between x = 100 and 200 km (see figure 4.12, left). The total salmon run consisted of ten thousand simulated salmon and these took over 20 days to enter the coastal domain. The number of salmon in each row followed a normal distribution in time. All salmon were swimming at 0.5 m s\(^{-1}\) and were oriented at an angle of 110° with respect to true North.

If the tidal currents did not affect the salmon distribution, the distribution would consist of evenly spaced horizontal lines at all times. But here the lines show pronounced displacements, especially approaching Vancouver Island, where the tidal currents are strong (see figure 4.12).

The return timing for this simulation is shown in figure 4.13 (bin size = 1 h). This time series shows an oscillation of semi-diurnal period superposed on a lower frequency signal due to the normal initial distribution of the salmon run.

To increase the level of complexity in the model, some randomness in the salmon orientation was included. In one case, the salmon swim at a compass orientation of
Figure 4.12: Position of salmon eight days after the start of the simulation of a sockeye salmon run. Their swim speed was 0.5 m s\(^{-1}\) and their compass orientation was towards the tip of Vancouver Island (110° with respect to true North).
Figure 4.13: Time series of return timing for the simulation of a sockeye salmon run. Return timing is defined as the number of salmon arriving near the tip of Vancouver Island (passing between the position of 125 and 135 km on the y-axis).
110°, with respect to true North, for two-thirds of the time. Every 30 min, they swim in a different orientation for 10 min. This random orientation was normally distributed between 20° and 200° (all with respect to true North). The randomness smoothed the rows of salmon, spreading their distribution. The empty patches and areas of high concentration, however, were still present (figure 4.14) and oscillations at a period of 12.4 h were also evident in the return timing.

4.4 Discussion

The results presented above show that the spatial distribution of salmon swimming at one body-length per second in a tidal current field develops patchiness and that their return timing displays oscillations at tidal frequency. These results were not dependent on starting time or position.

To understand the mechanism for the patchiness in the spatial distribution, some further tests were done. In particular, the model was run with (A) the mean tidal residual currents alone (periodic variation removed), (B) the oscillating tide only with the mean currents removed and (C) the depth-averaged current. In case A (figure 4.15), the distribution is almost uniform, with only a narrow band of higher concentration near the continental shelf break. In case B (figure 4.16), the patchiness in the distribution can be seen but the band of higher concentration along the shelf break is absent. In the case of experiment (C), the near-surface tidal current was replaced by the depth-averaged tidal currents, thus filtering the internal tide. The results (not shown) were similar to those of case B, but not as pronounced. Experiment (A) indicates that convergence of salmon particles at the shelf break as illustrated, for example, in figure 4.15 is associated mainly with the tidal residual currents. On the other hand, the patchiness in the distribution is caused by the oscillating part of the current, with the internal tidal component making
Figure 4.14: Position of salmon five days after the start of the simulation of a sockeye salmon run. Their swimming speed was $0.5 \text{ m s}^{-1}$ and their compass orientation was semi-random.
Figure 4.15: Position of the salmon after 6 days. This simulation was done with the mean tidal currents only (A). The salmon swim speed was 0.5 m s\(^{-1}\) and their compass orientation was towards the tip of Vancouver Island (110° with respect to true North).
Figure 4.16: Position of the salmon after 6 days. This simulation was done with the oscillating part of the tidal currents only (B). The salmon swim speed was 0.5 m s$^{-1}$ and their compass orientation was towards the tip of Vancouver Island (110° with respect to true North).
Chapter 4. Model results: effects of tidal currents

an important contribution.

The question remains whether the patchiness is a transient convergence/ divergence phenomenon varying at the semi-diurnal period. To address this matter, it is instructive to consider a simple one-dimensional model. Letting $\rho_s$ represent the density of salmon per area, the conservation of $\rho_s$ requires (Gill, 1982),

$$\frac{\partial \rho_s}{\partial t} + \frac{\partial (u \rho_s)}{\partial x} = 0. \tag{8}$$

Let the initial distribution of salmon given by $\rho(x, t = 0) = f(x)$. Finally, assume that the speed, $u$, consists of a behavioural component, $u_s$, and an oscillating tidal component; i.e.

$$u = u_s + A_t \cos(\omega t) \tag{9}$$

where $A_t$ is the amplitude of the tidal current and $\omega$ is the tidal frequency equal to 12.4 h. If $A_t = A_t(0)$, a constant, (8) reduces to a first order wave equation,

$$\frac{\partial \rho_s}{\partial t} + u \frac{\partial \rho_s}{\partial x} = 0, \tag{10}$$

whose solution is given by

$$\rho(x, t) = f(x - \int u dt). \tag{11}$$

In this case, the velocity field is non-divergent; the initial distribution advances forward without a change in shape. The salmon density is constant along a trajectory given by the characteristic equation $x = u_s t + A_t(0) \omega^{-1} \sin(\omega t)$.

In the more general case when $A_t = A_t(x)$ and a spatial variation in the tidal amplitude is included, zones of convergence and divergence in the salmon density appear. It is instructive to examine a simple numerical solution to (8) for a representative set of parameters. The salmon swim speed, $u_s$, was set to 0.5 m s$^{-1}$ and the shape of $A_t(x)$ includes a sharp gradient (figure 4.17).
As the fish distribution encounters the sharp amplitude gradient, the distribution is compressed (figure 4.17). Since the fish distribution moves back and forth with the tides, a series of peaks and trough are created as the group passes through the amplitude gradient. This leads to a permanent redistribution of the group which is maintained once it has progressed past the region with an amplitude gradient. In this example, the new fish distribution is similar to one obtained from the complete model. The one-dimensional model shows that only spatial changes in the current field can create oscillations as seen in figure 4.11.

The time series of return timing are obtained by counting the number of salmon present in a certain sampling area at each time step. For a spatially uniform group of salmon, with a width much larger than the sampling area, the very beginning of the time series of return timing will show oscillations as the first salmon enter the area of sampling, and are moved in and out of the area by the tidal currents for a distance comparable to the width of the sampling area. Similarly, as the last salmon leave the sampling area, the return timing will again show oscillations at the end of the time series. As the salmon in the middle part of the group swim through the sampling area, the total number of salmon in the area will remain constant (due to the spatially uniform distribution) and the return timing will also remain constant. The oscillations present throughout the return timing for the complete model (figure 4.11) are therefore associated with the patchiness in the spatial distribution that develops as the simulated salmon pass through regions of varying tidal amplitudes.

Tests with the one-dimensional model have shown that the height of the peaks are more pronounced for sharper amplitude gradient and are affected by the fish and current speed. For this process to be effective the length scale of the amplitude gradient, $L$, must be comparable to or smaller than an advective length scale, $L \leq A_t T$, where $T$ is the tidal period.
Figure 4.17: Results from a simple one-dimensional advection model. The fish distribution ($\rho_s$) swimming at 0.5 m s$^{-1}$ was advected by a current velocity $A_t(x) \cos(\omega t)$ where $\omega$ represents the frequency of the $M_2$ tide and the tidal amplitude, $A_t(x)$, is given in the lower panel. The fish distribution is shown every 12 h.
The above results may have significant implications for sampling strategies. Assuming that sockeye salmon swim no faster than one body-length per second, they will be significantly affected by the surrounding waters when they enter the coast of British Columbia waters, where the tidal currents can be as strong as 1 m s\(^{-1}\). If the salmon tend to have a very directed migration as reported by Quinn (1990) and swim at a fairly constant speed, their return timing and spatial distribution will not be uniform. Spatial distributions for all simulations showed empty patches and areas of high concentration of salmon with a size on the order of 10 × 10 km\(^2\). A sample taken in the middle of one of these areas would not be representative of the number of salmon present at a larger scale. If such patches occur, sampling should be done over a larger domain to account for it. Figure 4.11 shows a variation in the number of salmon returning over a tidal cycle, indicating that samples taken only once or twice a day could overestimate or underestimate the total number of returning salmon. Fish distribution should therefore be sampled at least every six hours (one-half cycle) to avoid such aliasing problems.
Chapter 5

Model results: effects of wind-driven currents

The dominant tidal current in the north coast of British Columbia is the $M_2$ constituent current of period 12.4 h. As seen in chapter 4, these tidal currents cause variability within the salmon spatial distribution and in their return timing. The wind-driven current vary over a larger temporal scale, since wind storms in the area have periods of 3 to 15 days. The effects of the wind-driven currents should therefore be seen at a much longer temporal scale than the tidal effects. The wind-driven currents in the summer are of the order of 0.1 m s$^{-1}$, which is about one-fifth of the salmon swim speed. Assuming that the wind-driven currents flow in the same direction for much of the salmon traveling time, the overall spatial changes due to the currents are expected to be of the order of 20% of the salmon traveling distance; or 70 km for a traveling distance of 350 km.

Results from various simulations of the salmon migration model are presented here. The currents used in these simulations were obtained from the hydrodynamic model which was forced by both the tides and the wind. The effects of the current on the spatial distribution, return timing and salmon diversion were examined.

5.1 Wind-driven coastal dynamics

Ekman dynamics

In the north hemisphere, the Ekman transport (water transport due to the wind stress) is directed at right angles to the surface wind stress (Gill, 1982). This can be inferred
from the solution of the linearized horizontal momentum equation:

\[
\begin{align*}
\frac{\partial u}{\partial t} - fu + f_u &= -\rho^{-1} \frac{\partial p}{\partial x} + \frac{1}{\rho} \frac{\partial \tau_x}{\partial z} \\
\frac{\partial v}{\partial t} + f_u &= -\rho^{-1} \frac{\partial p}{\partial y} + \frac{1}{\rho} \frac{\partial \tau_y}{\partial z}.
\end{align*}
\] (12)

Equation 12 indicates that the motion of the water \((u, v)\) is due to two forces: the horizontal pressure \((p)\) gradient and the vertical gradient of the wind stress \((\tau)\). The current due to the two forces can be considered separately: \((u_p, v_p)\) and \((u_E, v_E)\), where

\[
\begin{align*}
u = u_p + u_E, \\
v = v_p + v_E
\end{align*}
\] (13)

The part driven by the pressure gradient satisfies

\[
\begin{align*}
\frac{\partial u_p}{\partial t} - f v_p &= -\rho^{-1} \frac{\partial p}{\partial x} \\
\frac{\partial v_p}{\partial t} + f u_p &= -\rho^{-1} \frac{\partial p}{\partial y}
\end{align*}
\] (14)

and becomes the geostrophic current when the flow is steady. The part driven by the wind stress, the Ekman current, satisfy

\[
\begin{align*}
\frac{\partial u_E}{\partial t} - f v_E &= \rho^{-1} \frac{\partial \tau_x}{\partial z} \\
\frac{\partial v_E}{\partial t} + f u_E &= \rho^{-1} \frac{\partial \tau_y}{\partial z}
\end{align*}
\] (15)

This current is confined to the layer over which the wind stress acts which is called the Ekman layer. The stress is zero at the bottom of the Ekman layer, so integrating in the vertical over the Ekman layer yields:

\[
\begin{align*}
\frac{\partial U_E}{\partial t} - f V_E &= \rho^{-1} \tau_x \\
\frac{\partial V_E}{\partial t} + f U_E &= \rho^{-1} \tau_y,
\end{align*}
\] (16)
where

\[(U_E, V_E) = \int (u_E, v_E) \, dz.\] (17)

In steady conditions, equation 16 reduces to

\[V_E = -\frac{\tau_x}{\rho f}, \quad U_E = \frac{\tau_x}{\rho f},\] (18)

which indicates that the Ekman transport, the net current in the Ekman layer, is at right angle to the wind stress.

Wind-driven currents along the coast of northern British Columbia

The position of four of the moored buoys providing wind data to force the hydrodynamic model are shown in figure 5.18. Correlations (r) done for June 1 to September 30 in 1994 and 1995, between the u and v component of the wind stress obtained from these buoys (see tables 5.1 and 5.2) show that the winds are fairly uniform over the area. The correlations range from 0.7 to 0.9.

The wind stress derived from data at station 12 (figure 5.19) shows a variability of 3 to 15 days as expected. The surface current simulated by the hydrodynamic model at the position (x=200 km, y=150 km) shows a similar variability (see figure 5.20). The daily-averaged surface currents simulated by the hydrodynamic model are consistent with an Ekman dynamics response to the wind since the surface currents are directed

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Figure 5.18: Some of the marine weather station that provided wind stress to force the hydrodynamic model. Stations 5, 9, 12 and 13 represent respectively stations C46147, C46204, C46207 and C46208 of figure 3.4.
Figure 5.19: Wind stress at station 12 for the summer of 1994: u-component of the wind stress (following the y-axis on the model grid), v-component of the wind stress (following the x-axis on the model grid) and a vector representation of the wind stress.
Figure 5.20: Current simulated by the hydrodynamic model for the summer of 1994 at the grid point (x=200 km, y = 150 km): u-component of the current (defined here as parallel to the y-axis of the model domain), v-component of the current (defined here as parallel to the x-axis of the model domain), and the vector representation of the current.
Table 5.2: Correlations between the \( u \) and \( v \) components of the summer wind stress in 1995.

<table>
<thead>
<tr>
<th></th>
<th>( u )</th>
<th></th>
<th>( v )</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>12</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>0.71</td>
<td>0.88</td>
<td>0.89</td>
</tr>
<tr>
<td>9</td>
<td>0.72</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.78</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

at approximately right angles to the wind stress. This is consistent with observations along the west coast of the Queen Charlotte Islands, as reported by Thomson (1989) and Crawford et al. (1999). The time series of the \( v \) component of wind stress at station 12 was found to be highly correlated (0.72) with the \( u \) component of the simulated current at the position \((x=200 \text{ km, } y=150 \text{ km})\) (figure 5.21). Moreover, the correlations between the \( v \) component of the wind stress at stations 5, 9, 12 and 13 with the simulated current at position \((x=200 \text{ km, } y=150 \text{ km})\) and position \((x = 300 \text{ km, } y = 150 \text{ km})\) range between 0.58 to 0.72 (table 5.3).

The simulated surface currents are highly correlated with the wind-stress at right angle to their direction, consistent with Ekman dynamics. This implies that wind-driven Ekman currents are a good approximation to describe the surface currents of the model in Queen Charlotte Sound.

Table 5.3: Correlations between the wind stress \((v)\) and current \((u)\) in 1994

<table>
<thead>
<tr>
<th>position</th>
<th>5</th>
<th>9</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>((x=200 \text{ km, } y=150 \text{ km}))</td>
<td>0.71</td>
<td>0.62</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td>((x=300 \text{ km, } y=150 \text{ km}))</td>
<td>0.58</td>
<td>0.63</td>
<td>0.66</td>
<td>0.67</td>
</tr>
</tbody>
</table>
Figure 5.21: Comparison of the v-component of the wind stress at station 12 (solid line) and the u-component of the current at the grid point (x=200 km, y=150 km). The correlation between these two curves is 0.72.
5.2 Effects of wind-driven currents on a salmon run

Salmon runs were simulated using initial conditions similar to those described in section 4.3. Successive rows of salmon, once every 4 hours, entered the coastal domain; for each row the simulated salmon were evenly distributed along the 350 km y-coordinate between $x = 25$ and $225$ km; the total salmon run consisted of ten thousand simulated salmon. The number of salmon in each row followed a normal distribution in time. All salmon were swimming at $0.5$ m s$^{-1}$ and were oriented at an angle of $99^\circ$ with respect to true North.

Spatial distribution

Model simulations, which started salmon runs at different days (July 1, July 15, July 30 and August 14) during the summer of 1994 and 1995. The currents used for these simulations were obtained from the hydrodynamic model which was forced with wind stress data. Model results show that wind-driven currents can spread the salmon distribution at certain times by a width of the order of 100 km from their initial distribution and can deflect the salmon by a distance of the order of 50 km. For example, a simulation started on July 1, 1994 shows that the salmon distribution after 15 days (figure 5.22, left) is more widely spread than its initial distribution. The distribution for this simulation at the end of the salmon run (or after 20 days, figure 5.22, right) is much different; it shows half of the salmon traveling to the west side of Vancouver Island. Both distributions are patchy, which can be explained by spatial variation in the tidal field, as discussed in chapter 4. The deflection distances are of the order of 50 to 100 km, as expected.
Chapter 5. Model results: effects of wind-driven currents

Figure 5.22: Distribution of salmon 15 days (left panel) and 20 days (right panel) after the start of the simulated salmon run. The experiment simulated salmon entering the coast (at \( y = 350 \) km) on July 1, 1994. The salmon were swimming at 0.5 m s\(^{-1}\) and were oriented at an angle of 99° with respect to true North.
Chapter 5. Model results: effects of wind-driven currents

Return timing

The return timing for the simulations here is defined as the number of salmon arriving near the tip of Vancouver Island (passing between the position 125 km and 135 km on the y-axis of the model domain). The simulations show that the shape of the arrival time series deviates from the initial normal distribution when the wind-driven currents are included (figure 5.23). This shape varies depending on when the salmon run was traveling during the summer (figure 5.24) and also depending on whether they traveled in 1994 or 1995 (figure 5.25). The wind-driven currents were different during these times of travel due to various storms passing over the northern coast of British Columbia. The passing of storms are reflected in the various shapes of return timing. For example, the number of salmon decreases on September 1, 1994 for the experiment started on August 14 (day 18 on figure 5.24, bottom panel). The currents and the wind both show an event on that day (day 92, figure 5.19 and 5.20). Note also that the simulated salmon return timing obtained for these simulations also show oscillations at a semi-diurnal period, caused by the tidal currents.

Diversion

Results from the simulations also indicate that the wind-driven currents affect the proportion of salmon travelling east or west of Vancouver Island. The proportion of salmon travelling west of Vancouver Island were counted for simulations done for four different periods of travel in 1994 and 1995 (table 5.4). The width of the initial salmon distribution was 200 km and the deflections due to the wind were of the order of 50 km; this yields a change of the order of 25 % in the diversion, which is reflected in table 5.2.
Figure 5.23: Time series of return timing defined as the number of salmon arriving near the tip of Vancouver Island (passing between the position of 125 and 135 km on the y-axis). The days from 0 to 40 correspond to July 1 to Aug 10, 1994. The experiment simulates salmon entering the coast (at y=350 km) on July 1, 1994.
Figure 5.24: Time series of return timing defined as the number of salmon arriving near the tip of Vancouver Island (passing between the position of 125 and 135 km on the y-axis). The four experiments simulate salmon entering the coast on July 1, July 15, July 30 and August 14, 1994.
Figure 5.25: Time series of return timing defined as the number of salmon arriving near the tip of Vancouver Island (passing between the position of 125 and 135 km on the y-axis). The four experiments simulate salmon entering the coast on July 1, July 15, July 30 and August 14, 1995.
Summer variability in return timing

The salmon migration model was run to infer the return timing variability for the entire summers of 1994 and 1995. The initial conditions were set to simulate a constant number of salmon entering the coastal domain through the whole summer. Successive rows of salmon, one every 4 hours, entered the coastal domain; for each row, 20 salmon were evenly distributed along the 350 km y-coordinate between x = 0 and 200 km. The total run consisted of twelve thousand salmon. The number of salmon in each row was constant with time. All salmon were swimming at 0.5 m s\(^{-1}\) and were oriented at an angle of 99° with respect to true North. The simulated returning salmon distributions for July 15, 1994 and for a simulation with no tidal nor wind-driven currents are shown in figure 5.26. The currents caused a deflection of the order of 30 km to the west for that particular time. The return timing (bin size = 24 h) obtained for 1994 and 1995 (figure 5.27) show variability at a period of 3-18 days. This variability is also seen in the calculation of the power spectrum of the two time series (figure 5.28) which shows peaks at 5.3 d, 8.54 d and 18.3 d. This result suggests that the wind-driven currents can cause variability in return timing at periods associated with wind storms over the north coast of British Columbia.

Table 5.4: Percentage of salmon traveling west of Vancouver Island for different dates in 1994 and 1995

<table>
<thead>
<tr>
<th>Date</th>
<th>1994</th>
<th>1995</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 1</td>
<td>44.5</td>
<td>47.7</td>
</tr>
<tr>
<td>July 15</td>
<td>26.6</td>
<td>43.3</td>
</tr>
<tr>
<td>July 30</td>
<td>27.1</td>
<td>31.7</td>
</tr>
<tr>
<td>Aug 1</td>
<td>24.7</td>
<td>37.0</td>
</tr>
<tr>
<td>tides only</td>
<td>7.7</td>
<td>7.7</td>
</tr>
<tr>
<td>no current</td>
<td>6.1</td>
<td>6.1</td>
</tr>
</tbody>
</table>
Chapter 5. Model results: effects of wind-driven currents

Figure 5.26: Distribution of simulated salmon on July 15, 1994 (right panel) and with no tidal nor wind-driven currents included (left panel) for a continuous stream of salmon approaching the coast. The salmon were swimming at 0.5 m s\(^{-1}\) and were oriented at an angle of 99° with respect to true North.
Figure 5.27: Simulated return timing of salmon for continuous streams of salmon for the summer of 1994 (top) and 1995 (bottom).
Figure 5.28: Power spectrum of salmon return timing calculated from the combined simulated returns for 1994 and 1995. The analysis was done with a Hanning window of width 120 and a 50 % overlap.
Chapter 5. Model results: effects of wind-driven currents

5.3 Discussion

The salmon migration model showed that the wind-driven currents can spread and deflect either part or a whole group of salmon by a distance of 20\% of their travelling distance. The trajectories of these simulated salmon (figure 5.29) show that some are more deflected than others depending on where and when they travel. They can be deflected to either side of Vancouver island, hence creating a spreading of the distribution.

The wind-driven currents vary over the summer and the simulated salmon distribution varies accordingly. For example, on July 12, 1994 (figure 5.30), the currents are southward and fairly strong (up to 0.5 m s\(^{-1}\)) close to the coast. As a result, the whole distribution of salmon is pushed west of the island with a deflection of 70-80 km. Later that summer on August 20 (figure 5.31), the currents are still strong but they shifted to a south-eastward direction. The salmon at that time are more evenly distributed east and west of the island.

Model results showed that salmon path can be altered by the wind-driven currents. These currents are driven by the wind stress at right angles therefore the displacements in the salmon distribution are also due to the wind-stress at right angles to the salmon displacement direction. Corresponding to these displacements, the return timing of salmon shows variability over period of 3-18 days as the salmon are pushed in and out of the sampling area in the model. These results could have implications over salmon sampling strategy and could explain some of the variability seen in the data of salmon run returns.
Figure 5.29: Trajectory of four simulated salmon at the beginning of July 1994 for the experiment shown in figure 5.26 (right). The salmon were swimming at 0.5 m s\(^{-1}\) and were oriented at an angle of 99° from true North.
Figure 5.30: Distribution of simulated returning salmon on July 12, 1994 (right) and the daily average near-surface current from the hydrodynamic model with wind stress from moored buoys (thick line) on July 12, 1994 (left).
Figure 5.31: Distribution of simulated salmon on August 20, 1994 (right) and the daily average near-surface current from the hydrodynamic model with wind stress from moored buoys (thick line) on August 20 (left).
Interannual variability of the ocean conditions and its effects on salmon migration is now considered. The previous chapter showed that a large part of the variability in the surface current is driven by the normal component of the wind stress due to the Ekman layer response. A first estimate of the cross-shore surface current can therefore be calculated from the along-shore wind stress. Interannual variability is seen in the travelling route choice of returning salmon: either east or west of the island. The u-component of the current in the coastal ocean could contribute in part to this choice. Predictions of the diversion of salmon obtained from the u-component of the current can be used to assess this contribution.

This chapter shows how time series of the cross-shore spatially-averaged current in Queen Charlotte Sound area can be inferred from wind stress data obtained from moored weather stations buoys. Predictions of the spatially-averaged current are presented for the years 1992 to 1995. These predictions are then used to infer the time series of salmon diversion for the same years.

6.1 Predicting currents using a regression model

Regression model

A regression model was built to predict time series of the u-component of the mean current from the v-component of the wind data. Define the linear equation (Bourque
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and Kelley (1995); Draper and Smith (1981):

\[ y = mx + \epsilon \]  

(19)

where \( y \) is a vector with dimensions \([1 \times N]\), \( m \) is a vector with dimensions \([1 \times S]\), \( x \) is a matrix with dimensions \([S \times N]\) and \( \epsilon \) represent a vector of errors associated with missing physics with dimension \([1 \times N]\). The sum of the errors squared \( \epsilon'\epsilon \), is:

\[ \epsilon'\epsilon = (y - mx)'(y - mx), \]

(20)

\[ \epsilon'\epsilon = y'y - 2y'mx - x'm'mx \]

(21)

where ' means taking the transpose of the vector or matrix. Estimation of \( m \) is done by minimizing \( \epsilon'\epsilon \):

\[ \frac{\partial (\epsilon'\epsilon)}{\partial m} = -2yx' - 2mxx' = 0, \]

(22)

therefore,

\[ m = (xx')^{-1}xy' \]

(23)

Equation 19 can be rewritten as:

\[ u = C\tau_y + \epsilon \]

(24)

where \( u \) is a time series of the mean cross-shelf current in Queen Charlotte Sound, with dimensions \([1 \times 120]\), representing 120 days. \( \tau_y \) is a matrix containing four time series of wind stress from different moored buoys, with dimensions \([4 \times 120]\). The vector \( C \), with dimensions \([1 \times 4]\), contains four coefficients to be estimated. The vector \( u \) was estimated by taking the average of the u-component of the current simulated by the hydrodynamic model, for 1994, at seven positions on the model grid: (200 km, 150 km), (250 km, 150 km), (300 km, 150 km), (300 km, 150 km) (250 km, 200 km), (200 km, 300 km) and (250 km, 250 km) (figure 6.32). The four time series of wind stress (figure 6.33) are obtained
from wind data in 1994 at stations 5, 9, 12 and 13 (figure 5.17). The set of coefficients $C$ was estimated from equation 23:

$$ C = (\tau_y \tau_y')^{-1} u \tau'_y, $$

which provides a relationship between the wind stress, $\tau_y$, and the mean current $u$. The spatially-averaged current obtained from the wind stress for 1994 using

$$ u = C \tau_y $$

is shown in figure 6.34 (solid line). The correlation between this prediction and the mean current obtained directly from the hydrodynamic model (figure 6.34, dotted line) is high (0.83) which was of course expected since $C$ was inferred from the results of the hydrodynamic model current, where Ekman drift is dominant at the surface.

**Validation of the regression model**

The regression method forces the coefficient $C$ to yield a best fit between the regression prediction and the mean current which provides a prediction that appears to be good (figure 6.34). However, since this is an artifact of the regression method, a validation of the model needs to be done for other years to conclude that the predictive model is adequate. A validation of the regression model was obtained in this study by predicting the mean current from the wind stress in 1995 (figure 6.35) and by comparing this prediction to the hydrodynamic result for 1995 (figure 6.36). The prediction from the wind (figure 6.37, solid line) is very similar to the mean current obtained from the hydrodynamic model for 1995 (figure 6.37, dotted line). The correlation between the two curves is 0.81, again showing the dominance of the Ekman transport.
Figure 6.32: Near surface currents (u-component) in m s$^{-1}$, obtained from the hydrodynamic model for the summer of 1994: currents at 7 positions of the model domain [(200 km, 150 km), (250 km, 150 km), (300 km, 150 km), (350 km, 150 km), (250 km, 200 km), (200 km, 300 km) and (250 km, 250 km)] (top) and mean current obtained from 7 positions of the model domain (bottom).
Figure 6.33: Wind stress ($u$-component) for the summer of 1994 from station 5 (C46147), 9 (C46204), 12 (C46207) and 13 (C46208) of the Environment Canada moored buoys array.
Figure 6.34: Comparison between the mean current (u-component) obtained from the hydrodynamic model (dotted line) and that inferred from a regression method (solid line). The correlation between the two curves is 0.83.
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Figure 6.35: Wind stress (u-component) for the summer of 1995 from station 5 (C46147), 9 (C46204), 12 (C46207) and 13 (C46208) of the Environment Canada moored buoys array.
Figure 6.36: Near surface currents (u-component) in m s$^{-1}$, obtained from the hydrodynamic model for the summer of 1995: currents at seven positions of the model domain [(200 km, 150 km), (250 km, 150 km), (300 km, 150 km), (350 km, 150 km), (250 km, 200 km), (200 km, 300 km) and (250 km, 250 km)] (top) and mean current obtained from 7 positions of the model domain (bottom).
Figure 6.37: Comparison between the mean current (u-component) obtained from the hydrodynamic model (dotted line) and inferred from a regression method (solid line) for 1995. The correlation between the two curves is 0.81.
Regression model with missing wind data

The value of the vector $C$ in equation 26 was derived from data at four wind stations. However, for some years, only two or three stations were available. The calculation described above was therefore repeated and validated for cases where only station 9, 12 and 13 or stations 9 and 12 were available. The current predicted from the hydrodynamic model compared with the current predicted from the wind with two stations and with three stations is shown for 1994 in figure 6.38 and for 1995 in figure 6.39.

Current predictions

The various values of the vector $C$ yield the following equations to predict the current from the wind stations:

1. for stations 5, 9, 12 and 13:

$$ u = \begin{bmatrix} 3.970 \times 10^{-4} \\ 1.680 \times 10^{-4} \\ 2.384 \times 10^{-4} \\ 0.062 \times 10^{-4} \end{bmatrix} [ \tau_y^5 \tau_y^9 \tau_y^{12} \tau_y^{13} ] $$

\hspace{1cm} (27)

2. for station 9, 12 and 13:

$$ u = \begin{bmatrix} 1.893 \times 10^{-4} \\ 3.722 \times 10^{-4} \\ 1.578 \times 10^{-4} \end{bmatrix} [ \tau_y^9 \tau_y^{12} \tau_y^{13} ] $$

\hspace{1cm} (28)

3. for stations 9 and 12:

$$ u = \begin{bmatrix} 0.877 \times 10^{-4} \\ 5.742 \times 10^{-4} \end{bmatrix} [ \tau_y^9 \tau_y^{12} ] $$

\hspace{1cm} (29)

This set of equation was use to predict the $u$-component of the mean current in Queen Charlotte Sound for 1992, 1993, 1994 and 1995 (figure 6.40).
Figure 6.38: Comparison between the mean current (u-component) obtained from the hydrodynamic model (dotted line) and that inferred from a regression method (solid line) using two wind stations (top panel, $r=0.80$) and three wind stations (bottom panel, $r=0.82$) for 1994.
Figure 6.39: Comparison between the mean current (u-component) obtained from the hydrodynamic model (dotted line) and that inferred from a regression method (solid line) using two wind stations (top panel, $r=0.80$) and three wind stations (bottom panel, $r=0.81$) for 1995.
Figure 6.40: Mean near-surface current (u-component) in Queen Charlotte Sound inferred from the v-component of the wind stress using a regression method for 1992, 1993, 1994 and 1995.
6.2 Salmon diversion predictions

Results from chapter 5 indicate that the wind-driven current can deflect the salmon east or west of Vancouver Island. A simulation was therefore performed to produce time series of salmon diversion for 1994. The salmon diversion was defined as the proportion of salmon travelling west of the island with respect to the total number of salmon approaching the coast. The initial conditions were such that a continuous stream of salmon (figure 5.2) was introduced in the coastal area, as it was done in chapter 5. The number of salmon going west of the island was counted each day along with the total number of salmon approaching the tip of Vancouver Island. The ratio of these two time series produced a time series of diversion of salmon (figure 6.41, solid line). The diversion exhibits changes of period from 5 to 18 days. The u-component of the mean current (figure 6.32) compare poorly with this curve, which was expected because the simulated salmon have been affected by the current for seven days when they reach the island. To account for this effect, a moving average of seven days was performed over the u-component of the mean current (figure 6.41, dotted line). This filtered current is very similar to the diversion time series (figure 6.41, solid line) The correlation, done between June 10 to September 14, 1994 (day 10 to 105) is 0.84. The linear fit between these two time series (figure 6.42) is

$$d = 0.68 - 2.79u$$ \hspace{1cm} (30)

where \(d\) is the diversion and \(u\) is the u-component of the mean current. Using equation 30, the diversion for the summers of 1992 to 1995 are predicted directly from the u-component of the current (figure 6.43, solid lines). This prediction is not as complete as those performed by the salmon migration model since it does not include the v-component of the current, but it involves less computational time and space since it is inferred directly from the wind data. The correlation between the series using both methods is 0.81 for
Figure 6.41: Comparison between the seven-day-averaged mean current (dotted line) in Queen Charlotte Sound (u-component) and the salmon diversion (solid line) predicted by the salmon migration model for the summer of 1994. The diversion is defined as the number of salmon travelling west of Vancouver Island with respect to the total number of salmon reaching the island.
Figure 6.42: The diversion predicted by the salmon migration model as a function of the seven-day averaged mean current in Queen Charlotte Sound (u-component) for 1994. The linear fit equation is \( d = 0.68 - 2.79u \).
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Table 6.5: Proportion of simulated salmon travelling west of the island with respect to the number of salmon arriving near the island. The values are averaged over the summer for June to September and July to September, and averaged over a week.

<table>
<thead>
<tr>
<th>Year</th>
<th>June-Sept</th>
<th>July-Sept</th>
<th>July 2-July 8</th>
<th>mean</th>
<th>std</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>0.74</td>
<td>0.74</td>
<td>0.75</td>
<td>-0.0150</td>
<td>0.0482</td>
</tr>
<tr>
<td>1993</td>
<td>0.73</td>
<td>0.76</td>
<td>0.89</td>
<td>-0.0196</td>
<td>0.0430</td>
</tr>
<tr>
<td>1994</td>
<td>0.68</td>
<td>0.68</td>
<td>0.83</td>
<td>0.0001</td>
<td>0.0549</td>
</tr>
<tr>
<td>1995</td>
<td>0.71</td>
<td>0.71</td>
<td>0.72</td>
<td>0.0026</td>
<td>0.0539</td>
</tr>
</tbody>
</table>

1994 and 0.78 for 1995 which indicates that the regression method predicts most of the variability predicted by the numerical model of salmon migration.

The predicted salmon diversion does not show significant interannual variability. The average diversion for each year was calculated over June to September and over July to Sept (table 6.2). The largest interannual variability differences are of the order of 7%. The largest difference in currents averaged over June to September is of the order of 0.02 \( ms^{-1} \), or 4% of the salmon swim speed, and is seen between 1993 and 1994. The cross-shore currents in 1992 and 1993 are negative which is consistent with a larger number of salmon travelling west of the island. Larger interannual differences (up to 17%) were obtained when the diversion was averaged over a week, from July 2 to July 8. The variability over a week is consistent with the findings of chapter 5 which shows that storms can cause deflections of a salmon trajectory of the order of 50 km which, for a spatial distribution of 200 km width, correspond to 20%.
Figure 6.43: The salmon diversion inferred from wind stress data using a regression method for 1992, 1993, 1994 and 1995 (solid line) and the salmon diversion inferred from the numerical model of salmon migration for 1994 and 1995 (dotted line).
Chapter 7

Discussion

7.1 Implications for sampling strategies

Model results have shown that both salmon distribution and return timing can be affected by the coastal ocean currents at two different scales: at a semi-diurnal period of 12.4 h (figure 4.8) and at a storm period of 3-18 days (figure 5.6). The variability in salmon distribution and return time due to currents could cause aliasing problems in sampling which would lead to an overestimate or an underestimate of the salmon abundance. The first problem could arise if the sampling were done repetitively once or twice a day at the same time. If salmon was sampled semi-diurnally when the abundance is consistently at its peak due to tides, the total abundance would be overestimated. Similarly, sampling done when the abundance is consistently low, would underestimate the total abundance. A second problem could arise if the sampling were done only for a short period, i.e., continuously for one or two days. Again, the number of salmon sampled would not represent the whole run if sampling occurred during a period of high or low abundance which could last for 3 to 18 days. Moreover, samples taken in the middle of the patches created by the tidal currents would not be representative of the salmon abundance at a larger spatial scale. These potential problems have to be addressed in order to design more appropriate sampling strategies and assess uncertainty in past and future sampling schemes.
Chapter 7. Discussion

7.2 Comparison between model results and fisheries data

Salmon run abundance and arrival timing are assessed by the Pacific Salmon Commission data from stock groups catch estimates, test fishing, stock identification and escapement estimation (Pacific Salmon Commission, 1995). Catches from commercial fisheries are estimated in the Fraser River Panel Area (see figure 7.44) and are also obtained outside the Panel Area. Test fishing, conducted before and after fishing seasons and between fishing openings, yields abundance indices and provides samples for stock identifications. Daily escapements, the abundance of adult sockeye “escaping” fisheries, are estimated at Mission by stationary hydroacoustic sampling (Trevorrow, 1997; Banneheka, 1995).

These data are used to provide estimates of total runs either by stock or for all the Fraser River sockeye salmon. Reconstructed salmon data for various stocks are shown for 1992 (figure 7.45), 1993 (figure 7.46), 1994 (figure 7.47) and 1995 (figure 7.48). These times series represents the number of salmon entering the Canadian statistical Area 11 (see figure 7.44)

These series show some periods where salmon are missing. The present study shows that the variability in the data could be in part, explained by the effect of wind-driven currents; the model results showed a similar variability (figure 5.6), which is due to the wind-driven currents pushing the simulated salmon in and out of the sampling area of the model. Similarly, sockeye salmon could be pushed by coastal currents, as they vary from southwards to southeasterswards, which could change the number of salmon entering Johnstone Strait. This mechanism would create a variability similar to that seen in the salmon run data. Salmon behaviour are however still poorly known. The variability seen in the data could also be caused by a directional change due to behaviours such as high temperature avoidance or the following of signals from the salmon’s natal stream.
Figure 7.44: Fisheries management areas and commercial gear used in the Fraser River Panel Area and Canadian south coast waters (after Cave and Gazey, 1994)
Figure 7.45: Reconstructed salmon migration via Johnstone Strait for 1992 at Area 11. (from Pacific Salmon Commission, pers. comm.).
Figure 7.46: Reconstructed salmon migration via Johnstone Strait for 1993 at Area 11. (from Pacific Salmon Commission, pers. comm.)
Figure 7.47: Reconstructed salmon migration via Johnstone Strait for 1994 at Area 11. (from Pacific Salmon Commission, pers. comm.)
Figure 7.48: Reconstructed salmon migration via Johnstone Strait for 1995 at Area 11. (from Pacific Salmon Commission, pers. comm.)
Chapter 7. Discussion

7.3 Effects of coastal currents over the Northern Diversion Rate variability

The interannual variability study of chapter 6 shows that the maximum variability in diversion averaged over a whole summer is 7%. The Northern Diversion Rate for salmon travelling west of the island, as computed by the Pacific Salmon Commission, shows a much larger interannual variability (see figure 7.49). For example, a variability of the order of 30% is seen between 1994 and 1995. In order to produce such variability, the wind-driven currents would have to be consistently different between one year to the next by at least 0.15 m s\(^{-1}\), or 30% of the salmon swim speed. This has not been the case for the years 1992 to 1994. However, the Northern Diversion could have been be overestimated or underestimated by sampling done at times of particularly strong storms. Simulated diversion (figure 6.42) calculated over July 2 to July 8 (table 6.5) show differences of the order of 20%. This maximum diversion is consistent with the deflection of 40 km of a salmon distribution with a 200 km width. If the salmon distribution is narrower, a larger variability in salmon diversion can be seen. To illustrate this effect, the model was run with a narrower salmon distribution. Salmon were started at the 340 km y-coordinate, between the 75 and 150 km x-coordinates (figure 7.50). The simulated salmon diversion for 1994 and 1995 (figure 7.51) shows a much larger variability (up to 90%) than for a wider salmon distribution (figure 6.42). The mean simulated salmon diversion over the whole summer varies by 6% between 1994 and 1995 (table 7.6), but the mean diversion over a week (July 30 to August 5) vary by 83%. This implies that variabilities at storm periods could have affected the calculations of the Northern Diversion Rate.
Figure 7.49: Northern Diversion Rate, southern approach through Juan the Fuca Strait (from Pacific Salmon Commission, pers. comm.)
Figure 7.50: Distribution of salmon 20 days after the start of the experiment, which simulated a narrow salmon distribution. Salmon were swimming at 0.5 $ms^{-1}$ and were oriented at an angle of 99° with respect to true North.
Figure 7.51: Salmon diversion for 1994 and 1995 obtained from an experiment simulating a narrow salmon distribution
7.4 Salmon migration model limitations and improvements

One of the most obvious simplifications of the numerical model lies in the initial conditions which implies that the currents in the open ocean have no effects on the salmon distribution. The coastal model simulates the start of the coastal migration by introducing rows of salmon either perfectly lined or with a normal distribution. This implies that the salmon's open ocean life, with possible changes in distribution due to currents or behaviour, is ignored. Such possible changes include the deflection of salmon in different oceanographic domain of the British Columbia coast due to changes in the circulation of the Alaska Gyre (Thomson et al., 1994). The modeling could be improved by adding some randomness in the initial distribution, or by including an initial distribution consistent with the current patterns of the North Pacific for corresponding years.

The modeling strategy used in this study was to keep the salmon behaviour simple in order to better understand and interpret the model results. The following simplifications were made: salmon were swimming at the surface and with a constant swim speed and orientation, which implied that salmon do not feed during their return migration and that they are insensitive to temperature and salinity. These simplifications are likely unrealistic. The goal of this thesis, however, was not to predict real tracks of migrating salmon, but to isolate each component that could affect returning salmon to understand

<table>
<thead>
<tr>
<th>Year</th>
<th>June-Sept.</th>
<th>July 30- Aug. 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>0.56</td>
<td>0.07</td>
</tr>
<tr>
<td>1995</td>
<td>0.62</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 7.6: Proportion of salmon travelling west of the island with respect to the total number of salmon arriving near the island, for a narrow salmon distribution. The values are averaged over June to September and July 30 to August 5.
the effect of each component separately. This approach was started by investigating the effects of the currents alone at different time scales to understand the role played by tidal and wind-driven currents in salmon migration. This first step was necessary and had to be kept simple before proceeding to a more complicated model that would test proposed salmon behaviour.
Chapter 8

Conclusions

8.1 Summary

This study examined the effects of coastal currents on Pacific Salmon distribution and return timing. The method used to address this problem was to develop a spatially-explicit individual based model of coastal salmon migration. This numerical model has a physical component, which infers the ocean conditions from wind and tidal forcing, and a biological component, which follows salmon swimming at one body-length per second towards Vancouver Island.

Numerical experiments were done which included first the tidal currents alone and then both the tides and the wind-driven currents to infer the effects of coastal currents on salmon distribution and return. The cross-shore component of the mean current in Queen Charlotte Sound was then predicted for the years 1992 to 1994 from wind stress data using a regression method. The current predictions were used to study the effects of current interannual variability on salmon migration. This thesis produced three main conclusions:

1. Tidal currents cause a cycle of 12.4 h in the salmon return associated with patchiness in the salmon distribution. This cycle could lead to aliasing problems in salmon sampling.

2. Wind-driven currents cause a cycle with storms periods (3-18 days) in salmon returns associated with cross-shore deflections of the salmon paths of the order of
20 % of their travelling distance. This might explain some of the variability seen in reconstructed run migration of Fraser River Sockeye salmon.

3. The coastal current can change the proportion of salmon travelling east or west of Vancouver Island by approximately 7 % interannually, which is consistent with the cross-shore current variability. This result appears to be independent of the width of the salmon distribution. However, coastal currents can produce a large variability in simulated continuous salmon diversion. This implies that this variability could have affected the calculations of the Northern Diversion Rate.

8.2 Future Work

The next step in modeling experiments would be to include a salmon behaviour of sensitivity to temperature. The latest salmon studies reveal that salmon are sensitive to warm temperature and may alter their salmon routes to remain in colder waters (Welch et al., 1995; Welch et al., 1998). Moreover, recent numerical studies suggest that the effects of coastal temperature should be investigated (Kolody and Healey, 1998). This behaviour could be easily implemented in the individual-based model framework by including temperature avoidance in the biological component of the model and by including the surface temperature field which is already being predicted by the hydrodynamic model. Model results would be readily interpretable since the effects of currents on salmon migration are now understood based on my results.

Chapter 6 showed that surface currents in Queen Charlotte Sound can be predicted from the wind stress using a regression method. A relevant future study will be to hindcast the currents off British Columbia for a longer period of time. The hydrodynamic model will be run to produce currents at 20 m depth for a few years. The currents and the wind stress will be used to provide a regression model similar the one developed in
chapter 6. This statistical model will be used to predict the current at various areas of the northern coast of British Columbia for 40 years. These predictions will provide fisheries scientists with a knowledge of the coastal environment for a long time period.
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simple behaviour on the distribution of cod and haddock early life stages on Georges

barotropic response of the Gulf of Maine and adjacent regions to surface wind stress.
Appendix A

Climatology at the entrance of Johnstone Strait

Time series of the climatology of temperature and salinity were created to investigate the fresh water signature at Johnstone Strait. The time series were produced from a data set obtained by the Institute of Ocean Sciences and the University of British Columbia. The temperature and salinity data were collected at the entrance of Johnstone Strait with bottles and CTDs during various oceanographic cruises from 1951 to 1994. The mean of the temperature and salinity were calculated by interpolation for each month and for a series of depths at intervals of 5 m (figure A.1).

The time series show a warming of the surface water in the summer and a small increase in salinity during the spring. This indicates that the climatology shows no fresh water signature associated with spring river run-off in the area of the mouth of Johnstone Strait.
Figure A.1: Climatology at the entrance of Johnstone Strait: time series of the mean salinity (top) and average temperature (bottom) obtained from CTD and bottle data from 1951 to 1994.
Appendix B

Sensitivity of salmon migration simulations to initial conditions

The salmon migration numerical model was run with the tidal currents to investigate the sensitivity of simulated return timing and spatial distribution to salmon starting time, starting position and swim speed. For each case, the time series of return timing showed an oscillation at the semi-diurnal period (12.4 h). Alternating empty patches and areas of high concentration of salmon were also seen in the spatial distributions.

Return timing

The sensitivity of return timing to the salmon starting time was assessed (figure B.2). For all simulations, salmon were started at the positions shown in figure 4.1. They started either during spring low tides, spring high tides and neap high tides. All times series exhibit the same oscillation of period 12.4 h, due to the semi-diurnal tidal currents. The time series are slightly different which is to be expected since the salmon encountered different tidal fields as they traveled.

Tests were also done to examine the sensitivity of return timing to the salmon starting position (figure B.3). The salmon orientation had a different angle for each starting position (A: 81° with respect to true North; B: 113° with respect to true North). They were swimming towards the tip of Vancouver Island. Although the oscillation of period 12.4 h is not as clear as for the return timing of figures 4.3 and B.2, it can be seen for these tests.

The sensitivity of return timing to salmon swim speed is shown in figure B.4. The
Figure B.2: Sensitivity of return timing to starting time: return timing for salmon starting at spring low tides, spring high tides and neap high tides. The time scale corresponding to a full $M_2$ tidal cycle is shown on each panel. The x-axis corresponds to hours from the start of the simulation.
Figure B.3: Sensitivity of return timing to starting position: starting positions A and B, return timing for salmon starting at position A and position B. The time scale corresponding to a full $M_2$ tidal cycle is shown on the two bottom panels. The x-axis scale corresponds to hours from the start of the simulation.
Appendix B. Sensitivity of salmon migration simulations to initial conditions

Figure B.4: Sensitivity of return timing to salmon swim speed: return timing for salmon swimming at 0.8 m s\(^{-1}\), 0.5 m s\(^{-1}\) and 0.2 m s\(^{-1}\). The time scale corresponding to a full M\(_2\) tidal cycle is shown for each panel. The x-axis scale corresponds to hours from the start of the simulation.
Appendix B. Sensitivity of salmon migration simulations to initial conditions

return timings of salmon swimming at 0.8, 0.5 and 0.2 m s\(^{-1}\) were determined. All time series show the tidal oscillation with a 12.4 h period.

Spatial Distribution

Salmon entering the model domain at different times showed similar distributions after five days (figure B.5). The simulations were started during spring low tides, spring high tides and neap high tide. The empty patches are oriented slightly differently but are of similar size (~ 20 × 10 km\(^2\)).

The salmon groups were started at two positions: A (figure B.6, bottom left) and B (figure B.6, bottom right). The spatial distributions for the two simulations are different but empty patches can be seen in both cases. They are of similar size and their locations are different. This difference is not surprising since the salmon encountered different tidal currents fields along their path.

Figure B.7 shows the sensitivity of salmon distribution to swim speed. Simulations were done for salmon swimming at different speeds (figure B.7): 0.8 m s\(^{-1}\) (top left), 0.5 m s\(^{-1}\) (top right) and 0.2 m s\(^{-1}\) (bottom). Empty patches can be seen for all simulations. The slower salmon (0.2 m s\(^{-1}\)) show the most patchiness in their distribution.
Appendix B. Sensitivity of salmon migration simulations to initial conditions

Figure B.5: Sensitivity of salmon spatial distribution to starting time: spatial distribution after five days for salmon starting at spring low tides, spring high tides and neap high tides.
Figure B.6: Sensitivity of salmon spatial distribution to starting position: starting positions A and B and spatial distribution for salmon starting at positions A and B.
Figure B.7: Sensitivity of salmon spatial distribution to swim speed: spatial distribution for swim speeds of 0.8, 0.5 and 0.2 m s$^{-1}$. 

Appendix B. Sensitivity of salmon migration simulations to initial conditions
Appendix C

Model sensitivity to spatial resolution

The salmon migration model was run at a spatial resolution of 2.5 km and 5 km for comparison. The tidal currents used in the simulations of chapter 4 were not directly used for this test on resolution sensitivity. In order to reduce computational time and space, the tidal currents for both resolutions were derived from the coefficients of harmonic analyses.

The current \( z \) at time \( t \) can be expressed in its complex form Foreman, 1978 as:

\[
z(t) = u + iv,
\]

or

\[
z(t) = A \cos \Theta \cos(\omega t - g) - B \sin \Theta \sin(\omega t - g)
\]

\[
+ i(A \sin \Theta \cos(\omega t - g) + B \cos \Theta \sin(\omega t - g)),
\]

where \( \omega \) is the frequency of a particular tidal constituent, \( A \) is the semi-major axis length of that constituent, \( B \) is the semi-minor axis length, \( \Theta \) is the angle of inclination and \( g \) is the relative angle. So

\[
\begin{pmatrix}
u \\
v
\end{pmatrix} =
\begin{pmatrix}
\cos \Theta & -\sin \Theta \\
\sin \Theta & \cos \Theta
\end{pmatrix}
\begin{pmatrix}
A \cos(\omega t - g) \\
B \sin(\omega t - g)
\end{pmatrix}
\]

holds for each tidal frequency \( \omega \). A set of coefficients \( (A, B, \Theta \) and \( g) \) can be calculated from currents fields by least squared analysis for each tidal frequency. Corrections for the astronomical factors are included afterwards.
The hydrodynamic model was run with tidal forcing at both 2.5 km and 5 km spatial resolutions. Harmonic analyses were then performed on both results to obtain two sets of coefficients (A, B, Θ and g) for each of the 4 tidal constituents (M2 of period 12.42 h; K1 of period 23.93 h; S2 of period 12.00 h and O1 of period 25.82 h) and for a mean current of zero frequency. Results obtained for the two harmonic analyses yielded similar coefficients. Comparisons are shown in figure C.8 (coefficient AM2) and figure C.9 (coefficient ΘM2). Note that the currents offshore (x-coordinates less than 200 km) were stored as zeros for the 2.5 km resolution experiment to reduce computational time and space.

The tidal currents were reconstituted for the 5 km and 2.5 km resolutions by summing the tidal currents for each constituent obtained from equation 34. Overall, the obtained currents are similar for both model resolutions. The 2.5 km resolution yields slightly larger currents in shallower water (position A, figure C.10 and C.11, and position D, figure C.12 and C.13).

Salmon return simulations were then performed using the tidal currents at 2.5 km and 5 km resolutions obtained from the harmonic analysis described above. Similar features can be seen in the spatial distribution for both simulations (figure C.14).
Figure C.8: Results from the harmonic analysis: contours of the semi-major axis length for the $M_2$ tidal constituent, $A_{M_2}$, resulting from the model at a 5 km resolution and a 2.5 km resolution.
Figure C.9: Results from the harmonic analysis: contours of the angle of inclination for the $M_2$ tidal constituent, $\Theta_{M_2}$, resulting from the model at a 5 km resolution and a 2.5 km resolution.
Figure C.10: Comparison between predicted tidal currents at position A and B: east-west tidal currents from a 5 km resolution model (dash line) and from a 2.5 km resolution model (solid line) at position A and at position B.
Figure C.11: Comparison between predicted tidal currents at position A and B: north-south tidal currents from a 5 km resolution model (dash line) and from a 2.5 km resolution model (solid line) at position A and at position B.
Figure C.12: Comparison between predicted tidal currents at position C and D: east-west tidal currents from a 5 km resolution model (dash line) and from a 2.5 km resolution model (solid line) at position C and at position D.
Figure C.13: Comparison between predicted tidal currents at position C and D: north-south tidal currents from a 5 km resolution mode; (dash line) and from a 2.5 km resolution model (solid line) at position C and at position D.


Figure C.14: Sensitivity of salmon spatial distribution to model resolution: salmon distribution obtained from a 5 km resolution model and from a 2.5 km resolution model.