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Variability in a fjord-like coastal estuary I: Quantifying the circulation using a formal multi-tracer inverse approach

Olivier G.J. Riche [a,*], Rich Pawlowicz [b]

[a] School of Earth and Ocean Sciences, University of Victoria, 3800 Finnerty Road, Victoria, BC V8P 5C2, Canada
[b] Department of Earth and Ocean Sciences, University of British Columbia, 6339 Stores Rd., Vancouver, BC V6T 1Z4, Canada

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ABSTRACT

During 2002–2005, a comprehensive set of observations covering physical, biological, radiative and atmospheric parameters was obtained from the southern Strait of Georgia (SoG), Western Canada by the STRATOGEM program. Monthly time series of estuarine layer transports over 2002–2005 were estimated using a time-dependent 2-box model in a formal inverse approach. The formal inverse approach builds up upon a so-called "pseudo-inverse" and the Singular Value Decomposition methodology. The transports are then consistent with the temperature and salinity fields, as well as riverine freshwater inflow (R) and detailed atmospheric heat fluxes. Uncertainty was analyzed by resampling observations using bootstrap methods.

Analysis of these time series suggests that the SoG estuarine circulation is not very sensitive to the seasonal changes of R. Comparison of the surface layer transport (U1) and R yields the first observational relationship between the SoG estuarine circulation and R. The analysis of this relationship shows that U1 has a fractional form as R to the power of $1/n$ with $n < 1$. Such fractional relationship shows that the flows change only slightly with the freshet. A 5-fold change in R results only in a 40% change in U1. However, freshwater range and uncertainty in the data prevented us from clearly determining the fraction n.

Analysis of the transports in light of the residuals in the mass, heat and salt budgets suggests that our inversion procedure works properly and improves on the SVD inverse procedure. Analysis of the transports sensitivity to inversion parameters shows that the transports are close to both the a priori and true transports and that they are dependent on both a priori information and data.

1. Introduction

The first step in any attempt to understand the dynamics of an estuarine system must be an estimate of the circulation and mass transports within the system. These transports govern the distribution of nutrients and/or pollutants in the system, and their exchange with shelf waters, and hence also have an important controlling effect on biological activity in the estuary. This study attempts to objectively quantify the estuarine transports in the Strait of Georgia (SoG), a fjord-like estuarine system located in British Columbia, Canada (Fig. 1). A subsequent paper will deal with the implications of the physical circulation on biological productivity in this region.

In spite of the importance of transport estimates, obtaining quantitative values from direct measurements of the circulation in estuaries (including this one) are often impractical as current measurements capable of adequately resolving spatial variations are difficult to obtain, even over a few key transects (Godin et al., 1981). Instead, various formalisms are often used in order to estimate these transports from the measurements of different scalars. The simplest approach is the diagnostic use of quasi-steady state mass and salt budgets based on "Knudsen" relations (Dyer, 1973). In this approach the estuarine circulation is directly linked to freshwater inflow rates and the increasing salinity of the outflow as it moves seaward.

The lack of explicit time dependence in the Knudsen relations may be a problem, but as most datasets are not comprehensive enough to address this issue the lack of methodological rigour is perhaps irrelevant. Many estuarine studies concern themselves solely with the mean transport (Austin, 2002; Pawlowicz et al., 2007) or just assume a quasi steady state (England et al., 1996; Mackas and Harrison, 1997; Savenkoff et al., 2001; Pawlowicz, 2001).

Box models can be used to extend the Knudsen approach by calculating not only horizontal flows, but also vertical flows (Gordon et al., 1996), adding time-dependence and combining

* Corresponding author.
E-mail addresses: oriche@alumni.ubc.ca (O.G.J. Riche), rpawlowicz@eos.ubc.ca (R. Pawlowicz).

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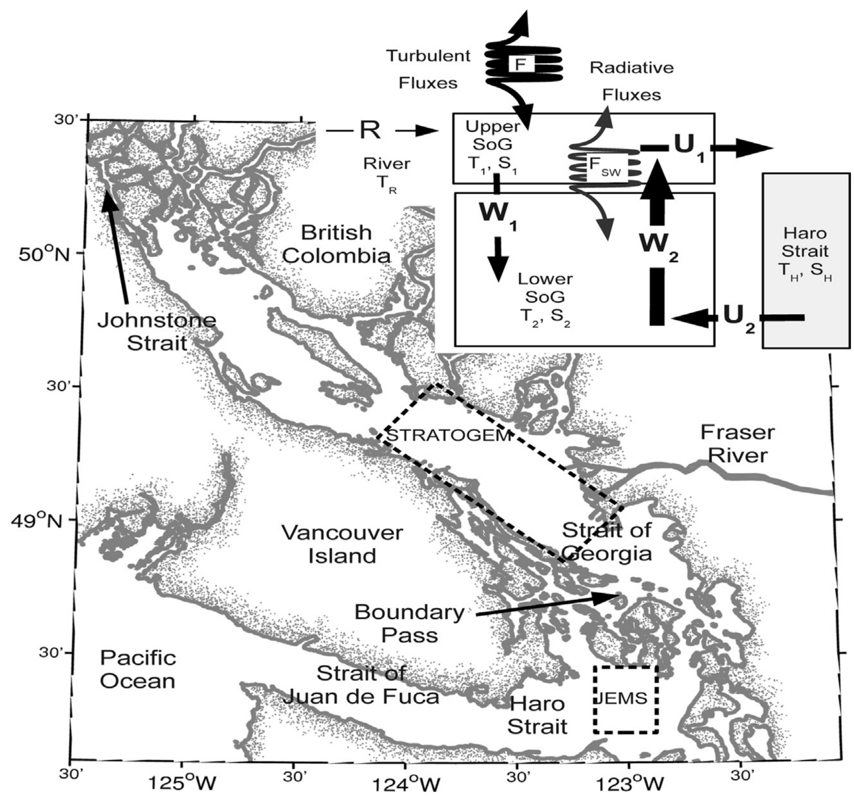

Fig. 1. Geography of the Salish Sea. The dashed squares indicate the sampling area of the STRATOGEM and JEMS programs (see Section 2.2). Insert, physical fluxes and processes in the box model. The left-hand boxes represent the SoG, and the right-hand box the Haro Strait (HS). The thick arrows represent the transports in and out the SoG (U_1, U_2, W_1 and W_2). In the model, the surface SoG water enters the surface of HS (U_1) while the deep HS water enters the deep SoG (U_2). The arrow thickness approximates the relative magnitude of transports. The upper left arrow represents the freshwater inflow (R). The thick wavy arrow represents the turbulent and radiative heat fluxes (F). FSW is the shortwave component of F (thin wavy arrow) that penetrates deeper into the SoG than the longwave component.

additional tracer budgets (usually temperature (Roson et al., 1997; Pawlowicz and Farmer, 1998) and sometimes oxygen (Pawlowicz et al., 2007) and nutrients (Savenkoff et al., 2001)), and/or adding more boxes (Burrard Inlet Environmental Action Program, 1996; Gordon et al., 1996). In spite of this increasing complexity the box-model approach can still provide a more flexible and less resource-consuming approach than high-resolution 3D-numerical models for estimating the circulation. Extended box models can be analyzed in various ad-hoc ways (Pawlowicz et al., 2007) or in more formal inverse approaches (Savenkoff et al., 2001).

Prognostic approaches are also used. These range from box-models which incorporate simplified and tuned dynamics (Li et al., 1999), to fully 3D numerical modelling (Masson and Cummins, 2004). However, the tuning required in prognostic approaches in order to make results "match" observations of scalar variables is somewhat ad-hoc, and it is not always obvious whether or not particular details of the implementation are aiding or detracting from the match. In many of these models, freshwater inflow rates are again a fundamental forcing factor.

Theoretical analyses of estuarine circulations, developed using idealized numerical models, have also been proposed in which estuary dynamics are modelled by scaling arguments (Chatwin, 1976; MacCready, 1999; Geyer et al., 2000; Hetland and Geyer, 2004; MacCready and Geyer, 2010). In particular, the estuarine flow is again scaled to the freshwater flow and the tidal flow. One interesting conclusion is that vertical turbulent mixing (modelled as tidal mixing in these studies) tends to limit the estuarine response at high flow levels (MacCready and Geyer, 2010). The estuary response tends not to be proportional to the freshwater flow, but rather scales with a small fractional power of the freshwater flow (MacCready and Geyer, 2010). Thus the magnitude of the estuarine circulation may be insensitive to changes in freshwater inflow when the inflow is "large". However, these ideas have not been tested in real systems.

The aim of this paper is then two-fold. First, to estimate the seasonal variations in estuarine transport in the Strait of Georgia. A comprehensive new dataset, comprising 3 years of monthly observations, is used in this analysis. Results therefore provide the first accurate description of the seasonal transport changes and their phasing, and of their interannual variability, in the SoG. These estimates are made using a formal inverse procedure, which allows for the estimation of uncertainties associated with numerical values obtained. Uncertainties are obtained using a bootstrap process (Efron and Tibshirani, 1993; Pawlowicz, 2001) which inherently models the structure of the data with minimal need for assuming independence and 'Gaussian' statistics, and for arbitrarily separating measured variables into those with associated errors (the "forcing" terms), and those assumed to be known exactly (those describing the scalar fields). In addition, sensitivity studies are carried out to determine the effect of assumptions inherent in the box-model formalism.

Second, we analyze these estimates in relation to theoretical scalings to determine the effect of freshwater flow on the transports. A lack of sensitivity to freshwater inflow rates is found. However, in contrast to previous theoretical studies, actual transports are used in the comparisons and not the output of idealized numerical models. Our analysis thus provides geophysical evidence for these scalings.