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Chlorophyll distribution in a temperate estuary: The Strait of Georgia and Juan de Fuca Strait

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ABSTRACT

Data collected during 7 years of seasonal surveys are used to investigate the distribution of phytoplankton biomass within the estuarine waters of the Strait of Georgia and Juan de Fuca Strait. Variability of the chlorophyll distribution is examined in relation to the density stratification, light availability and nutrient concentration. In the Strait of Georgia, both the horizontal and vertical distribution of chlorophyll are found to be linked to the presence of a near-surface layer of increased density stratification. Despite important year-to-year variability, the seasonal cycle of chlorophyll in the Strait of Georgia is dominated every year by relatively large near-surface concentrations in the spring that are linked to the seasonal increase in solar radiation onto the stratified near-surface layer. In the vertical, a sub-surface peak is observed around 10 m depth, corresponding to the depth of maximum water column stability. Nutrients within the euphotic zone are in general abundant, with the exception of the Strait of Georgia in summer where phytoplankton growth is potentially limited by low nitrate concentration near the surface. The depth of the euphotic zone is estimated along the thalweg of the estuary from transmissometer profiles. It appears to vary relatively little within the estuary from a minimum of 20 m in spring, near the mouth of the Fraser River, to an autumnal maximum of about 30 m in the northern Strait of Georgia. Finally, the estimated self-shading contribution to light attenuation is shown to be generally significant (5–10%) in the surface waters of the Strait of Georgia, during spring and summer, reaching values as high as 35% during the spring bloom.

1. Introduction

The Strait of Georgia and Juan de Fuca Strait are the main components of a large coastal estuarine system on the southern coast of British Columbia (Fig. 1). The Strait of Georgia is a semi-enclosed sea extending about 220 km in length and reaching depths of up to 420 m within its central section. It is an important nursery and rearing ground for many aquatic species such as Pacific salmon and herring. Juan de Fuca Strait is a 100 km long channel and the main connection for the Strait of Georgia and Puget Sound to the Pacific Ocean. A large volume of freshwater enters this coastal basin annually, mainly from the Fraser River in the southern Strait of Georgia. This drives an estuarine circulation which is in turn affected by wind stress and strong tidal mixing (e.g., Li et al., 2000). Freshet typically peaks in mid-June with an approximately sevenfold increase in volume flux from low winter values (e.g., Masson, 2006). As in most temperate estuaries, the stability of the water column is mostly determined by salinity stratification which is in turn strongly influenced by the freshwater input. The resulting stratification can have pronounced spatial, seasonal and interannual variations and is expected to be a determining influence on the local phytoplankton population variability (e.g., Cloern, 1996). Although the nutrient load in the Fraser River is relatively low, nutrients are generally abundant due to the inflow of nutrient rich water entering at depth into Juan de Fuca Strait from the continental shelf to subsequently enter the Strait of Georgia (Mackas and Harrison, 1997).

The effect of various physical processes on the abundance and distribution of phytoplankton in the region has been the subject of some field investigations (e.g., Yin et al., 1997a) and of a few modeling efforts (e.g., St. John et al., 1993; Li et al., 2000). Phytoplankton abundance in the Strait of Georgia has been shown to vary under the influence of the Fraser River plume and tidal currents both seasonally, with a marked vernal maximum and a smaller fall peak, and spatially (Stockner et al., 1979; Yin et al., 1997b). The vertical chlorophyll distribution is also known to vary seasonally, with the near-surface maximum migrating away from the surface during summer (Parsons et al., 1970). In the southern Strait of Georgia, high turbidity and near-surface stratification associated

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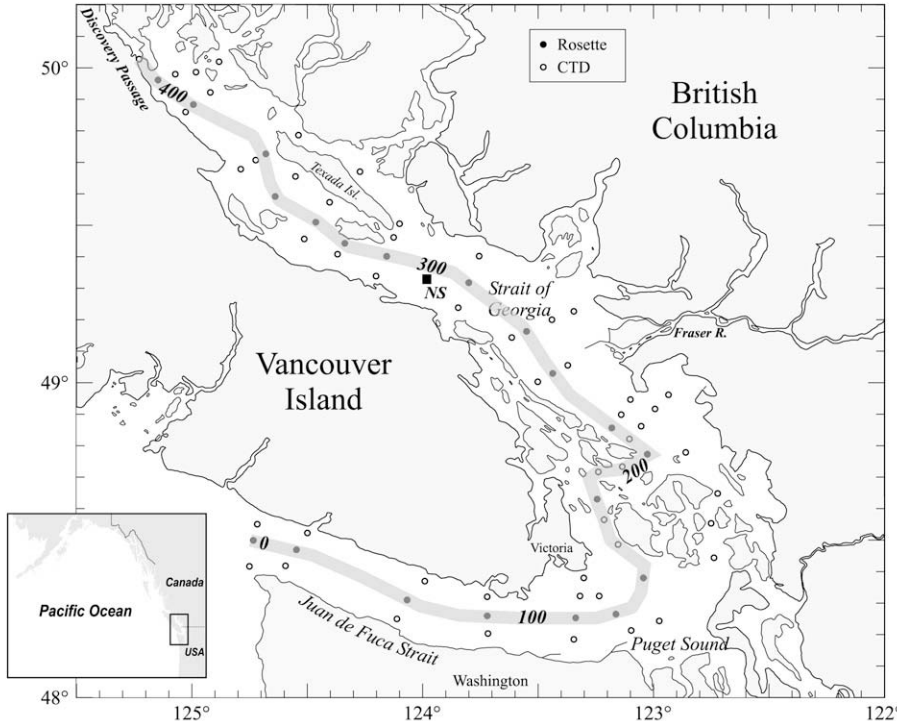

Fig. 1. Study area with location of sampling stations. The dark thick line indicates the path of the vertical section (thalweg) used in Figs. 4–6, with the numbers giving the distance, in km, from the origin located at the mouth of Juan de Fuca Strait (km 0). NS indicates the location of the long term Nanoose Station.

with the Fraser River plume strongly effects chlorophyll concentrations near the river mouth (Stockner et al., 1979; Parsons et al., 1981). Chlorophyll *a* concentrations have been found to range from minimum winter values smaller than 1 mg m^{-3}, to values as large as 15 mg m^{-3} during spring bloom (Harrison et al., 1983). In contrast, in Juan de Fuca Strait, phytoplankton standing stock is consistently low throughout the year despite high nutrient concentrations. This has been attributed to the presence of a deep mixed layer and rapid seaward advection (Mackas et al., 1980), or, alternatively, to zooplankton grazing in phase with phytoplankton production (Li et al., 2000).

In such a coastal ecosystem, variable physical forcing (e.g., river runoff, tides, and wind) and complex biological dynamics (responses to light, nutrients, grazing, etc.) typically result in high temporal and spatial variability ("patchiness") of phytoplankton distributions (e.g., Mackas et al., 1980). Accordingly, this intrinsic variability has made it difficult to sample the estuary adequately, and previous studies on the local phytoplankton dynamics have had limited spatial and temporal coverage. However, the systematic nature (every season at the same stations), relatively long duration (7 years), and extensive coverage (70 stations) of the present data set allow us to gain new insight into the mean chlorophyll distribution within the entire estuary along with its variability. Although the seasonal nature of our sampling program only coarsely resolves the time dependence of the plankton biomass, the 7 years of systematic sampling does allow an unprecedented detailed examination of the mean distribution, its seasonal cycle as well as the year-to-year variability.

The objectives of this study are then to examine the pattern of phytoplankton spatial and temporal variability in the Strait of Georgia/Juan de Fuca Strait system and to relate this to the changes in characteristics of the water column. In Section 2, details of the various collected time series are discussed, including the close relationship between measurements of extracted chlorophyll and in situ fluorescence. Both the mean horizontal and vertical distribution within the coastal basin are presented in Section 3 and shown to be linked to the strength of the near-surface mean density stratification. This is followed by a discussion of the seasonal and interannual changes in the distribution of phytoplankton biomass. Light and nutrient conditions are discussed in Sections 4 and 5, respectively, in terms of their influence on the chlorophyll distribution. Conclusions are given in Section 6.

2. Data

This study makes use of CTD (Conductivity, Temperature, Depth), transmissometer and fluorometer profiles collected seasonally from 2001 to 2007, at about 70 stations over the region (Fig. 1). In addition, water samples from a rosette were used to measure nutrients and chlorophyll at the 20 stations located along the thalweg, the deepest line along the estuary (Fig. 1). The data set has served as the basis for a quantitative water mass analysis for the basin (Masson, 2006), as well as for a study of the distribution and cycling of suspended particles (Johannessen et al., 2006). We now extend the analysis to the study of the phytoplankton biomass distribution derived from the chlorophyll and fluorescence data. The stations are sampled four times a year: in April near the time of the spring bloom, in June/July near the time of the Fraser River freshet, in September/October, and finally in December/January. The dates for each of the surveys are given in Table 1. For brevity, these four sampling periods are referred to, in the following, as spring, summer, fall, and winter, respectively.

Vertical profiles of in situ chlorophyll *a* were collected at each station with a Seapoint Chlorophyll Fluorometer (SCF). The instrument was used in pump-through sample volume option, with a fixed gain setting (10×), corresponding to a chlorophyll concentration range of 0–15 mg m^{-3}, and a constant sensitivity of 0.33 V μg^{-1} l. This particular gain setting was chosen as the most appropriate one in terms of the compromise between resolution and range of values. On a few occasions, the chlorophyll