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Inherent optical properties and optical mass classification of the waters of the Strait of Georgia, British Columbia, Canada

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ABSTRACT

Bio-physical and *in situ* hyperspectral optical data were measured during April and July, 2006, in the euphotic waters of central and southern Strait of Georgia, British Columbia, Canada. Particulate absorption and scattering were derived from the optical measurements of beam attenuation and chromophoric dissolved organic matter (CDOM) absorption. The concentration of CDOM was measured with a fluorometer, and water samples were collected for total suspended material (TSM) and chlorophyll *a* (chl *a*). The results showed that waters closer to the Fraser River discharge presented the highest concentrations of TSM (18.2 mg L^{-1}) and CDOM (32.1 ppb Quinine Sulphate Dihydrate Equivalent (QSDE)), whereas in deeper waters and waters farther from the plume, both TSM (0.2 mg L^{-1}) and CDOM (6.0 ppb QSDE) were relatively lower, and chl *a* relatively higher (11.3 μg L^{-1}), reaching the lowest values at the bottom of the euphotic layer (0.3 μg L^{-1}). The waters of the Strait of Georgia's euphotic zone showed well-defined attenuation coefficients and absorption-to-scattering ratios, which allowed for the optical classification of riverine plume (OM1), estuarine (OM2), and northern and deeper (OM3) waters. Generally, particulate scattering dominated the attenuation of light in these waters. The particulate scattering was mostly influenced by inorganic particles, especially in OM1. High loads of inorganic particulate scatterers possibly increased the diffuse light into OM2. Conversely, the relatively higher absorption by CDOM in deeper waters indicates the possibility of competition with phytoplankton for short wavelength radiation. The data and analyses in this study provide important baseline optical information for the waters of the Strait of Georgia.

1. Introduction

Coastal waters are very important with regard to ecological and economic issues. These waters are optically dominated by complex assemblages of organic and inorganic matter that has hindered the use of ocean colour satellites and remotely-sensed data for deriving biogeophysical quantities (Bergmann et al., 2004; Chang et al., 2006). In spite of this, optical data have been used for coastal studies (Jerlov, 1976; Doxaran et al., 2006) and optical classification of water bodies (Chang et al., 2002; Reinart et al., 2003), thus providing information on marine primary productivity (Oliver et al., 2004), fisheries (Santos, 2000), coastal sedimentation and sediment dispersal (Bowers and Binding, 2006), harmful algal blooms (Cullen et al., 1997), organic matter content (Chen et al., 2004), raw sewage disposal (Baker and Spencer, 2004), and pollution (Arst, 2003).

Photosynthesis would not be possible without light. However, it is not so much the availability of light that is relevant as the magnitude and quality of the available light that will determine if phytoplankton communities will flourish (Levinton, 2001). Water absorbs visible light (400–700 nm), and consequently there is a decrease of light with depth. The presence of dissolved and particulate materials will also have an impact on the light fields because they will not only absorb but also scatter light. These effects are not constant throughout the electromagnetic spectrum but differ quite significantly according to the material interacting with the available light (Mobley, 1995). Chromophoric dissolved organic matter (CDOM) and total suspended material (TSM) play an important role in the attenuation of photosynthetically-available radiation (PAR, 400–700 nm), and therefore on primary productivity (Coble et al., 2004). This has been demonstrated in several regions, such as the West Florida Shelf (Del Castillo et al., 2000), the East Sound, WA (Twardowski and Donaghay, 2001), the Rhode River, MD (Gallegos and Neale, 2002), the Baltic Sea (Woźniak et al., 2003), the Lower St. Johns River, FL (Gallegos, 2005), and the English Channel (Vantrepotte et al., 2007).

CDOM competes with phytoplankton for photons, particularly in the blue region of the spectrum (~400–500 nm; Blough and Del Vecchio (2002)). Furthermore, the absorption of light by CDOM leads to the breakage of molecular bonds and the photochemical formation of chemically-different organic compounds (Schofield et al., 2004) that can ultimately impact primary productivity (Bissett et al., 2001). Suspended material also affects primary

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productivity by attenuating light necessary for photosynthesis (Van Duin et al., 2001). TSM can determine the magnitude of the beam attenuation ($c(z, \lambda)$) of coastal ocean waters, and is responsible for most of its temporal and spatial variability (Mobley, 1994). The magnitude of $c(z, \lambda)$ (where z is depth and λ is wavelength) is greater in estuarine areas than in open ocean waters because of the high concentrations of mineral particles. Similarly to other estuaries (Gallegos et al., 2005; Doxaran et al., 2006), high $c(z, \lambda)$ has been observed in the waters of the Strait of Georgia (SoG) under the influence of the Fraser River (Johannessen et al., 2006). However, the relative contributions of particles and CDOM to light attenuation in the SoG are presently not known.

This study combines optical data from *in situ* and laboratory measurements to provide the first qualitative and quantitative analyses of the spatial variability of the inherent optical properties (IOPs) of the euphotic zone of the SoG. We also define three water masses according to their IOPs, a technique which may be extrapolated to other coastal seas influenced by large riverine systems. Classification of water masses according to their optical characteristics has been done typically with the use of radiometric quantities and apparent optical properties (AOPs) (Aarup et al., 1996; Højerslev et al., 1996). This was mainly because of the wide availability of AOP sensors and the lack of optical sensors capable of measuring IOPs due to the complexity of their measurement. The use of IOPs in the classification of water masses is nevertheless more reliable because unlike the AOPs, the IOPs depend not on the ambient light distribution but solely on the waters and on their contents (Mobley, 1994).

1.1. Area of study

The Strait of Georgia in British Columbia, Canada (Fig. 1), is approximately 222 km long and 28 km wide with an average depth of 155 m (Thomson, 1981). The movement of water in this system is dominated by estuarine circulation characterized by a two-layer exchange flow driven by strong freshwater discharge, particularly from the Fraser River, i.e., a seaward (southward) surface flow with lower salinity and a landward (northward) subsurface flow carrying more saline and nutrient-rich waters from the Pacific Ocean to the SoG (Li et al., 2000). Intense tidal mixing occurs in Haro Strait and at Boundary Pass, where nutrient-rich deeper waters from the Pacific Ocean are mixed with surface waters (Masson and Cummins, 2004). This region is also influenced by semi-diurnal tides and seasonal variation in wind patterns and riverine discharge (Tully and Dodimead, 1957; Waldichuk, 1957).

Approximately 75% of freshwater runoff into the SoG is attributed to the Fraser River, which has the third largest discharge in the Northeastern Pacific Ocean and is the largest source of sediment on the west coast of North America (Thomson, 1981). The discharge of the Fraser River is dominated by snowmelt, leading to low winter and high summer discharge, with a strong freshet in June each year (Environment Canada, 2006). This high discharge enters the SoG in the form of a riverine plume, which carries high loads of inorganic suspended matter and dissolved matter (Johannessen et al., 2003). The inorganic suspended matter is classified into wash load and bed-material load, the former constituted of clays, silts, and very fine sand in continuous suspension, and the latter formed by coarser bed material that is often transported along the bottom (Kostaschuk et al., 1998). Most of this material sinks to the bottom, where it tends to be trapped in sediments of the SoG (Johannessen et al., 2005). The greatest light attenuation due to suspended matter occurs in surface waters, particularly in the spring and summer (Johannessen et al., 2006).

The SoG is a highly-productive, semi-enclosed coastal marine system important to fisheries and rearing of young salmon and herring (Stockner et al., 1979; Li et al., 2000). Primary productivity is limited by nutrients and grazing in the spring and summer, and by light in the winter (Takahashi et al., 1973; Stockner et al., 1979). A series of short phytoplankton blooms usually occurs in the spring, driven by a combination of factors, such as entrainment of inflowing nutrient-rich deep seawater into the surface layer (Thomson, 1981; Harrison et al., 1991), tidal currents, winds (Yin et al., 1996, 1997a,b), and light availability (Allen and Harris, 2004; Collins, 2005). These blooms often continue into the summer months and occasionally occur in the fall or winter. Recent studies (Collins, 2005) have shown that wind plays the most important role on the variance of the timing of the spring bloom, i.e. water stratification is disrupted by high winds, delaying the development of the phytoplankton blooms. Among the other variables controlling the time of the spring bloom, light availability was considered the most important (Collins, 2005).

The phytoplankton species assemblage is dominated by diatoms, particularly during blooms and around the Fraser River plume (Harrison et al., 1983; Hobson and McQuoid, 1997) with *Skeletonema* spp. and *Thalassiosira* spp. being the most common throughout the year and during the spring blooms, respectively. In general, diatoms dominate over other phytoplankton groups in the spring and summer around areas influenced by the Fraser River plume (Harrison et al., 1983).

The SoG has not been the subject of many optical studies, except for a brief mention of extinction coefficient by Stockner et al. (1979) and Harrison et al. (1983), and Johannessen et al. (2006), who used beam attenuation coefficient at 660 nm as a proxy for the distribution of suspended particles, and Masson and Peña (2009), who used the same transmissometer data together with measurements of $PAR(z)$ to estimate the depth of the euphotic zone and phytoplankton self-shading.

There are no absorption data available for the waters of the SoG from which to assess the contribution of CDOM to light attenuation. However, CDOM is a component of the total dissolved organic matter (DOM) pool (Coble, 2007), and dissolved organic carbon (DOC) has been estimated to comprise more than 80% of the total organic carbon in the SoG (Johannessen et al., 2003), implying that CDOM may well have a significant effect on the underwater light climate of the Strait.

2. Methodology

2.1. Discrete water samples – acquisition and processing

A total of 38 stations was sampled during April 25–29 (11 stations) and July 12–18, 2006 (27 stations) onboard the MSV John Strickland (Fig. 1). The sampling stations were positioned (1) to capture the optical variability of the waters of the SoG, from upper central waters, close to Texada Island, to southern waters under stronger influence of the Fraser River plume, and (2) to coincide with sampling locations used by Pawlowicz et al. (2004), Collins (2005), and Johannessen et al. (2006) for the purpose of future comparisons with on-going research in the region. The influence of daily oscillations of tides, currents, winds, and river discharge precluded synoptic sampling. However, these are the first such data for the region. For each station, water samples were collected from at least three depths: subsurface (0.5 m), at the chlorophyll *a* (chl *a*) maximum (2–8 m in April and 0–9 m in July, as indicated by a WET Labs profiling fluorometer), and just below the depth of 1% surface irradiance, $Z_{1\%}$, (4–20 m in April and 3–22 m in July). $Z_{1\%}$ was defined based on real-time measurements of in-water spectral downwelling irradiance, $E_d(0-, z, PAR)$, and above-water spectral downwelling irradiance, $E_s(0+, PAR)$, collected with Satlantic Mini-spec OCR-3000 sensors on a vertical profiler and above water (see Table 1 for a list of symbols and acronyms). The water samples