DISTRIBUTION, CHARACTERISTICS AND
POTENTIAL IMPACTS OF CHROMOPHORIC
DISSOLVED ORGANIC MATTER (CDOM) IN
HUDSON STRAIT AND HUDSON BAY, CANADA

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Abstract

The characteristics of chromophoric dissolved organic matter (CDOM) were studied
in Hudson Bay and Hudson Strait in the Canadian Arctic. Hudson Bay receives a dis-
proportionately large influx of river runoff. With high dissolved organic matter (DOM)
concentrations in arctic rivers the influence of CDOM on coastal and ocean systems can
be significant, yet the distribution, characteristics and potential consequences of CDOM
in these waters remain unknown. We collected 470 discrete water samples in offshore,
coastal, estuarine and river waters in the region in September and October 2005. Mixing
of CDOM appeared conservative with salinity, although regional differences exist due to
variable DOM composition in the rivers discharging to the Bay and the presence of sea-ice
melt, which has low CDOM concentrations and low salinity. There were higher concen-
trations of CDOM in Hudson Bay, especially in coastal waters with salinities < 28, due
to river runoff. Using CDOM composition of water masses as a tracer for the freshwater
components, revealed that river runoff is largely constrained to nearshore waters in Hud-
son Bay, while sea-ice melt is distributed more evenly in the Bay. Strong inshore-offshore
gradients in the bio-optical properties of the surface waters in the Hudson Bay causes large
variation in penetration of ultraviolet radiation and the photic depth within the bay, poten-
tially controlling the vertical distribution of biomass and occurrence of deep chlorophyll
maxima which are prevalent only in the more transparent offshore waters of the bay. The
CDOM distribution and associated photo-processes may influence the thermodynamics
and stratification of the coastal waters, through trapping of radiant heating within the top
few meters of the water column. Photo-production of biologically labile substrates from
CDOM could potentially stimulate the growth of biomass in Hudson Bay coastal waters.
Further studies are evidently needed to investigate the importance of terrestrial DOM in
the Hudson Bay region, and the impact of hydroelectric development and climate change
on these processes.

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1 INTRODUCTION

The Hudson, James, and Ungava Bay drainage basins supply the equivalent of about 18% of the total discharge to the Arctic Ocean, with considerable interannual variability and uncertainty (Shiklomanov et al., 2000). This shallow, shelf-like sea system receives proportionately a larger influx of runoff than the Arctic Ocean (freshwater yield of 0.6–0.8 m compared to 0.3 m), because its area (1.23×10^6 km²) is less than 12% that of the Arctic Ocean. Recent studies have shown that Arctic rivers carry a substantial load of organic matter, and the terrestrial carbon transported by these rivers plays an important role in the carbon budgets of high latitude seas (Stein and Macdonald, 2004). Despite the evidence that Arctic marine waters are influenced to a great extent by terrestrial organic matter (Opsahl et al., 1999; Pegau, 2002; Dittmar and Kattner, 2003), studies on the distribution and characteristics of chromophoric (or colored) dissolved organic matter (CDOM, also called gelbstoff or yellow substance) in these regions are limited (Guay et al., 1999; Scully and Miller, 2000; Amon et al., 2003; Guéguen et al., 2005). However, Hudson Bay itself and its drainage basin have received even less attention, even though the freshwater exported by the region can influence, for example, the thermohaline circulation in the North Atlantic (Déry et al., 2005). A more detailed account of the river discharge, drainage basin characteristics and potential downstream effects of freshwater input of the system can be found in Déry et al. (2005).

Although Hudson Bay and Strait are influenced by high terrigenous freshwater fluxes, studies on the transport of organic matter and CDOM are virtually non-existent. Terrigenous DOM is the main source of natural CDOM to the oceans in nearshore areas, where runoff mixes with seawater. CDOM, the fraction of the dissolved organic carbon pool that absorbs light in the ultraviolet and visible ranges (Kirk, 1994), contributes a significant fraction of the dissolved organic matter (10-90%; Thurman, 1985) and the bulk dissolved organic carbon pool (up to 60%; Ertel et al., 1986). The CDOM also undergoes changes, e.g. photobleaching, that may affect, for example, nutrient availability (Bushaw, 1996) and CO₂ production (Clark et al., 2004). In aquatic environments, DOM can strongly bind organic and inorganic pollutants and thereby affect their transport, bioavailability, toxicity, and ultimate fate. CDOM plays an important role in the biogeochemistry of natural waters (Hansell and Carlson, 2002) and in the optical properties of ocean water, affecting for example, the penetration of ultraviolet radiation (known to inhibit phytoplankton productivity) and light available for primary production (Guéguen et al., 2005). CDOM also influences upwelling irradiance and complicates satellite retrieval of ocean biomass (Siegel et al., 2005). Therefore, knowledge of the (regional) distribution and characteristics of CDOM is crucial to the application of remote sensing to estimate biomass in the Hudson Bay region. The absorption of solar radiation may also affect the thermodynamics of the upper ocean (Kirk, 1988). For example, Pegau (2002) found that absorption by CDOM can increase heating by 30% in the visible wavelengths (λ = 350–700 nm) in the top 10 m of the
Arctic Ocean, which can result in higher melting rates of ice and also provide a buoyancy flux through heating. Furthermore, the CDOM characteristics of waters, being quasi-conservative, can potentially be used as a tracer of water masses as described by Aarup et al. (1996). Because of the importance of CDOM in all the abovementioned processes, it is important not only to assess the vertical and horizontal distribution of CDOM but also its optical characteristics (Hansell and Carson, 2002). Another characteristic important to Hudson Bay is hydropower development, which has diverted and altered the normal annual cycle and magnitude of inflowing water from several of the larger river systems surrounding the bay (Déry et al., 2005) Impoundment of these river systems can affect not only the timing of discharge from these systems but also the location of delivery especially in respect to the cyclonic circulation around Hudson Bay. Given the observed warming of the Arctic it follows that DOM inputs to this system are likely also changing (Lawrence and Slater, 2005).

Sea ice may also play a central role in processes controlling the distribution of CDOM within Hudson Bay surface waters. First, sea ice provides a shield against photobleaching of CDOM for most of the year, the Bay being ice covered completely for up to 8–9 months. Second, sea ice provides additional freshwater (yield estimated at 1.6 m, Prinsenberg, 1984) and potentially CDOM (Scully and Miller, 2000). Sea ice in Hudson Bay tends to form throughout the Bay in winter with larger than average production occurring within the polynya at the NW extreme of the bay. Ice is exported from this region throughout the winter cyclonically around Hudson Bay with total circulation residence times on the order of weeks to months. In spring, melt also affect the delivery of CDOM to the water column (Scully and Miller, 2000) and by interfacing with the spring freshet from the various river systems emptying into Hudson Bay. The delivery of sea ice/snow melt water to the mixed layer is a complex interplay of in situ melting and advection of melting sea ice and sea ice melt within the cyclonic flow of the ice and surface waters around Hudson Bay. The distribution of sea ice melt has been only approximately quantified, it seems reasonable that increased amounts of melt water can be expected in the SW and SE sectors of Hudson Bay. This is where the remnant ice retreats to in the spring and finally melts, partly explaining why the freshwater inventories are found to be largest here (Prinsenberg, 1984). CDOM characteristics together with salinity might provide a new tool to discriminate freshwater sources of the two freshwater end-members.

Systematic studies on relations between water mass characteristics and physical and biological processes have been examined in the Hudson Bay area only rarely (Anderson and Roff, 1980a; Harvey et al., 1997). Here, we focus on Hudson Bay and Hudson Strait, where most of the riverine inputs come from a few larger rivers, especially notable being the Nelson River (Manitoba) and the La Grande River (Quebec) after hydropower development, and the remaining inputs from numerous smaller rivers and streams (Déry et al., 2005). In this paper we report, for the first time to our knowledge, the optical properties and distribution of CDOM in this region, and discuss the potential consequences of CDOM in the system. Specifically our objectives are
to show the optical characteristics of CDOM, the vertical and horizontal distribution of CDOM in this system and then discuss the implications of this distribution for CDOM as a tracer of water masses in Hudson Bay (especially that of freshwater components). Finally, we investigate the role of CDOM on radiative exchange within the mixed layer and the associated impacts it may have on primary production and radiant surface heating, and highlight the potential role of DOM in fluxes of nutrients to Hudson Bay.

2 METHODS

2.1 Study area and sampling

The data for this study were collected during the ArcticNet (http://www.arcticnet-ulaval.ca) 0502 expedition, onboard the Canadian research icebreaker NGCC Amundsen, between 15 September and 26 October 2005 in Hudson Strait and Hudson Bay (Figure 1). Usually three to six depths were sampled, with two to three targeted in the mixed layer (surface, 10 m and 25 m). In the coastal areas, where water depths were 50 m or shallower, only two to three depths were sampled. In this manner, we collected about 450 discrete seawater samples from 12-L Niskin bottles on the ship’s rosette. The rosette was equipped with a SBE-911plus (Sea-Bird Electronics, Inc.) conductivity-temperature-depth (CTD) sensor with an auxiliary chlorophyll fluorometer (Seapoint Sensors, Inc.). About 60 additional samples were collected together with CTD profiles (SBE 19plus, Sea-Bird Electronics, Inc.) using a zodiac or helicopter, mainly in the proximity of major rivers (see Table 1). Before each hydrocast, and particulary prior to disturbance of the mixed layer by the ship, a surface water sample was collected with the use of a pre-rinsed bucket from the foredeck of the ship or in case of the zodiac/helicopter directly into an amber acid-rinsed 2-L HDPE bottle, which was rinsed three times with sample water before being filled, and returned to the ship. Samples at depth from rivers and estuaries were collected with a Kemmerer type water sampler and transferred into a 2-L bottle. These bottles were returned to the ship, kept refrigerated in the dark, and were processed as described below, within 10 h of collection.

[Figure 1 about here.]

On the ship a water sample was drawn directly (from the bucket, the 2-L or the Niskin bottle) into an acid-soaked polyethylene (PE) syringe (10% HCl overnight and thereafter rinsed with Milli-Q). The syringe was rinsed three times with an aliquot of seawater, and then the sample was filtered through a Whatman GF/F filter mounted in a PE filter holder into an acid-soaked (similarly as the PE syringe) amber glass bottle. The first 50–100 mL of filtrate was discarded (and used to rinse the filter holder and the filter). The bottle was rinsed three times with 5 mL
aliquots of filtered seawater before being filled with approximately 40 mL of filtered sample. From the same volumes, salinity samples were collected into 200 mL glass bottles (rinsed three times with sample water before filling) and measured onboard the ship with a Guildline Autosal 8400 salinometer (precision generally better than 0.002). Samples were standardized against IAPSO Standard Sea Water.

[Table 1 about here.]

Samples for dissolved organic carbon (DOC) determination (n=50) were collected within Hudson Bay from selected rosette hydrocasts or from estuaries and rivers entering Hudson Bay. Each sample was collected into an acid-soaked PE syringe (from the same volume as CDOM and salinity samples), rinsed three times with sample water, the first 50–100 mL of the filtrate was discarded and used to rinse the filter (precombusted Whatman GF/F at 450 °C overnight), then the sample was collected into a precombusted glass vial (rinsed three times with aliquots of filtrate) with an acid-washed teflon lined cap, and acidified (pH<2). The DOC samples were kept at +4°C in the dark until analysis. DOC was determined with a high temperature combustion autoanalyser Shimadzu TOC-5000 (mean of three replicate injections of each sample with a typical coefficient of variation <2%).

2.2 CDOM analysis

Absorbance of CDOM was measured with an UV-Visible spectrophotometer (S2000, Ocean Optics Inc.) at a wavelength range of 200 to 850 nm using a 10 cm quartz cuvette. Purified water from a Milli-Q system (kept at room temperature) was used as reference. The cuvette was rinsed with aliquots of Milli-Q and sample water between samples to avoid sample carryover. The samples were measured as soon as possible after they had been warmed to room temperature while kept in the dark onboard the ship (usually within 18 h of collection). The dark current was corrected on the spectrophotometer for each single sample spectra and a reference spectra (a separate cuvette with Milli-Q water) was measured every 3-6 samples to account for possible instrument drift. The spectrophotometer was turned on for >1 h prior to the measurements. In the UV spectral range the measurements were well above detection, whereas at the longer visible wavelengths the absorption fell below detection. A conservative detection limit of 0.14 m⁻¹, corresponding to 0.006 absorbance units on the spectrophotometer, was estimated from repeated scans of Milli-Q water processed as a sample. Except for the most transparent samples in Hudson Strait the maximum detectable wavelength was longer than 400 nm. The measured absorbance was converted to absorption coefficient (m⁻¹) according to the equation: \( a(\lambda) = 2.303 * A(\lambda)/L; \) where \( A \) is the absorbance at wavelength \( \lambda \) and \( L \) is the path-length of the optical cell in meters (here 0.10 m).
The absorption of CDOM can be expressed using an exponential equation (Bricaud et al., 1981),

\[ a_\lambda = a_{\lambda_0} e^{S(\lambda - \lambda_0)} \]  

(1)

where \( a_\lambda \) and \( a_{\lambda_0} \) are absorption coefficients at a defined wavelength and a reference wavelength, respectively. We chose \( a_{355} \) (absorption coefficient at 355 nm) to represent the CDOM concentration in a sample. The spectral slope coefficient \( S \) (nm\(^{-1}\)), a measure of how rapidly the absorption decreases with increasing wavelength (Green and Blough, 1994), was obtained using a non-linear fit (NLF, Method 2 in Stedmon et al., 2000) over the range from 250 to 400 nm, similar to Guéguen et al. (2005) to allow a direct comparison to this geographically relevant study. However, the choice of representative wavelength range is difficult because most previous studies calculated \( S \) through a linear fitting (LF) of the log-linearized absorption spectra and used highly variable spectral ranges for the computation, which makes the intercomparison between various studies difficult (Blough and Del Vecchio, 2002; Twardowski et al., 2004). A comparison of the two fitting procedures using our data showed a more or less consistent upward bias of values of \( S \) acquired by NLF, which is consistent with the reports by Blough and Del Vecchio (2002). Here, we have used NLF to estimate \( S \) as it is considered superior to LF (Stedmon et al., 2000).

The DOC specific absorption coefficient at 254 nm \( a_{254}^* \) (m\(^2\) g\(^{-1}\)) was calculated by normalizing \( a_{254} \) to the DOC concentration in the sample; this measure is sometimes also called the specific UV absorbance (SUVA; Hur et al., 2006; Weishaar et al., 2003). After quality check, 470 samples with both absorbance and salinity values were available.

3 RESULTS

3.1 CDOM characteristics

The optical characteristics of CDOM, \( a_{355} \) and \( S \), as a function of salinity in the range 25 to 35 for the data set, are shown in Figure 2. The values for \( a_{355} \) and \( S \) for the whole data set (salinity 0 to 35) ranged between <0.14 to 44.4 m\(^{-1}\) and 0.012 to 0.028 nm\(^{-1}\), respectively. The absorption and \( S \) values encompass almost the full range of values observed in rivers, coastal and oligotrophic ocean surface waters (Blough and Del Vecchio, 2002; their Table I), show highly variable optical properties of the waters in the Hudson Bay region. The distribution of \( a_{355} \) compared to salinity (Figure 2A), implies several end-members for CDOM. At a salinity of about 28 there is a clear change in the slope of the salinity–\( a_{355} \) relationship, with higher values of \( a_{355} \) at lower salinities indicating an increased influence of riverine input of CDOM. In essence, salinities lower than 31 were observed only in Hudson Bay, and within the Bay salinities less than 28 were limited to nearshore waters associated with significant riverine input (Ingram and
Prinsenberg, 1998). The decrease in $S$ with decreasing salinity (Figure 2B) also points towards a low-salinity riverine source (Green and Blough, 1994; Blough and Green, 1995).

[Figure 2 about here.]

For rivers the values for CDOM and DOC varied considerably (Table 2). Compared to more saline waters the $S$ values were lower, ranging from 0.012 to 0.018 nm$^{-1}$ (Table 2). For rivers in northeastern Hudson Bay, namely Povinningutuk, Innuksuac and Nastapoca, $a_{355}$ was as low as for Hudson Bay coastal waters in the same region, and considerably lower than for the other rivers. In contrast, $S$ was generally higher than for these rivers. Similarly, a large variation in DOC levels (200 to 1100 $\mu$M) and in the specific absorption coefficient (Table 2) was observed in the rivers. The above observations indicate a variable DOM composition supplied by the rivers and, in particular, a large variability in the optically active fraction of DOM.

[Table 2 about here.]

Within the salinity gradients of the sampled estuaries (Table 1) CDOM exhibited close-to conservative mixing (Figure 3; Table 2). However, the characteristics of the estuaries differed, with northeasterly watersheds having waters with CDOM (and DOC) values as low as in the marine waters in the area (e.g. Povinningutuk, Figure 3). In the south and southwest Hudson Bay, the CDOM levels were considerably higher in the rivers than in the marine waters (Figure 3). The same appeared to be the case for DOC levels, although the $a_{254}$ values varied considerably, being lowest in the northeast (Povinningutuk and Nastapoca rivers) and in the west (Hayes and Nelson rivers).

[Figure 3 about here.]

### 3.2 CDOM distribution

To examine the distribution of CDOM in the study region we have partitioned the samples into those from Hudson Bay (HB), Hudson Strait (HS) and Foxe Channel (FC) (Table 3). These areas are oceanographically distinct; HB is an enclosed sea with significant runoff, FC is an ice-covered basin with inflow from the Arctic Ocean through the Canadian Arctic Archipelago, and HS provides the outlet for HB outflow and means for Baffin Bay water to enter FC and HB. In Hudson Bay we have further partitioned samples into those from offshore and those from coastal waters using a threshold salinity of 28, with coastal waters in the Hudson Bay having a mixed-layer salinity from 24 to 28 (thereby excluding the samples in proximity of the major rivers). We have adopted this approach partly because the $a_{355}$ values increase considerably at salinities lower than 28 (Figure 2), which indicates the strong influence from river runoff at
these salinities. The water column was further divided into mixed layer water and deep water to compare the CDOM characteristics of the two water masses. Mixed layer depths (MLD) were computed using the methods of Glover and Brewer (1988) and Lorbacher et al. (2006) applied to the CTD profiles. Every profile was manually checked to determine whether the MLD estimate was reasonable. If the two estimates differed considerably the one more representative of the water column TS structure was chosen.

[Table 3 about here.]

Mixed layer CDOM characteristics did not differ significantly between the Hudson Strait and Foxe Channel stations (generally \( a_{355} < 0.25 \) m\(^{-1} \); Table 3). The absorption by CDOM is highest in Hudson Bay coastal waters due to significant terrestrial runoff (Figure 4), which also lowers the salinity of these waters. There is also considerable variation in the \( a_{355} \) values in Hudson Bay, which in turn reflects the large range of salinities in the mixed layer. Mixed layer salinities in Hudson Strait and Foxe Channel were >31.3, compared to about 30 (on average) in Hudson Bay. CDOM increases from the entrance of the Bay (\( a_{355} < 0.6 \) m\(^{-1} \)) moving clockwise along the coast to the entrance of James Bay (\( a_{355} 3.5 \) m\(^{-1} \)). Along the southwestern coast, between James Bay and the Nelson River estuary, the \( a_{355} \) values are about 1–3 m\(^{-1} \). The offshore stations in Hudson Bay have \( a_{355} \) values <0.5 m\(^{-1} \) (Figure 4). In both Hudson Strait and Foxe Channel there is no significant difference between surface and deep water \( a_{355} \) (Table 3), not surprising since tidal mixing is strong in this region (Drinkwater and Jones, 1987). Strong mixing is also illustrated by the relatively small difference in mixed layer and deep water salinities in these areas (Table 3). In Hudson Bay the surface mixed layer had usually higher \( a_{355} \) values than the deep waters (Table 3). This was especially evident in coastal waters.

[Figure 4 about here.]

4 DISCUSSION

The observations by Scully and Miller (2000) in the North Water (NOW) polynya of \( a_{310} \) ranging from 0.45 to 0.6 m\(^{-1} \) compare well with our observations in Hudson Strait and Foxe Channel but are considerably lower than the values determined for Hudson Bay waters (Table 3). Scully and Miller (2000) inferred the source of the relatively high \( a_{310} \) values in the surface waters in the NOW polynya to be the release of excessive amounts of CDOM from melting sea ice. They also noted that CDOM in surface water was higher than at depth, something we did not observe in Hudson Strait or Foxe Channel, despite considerable amounts of sea ice melt being reported for these waters (Tan and Strain, 1996). However, direct observations of CDOM in first-year sea ice in the NOW area by Belzile et al. (2000) and in sea-ice melt in the Arctic Ocean by
Pegau (2002), show that most of the sea ice contains relatively low CDOM levels (compared to parent seawater), and therefore it seems unlikely that melting sea ice could provide significant additional CDOM to the mixed layer in Hudson Bay or Hudson Strait. Scully and Miller (2000) provided CDOM data for only a 2 cm layer at the bottom of the ice, and this biologically active layer would contain considerably higher organic matter than the rest of the ice.

In the Arctic Ocean Pegau (2002) observed that the CDOM levels in surface waters were higher than expected. In surface waters $a_{355}$ was about 0.25 m$^{-1}$ (based on his estimate of CDOM absorption at 440 nm and a $S$ of 0.015 nm$^{-1}$). Our observations for Hudson Strait and Foxe Channel are consistent with Pegau’s values. In the Beaufort Sea and the Mackenzie Shelf region of the western Arctic, where terrestrial inputs from the Mackenzie River dominate surface waters (Macdonald et al., 1998), the CDOM characteristics were comparable to our data set from the Hudson Bay region. The range of values observed by Guéguen et al. (2005), $a_{300}$ 0.7–12.2 m$^{-1}$, and $a_{355}$ 0.2–4.9 m$^{-1}$, are within the range observed in the Hudson Bay region, although at salinities <25 the $a_{355}$ values are consistently higher in Hudson Bay, while at salinities >30 $a_{355}$ is lower in the Hudson Strait than in the Beaufort Sea (cf. Guéguen et al., 2005, their Fig. 4).

These differences in the relationship between $a_{355}$ and salinity imply that the freshwater source in the Hudson Bay has a higher CDOM concentration, while the marine waters entering the area are lower in CDOM than the respective end-members in the Beaufort Sea. $S$ values in the region fall within the same range as observed in the Beaufort Sea (Guéguen et al., 2005) and the Greenland Sea (Stedmon and Markager, 2001). The values of $S$ in the coastal waters of Hudson Bay are representative of waters influenced by river inputs (Blough and Del Vecchio, 2002; and references therein). The fairly constant $S$ at low salinities (ca. <28; Figure 2) implies that terrestrial CDOM dominates and is relatively unaltered in optical properties. The change in $S$ at higher salinity may be caused by additional sources or sinks of CDOM, such as mixing with multiple water masses, production of marine CDOM, or enhanced photobleaching when CDOM has been sufficiently diluted (Del Vecchio and Blough, 2002).

Based on the few studies conducted in Arctic waters, the CDOM levels in Hudson Bay appear to be similar or higher than in the Beaufort Sea or Mackenzie River delta (Guéguen et al., 2005), and considerably higher than in the Greenland Sea or central Arctic Ocean (Stedmon and Markager, 2001; Pegau, 2002), not surprising given the large and ubiquitous river inputs to the system. The steady decrease in $a_{355}$ with salinity indicates that terrestrial inputs govern the CDOM distribution in the Hudson Bay region. Marine waters entering the system (through Hudson Strait or Foxe Channel) have CDOM values comparable to those in high-arctic waters.

Contrary to the findings in Scully and Miller (2000) for the NOW polynya, sea-ice melt appears to have lower CDOM levels than parent seawater in Hudson Bay and other regions (Pegau, 2002) which would, accordingly, dilute CDOM levels in surface waters in regions where sea-ice melt dominates the freshwater inputs (such as Foxe Channel and Hudson Strait; Tan and Strain, 1996). Based on a recent global study (Lee and Hu, 2006), Hudson Bay and Hudson Strait
firmly belong to Case-2 waters, where the inherent optical properties of the water cannot be
described by phytoplankton (usually represented by chlorophyll) alone (Morel and Prieur, 1977).
This conclusion is also strongly supported by our observations of terrestrial control of CDOM in
these waters. Therefore, locally validated algorithms for remotely sensed optical parameters will
be required in the Hudson Bay region, since most ocean color products are based on bio-optical
models or algorithms that are valid for Case-1 waters only. These algorithms could be tuned to
local conditions, avoiding reprocessing of entire data sets (Cota et al., 2004).

The low DOC concentration in the clear-water rivers in the northeast of the study region is
consistent with the low DOC concentrations of rivers draining into the Ungava Bay at latitudes
that are located in a region of continuous permafrost (Hudon et al., 1996). To our knowledge
the only previous reports on DOC in Hudson Bay rivers are limited to the southeast (Hudon
et al., 1996) and a few studies conducted in the Churchill and Nelson River estuaries (Baker
et al., 1993; Baker et al., 1994). Hudon et al. (1996) report values of about 250 to 350 μM in
the Great Whale, Little Whale and Nastapoca Rivers. Values in excess of 1000 μM have been
reported from the Churchill River both in summer (Baker et al., 1994) and winter (Z. Kuzyk,
DFO, unpublished data). For the Nelson River values of around 600 μM have been reported
for late summer (Baker et al., 1993). Our observations compare favourably to these, taking into
account seasonal and interannual variability and the limited number of samples to date.

Several optical indices of aquatic DOM have been used to discriminate its composition, such
as ratios of absorption at two different wavelengths or specific (or molar) absorptivity (Chin et
al., 1994; Hur et al., 2006). Of the optical absorption indices, the specific absorbance measured
at 254 nm performed better as a discrimination index for humic and fulvic acids than any
absorbance ratio (Hur et al., 2006). An increase in \(a^*_{254}\) indicates an increase in the humic to
fulvic acid mass ratio (Hur et al., 2006). \(a^*_{254}\) measurements are good predictors of general
chemical characteristics of DOC, but they do not provide information about reactivity of DOC
derived from different types of source materials (Weishaar et al., 2003). Specific absorptivity
is strongly correlated with percent aromaticity (Chin et al., 1994; Weishaar et al., 2003) and
molecular weight (Chin et al., 1994), and may also give a rough estimate of the reactivity of
the DOM according to Chin et al. (1994). Higher \(S\) values indicate fulvic acids, lower aromatic
content and lower molecular weight compounds (Blough and Green, 1995).

The rivers discharging into Hudson Bay show highly variable optical properties of CDOM, as
represented by \(a_{355}\), \(S\), and \(a^*_{254}\). It is noteworthy that the rivers in the northeastern part of
Hudson Bay were low in CDOM and DOC and had low \(a^*_{254}\) values, but a tendency for relatively
high \(S\) values. Rivers in the south had low DOC and \(S\), and high \(a^*_{254}\) values. The rivers in the
west had the highest DOC load, relatively high \(S\) and relatively low \(a^*_{254}\) values. The variation
in \(S\) and \(a^*_{254}\) indicates considerable compositional differences in DOM around the Hudson Bay
drainage basin.
From the limited sampling of riverine water during this cruise, which was primarily a marine
programme, it is not possible to infer with confidence the processes leading to the large CDOM
variance in the Hudson Bay drainages. However, the biogeographic range in the drainages,
which include permafrost, sporadic permafrost, coastal lowlands, shield, tundra and boreal
forest, provides ample opportunity for variance in CDOM production and storage even without
considering recent river diversions in the Nelson/Churchill and La Grande systems. For example,
in the northeastern tundra with continuous permafrost, which is well-drained (wetlands < 5%),
DOM appears to be rich in fulvic acids and of low aromaticity. Southern rivers, which drain
taiga shield with low percentage of wetlands, appear relatively impoverished in fulvic acids
and aromatic compounds. The rivers in the west, with relatively high S and low \( a_{254} \) values,
contain a mixture of wetlands (Hudson lowlands) and boreal shield (Hayes and Churchill) and
even prairie grasslands (Nelson). Western rivers (Nelson, Hayes and Churchill Rivers) carry
a significantly higher load of organic carbon than rivers either further south or in the east.
The variable composition of DOM between rivers and its potential downstream effects deserve a
great deal more attention, both its potential for downstream effects and as a tracer of freshwater
pathways in the Bay.

The penetration of UV radiation into marine water is principally controlled by CDOM (Smith
and Baker, 1979). The UV penetration depths based on CDOM alone shows a clear decrease
along the coastal waters in the southern and eastern Hudson Bay (Figure 5). The 310 nm
10% penetration depth, the depth where downwelling radiation is 10% of the surface incident
irradiance at this wavelength, varies from less than 0.5 m in the southern Hudson Bay coastal
waters to about 4–6 m in Hudson Strait, Foxe Channel and in the central Hudson Bay. The
shallow penetration depths in the marginal waters of the Bay are comparable to those observed
by Kuhn et al. (1999) in the estuary and Gulf of St. Lawrence (0.4 to 2.3 m based on in
situ light profiles). Compared to observations of CDOM in the NOW polynya by Scully and
Miller (2000) Hudson Bay has considerably lower penetration depths while Foxe Channel and
Hudson Strait waters appear to be more transparent than water in the NOW region. Gibson et
al. (2000) noted that CDOM, not ozone, is the controlling factor in UV penetration in Arctic
waters (including Hudson Bay). Therefore changes in terrestrial input of CDOM in Hudson Bay
and processes that control its horizontal distribution govern the effective UV dose rate in the
Hudson Bay region. Changes in ice coverage, and especially the length of the open water season
(in the bay itself and in the rivers), may increase the potential for photobleaching of CDOM,
and therefore increase the penetration of UV light in the bay.

[Figure 5 about here.]
4.1 Freshwater components in the bay by CDOM as a tracer

Optical properties of water masses (such as CDOM absorption) can be utilised as quasi-conservative tracers of water masses (Aarup et al., 1996). In the case of Hudson Bay, where runoff and ice melt provide equally important components of the freshwater budget (Prinsenberg, 1984), it is clearly of interest to discriminate between these sources. Traditionally, salinity and oxygen isotope data have been used in arctic waters to discriminate between the sources of freshwater (Tan and Strain, 1996). It is well known that absorption by CDOM is not ultimately conservative, and that its absorbance decreases when exposed to ultraviolet radiation (photobleaching) and, less importantly, from microbial degradation (Vähätalo and Wetzel, 2004). However, several factors favor the use of CDOM as a tracer of river runoff in Hudson Bay. First, the Bay is covered with ice and snow for most of the year (completely for 8-9 months), which limits the photobleaching of CDOM (cf. Pegau, 2002). Second, the high CDOM concentration limits the depth to which photobleaching can occur (self-screening), especially in the coastal waters in Hudson Bay, and this proves to be a critical factor in the degree of photobleaching that can occur (Del Vecchio and Blough, 2002). When the average photodegradation depth of the photochemically active UV wavelengths is very small with respect to the mixed layer depth, as appears to be the case for the coastal Hudson Bay, small absorption losses are expected (Del Vecchio and Blough, 2002). Furthermore, the generally strong relationship between salinity and $a_{355}$ in Hudson Bay indicates quasi-conservative behavior of CDOM (at least regionally).

Here, we restrict this analysis to Hudson Bay where previous information on the distribution of the freshwater components is non-existent. Provided a reasonable and tightly clustered set of values can be assigned for the characteristic end-members, the fractional composition of a water sample with a measured salinity $Sal$ and $a_{355}$ can be estimated for the three components, seawater (subscript $sw$), sea-ice melt ($sim$) and river runoff ($r$) as follows (cf. Aarup et al., 1996);

$$F_{sim} + F_r + F_{sw} = 1$$

$$F_{sim} Sal_{sim} + F_r Sal_r + F_{sw} Sal_{sw} = Sal$$

$$F_{sim} a_{sim} + F_r a_r + F_{sw} a_{sw} = a_{355}$$

For Hudson Bay the seawater end-member is assigned according to the properties of deep water entering the Bay ($Sal_{sw} = 33.1$, $a_{sw} = 0.25 \text{ m}^{-1}$). The sea-ice end-member ($Sal_{sim} = 5$, $a_{sim} = 0.30 \text{ m}^{-1}$) is estimated based on sea-ice salinity data from the Churchill area, in the western Hudson Bay (Mats Granskog, unpublished data, 2005) and the data reported by Belzile et al. (2000) on CDOM absorption in first-year sea ice from the NOW region, where $a_{355}$ was in the range of 0.1 to 0.5 $\text{ m}^{-1}$ (see their Figure 4). To assign a representative CDOM absorption value for the river runoff is more difficult. The only data for CDOM in Hudson Bay, to our
knowledge, is what we have presented here. To estimate a bulk value for all runoff to Hudson Bay, we calculated a volume-weighted average, based on annual river discharges in Déry et al. (2005) and our river and estuarine data. The CDOM composition of the James Bay rivers was estimated from the zero intercept of a linear regression of $a_{355}$ against salinity for the stations at the entrance of the James Bay (salinity range 24 to 32, $R^2 =0.96$, n=20). The sampled rivers and rivers draining to James Bay account for about 80% of the total volumetric river flow to the Hudson Bay (Déry et al., 2005). Using this information yields a runoff end-member of $Sal_r = 0.1$ and $a_r = 13.5$ m$^{-1}$. Deviations from linearity in mixing of CDOM and salinity can be caused by in situ production or loss of CDOM, from conservative mixing of more than two end-members or a combination of these (Blough and Del Vecchio, 2002).

The solutions to the algebraic equations are sensitive to uncertainties in the assignment of end-member values. Of the end-members, the greatest uncertainty applies to the river water, essentially due to lack of data. A variation of ±10% in $a_r$ (12 to 15 m$^{-1}$) would induce a ±10% change in the $F_r$ estimate, corresponding to about a <0.3 m error in the estimate for runoff in the mixed layer (see below). Variation in salinity of the end-members induces only minor changes to the presented estimates. Locally, due to the variation in CDOM input around the Bay, we may either under- or overestimate the riverine contribution (the opposite is then true for the sea-ice melt component estimate) when using a Bay-averaged end-member. In regions where the local freshwater end-member is known, such as, for example, the southwest where runoff from the Nelson River can be assumed to dominate, locally derived end-member values may perform better.

When the assigned end-member values are used to solve equations 2 to 4 to determine river water ($F_r$) and sea-ice melt ($F_{sim}$) fractions for individual water samples in the Bay the results show that river water is restricted mainly to nearshore coastal waters in the southwest. The river water contribution generally decreases while the water transports cyclonically around the margin (Figure 6), but peaks at the outflow from James Bay. For the stations in the Bay, runoff contributed on average 1.2±1.4 m (range 0.1 to 6.9 m) of freshwater in the mixed layer, while the corresponding values for sea-ice melt were 1.6±1.0 m (0.0 to 3.9 m). The amount in the mixed layer should roughly correspond to the annual input to the Bay. The values for sea-ice melt estimated from CDOM and salinity compare favorably to the estimated 1.6 m of sea-ice melt averaged over the whole Bay (Prinsenberg, 1984). The contribution of runoff is higher than the yield, estimated at 0.6–0.8 m of freshwater contributed annually and averaged over the entire surface of the Bay (Prinsenberg, 1984), but this may easily be explained by the location of the sampling stations which favour the nearshore where river input are highest. Sea-ice melt is more evenly distributed than river runoff, but is found in greater quantities in the south, in keeping with the general transport of ice southward where it last disappears in the Bay. In the offshore waters and in the northeast sea-ice melt appears to dominate the freshwater budget (Figure 6).
An advantage of using CDOM as a tracer is the simplicity and economy of the measurement and the possibility to look at preliminary data on board ship. On time-scales short enough to limit photobleaching (such as immediately after ice melt) and regional scales (such as in estuaries) CDOM provides an easy measure to evaluate the distribution of freshwater components. The traditional method of using oxygen isotopes is not without problems, given variability in oxygen isotopic composition of the rivers, precipitation and in waters of the HB region (Tan and Strain, 1996). The use of CDOM together with δ18O might offer considerable refinement in the determination of freshwater sources for this system. By itself, CDOM implies highly reasonable freshwater inventories and distributions (Figure 6) given the general oceanographic controls of freshwater and sea ice pathways for the Bay (Prinsenberg, 1986b).

[Figure 6 about here.]

4.2 The effect of CDOM on the absorption of radiation

In the central Arctic Ocean Pegau (2002) observed that the CDOM load affected the upper ocean heat budget significantly by trapping about 30% more heat in the upper 20 m than previously thought. The CDOM levels in the central Arctic Ocean are comparable to our observations in the Hudson Strait and Foxe Channel, but much lower than in the Hudson Bay. This implies an even stronger role for CDOM in the heat budget of the Hudson Bay region. One must also recognize that changes in transmission (absorption) caused by CDOM loading will have far different consequences for radiant heating by deep penetrating visible wavelengths compared to near-infrared wavelengths, which are completely attenuated in the upper few meters (Ohlmann et al., 2000). About 40–50% of the solar energy is at wavelengths shorter than 800 nm, where CDOM absorption can have an influence on the vertical distribution of radiant heating in the upper ocean heat budget, especially in coastal waters in contrast to open ocean where chlorophyll absorbance is dominant (Chang and Dickey, 2004). In coastal waters the rate of radiant heating may be much greater than in the open ocean (Chang and Dickey, 2004), and therefore play an important role in the stratification of coastal waters. For example, for water of salinity 25 and temperature 0 °C, heating by 10 °C would have an equivalent effect on density as a reduction of salinity by 1. In Hudson Bay the highest surface temperatures are generally observed in coastal waters around the bay, and before the water exits to the Hudson Strait (Prinsenberg, 1986a). This is attributed to the accumulation of heat as the waters transport cyclonically around the margin of the bay (Prinsenberg, 1986a). The significant gradients of CDOM (and bio-optical properties in general) in Hudson Bay could, therefore, result in significant differences in the vertical distribution of radiant heating. We made an estimate of the relative radiant heating rate assignable to variations in the bio-optical properties of surface waters for different regions in Hudson Bay as listed in Table 4.
The radiant heating rate $RHR(z)$ is defined as the average rate the solar radiation (here 300 to 700 nm) heats a layer of thickness $z$ (Ohlmann et al., 2000; Chang and Dickey, 2004). We estimated the irradiance at depth $(E_z)$ using a simple exponential decay law (equation 5).

$$E_z = E_0 e^{K_d z}$$

$$RHR(z) = \frac{E_{z1} - E_{z2}}{\rho c_p \Delta z}$$

where $z_1$ and $z_2$ are the depths at the top and bottom, respectively, of a layer, and $\Delta z = z_2 - z_1$ is the layer thickness. The diffuse attenuation coefficient ($K_d$) is the sum of pure water absorption and scattering, particulate absorption and scattering and CDOM absorption in the wavelength range between 300 and 700 nm. Pure water absorption and scattering are taken from Smith and Baker (1981) and Buitveld et al. (1994), respectively. Particulate absorption and scattering depend on chlorophyll concentration as described in Ohlmann et al. (2000). The spectra have been extended to the ultraviolet range as outlined in Ohlmann et al. (2000). CDOM absorption spectra and chlorophyll values were taken from our observations for typical values in the mixed layer for two coastal areas and the offshore (i.e. central bay) waters in the Hudson Bay (Table 4). $\rho$ is the density and $c_p$ is the specific heat of seawater (at a salinity typical for the mixed layer for the regions in Table 4). The incident radiance at the surface ($E_0$) was determined by the SBDART model for the 300–700 nm range (Ricchiazzi et al., 1998), for typical sub-arctic clear sky conditions in summer in Hudson Bay.

Figure 7 illustrates $RHR$ differences for Region 1 and Region 2 water referenced to Region 3 using the equation: \[RHR_{region\ 1 or\ 2} - RHR_{region\ 3}] / RHR_{region\ 3}. In the coastal waters (Region 1 and 2) a major fraction of the solar radiation is absorbed within two to three metres of the surface, which is shown by the excess of RHR compared to Region 3 (Figure 7). For the less turbid Region 3 (offshore) water, more radiation penetrates to deeper depths. However, not only CDOM but also the higher chlorophyll concentrations in the coastal waters contribute to excess heating of the upper meters compared to offshore waters. The absorption and scattering are so strong in these turbid coastal waters that the majority of radiant heating is trapped within the top 2–3 m of the surface. The vertical heating is even more dramatically shifted to the upper few meters of the water column compared to the effect of moderate CDOM levels in the central Arctic Ocean (cf. Pegau, 2002, his Fig. 4). In cloud free conditions the upper 2 m layer may be warming by as much as 0.5 °C day$^{-1}$ faster in the coastal waters than in offshore waters at the height of the summer due to differences in bio-optical properties.

Observational studies on $RHR$ in coastal waters are rare, but those available indicate that in turbid waters the daily heating rate may be of the order of 0.3 to 0.5 °C day$^{-1}$ (Chang
and Dickey, 2004, and references therein). The trapping of heat near the surface may partly explain the observation that surface waters along the Hudson Bay coasts are warmer than their offshore counterparts, and also contributes to increasing stratification in these areas. However, the mixed layer depth, cloud cover, solar zenith angle and variable bio-optical properties of the waters will result in varying RHR with depth (Ohlmann et al., 2000; Chang and Dickey, 2004). Our simplistic first-order approximation reveals that the variations in the vertical RHR should be taken into consideration especially in coastal waters of the Hudson Bay, where the bio-optical properties of the waters differ significantly from the offshore to nearshore waters. As in the Arctic Ocean, the accumulation of radiative heating near the surface in CDOM-rich coastal waters may then accelerate ice melt in these regions compared to offshore waters (cf. Pegau, 2002).

[Figure 7 about here.]

4.3 Role of CDOM in other photoprocesses in Hudson Bay

Based on the typical bio-optical properties discussed above, the photic depth varies from >20 m in the Hudson Strait and Hudson Bay offshore waters to <10 m in coastal waters of the Hudson Bay (not shown). Deep chlorophyll maxima (DCM) are an important and ubiquitous biological feature of arctic waters (Carmack et al., 2005). Such maxima occur frequently both in the Hudson Strait and the Hudson Bay, based on chlorophyll fluorescence profiles collected during the cruise and on previous observations in the region (Anderson and Roff, 1980b; Harvey et al., 1997). The DCM likely reflects the location in the water column where both light and nutrients are sufficiently available to support production, although it has alternatively been proposed that in oligotrophic waters DCMs may be a result of UV avoidance (Saros et al., 2005). Within our region of study, the depth of the DCM generally decreased going from Hudson Strait into Hudson Bay. Hudson Bay coastal waters generally had a mixed layer with the highest chlorophyll concentrations within the layer and no distinct DCM. This agrees with earlier observations in the southeastern Hudson Bay (Harvey et al., 1997). The strong inshore-offshore gradient in bio-optical properties and thereby photic depth, may partly explain absence of DCMs in the coastal waters of the Bay.

For stratified coastal waters, nutrients are usually supplied by entrainment of deep nutrient-rich water (Anderson and Roff, 1980b), or by river inflow. In Hudson Bay, river waters are generally impoverished in inorganic nutrients relative to subsurface Hudson Bay waters, which implies that rivers supply only a small portion of the (inorganic) nutrients supporting primary production in Hudson Bay (Hudon et al., 1996). However this assumption neglects the potential role of riverine organic matter to supply nutrients. In surface waters with low bioavailable nitrogen, such as Hudson Bay, photochemistry likely produces additional bioavailable species of nitrogen
(Vähätalo and Zepp, 2005). Through photochemical and microbial decomposition of CDOM, nutrients and energy bound in recalcitrant humic substances become available to food webs (for recent review see Mopper and Kieber, 2002). On a time-scale of weeks to months (i.e., the length of the open water season in Hudson Bay) photodegradation of CDOM is much more significant than microbial degradation (Vähätalo and Wetzel, 2004). Photoammonification of biologically recalcitrant dissolved matter is a significant source of labile nitrogen in CDOM-rich coastal waters (Bushaw et al., 1996; Vähätalo and Zepp, 2005). To test our hypothesis, dedicated experiments need to be conducted in the Hudson Bay, similar to those of Vähätalo and Zepp (2005) in the Baltic Sea, where photoammonification was deemed important despite significant nitrogen inputs through rivers and atmosphere.

CDOM can also be photomineralized directly into various inorganic carbon gases (Johannessen and Miller, 2001). In support of potential photoproduction of DIC from CDOM in Hudson Bay, there was a positive relationship between CDOM and surface water $pCO_2$ ($R^2 = 0.72$, salinity $>24$; Tim Papakyriakou and Brent Else, unpublished data, 2006). The photoproduction of DIC by this process, which has been shown to be strongest within the top few meters of the ocean, thereby potentially supports $CO_2$ evasion to the atmosphere in CDOM-rich coastal waters. This may also be an important sink for riverine DOM in this system. However, dedicated experiments, as for photoproduction of nitrogen, need to be carried out to quantify this process.

## 5 Conclusions

General circulation models forecast that the Hudson Bay region will experience some of the more dramatic environmental changes in the coming century (Gagnon and Gough, 2005). Particularly, the melt of permafrost in the drainage basin may affect the rates and timing of freshwater discharge, and trigger potential feedbacks through soil carbon activation that can affect organic matter composition in arctic waters (Lawrence and Slater, 2005; Guo and Macdonald, 2006). Change in the coupling of drainage basin organic carbon reservoirs with the ocean via river inflow and coastal erosion will, in turn, have consequences for the exposure to UV radiation in the marine environment. Indeed, these sorts of changes will be of larger magnitude than effects related to ozone reduction (Gibson et al., 2000).

Our results show that CDOM is largely controlled by terrestrial input to the margins of the Hudson Bay and Hudson Strait system, with the interior regions of the system exhibiting CDOM absorption levels similar to the central Arctic Ocean and Beaufort Sea. Accordingly, the surface coastal waters in the Hudson Bay have significantly higher CDOM levels which are transported cyclonically around the perimeter of the bay. The processes of delivery and circulation result in significant inshore-offshore gradients in for example, UV light attenuation, photic depth and radiant heating in the bay, which themselves influence other photoprocesses such as the potential
photochemical production of nutrients. The CDOM data presented here highlight the need to investigate the composition and role of organic matter as 1) a potential additional source of biologically labile substrates in the otherwise low-nutrient Hudson Bay, thereby being a key factor in the higher biomass observed in Hudson Bay coastal waters and 2) a key player in the light environment in the system, thereby largely controlling the penetration of UV radiation, vertical distribution of biomass and the radiant heating of the surface ocean. We also infer that sea-ice melt likely dilutes CDOM levels in the mixed layer in Hudson Bay and Hudson Strait. The direct application of CDOM to trace river runoff in this system needs to be verified independently by, for example, use of oxygen isotopes, or other appropriate tracers, since CDOM provides a simple, inexpensive, real-time method to distinguish freshwater (sea-ice melt and river runoff) components. The CDOM fingerprint of terrestrial runoff in the region is clear, and therefore the use of remotely sensed ocean color may be an efficient tool to study the dispersal and dynamics of river runoff during the ice-free season. Furthermore, ocean color can indirectly be used to detect potential source and sink regions of atmospheric CO₂.

This work has ramifications both for climate change in subarctic Canada as well as implications for hydropower development. As we move into the next decades it will become increasingly important to understand the role that riverine DOM has on the various processes presented here. Increased melt of permafrost will alter the magnitudes and characteristics of DOM delivered to Hudson Bay (Lawrence and Slater, 2005). Hydroelectric development changes both the location and the timing of the hydrograph from that of the natural watershed. With a transfer of water delivery from summer to winter there remain many unknowns regarding the impact this altered delivery might have on physical and biological processes in Hudson Bay, including the total flux of DOM to the system, the distribution of CDOM-rich coastal waters with respect to the cyclonic circulation in the Bay, pathways for nutrients, the role on mixed layer thermodynamics, growth/decay of sea ice and the associated impacts on the light environment.

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<th>Comments</th>
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<td>Innuksuac</td>
<td>River and estuary gradient (0 – 23)</td>
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<td>Little Whale</td>
<td>River</td>
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<tr>
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<tr>
<td>Churchill</td>
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<table>
<thead>
<tr>
<th>River</th>
<th>$a_{310}$ (m$^{-1}$)</th>
<th>$a_{355}$ (m$^{-1}$)</th>
<th>$S$ (nm$^{-1}$)</th>
<th>DOC ($\mu$M)</th>
<th>$a_{254}^*$ (m$^2$ g$^{-1}$)</th>
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<table>
<thead>
<tr>
<th>Region</th>
<th>MLD (m)</th>
<th>n</th>
<th>Salinity</th>
<th>$a_{310}$ (m$^{-1}$)</th>
<th>$a_{355}$ (m$^{-1}$)</th>
<th>S (nm$^{-1}$)</th>
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<td>31.73±0.27</td>
<td>0.54±0.04</td>
<td>0.21±0.02</td>
<td>0.024±0.0006</td>
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<td>HS</td>
<td>16.5±5.3</td>
<td>19</td>
<td>32.40±0.56</td>
<td>0.60±0.10</td>
<td>0.24±0.05</td>
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<td>16.3±5.8</td>
<td>68</td>
<td>29.59±1.25</td>
<td>1.38±0.71</td>
<td>0.56±0.32</td>
<td>0.022±0.0023</td>
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<td><strong>Deep water - Salinity&gt;28</strong></td>
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<tr>
<td>FC</td>
<td>18.7±6.1</td>
<td>30</td>
<td>32.45±0.54</td>
<td>0.56±0.04</td>
<td>0.23±0.03</td>
<td>0.023±0.0008</td>
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<td>51</td>
<td>33.29±0.45</td>
<td>0.50±0.07</td>
<td>0.20±0.04</td>
<td>0.023±0.0013</td>
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<td>31.54±1.37</td>
<td>1.09±0.60</td>
<td>0.45±0.27</td>
<td>0.021±0.0016</td>
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<td><strong>Hudson Bay coastal waters - all depths - 24&lt;Salinity&lt;28</strong></td>
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<tr>
<td>HB</td>
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<td>26.62±1.40</td>
<td>4.08±2.25</td>
<td>1.81±1.09</td>
<td>0.019±0.0019</td>
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Table 4: Typical bio-optical properties for waters in three different regions in the Hudson Bay for the computation of radiant heating rate. Properties are based on observations in the mixed layer in September and October 2005.

<table>
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<tr>
<th>Region</th>
<th>Area</th>
<th>( a_{355} ) (m(^{-1}))</th>
<th>chl-a (mg m(^{-3}))</th>
<th>Comments</th>
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<td>1.0</td>
<td>Coastal waters</td>
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<td>Eastern Hudson Bay</td>
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<td>1.0</td>
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<td>Hudson Bay offshore</td>
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<td>0.4</td>
<td>Offshore waters</td>
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