Biogeosciences Discuss., 12, 305–344, 2015
www.biogeosciences-discuss.net/12/305/2015/
doi:10.5194/bgd-12-305-2015

Biogeosciences
Discussions
Open Access

A 50 % increase in the amount of terrestrial particles delivered by the Mackenzie River into the Beaufort Sea (Canadian Arctic Ocean) over the last 10 years

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Received: 12 November 2014 – Accepted: 28 November 2014 – Published: 7 January 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Global warming has a significant impact at the regional scale on the Arctic Ocean and surrounding coastal zones (i.e., Alaska, Canada, Greenland, Norway and Russia). The recent increase in air temperature has resulted in increased precipitations along the drainage basins of Arctic Rivers. It has also directly impacted land and seawater temperatures with the consequence of melting the permafrost and sea-ice. An increase in freshwater discharge by main Arctic rivers has been clearly identified in time series of field observations. The freshwater discharge of the Mackenzie River has increased by 25 % since 2003. This may have increased the mobilization and transport of various dissolved and particulate substances, including organic carbon, as well as their export to the ocean. The release from land to the ocean of such organic material, which was sequestered as frozen since the last glacial maximum, may significantly impact the Arctic Ocean carbon cycle as well as marine ecosystems.

In this study we use 11 years of ocean-colour satellite data and field observations collected in 2009 to estimate the amount of terrestrial suspended solids and particulate organic carbon delivered by the Mackenzie River into the Beaufort Sea (Arctic Ocean). Our results show that during the summer period the concentration of suspended solids at the river mouth, in the delta zone and in the river plume has increased by 46, 71 and 33 %, respectively, since 2003. Combined with the variations observed in the freshwater discharge, this corresponds to a more than 50 % increase in the particulate (terrestrial suspended particles and organic carbon) export from the Mackenzie River into the Beaufort Sea.

1 Introduction

The Arctic Ocean plays an important role in the global carbon cycle as it contributes to up to 14 % of the global ocean uptake of atmospheric carbon dioxide (Bates and Mathis, 2009). Observations over the last 20 years have revealed significant impacts of climate

BGD
12, 305–344, 2015

change at high latitudes, notably in the Arctic Ocean and surrounding coastal zones (Serreze et al., 2000; Macdonald et al., 2006). Air temperature has increased by 1 °C since 1980 (Overland et al., 2011). Precipitations over the drainage basin of the Arctic Ocean, the largest after the Atlantic Ocean, have overall increased by 100 mm a^{-1} since 2000 but with strong regional differences (Rawlins et al., 2006). Consequently the freshwater discharge from major Arctic rivers has also increased (e.g., Fig. 1; Shiklomanov et al., 2007; Wisser et al., 2010; Shiklomanov and Lammers, 2011). Finally, the permafrost has been found to gradually thaw (Smith et al., 2005; Zhang et al., 2012; Price et al., 2013). The permafrost is known to contain large amounts of frozen organic matter sequestered since the last glacial maximum. The combination of permafrost thawing and increase of Arctic rivers freshwater discharge (Li et al., 2009) may lead to an increase in the flux of terrestrial substances delivered by rivers into the Arctic Ocean.

More than ten years ago, Syvitski (2002) used a stochastic model to estimate the impact of climate change (warming of Arctic regions) on sediment discharge by Arctic rivers. His study predicted a 22 % increase in the flux of sediment carried out by rivers for every 2 °C warming of the averaged drainage basin temperature and an increase of 10 % in sediment load for a 20 % increase in river discharge. Recent advancements in measuring capabilities may now give us the possibility to confirm, or not, the realism of such predictions.

While field observations have been and are still scarce in such remote regions (e.g., along the drainage basins of North American and Siberian rivers), a methodology has been recently developed to remotely sense the variations of suspended particulate matter (SPM) concentrations at the mouth of Arctic rivers using ocean colour radiometry (Doxaran et al., 2012). This method can be combined with field measurements of the river discharge and particulate organic content to estimate the actual amount of terrigenous particles (suspended particulate matter (SPM) and particulate organic carbon (POC)) supplied to the ocean by any Arctic river and study its seasonal and interannual variations since ocean colour satellite data are available for more than a decade (see for instance Doxaran et al., 2009 for SPM).

The present study focuses on the mouth and turbid plume of the Mackenzie River in the Beaufort Sea (Canadian Arctic Ocean). This river is the largest single source of terrestrial particles entering the Arctic Ocean. The regional ocean colour algorithm developed by Doxaran et al. (2012) for this area is based on a large bio-optical in situ dataset collected in 2009 during the MALINA oceanographic campaign. It has been successfully tested on a selection of cloud-free and sea-ice-free ocean colour satellite images recorded during the 2009, 2010 and 2011 summer periods. It is here first improved to efficiently discriminate the floating sea-ice, clouds, haze and highly turbid waters near the mouth of the Mackenzie River by tuning processing flags and visually inspecting every single pass. It is then applied to an 11 year long dataset of ocean colour observations from the Moderare Resolution Imaging Spetroradiometer (MODIS) onboard the Aqua satellite platform. Results are used to estimate the monthly fluxes of SPM and terrestrial POC delivered by the Mackenzie River to the Beaufort Sea during the melting season in order to reveal possible trends resulting from the observed increase in freshwater discharge since 2003 (Fig. 1). The evolution of the floating sea-ice cover and extension of the Mackenzie River plume are also analyzed and discussed.

2 Data and methods

2.1 Study area

The southeast of the Beaufort Sea is characterized by the presence of a large and shallow continental shelf bordered to the east by the Amundsen Gulf, to the west by the Mackenzie canyon, to the south by the delta of the Mackenzie River, and to the north by the Beaufort Sea and Canada Basin (Fig. 2, Carmack and MacDonald, 2002). Two river mouths characterize the shallow delta zone, one in the west side where both the river flow and water turbidity are usually large and one in the east side with a low river

BGD
12, 305–344, 2015

flow. During the winter period, sea-ice accumulates north of the delta zone resulting in the formation, along the 20 m isobath, of a ridged ice barrier of considerable thickness (> 20 m) grounded to the sea bottom, known as stamukhi zone or stamukha (Macdonald et al., 1995). During that period, the water from the Mackenzie River is trapped in the delta zone and forms what is essentially a lake of turbid freshwater (Carmack and Macdonald, 2002). The spring ice break-up begins with the flooding of the Mackenzie River. When the river flow is maximal (June) the turbid freshwaters inundate the coastal zone and contribute to the progressive breaking of the stamukha (Fig. 2). The warm and turbid river plume can then spread over an area of several thousand km^2 up to an offshore limit of permanent floating sea-ice (Macdonald et al., 1995). The extension and dynamics of the plume are mainly controlled by wind conditions. During the summer period, melting sea-ice and inputs from the Mackenzie River result in a 5 to 10 m surface layer of freshwater over the continental shelf. In September, the shelf is usually completely free of sea-ice up to around 72° N. Suspended particles supplied by the river are transported across the continental shelf either in a surface plume or a benthic nepheloid layer. This transport is controlled by circulation patterns on the shelf, which are driven by wind forcing, river discharge and sea ice coverage (Ehn et al., 2014).

2.2 Satellite data and SPM algorithm

2.2.1 Ocean colour satellite data

As in Doxaran et al. (2012), the selected ocean colour satellite data are those recorded by the MODIS (for Moderate Resolution Imaging Spectroradiometer) sensor onboard the Aqua platform. This sensor provides every day at least one image of the study area since 2002 and has several bands in the near-infrared (NIR) and short-wave infrared (SWIR) spectral regions which are required for atmospheric corrections over turbid coastal waters (Wang and Shi, 2007). A single satellite sensor was used in this study in order to generate a consistent time series of SPM concentration.

BGD
12, 305–344, 2015

MODIS-Aqua level 1 data were downloaded from the National Aeronautics and Space Administration (NASA) Ocean colour website (http://oceancolor.gsfc.nasa.gov) and processed using the SeaWiFS Data Analysis System (SeaDAS 7.0.2) software (http://seadas.gsfc.nasa.gov/). The 11 year time series spans from 2003 to 2013 and includes the months of May to September, which correspond to the daylight period and ice-free season in most of the Arctic Ocean. No data were available between October and April due to ice-cover and the polar night; however, these missing data do not impact our results significantly. In April, the river discharge is close to its annual minimum (reached in March, results not shown) and sediment transport is low. In October, the river discharge is low and the onset of the winter freeze-up reduces the export of sediment from the permafrost to the Mackenzie River.

Removal of the atmospheric contribution to the total signal was performed using the NIR-SWIR algorithm of Wang and Shi (2007); this correction method was proved to be the most appropriate for the highly turbid waters (high SPM load) present in the mouth the Mackenzie River (Doxaran et al., 2012). Due to high loads of SPM in the Mackenzie delta, a number of marine pixels were often classified as clouds or ice-covered in the standard SeaDAS processing (i.e., using the default mask threshold values) due to high reflectances values in the near-infrared. This issue was tackled by increasing the cloud albedo threshold for cloud flagging in the atmospheric correction procedure from the initial value of 0.027 to 0.4 in a small area bounded eastwards from −133.4 to −138.9° E and northwards from 68.7 to 69.3° N (Fig. 2). Relaxation of the cloud albedo criteria was associated with a careful visual check of every individual pass to avoid contamination by clouds in the delta, which occurred as speckles of very high SPM concentrations. Finally, observations over the delta, when available, were merged with the observation carried out with the standard atmospheric correction scheme to obtain maps of the whole study area (Fig. 3). The atmospheric correction procedure yielded remote sensing reflectances, R_{RS} in sr^{-1}, at 555 and 748 nm, which were used to derive the suspended particulate matter concentration (see next section). Satellite products were generated at a spatial resolution of 1 km at nadir.

BGD
12, 305–344, 2015

From an initial total of about ten thousands images downloaded over the study area between 2003 and 2013, and despite the large number of MODIS-Aqua revisits at high latitudes, only 562 images were finally exploited in the present study. This emphasizes the need for a constellation of low-earth-orbit ocean colour satellites to increase the number of observations in such areas, which are highly affected by clouds and sea ice. Due to the very high sea-ice and cloud covers, the data recorded during the month of May finally proved to be unusable for SPM retrieval and were discarded from our analysis. Interestingly, the number of images per month increases with time along the observation period (2003–2013). This is consistent with the receding of sea-ice concentration over the last decade. The highest number of images in a month was reached in July 2012 (Fig. 4), year of the record-low sea-ice extent (Perovich et al., 2013). Whereas the minimum of sea-ice extent occurs in September (a usually very cloudy month in this region), the highest number of satellite observations occurs in July when daylight lasts more than twenty hours with higher sun zenith angles compared to the month of September allowing a greater number of observations in July than in September. The number of available images for each month was recorded to weight the linear regression of monthly SPM concentration against time during time series analysis.

2.2.2 SPM algorithm and flux estimation

The suspended particulate matter (SPM) concentration varies over four orders of magnitude (typically from 0.1 to more than $100\,\mathrm{g\,m^{-3}}$) from the highly turbid waters of the Mackenzie delta to the oligotrophic region of the Beaufort Sea (e.g., Doxaran et al., 2012). At high SPM concentration, the seawater reflectance signal tends to saturate in the visible part of the spectrum and only the signal in the near-infrared (NIR) remains sensitive to SPM variations (Doxaran et al., 2002; Shen et al., 2010). Therefore, as one of the main objectives of the study was to quantify SPM concentration and estimate SPM flux at the mouth of the Mackenzie River, a relationship had to be established between R_{RS} in the NIR and the SPM concentration. Doxaran et al. (2012) established such a regional relationship, using the 748 nm (MODIS band 15) to 555 nm

BGD
12, 305–344, 2015

(MODIS band 4) remote sensing reflectance ratio, based on field bio-optical measurements carried out in the study area during the MALINA oceanographic campaign. This second order polynomial relationship is valid for a wide range of SPM concentrations spanning from 1 to 150 g m^{-3}, i.e., valid from the mouth of the Mackenzie River up to the offshore limit of the river plume. This second order polynomial expression can accurately be described by two linear relationships: one developed for moderately turbid waters and a second one developed to deal with high concentration of SPM. To avoid a brutal change in the SPM concentration as a function of the $R_{RS}(748) : R_{RS}(555)$ spectral band ratio, a non-linear equation (Eq. 1) was used to describe transition between both linear relationships:

$$
\begin{aligned}
\text{SPM} &= 0.8386 \times R_{RS}(748:555) \quad \text{if } R_{RS}(748:555) < 87\,\% \\
\text{SPM} &= 70 + 0.1416 \times R_{RS}(748:555) + 2.9541 \\
&\quad \times \exp[0.2092 \times (R_{RS}(748:555) - 87)] \quad \text{if } 87\,\% \leq R_{RS}(748:555) \leq 94\,\% \\
\text{SPM} &= 3.922 \times R_{RS}(748:555) - 285.4 \quad \text{if } 94\,\% < R_{RS}(748:555)
\end{aligned}
$$

where SPM is the SPM concentration in g m^{-3} and $R_{RS}(748:555)$ is the ratio of remote sensing reflectance at 748 to 555 nm.

The use of two linear relationships is needed as the remote sensing reflectance signal in the NIR linearly increases with increasing SPM concentration up to about 90 g m^{-3} then starts to saturate at higher concentrations. Moreover, the sensitivity of the $R_{RS}(748)$ signal is lower and therefore not optimal in the lowest SPM range, namely 1 to 10 g m^{-3}, which corresponds to the offshore limit of the river plume. In that case, shorter wavelengths such as 555 nm (i.e., the green part of the spectrum) are better suited (Nechad et al., 2010). As a consequence, our regional algorithm is expected to accurately retrieve the SPM concentration in the delta zone and map the extension of the river plume, but is potentially associated with higher uncertainties in the retrieval of SPM concentrations in the less turbid waters of the river plume (i.e., SPM lower than 10 g m^{-3}). To circumvent this issue, the Mackenzie plume was here characterized

BGD
12, 305–344, 2015

by the water mass with surface SPM concentrations higher than $10\,\mathrm{g\,m^{-3}}$, a rather conservative threshold.

The semi-empirical relationship was established based on field measurements collected during the 2009 summer period. It is assumed here to be valid for the entire period of satellite observations (2003–2013). The uncertainty associated with the remotely sensed SPM concentrations derived from our algorithm is estimated as ±25 % based on (i) match-ups with in situ data (when applying a similar SPM quantification algorithm to another study area: the Gironde estuary, France, Doxaran et al., 2009) and (ii) in situ measurements in the Mackenzie delta zone (see Fig. 6 in Doxaran et al., 2012).

The SPM flux was computed each month, from June to September, simply by multiplying the monthly-averaged SPM concentration (in $\mathrm{g\,m^{-3}}$) by the monthly-averaged freshwater discharged by the river (in $\mathrm{m^3\,s^{-1}}$) for the same month and by the duration (in s) of each month. This approach is simplistic but gives a robust estimate of average SPM fluxes in the very shallow river mouth and delta zones. It does not require measurements of vertical profiles of current velocities. The estimates were computed for two specific geographical zones: (i) the river mouth defined as a box: 68.7–69.5° N and 133–137° W where the offshore limit is about the 5 m isobath and (ii) the delta zone, also defined as a box: 68.7–70° N and 132–139° W where the offshore limit is about the 20 m isobath.

2.2.3 Sea-ice concentration

Satellite-derived sea-ice concentration, expressed in percentage (%), corresponds to the area of a pixel covered by sea-ice relative to the total area of that pixel, such that a value of 100 indicates a pixel that is totally covered by sea-ice and a value of 0 indicates a pixel free of sea-ice. It is computed using linear combination of the ratio of brightness temperatures measured in the microwave spectrum using the NASA Team 2 algorithm (Markus and Cavalieri, 2000).

BGD
12, 305–344, 2015

Daily sea-ice concentration data were downloaded from the ftp server of the Zentrum für Marine und Atmsophärische Wissenschaften (ZMAW, ftp://ftp-projects.zmaw.de) between 2003 and 2013. A series of three sensors with a spatial resolution of 6.25 km was used to cover the time period of MODIS-Aqua observations. From 2003 to 2011; data from the Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E) were used until it stopped producing data. The new satellite AMSR2, launched in January 2013, was used to estimate the sea-ice concentrations in 2013. The gap between the AMSR-E and AMSR2 sensors (2012) was filled using data from the Special Sensor Microwave Imager/Sounder (SSMIS). Sea-ice concentration was used to flag potentially contaminated water pixels (isolated water pixels surrounded by highly reflective sea-ice sometimes present erroneous high reflectance values due to adjacency effects). In that respect, ocean colour data collected over pixels with a sea-ice concentration greater than 10 % were removed from our analysis following Bélanger et al. (2007). The data were also used in time series analysis to obtain information on the variations of sea-ice cover over time in the region of interest.

2.2.4 Daily observations of SPM and sea-ice concentrations

Figure 5 illustrates the resulting observations made on each individual MODIS satellite image when combined to the daily mapped sea-ice concentration data. This example shows the spectacular spring ice break-up event (typically occurring in early or mid-June) and highlights the rapid stamukha breakdown, which allows the turbid freshwaters of the Mackenzie River initially constrained in the delta zone to spread over the Beaufort shelf. Figure 5 also highlights the contrast between the spring and the mid-summer period (early August) when, during the latest, the coastal zone is totally free of ice. On 12 June in 2004, a wide ice barrier extends all along the coast with sea-ice concentrations still close to 100 % in the Mackenzie delta zone, in the Amundsen Gulf and over most of the open ocean waters of the Beaufort Sea. Note that SPM concentrations in the ice-free waters (between the stamukha and floating sea-ice) are already high (about 10 $g\,m^{-3}$) as turbid plumes can spread out in the continental shelf from below the stamucha (e.g., see Fig. 2 for illustration). Not surprisingly, a week later (on 19 June), the breaking of the stamukha occurs first right in front of the Mackenzie River mouth (west side) where the river flow is maximum. The turbid plume clearly remains up to the offshore sea-ice edge, with SPM concentrations greater than 10 $g\,m^{-3}$. Two weeks later, on 28 June, the sea-ice concentration along the coast has significantly decreased and the highest SPM concentrations (up to 100 $g\,m^{-3}$) are located in the delta zone. The extension of the turbid plume has declined: the main direction of the plume closely follows the bathymetry towards the Mackenzie canyon while clear waters appear around the plume. Finally, one month and a half later (5 August), during the mid-summer period, the sea ice has almost disappeared along the coast and notably at the entrance of the Amundsen Gulf. Offshore the sea-ice remains but has retreated northwards following its seasonal cycle. The extension of the river plume reaches its maximum size with highly turbid waters at the river mouth and in the delta zone contrasting with clear waters offshore.

These four daily snap-shots provide an initial overview of the SPM and sea-ice seasonal dynamics over the study area. However, performing a multi-year and seasonal analysis of these two parameters requires the use of monthly-averaged composites.

2.2.5 Monthly compositing and time series analysis

Two main areas of interest are distinguished in the present study: (i) the river delta, as defined in Fig. 2 and (ii) the river plume defined as the area where SPM was greater than 10 $g\,m^{-3}$. Whereas the delta surface area remains constant in time, the surface area of the plume changes as a function of the SPM concentration dynamics over the shelf of the Beaufort Sea in turn driven by the river discharge, wind and sea-ice cover conditions. Monthly gridded images were computed on a pixel-per-pixel basis using the arithmetic mean of all the measurements available in a given month. The monthly mean SPM concentrations for the Mackenzie delta and plume (i.e., one value per month) were computed also by arithmetic mean within the area of interest, and the number of pixels used to compute each mean was recorded (N_{month}).

The limited number of months with conditions suitable for ocean colour observations due to ice cover and the polar night (i.e., about 4 months a year) prevents the use of common time series decomposition tools since it is not possible to obtain an entire annual cycle. We therefore preferred to use linear regressions of each satellite product (SPM, sea-ice concentration) against time to infer its trend. When performing the linear regression of monthly SPM concentration against time, the number of pixels available for each month, i.e. N_{month}, was used to weight the contribution of each month in the time series, and give more importance to month with more data. The time series analysis was carried out from 2003 to 2013 (11 years) from the month of June to the month of September.

3 Results

3.1 Seasonal dynamics of sea-ice and suspended particulate matter

We first look at the "seasonal" dynamics of SPM and sea-ice in the region of interest. Here, the term "seasonal" refers to the monthly variations over the four months period (June to September) which corresponds to the maximal Mackenzie River discharge (Fig. 1). Also before analyzing the multi-year variations and potential trends, we highlight how different can be successive years in terms of sea-ice coverage and SPM dynamics.

Similar situations were observed in 2003 and 2004: in June, the ice extends all along the coast except in front of the west branch of the Mackenzie River mouth (Fig. 6). The water is highly turbid in the delta zone and also on the continental shelf bounded in the north by the offshore sea ice edge ($\sim 70.2^{\circ}$ N) and in the east by the entrance of the Amundsen Gulf. One month later, in July, the coast is free of ice while the floating sea ice still covers the same area in the Beaufort Sea; a maximum turbidity zone has developed in the delta zone with SPM concentrations up to 100 g m^{-3} and the turbid plume still extends from the river mouth up to the offshore limit of sea ice. Progressively, in

BGD
12, 305–344, 2015

August then September, the extent and concentration of floating sea ice both decrease as the concentration of SPM on the continental shelf and in the delta zone.

The situation is much more peculiar in June 2006 as the whole Beaufort Sea is covered by sea-ice except along the coastline and in the Mackenzie delta. These unusual June conditions return to the average conditions in July as the floating sea ice has moved northwards: extremely turbid waters then concentrate in the delta zone while turbid plumes extend along the continental shelf. Once again in August and September SPM concentrations progressively decrease on the shelf while remaining high in the delta zone. Opposite conditions are observed at the beginning of the 2008 summer period with a minimum floating sea ice cover observed from June to September (Fig. 7). SPM concentrations gradually decrease along the shelf during this period while remaining very high in the delta zone.

A high number of cloud-free days in 2011, 2012 then 2013 (Fig. 4) yield a maximum of satellite observations (Fig. 8). In 2011, the stamukha zone can still be observed in June as it progressively breaks, resulting in the presence of floating sea ice along the coast. High SPM concentrations extend from the delta zone to the continental shelf with the main river plume extending towards the Mackenzie canyon. In August and September, high SPM concentrations are only detected in the delta zone while clear waters cover most of the continental shelf. The minimum sea-ice cover is observed during the 2012 summer period, allowing turbid plumes with high SPM concentrations to extend up to 72.5° N. Despite these favorable sea-ice and cloud cover conditions, the monthly variations of SPM from June to September remain similar to the monthly variations during the previous years. Finally, opposite conditions to 2012 and 2011 are encountered in 2013 with sea ice covering most of the Beaufort Sea in June, as in 2006, with only the delta zone being free of ice. As the floating sea ice slowly migrates north from July to September, the discharge of the Mackenzie freshwaters occurs later such that turbid waters extend over the continental shelf until August. The situation in September is finally similar to the previous years, with high SPM concentrations constrained to the delta zone and clear waters offshore.

3.2 Multi-year dynamics of sea-ice and SPM

The month of June is probably the most interesting to consider regarding the extent of sea ice in the Beaufort Sea. The sea-ice cover depends primarily on the atmospheric conditions (air temperature and wind) during the long winter period when ice has formed and extended south from the very high latitudes (greater than 80° N). Close to the shore, the sea-ice cover also depends on the air temperature and wind conditions along the coast, which determine the sea-ice concentrations and thickness of the stamukha. Sea-ice is also affected by the heat content of the underlying ocean, which varies from year to year, including because of changes in large scale circulation. Finally, the June sea-ice extent is influenced by the freshwater discharge of the Mackenzie River during the spring period (April, May and June), which defines the upstream pressure imposed by the river to the ice barrier formed around the delta zone and controls its breaking.

In June 2003, 2004 and 2005 similar conditions of sea ice and stamukha extents were observed, with (i) floating sea-ice spreading over most of the Beaufort Sea south up to 70.5° N and (ii) ice formed all along the coast up to the Amundsen Gulf. High SPM concentrations were then located in the delta zone while turbid plumes were extending up to the offshore limit of the sea ice. The following summer periods (July to September 2003 to 2005) also showed similar patterns with a gradual regression of sea ice moving northwards and a decline in the SPM load and offshore extension of the turbid plumes, which were progressively constrained to the coast (delta zone). The years following 2005, i.e. 2006 to 2013 showed more pronounced monthly variations with very different situations encountered in June, such as an almost full coverage of the Beaufort Sea with sea-ice in 2006 and 2013, and quasi ice-free conditions over the whole Beaufort Sea (up to 72.5° N) in 2012. Between these two extreme situations (i.e. from full to null sea-ice coverage conditions in June), transition years (e.g., 2007, 2008 and 2009) showed intermediate sea-ice conditions but on average the sea-ice extent over the Beaufort Sea in June significantly decreased from the 2003–2005 period to the most recent years. SPM dynamics over the summer period showed rather similar successive patterns during the last 11 years: first the discharge of the highly turbid waters of the Mackenzie River trapped in the stamukha, then the offshore transport of SPM mainly towards the Mackenzie canyon and finally at the end of the summer period the trapping of SPM in the delta zone in contrast to clear waters (low SPM loads) over the Mackenzie shelf.

It should be also noted that the number of MODIS-Aqua satellite observations over the study area, so the number of cloud-free and sea-ice-free days, significantly increased from 2003 to 2013. Therefore before examining in detail the variations of SPM concentrations over this 11 years period, our analyses already reveal significant changes in both the sea ice and cloud covers in the Beaufort Sea region.

3.3 Multi-year SPM concentrations and fluxes at the Mackenzie River mouth

The freshwater discharge of the Mackenzie River (data for the station 10LC014; 67°27′21″ N and 133°45′11″ W) from 1972 to 2013 were downloaded from the Environment Canada website (www.wateroffice.ec.gc.ca). It shows large seasonal variations (Fig. 1) with a maximum during the summer period (from June to September) and lower values during the rest of the year (Macdonald et al., 1995; O'Brien et al., 2006). Over the last 11 years, this discharge typically varied between 4000 $m^3 s^{-1}$ (winter) and 25 000 $m^3 s^{-1}$ (summer). Despite large year-to-year variations, a trend is found over this period with a significant increase of 22 % from 2003 to 2013.

The analysis of the monthly SPM maps generated from 2003 to 2011 provides a qualitative overview of the spatial and temporal variations of SPM concentrations in the Mackenzie mouth and delta, as well as in the Beaufort Sea. In order to quantify these variations and highlight a potential trend, these monthly-averaged SPM concentrations were plotted as a function of time, first only considering the Mackenzie delta zone (see Fig. 2 for detailed geographical location).

For the 11 years of the time series, the four monthly-averaged SPM concentrations (June to September) revealed the SPM variations during the summer period (i.e., when

BGD
12, 305–344, 2015

the Mackenzie River mouth is directly connected to the Beaufort Sea), which gives a first overview of the load of SPM exported from the river to the coastal ocean (Fig. 9). These SPM concentrations vary from about 70 to 100 g m^{-3} during the 11 years period, which is in agreement with field measurements collected along river transects (Doxaran et al., 2012). On average over a selected summer period, relative variations of ±25 % are retrieved, except in 2003 when relative variations of ±65 % occurred. Note that the results obtained in 2003 may be associated to larger uncertainties due to the relative low number of cloud-free satellite images available. The highest SPM concentration over a summer period in the Mackenzie delta is usually, but not systematically, observed in June or July (e.g., in 2013 when a high number of cloud-free MODIS images were available). Despite these month-to-month variations, a striking result lies in the multi-year trend observed during our 11 years observation, which overall corresponds to an increase of the mean SPM concentration in the delta zone from 2003 to 2013. Over this 11 year period, the mean concentration has increased from 71 to 107 g m^{-3}, which represents a significant increase of 51 % since 2003. This linear increasing trend is obvious (R^2 = 0.61) when considering the mean SPM concentration averaged each year over the four-month observation time window (June to September). Such an increase of more than 50 % observed over the 11 year period is much higher than the uncertainty of the SPM concentration estimated from MODIS satellite data using our algorithm (±25 % according to Doxaran et al., 2009, 2012), uncertainty which is significantly minimized when producing monthly averages of SPM concentrations (assuming there is no correlation between SPM and clouds). Moreover due to regular vicarious calibrations of the MODIS-Aqua sensor (Franz et al., 2007; Meister et al., 2012), a temporal degradation in the satellite data quality cannot explain the variations observed. This tends to confirm the consistency of the result presented here. It is also important to remind that a unique satellite sensor was used in this study and the exact same algorithm (atmospheric corrections of satellite data and inversion of the seawater signal into SPM concentration) was applied, precisely in order to avoid any bias or discrepancy related to sensor calibration and minimize the uncertainty of the satellite-derived SPM

BGD
12, 305–344, 2015

concentration. This gives us confidence in the validity of the increasing trend in monthly SPM concentration observed over the Mackenzie River delta and Beaufort Sea.

To further confirm this assumption, we examine the relationship between the monthly-averaged (i) Mackenzie freshwater discharge (in $m^3 s^{-1}$) and (ii) SPM concentration in the delta zone. A correlation can be expected between the two variables which both increased, by 22 and 51 % respectively, from 2003 to 2013. However, SPM concentration correlated with freshwater discharge ($R^2 = 0.71$, p value < 0.05) when considering only the months of May (1 point) and June (11 points), whereas no correlation ($R^2 = 0.07$) was established when all the months (May to September) were accounted for (Fig. 9b). This suggests that the export of SPM from the Mackenzie River to the Beaufort Sea is largely driven by the Mackenzie River runoff during a short period of two months (May and June, i.e., late spring and early summer) corresponding to the maximum freshwater flow. Other mechanisms and processes may be involved during the other summer months, such as permafrost thawing, intense precipitation events that locally inject pulses of SPM in the Mackenzie River and delta which is later exported to the Beaufort Shelf. In spring (May and June) the SPM simply goes through the delta zone to enter the coastal ocean (the spring freshet is often the period of most flux in many rivers as the velocities are sufficient to keep particles in suspension). As soon as the river freshwater discharge decreases (July to September), the SPM is trapped in the delta zone where particle settling and resuspension due to tidal currents and wind stress will control the variations of SPM concentrations and export towards the continental shelf.

Having observed and quantified the increase of the Mackenzie freshwater discharge and SPM concentration at the river mouth, the next logical step is to look at the resulting variation in the SPM flux delivered by the river to the Arctic Ocean. The result is an estimation of the mass of SPM in grams (g) transported downstream through the river mouth. The SPM flux obtained corresponds to the solid discharge of the Mackenzie River into the Beaufort Sea, i.e., the mass of SPM delivered by the river each month during the June to September summer period. The same SPM flux calculation is made

BGD
12, 305–344, 2015

in the delta zone but cannot be considered as a horizontal downstream transport as this zone is also affected by SPM vertical dynamics (particle settling and resuspension of bottom sediments). Note that here we call river mouth the downstream limit of the Mackenzie River, i.e., the geographical zone defined as the box: 68.7–69.5° N and 133–137° W. The delta zone is the geographical zone defined as the box: 68.7–70° N and 132–139° W.

The results obtained in the river mouth emphasize the large monthly variations in the SPM flux (a factor of 6) during the summer period (Fig. 10a). The SPM flux is typically higher in June and July than in August and September, which can be explained by the variations of the Mackenzie River freshwater discharge. A strong interannual variability in the SPM flux is also observed, which is directly related to the interannual variability in the freshwater discharge. The timing of the break-up of the stamukha probably plays an important role in the interannual variability of the SPM flux by slowing down the river flow into the delta zone. As for the SPM concentrations (Fig. 9), a trend of increasing SPM flux is observed from 2003 to 2013. Fitting this time series using a linear regression reveals a significant positive trend (p value < 0.05) with a relative slope of 46 % increase over the 11 year long period of observation. This result corresponds to about twice the increase observed in the river freshwater discharge (Fig. 1). Such an increase in the SPM flux may reflect enhanced erosion processes occurring along the drainage basin as a result of the warming air temperature and perhaps an acceleration of the thawing of the permafrost.

Similar observations are made in the delta zone (Fig. 10b). It is interesting to note that the SPM fluxes in the delta zone and at the river mouth are linearly correlated ($R^2 = 0.81$) with SPM concentrations and SPM fluxes in the delta zone being approximately 30 % lower. This clearly indicates that rapid and intensive settling of particles occurs in the delta zone (e.g., Rontani et al., 2014). A second interesting observation is that the increase in SPM concentrations and therefore in the resulting SPM flux from 2003 to 2013 is higher in the delta zone (+71 %) than in the river mouth (+46 %). This certainly reflects an increase in water turbidity, i.e., in SPM load, in the delta

BGD
12, 305–344, 2015

zone where particles rapidly settle to form a bottom nepheloid layer and/or deposit. Resuspension processes due to tidal currents and wind stress probably contribute in a non-negligible manner to the higher SPM concentrations observed in this very shallow (2 to 5 m depths) zone, however, our method does not allow the separation of the different processes involved in the characterization of the SPM fluxes. When considering the SPM fluxes each year averaged over the whole summer period, a linear fit is obtained with a significant correlation ($R^2 = 0.43$) at the river mouth (Fig. 10c). Note however two peculiar years (2004 and 2010) associated to lower than expected SPM fluxes. This relationship may be useful to model and predict in the near-future amount of SPM and associated organic carbon delivered by the Mackenzie River into the Beaufort Sea. Using this interannual linear trend, a significantly lower increase in SPM flux is obtained from 2003 to 2013: +36 % instead of +46 % when considering the monthly-averaged SPM fluxes (Fig. 10a). This clearly means that the method used to estimate the changes in SPM concentrations and fluxes impacts the result. While we can confidently conclude on the positive trends observed in the SPM concentration and fluxes, the magnitude of the variations reported here should be carefully used in other studies.

3.4 Impact on the Mackenzie continental shelf

We finally analyze the impact of the increase in SPM concentrations and fluxes in the river mouth and delta zone on the Mackenzie continental shelf (Fig. 11). Only the SPM concentrations (estimated using satellite data within the first few meters below the air–water interface, Doxaran et al., 2012) are considered here. Given the data available in this study, it is impossible to compute the SPM flux as we do not have access to the surface current velocity and direction. The extent of the plume over the study area is defined as the area where SPM concentrations are higher than 10 g m^{-3}. This arbitrary threshold value was chosen because of the higher accuracy of our remote sensing algorithm in the 10 to 100 g m^{-3} SPM concentration range. The resulting mean SPM concentration in the river plume is logically lower than in the delta zone. They typically vary from 40 to 80 $g\,m^{-3}$ (with few values as low as 20 $g\,m^{-3}$) (Fig. 11a), compared to variations from 60 to 120 $g\,m^{-3}$ in the delta zone (Fig. 8). This simply highlights the balance between horizontal transport of SPM within surface waters and settling within the water column, as well as degradation processes (see details in Rontani et al., 2014). Monthly variations of SPM concentrations in the river plume are slightly smoother than in the river mouth and delta zone, probably due to the large surface covered by the plume. A very similar trend of increasing concentrations is observed along the 11 year period (+33 %). The turbidity of the water along the Mackenzie continental shelf is also rising and this certainly will have a direct impact on the marine ecosystems, since it will modify the nutrient balance (possible increase in primary production) but also will reduce the light availability within the water column (decrease in primary production) (see Forest et al., 2013 for detailed analyzes). Increasing volumes of turbid freshwater delivered into the Mackenzie continental shelf will also impact on the stratification of water masses (e.g., buoyancy of surface waters) and alter primary production.

The extent of the Mackenzie River plume mainly experienced strong month-to-month variations, being typically at a maximum in June then progressively decreasing until August and September. This clearly reflects the observations made on the SPM maps (Figs. 6–8): the river plume spreads out over the shelf during the break-up of the stamukha and regresses to the coast, mainly in the delta zone, during the summer period as the river discharge and thus freshwater transport decrease. There is no significant interannual trend observed concerning the plume extent as it is mainly dependent on the sea-ice coverage and the regional hydrodynamic (Ehn et al., 2014). While SPM concentrations increase within the surface waters of the plume, its extension in the Beaufort Sea remains unchanged due to the presence of the pack of floating sea ice. A direct impact of the decrease in sea-ice extent has been observed on primary productivity of Arctic waters (Arrigo et al., 2008; Tremblay et al., 2011). However, it is not understood yet whether this increase in terrestrial substances along the continental shelf contribute to the development of phytoplankton blooms under the Arctic sea ice (Arrigo et al., 2012).

BGD
12, 305–344, 2015

4 Discussion

An important result presented in the previous section concerns the significant increase of SPM flux at the mouth of the Mackenzie River observed over the last 11 years, with potential effect not only on the marine ecosystem but also on the northern community. Erosion of the shoreline has dramatic consequences for the local community and an increase in sediment transport and deposit along the Beaufort shelf could mitigate the impact of the erosion. However, numerical model of ocean circulation would be required to properly assess the fate of the extra sediment exported. Another important aspect of our findings concerns the mass of terrestrial SPM (and subsequent POC) exported from the Mackenzie River to the Beaufort Sea and to balance this budget with the sedimentation rates in the delta zone and continental shelf. Taking into account the degradation process of the organic material within the water column (Bélanger et al., 2006) and the fate of bottom sediments (Chaillou et al., 2007), it is necessary to quantify the percentage of terrestrial organic matter that will be buried into marine sediments and attempt to explain it by taking into account the highly refractory state of POC transported by rivers (Hedges et al., 1997; Keil et al., 1997).

At the mouth of the Mackenzie River, water masses are transported downstream to enter the delta zone to supply it with dissolved and particulate materials. As a first approximation, the SPM flux estimated in the present study corresponds to the mass of SPM delivered by the river to the delta during the four-month summer period (June to September). On average from 2003 to 2013, the total mass of SPM estimated during this period is about $20(\pm 5) \times 10^{12}\,\mathrm{g\,a^{-1}}$, which is in good agreement with previous estimates made using a selection of cloud-free satellite images recorded in 2009, 2010 and 2011 (Doxaran et al., 2012). Assuming a constant SPM organic content of 1.8 % (Yunker et al., 1993; Doxaran et al., 2012), this leads to a total of $0.4(\pm 0.1) \times 10^{12}\,\mathrm{g\,C\,a^{-1}}$ of terrestrial POC entering the delta zone through the Mackenzie River mouth. These values must be compared to previous estimates made based on field measurements (freshwater discharge and sediment loads) collected in the Mackenzie River hundreds of kilometers upstream the delta zone (Macdonald et al., 1998): $120(\pm5)\times10^{12}\,\mathrm{g\,a^{-1}}$ for SPM and $2.0(\pm0.5)\times10^{12}\,\mathrm{g\,C\,a^{-1}}$ for POC. There are a several reasons to explain such differences (factor 5 to 6) on SPM and POC estimated in our study and those reported in Macdonald et al. (1998). First, the satellite observations used in the present study cover only four months over the year, i.e. June to September, a period during which occurs about 50 % of the freshwater discharge (McClelland et al., 2012). Assuming a constant SPM concentration in the river along the year, extrapolating our results to the winter period would lead to total of $40(\pm5)\times10^{12}\,\mathrm{g\,a^{-1}}$ for SPM, i.e., still a factor 3 difference with the delivery estimated by Macdonald et al. (1998). As the organic SPM content is higher during the winter (being 5 % instead of 2 % during the summer period, Yunker et al., 1993), our summer estimates can be extrapolated to $1.3(\pm0.1)\times10^{12}\,\mathrm{g\,C}$ for the annual POC delivery into the delta which still represents a 50 % difference with Macdonald et al. (1998) estimates.

It is important to attempt to explain such differences. On one hand, estimates based on field measurements by Macdonald et al. (1998) relied on data collected at least 100 km upstream of the delta zone (i.e., at the Arctic Red River station). The complex network of secondary streams branching out of the river in the upper Mackenzie delta may act as an efficient trapping for SPM, which would imply that an annual delivery of 120×10^{12} g into the delta zone is overestimated. This would correspond to mean depth-averaged SPM concentration in the order of $500\,\mathrm{g\,m^{-3}}$ at the river mouth all along the year, which is typically more than twice the values actually observed in the field during the MALINA oceanographic campaign and also significantly higher than SPM concentrations remotely sensed using MODIS satellite data (Doxaran et al., 2012). On the other hand ocean colour satellite observations are very scarce at best and therefore not exploitable in April and May, two months usually associated to high river runoff and break-up of the stamukha, thus potentially associated to a maximum solid discharge into the delta. Moreover, the mean SPM concentrations obtained from satellite data slightly vary depending on the limits of the geographical zone in which the averaged is computed as fine particles in suspension in the river freshwaters rapidly form flocs or

BGD
12, 305–344, 2015

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

aggregates as soon the water salinity becomes positive (Eisma et al., 1991). Therefore suspended particles rapidly settle when they enter the delta zone, which leads to lower concentration within the superficial layer of the water column. Finally, satellite observations measure only the SPM concentration in the first meter (if not less) below the air–water interface due to the rapid attenuation of the radiative signal, such that the presence of a bottom nepheloid layer (BNL) cannot be detected. The BNL is usually present at the downstream limit of the delta (Doxaran et al., 2012) and along the inner continental shelf (Ehn et al., 2014) and could play an important role in the SPM export from the river to the delta. In such a case the SPM fluxes estimated using satellite data would provide an underestimation of the actual SPM loads delivered by the river to the delta. The true annual discharge of SPM by the Mackenzie River into the Beaufort Sea is probably in between 40 and 120×10^{12} g. Only high frequency measurements aboard in situ autonomous platforms installed at the mouth of the Mackenzie River and equipped with several turbidity sensors from the bottom (to sample the BNL) to the surface (to calibrate satellite data), together with detailed observations of current velocity profiles along and across the river mouth, could provide the information needed to conclude and accurately compute the SPM fluxes exported by the Mackenzie River.

5 Conclusions and perspectives

For the first time to our knowledge, ocean colour satellite data at moderate spatial resolution (1 km) have been routinely processed over the recent 11 years long period (2003–2013) to estimate and map the SPM concentrations at the mouth and along the plume of the Mackenzie River, in the Canadian Arctic Ocean. The regional algorithm developed by Doxaran et al. (2012) initially applied to selected cloud-free MODIS scenes in 2009, 2010 and 2011 was here optimized to minimize the effects of sea-ice, cloud and haze masks while also retrieving the seawater reflectance over the highly turbid waters of the Mackenzie delta zone. This improved algorithm was applied to MODIS-Aqua satellite data to extract a maximum of information on SPM dynamics in

BGD
12, 305–344, 2015

the study area. As a result SPM maps were produced each year from the beginning of June to the end of September, the remaining months were discarded due to a lack of observations, a result of the combined effect of low solar light and sea-ice covering most of the study area. It was interesting to note that probably due to effects of climate change on the receding of sea-ice extent at high latitudes, a significant increase in the number of images with valid pixels was recorded in May and October after 2010. Lastly, sea-ice cover and SPM concentrations were superimposed to discard ocean colour data possibly contaminated by the presence of sea-ice and to study the combined dynamics of sea ice and SPM over the study area.

The monthly-averaged SPM and sea-ice maps produced were used to analyze the "seasonal" to interanual dynamics of SPM at the river mouth, in the delta zone and in the river plume. The highest SPM concentrations and largest extension of the plume were systematically observed in June, following the break-up of the stamukha and usually corresponding to the annual peak of the river freshwater discharge. As the river flow progressively declined in August and September, SPM concentrations gradually decreased in offshore waters but remained high in and around the delta zone where SPM did accumulate. This probably results from other processes involved in the transport of SPM, such has erosion due to permafrost thawing or extreme rain events. In addition to strong interannual variations, a trend was observed in both the delta zone and river plume, respectively corresponding to 50 and 35 (±5) % increases in the SPM concentrations. Combined with the simultaneous augmentation of the Mackenzie River freshwater discharge over the same period (+22 %), the resulting SPM flux estimated at the river mouth significantly increased from 2003 to 2013 (+46 %) probably due to enhanced erosion processes along the drainage basin of the river. While in the same order of magnitude, the total masses of SPM (and terrestrial POC) exported by the Mackenzie River into the Beaufort Sea estimated using field measurements (Macdonald et al., 1998) and satellite data (our study) are significantly different, the latter being lower. The combined use of field and remote sensing techniques will be necessary in order to minimize the uncertainties associated with these estimations. These results are in agreement with the modeling study of Syvitski (2002), who predicted an increase of 20 % of sediment load for every increase in 10 % of Arctic river discharge. In our case, we found an increase of 46 % of SPM concentration in the Mackenzie River delta for an increase of 22 % in the freshwater river discharge.

The observed increase in the river discharge of SPM and turbidity (SPM concentrations), combined with changes in other key environmental factors in the coastal Arctic Ocean (Tremblay et al., 2011), will certainly have a rapid impact on the fate of the terrestrial organic carbon and on the marine ecosystems: ocean colour satellite observations have already suggested an increase in the annual primary production in the Arctic Ocean (Arrigo et al., 2008).

Author contributions. D. Doxaran actively contributed to in situ bio-optical measurements in the study area, designed the regional SPM algorithm used in this study; he also contributed to its routine application to ocean colour satellite data. E. Devred downloaded and processed the full time-series of ocean colour satellite observations and analyzed the trends observed in the variations of SPM concentrations and fluxes. M. Babin is at the origin of the whole study and was the P.I. of the MALINA project (and oceanographic campaign). D. Doxaran prepared the manuscript with contributions from all co-authors.

Acknowledgements. This study was funded by ANR, the French Agence Nationale de la Recherche (MALINA project, P.I. M. Babin). We acknowledge the NASA GSFC for providing free access to MODIS satellite data and SeaDAS software, Environment Canada, namely the Water Office www.wateroffice.ec.gc.ca, for providing the daily water discharge of the Mackenzie River main tributaries.

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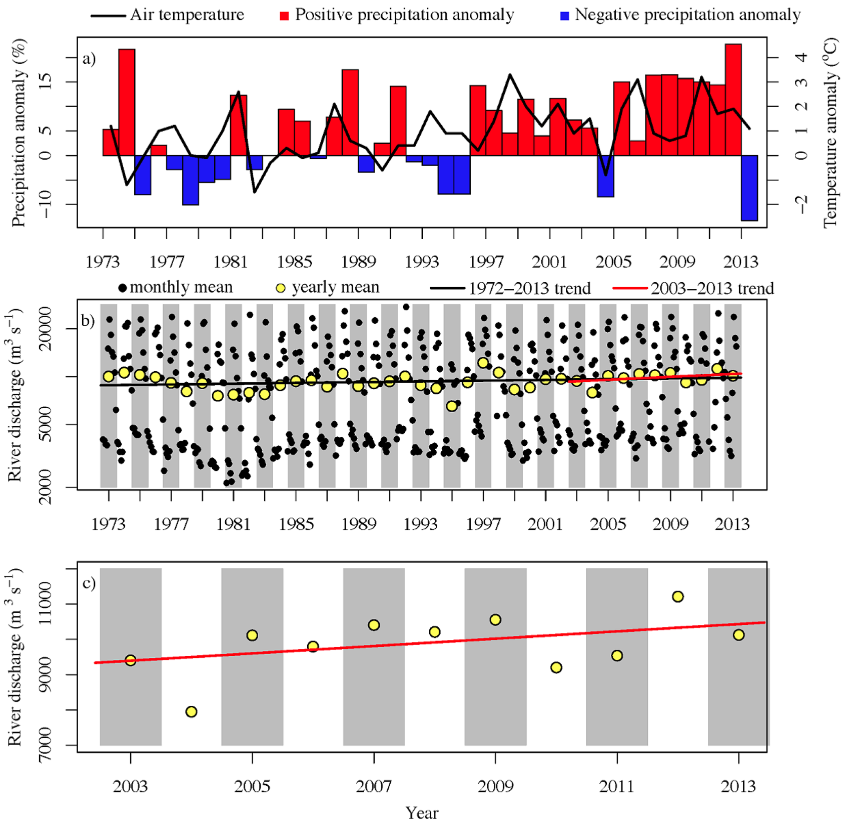

Figure 1. Variations of air temperature and precipitation anomalies observed in the Mackenzie drainage basin from 1973 to 2013 **(a)**. Variations of the Mackenzie freshwater discharge (monthly and yearly averages); trends observed between 1973 and 2013, and between 2003 and 2013 **(b)**. Zoom on the variations of the Mackenzie freshwater discharge between 2003 and 2013 **(c)**.

BGD
12, 305–344, 2015

A 50 % increase in the amount of terrestrial particles

D. Doxaran et al.

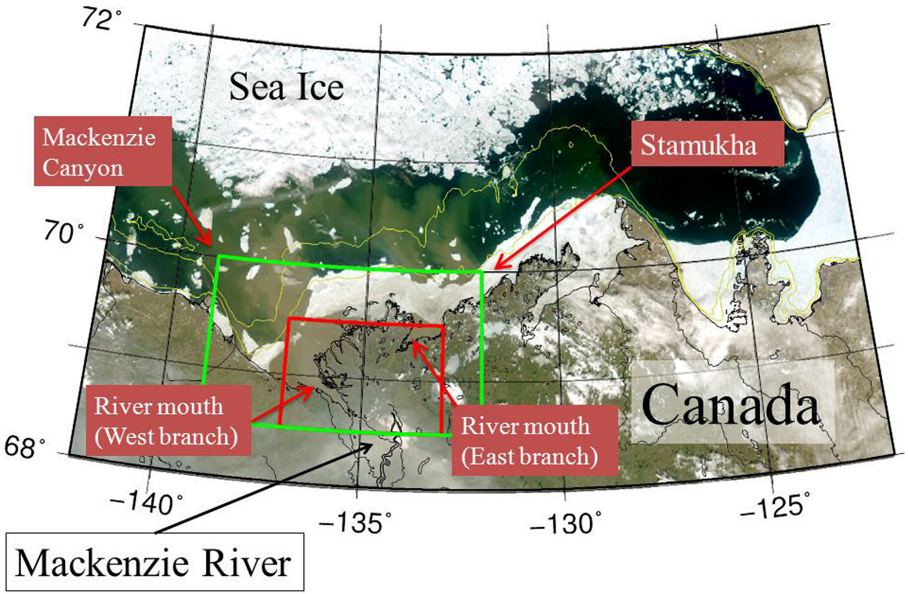

Figure 2. Quasi-true colour MODIS-Aqua image recorded on 24 June 2004 (250 m spatial resolution). The study area includes the: (i) Mackenzie River mouth West and East branches (red box) and delta zone (green box) and (ii) the Beaufort Sea in the Canadian Arctic Ocean. During winter time the connection between the river delta and adjacent coastal waters is closed by the stamukha while drifting sea-ice develops offshore.

BGD
12, 305–344, 2015

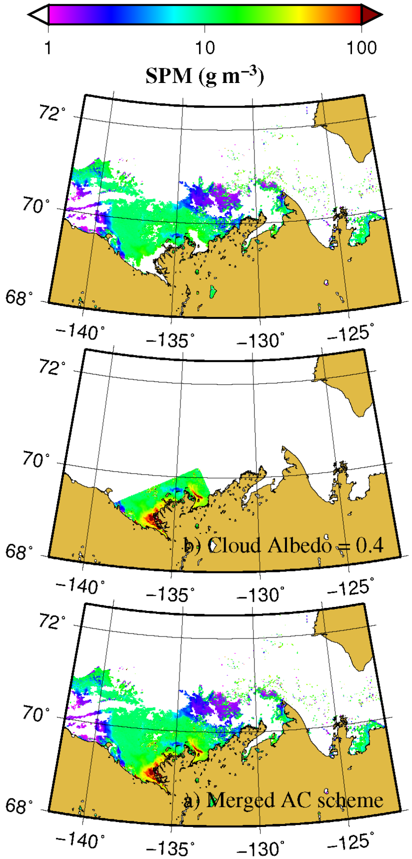

Figure 3. Example of processing (atmospheric corrections to retrieve the remote sensing reflectances at 555 and 748 nm then inversion of the 748 : 555 reflectance band ratio into SPM concentration) applied to L1B MODIS-Aqua data on 4 July 2007: **(a)** NIR-SWIR atmospheric correction with default mask thresholds; **(b)** NIR-SWIR atmospheric correction with cloud-albedo threshold set to 0.4 (instead of 0.027) in the river delta zone; **(c)** merged product.

BGD
12, 305–344, 2015

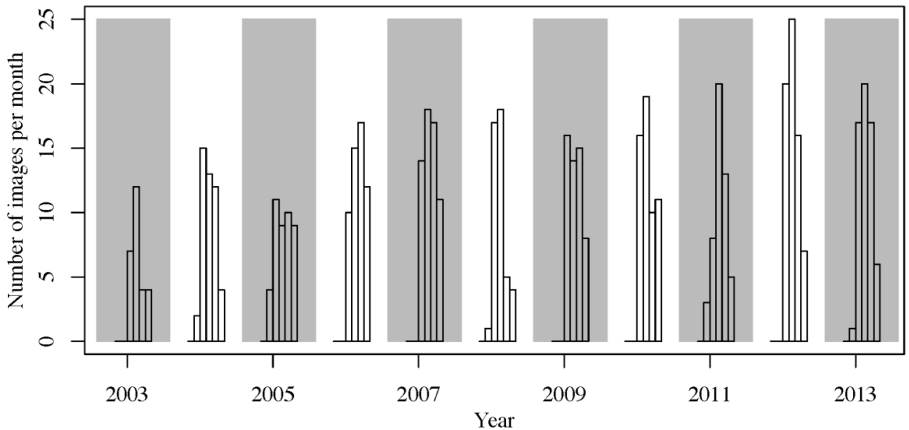

Figure 4. Number of L2 images available for each month of the time series (images selected after visual inspection).

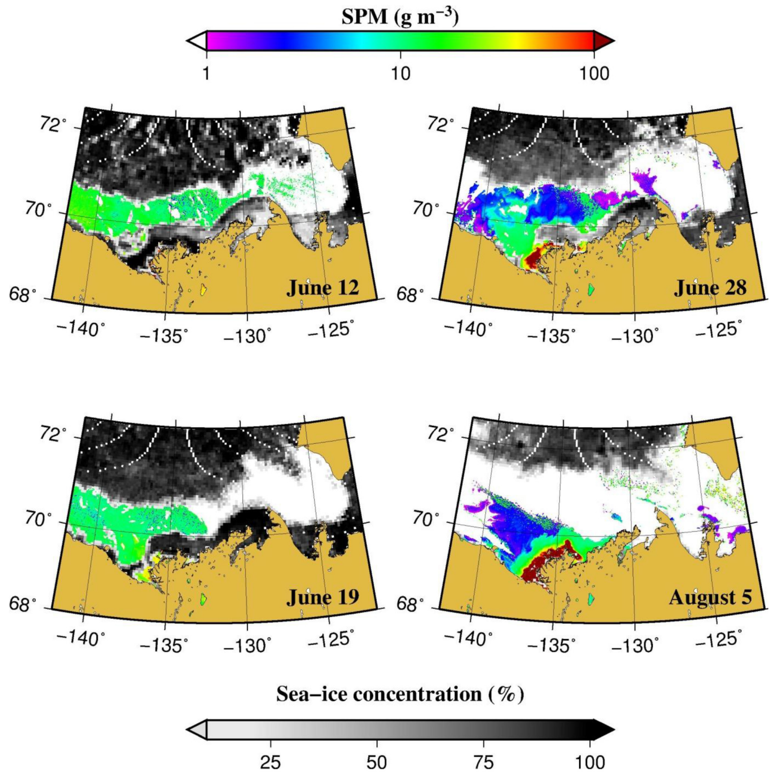

Figure 5. Typical SPM and sea-ice concentrations (in $g\,m^{-3}$ and %, respectively) maps obtained over the study area in selected days in June, July and August 2004. From June to July the breaking of the stamukha results in the discharge of turbid freshwater from the Mackenzie River into the Beaufort Sea. Even during the summer period the delta zone remains the most turbid area (maximal SPM concentrations).

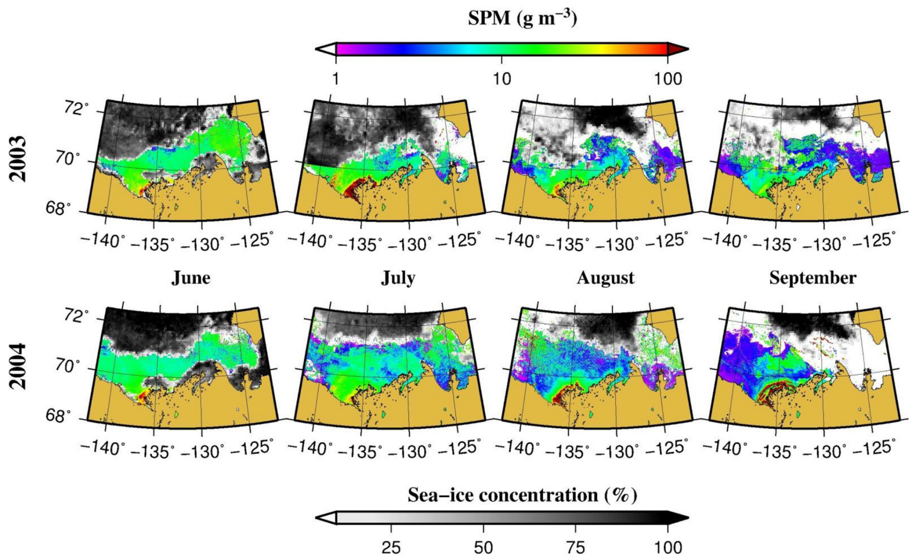

Figure 6. Monthly (June to September) composites of sea-ice and surface water SPM concentrations in 2003 and 2004.

BGD
12, 305–344, 2015

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D. Doxaran et al.

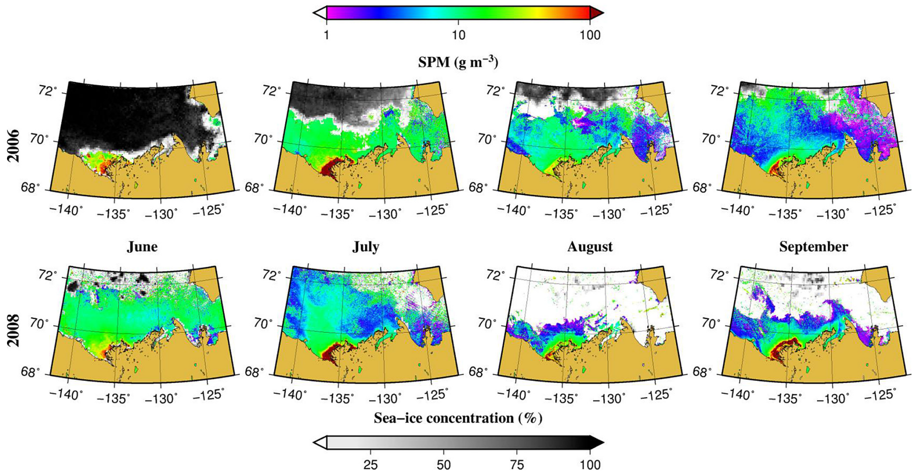

Figure 7. Same as Fig. 6 in 2006 and 2008.

BGD
12, 305–344, 2015
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D. Doxaran et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

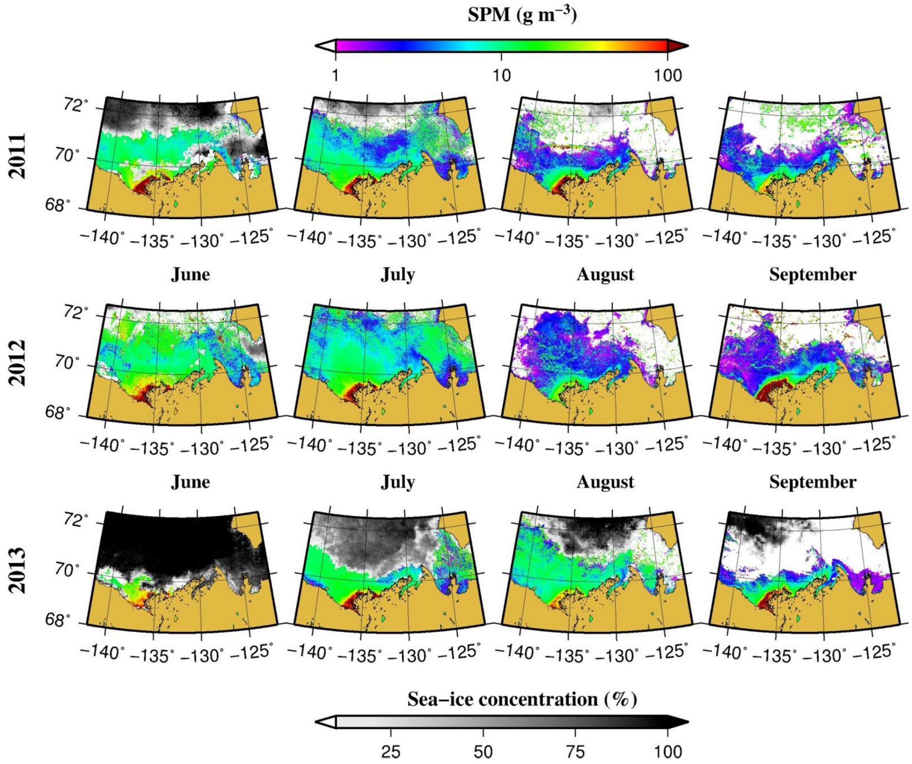

Figure 8. Same as Fig. 6 in 2011, 2012 and 2013.

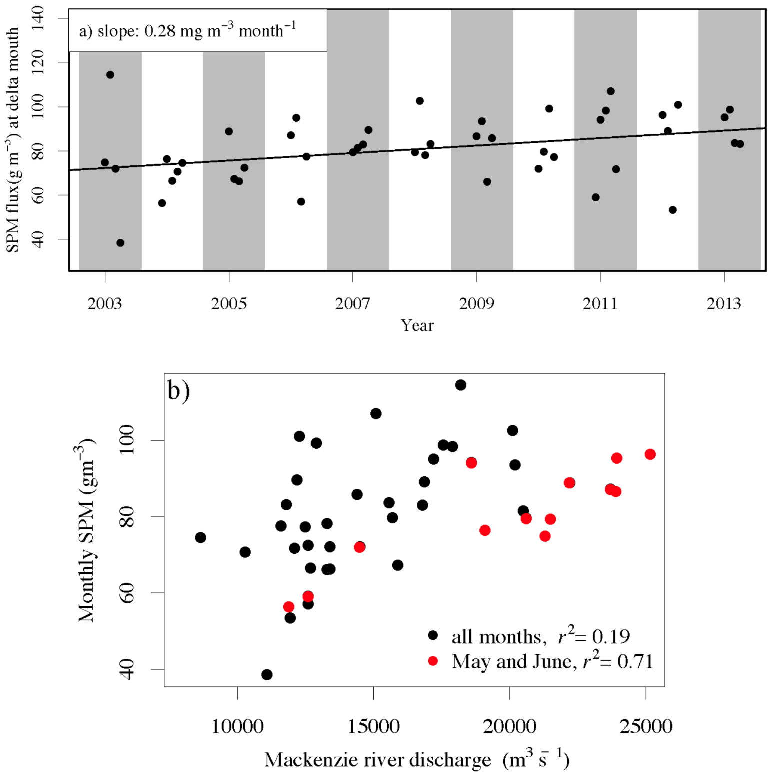

Figure 9. Multi-year (2003–2013) variations and trend of the monthly-averaged SPM concentration at the Mackenzie River mouth **(a)**. Plot of the monthly-averaged SPM concentration as a function of the monthly-averaged freshwater discharge: considering all months (white circles) then only considering the months of May and June (red circles) **(b)**. The determination coefficients (R^2) correspond to the best linear fits.

BGD
12, 305–344, 2015

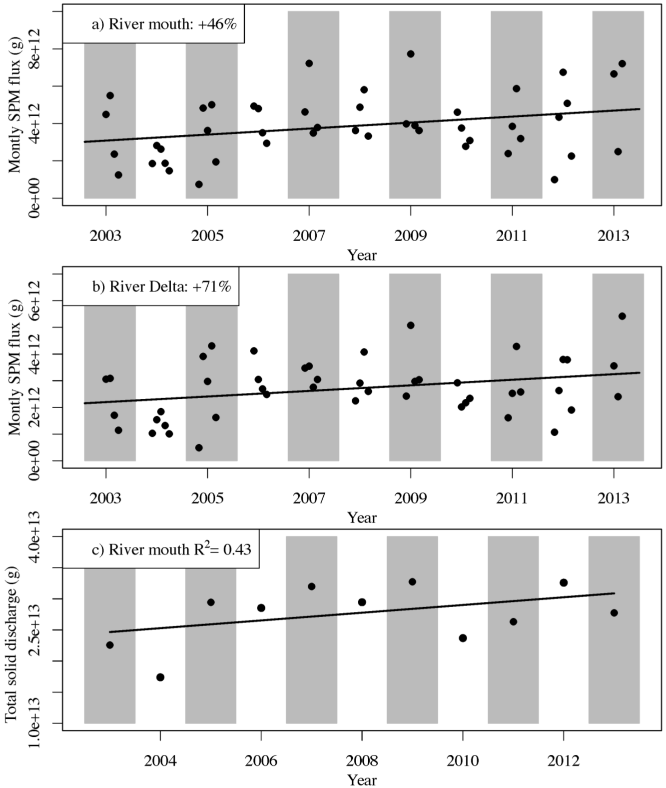

Figure 10. Monthly-averaged SPM flux (in g) estimated at the river mouth (geographical zone defined as a box: 68.7–69.5° N and 133–137° W) in June, July, August and September, from 2003 to 2013 **(a)**. Same in the delta zone (geographical zone defined as a box: 68.7–70° N and 132–139° W) **(b)**. Total SPM flux (in g) estimated during summer period (June to September) from 2003 to 2013 **(c)**. The best-fitted linear trend is overplotted.

BGD
12, 305–344, 2015

A 50 % increase in the amount of terrestrial particles

D. Doxaran et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

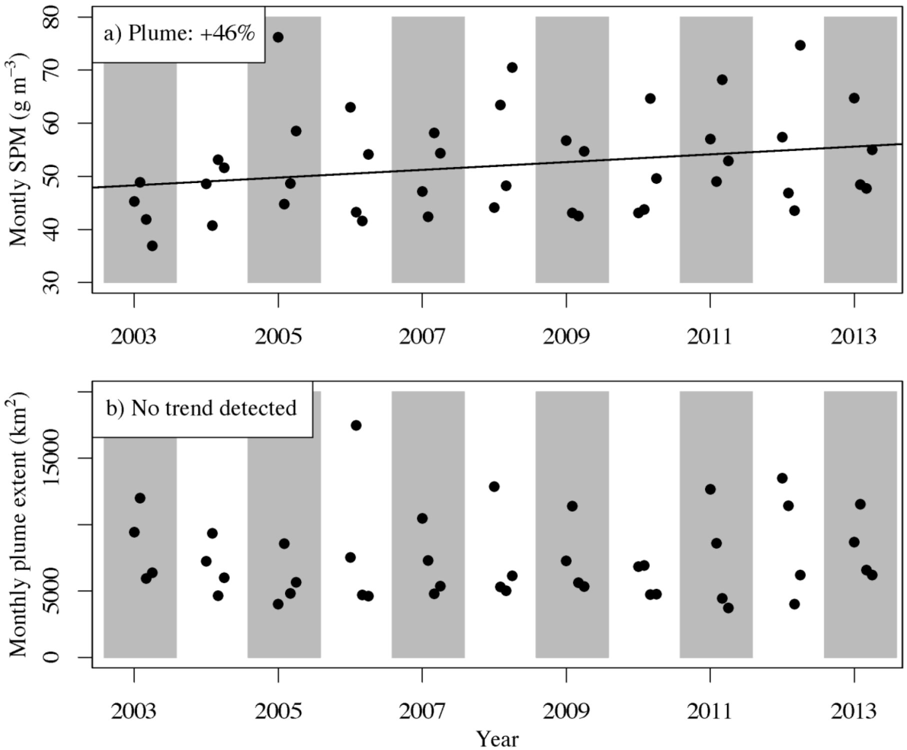

Figure 11. Multi-year (2003–2013) trends in the variation of the monthly-averaged SPM concentration over the Mackenzie River plume **(a)** and extent of the river plume **(b)**.

BGD
12, 305–344, 2015

A 50 % increase in the amount of terrestrial particles

D. Doxaran et al.