Interactive comment on "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" by D. Doxaran et al.

Anonymous Referee #2
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The Arctic region is changing rapidly due to global warming, triggering rapid social and economic changes and impacting both terrestrial and marine ecosystems. Using a combination of satellite ocean color observations and field measurements, this manuscript addresses changes in export of total suspended particulate matter from the Mackenzie River to the Beaufort Sea over the past decade. The authors report a more than 50% increase in the export of suspended particles, and they also discuss changes in cloud-cover and sea-ice conditions and extent over the studied 11-year period (2003-2013). This is a well written and well-organized paper. The analysis, results and discussion presented would be of interest to the terrestrial and ocean biogeochemistry communities, as well as the ocean color community particularly given the challenges in remote sensing of high latitude waters.

Major comments:

1. Given the need for high spatial resolution images in the area (highly dynamics and spatially inhomogeneous coastal waters and river delta), it would be good if the authors could provide some brief discussion in the paper on whether they explored using the MODIS high resolution bands (combination of 555 nm and 645 nm) for TSS retrievals particularly in the case of moderately turbid waters (no saturation).

Answer.
Thank you for this comment. We initially thought the spatial resolution of 1-km was appropriate considering the spatial dimensions of the study area (100 km from the West river mouth to the East river mouth, river plume extending up to 250 km offshore). This choice was also motivated by the size of the satellite data and products over the 11-year period (2003-2013). Using a spatial resolution of 1-km allowed us to map the SPM concentrations in the river mouth and river plume over the time period.
We agree with the reviewer that a great deal of additional information could have been obtained using the MODIS high resolution bands. The two bands associated with a spatial resolution of 250 m are in the red (645 nm) and near-infrared (859 nm) spectral regions (see Figure 1). They are potentially well adapted to estimate SPM concentrations in turbid coastal waters. As an illustration we show (Figure 1) the radiance recorded at the top-of-the-atmosphere over the Mackenzie River mouth (MODIS-Aqua image, 24 June 2004, 859 nm). It shows in detail the breaking stamukha zone, floating sea ice and turbidity features in the West and East river mouths as well as in the delta zone. It is obvious that using the 250m spatial resolution would provide a better understanding of the dynamic of suspended particles in the delta zone, notably during the breaking of the stamukha, and would allow

discriminating the dynamics of suspended particles in the West and east river mouths in order to quantify the contribution of each river branch in the discharge of SPM into the Beaufort Sea. Now we consider such a specific focus to be out of the scope of the present study. It would require a dedicated study as it is now clearly mentioned in section 5 'Conclusions and perspectives'.
We also have used the NIR/SWIR correction adapted for highly turbid water and these bands are only available at the 1km resolution.

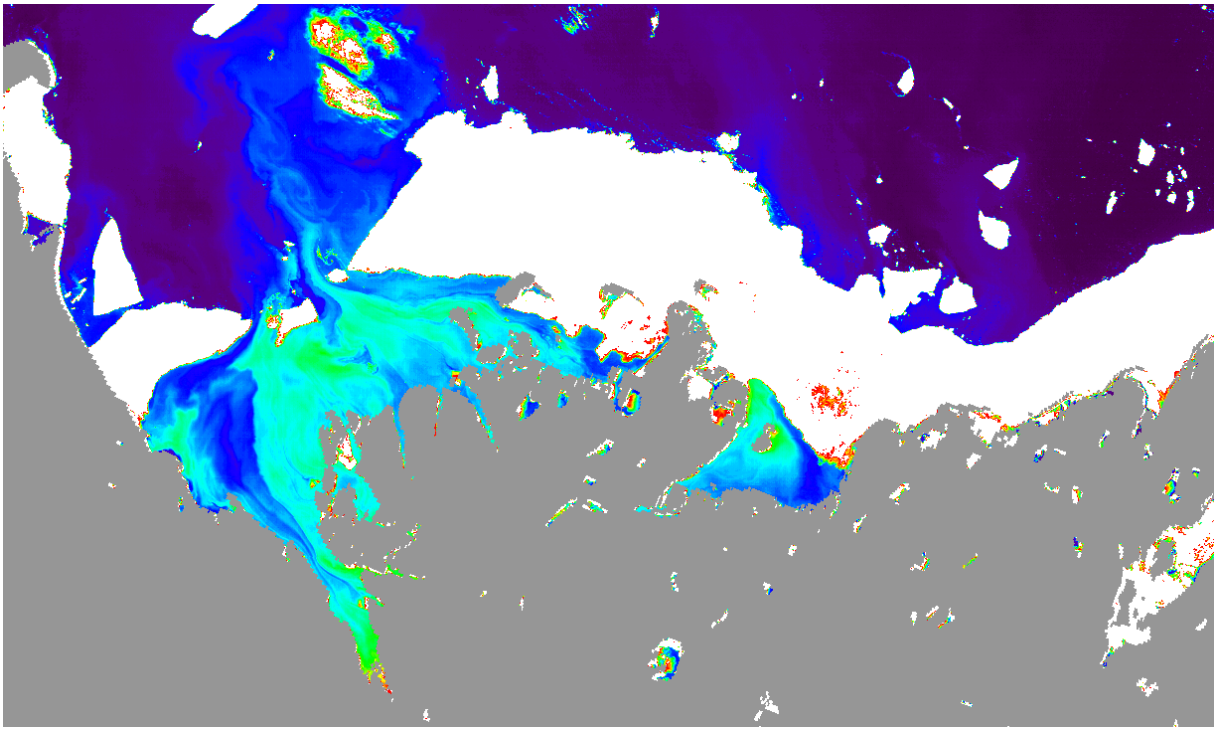

Figure 1. Radiance recorded at the top of the atmosphere (MODIS-Aqua, band 2: 859 nm, 24 June 2004) at a spatial resolution of 250 m: zoom on the Mackenzie River mouth (delta zone and stamukha).

2. Regarding the SPM retrieval, the authors mention that "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)." Changes due to warming temperatures are expected to influence not only the amount but also the quality and composition (source) of particulate matter in the Arctic, which in turn affects the bio-optical retrievals and relationships between Rrs, absorption, backscattering and SPM concentrations. In addition to long term changes, there are seasonal changes and year-to-year variability in quality and composition. It would be good if the authors could discuss implications for estimates of SPM fluxes in their manuscript.

Answer.
We agree with this comment: our field dataset is quite limited (2009 summer period) in order to build a regional algorithm applied to 11 years of ocean colour satellite data (2003-2013). Over this period, significant changes in the composition (thus refractive index) and size

distribution of particles in suspension in the Mackenzie River mouth and turbid plume have probably affected their optical properties (i.e., their mass-specific light absorption and backscattering coefficients). There is no evidence for such significant changes (due to the lack of field bio-optical measurements in this remote area). Moreover we developed a semi-empirical relationship between the SPM concentration and a spectral band ratio of seawater reflectance. The near-infrared (748 nm) to green (555) spectral band ratio is very similar to the band ratio algorithm developed by Doxaran et al. (2002, 2006 and 2009) for the Gironde estuary. These authors have demonstrated that the relationship between this spectral band ratio and SPM concentration remains robust over a wide range of conditions as it is only weakly affected by changes in the SPM mass-specific optical properties. In estuaries, the size distribution and composition of suspended particles within surface waters strongly vary along daily to fortnightly daily cycles as well as over seasonal cycles (river discharges). Despites these strong variations, single relationships have been established between near-infrared to red (or green) spectral band ratios of seawater reflectance and SPM concentrations. For that reason, as explained in the text, we believe that the regional semi-empirical relationship established from field measurements carried out during the summer 2009 period at the mouth of the Mackenzie River is valid for the entire period of satellite observations (2003–2013). At the same time we are looking for any existing bio-optical or biogeochemical measurements in this area that could support our statement or be used to account for any changes in the composition and size distribution of SPM that would have occurred over time in the Mackenzie River mouth and turbid plume.

Reference:

Doxaran, D., Cherukuru, R.C.N. and Lavender, S.J., 2006. Inherent and apparent optical properties of turbid estuarine waters: measurements, modelling and application to remote sensing. Applied Optics, 45, 2310-2324.

Detailed comments:

3. The authors mention that the SPM algorithm "was established based on field measurements collected during the 2009 summer period". The field measurements were measurements of total suspended solids on water samples collected from surface waters or integrated to a certain depth? It is not clear. The details are probably discussed in Doxaran et al (2012), but it would be good to include a brief sentence in this manuscript as well.

Answer.

We added a brief sentence to remind our field measurement protocols:

“in-water and above-water radiometric measurements were used to compute the R_{RS} signal; water samples were collected at 0.2 m depth using either a Niskin or a glass bottle for the determination of the SPM concentration (see Doxaran et al. 2012 for details)).”

So the concentration of total suspended solids was measured on water samples collected from surface waters which are viewed and sensed by ocean colour satellite data.

4. Where was the freshwater discharge measured?

Answer.

We use data from the main gauging station of the Mackenzie River in its downstream part. The station is Arctic Red River (67°27'21"N, 133°45'11" W), located approximately 75 km upstream the river mouth defined in our study. The first reason for selecting it is that it has been used historically by scientists to estimate the Mackenzie River water and sediment discharges into the Beaufort Sea (Syvitski 2002, O'Brien et al. 2006) reason for selecting this station is that is the last one (i.e., most downstream one) before the main channel divides into multiple branches.

5. Figure 9a: change "SPM flux" to "SPM concentration".

Answer.
Done, thank you.

6. It is not clear where the assumption of "a constant SPM organic content of 1.8%" is based on; it would be good to provide some additional information here and what variability would be expected over the June-September period and along the transects studied in the manuscript.

Answer.
This assumption is based on our field measurements during the 2009 summer period (MALINA oceanographic campaign) and measurements that have been reported in the literature (Yunker et al. 1993, Emmerton et al. 2008). Based on these datasets, the POC:SPM ratio along the transects studied in the manuscript (what we define as the river mouth) varies from 1.1% to 3.4%, with a mean value of 1.8%.
This was unclear in the text and there was a mistake, so the sentence was modified into:
"Assuming a constant POC:SPM organic content of 1.8% (mean value reported by Yunker et al. 1993, Emmerton et al. 2008 and Doxaran et al. 2012, while values as low as 1.1% and as high as 3.4% have been observed in the river mouth area during the June-September period), this leads to…"

Reference (added in the manuscript):
Emmerton, C. A., Lesack, L. F.W., and Vincent,W. F.: Nutrient and organic matter patterns across the Mackenzie River, estuary and shelf during the seasonal recession of sea-ice, J. Mar. Syst., 74, 741–755, 2008.

7. Page 327, line 3; "within the superficial layer of the water column", replace by "within the upper layer of the water column measured by the ocean color sensor"

Answer.
Done.