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.

D.;G. Bowers oss063@bangor.ac.uk
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Review by D.G. Bowers

The flux of solid material from the land to the ocean is one of the key geophysical processes on our planet. One of the most rapidly changing areas at the moment is the Arctic and this paper presents a clear account of how the fluxes of particulate material from a major estuary to the arctic can be estimated using satellite and ground observations. The results are surprising: The mass flux of suspended sediment from the chosen river has increased by 50% over the last 50 years.

The paper is well-written, the science is carried out rigorously and it is presented in a transparent way. The results are important and the paper should be published. I have just two points to raise with the authors about their methods and there are some small points about presentation.

Methods:

1. The flux is calculated by multiplying river discharge by suspended sediment concentration. The river discharge is measured at a gauging station and the concentration at the river mouth. Is the gauging station far from the river mouth? If so, the river discharge will probably increase (perhaps by quite a lot) between the station and the mouth as tributaries join the river. This won't affect the pattern of the results, probably, but may change the absolute value of the flux.

Answer. Thank you for this excellent comment. We are actually considering 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. Then a network of several gauging stations sample the most important branches of the river in the delta zone but definitely not all the tributaries (see wateroffice.ec.gc.ca for detailed information). Consequently we agree: the freshwater actually discharged into the Beaufort Sea is probably higher (5% or 20% higher? Difficult to know accurately without a dedicated study) than the volume actually measured at the Arctic Red River station. This certainly explains a significant part of the difference between the SPM fluxes estimated in previous studies (Macdonald et al 1998) and in the present study. This comment has been added in the Discussion section. A dedicated study focused on the sections and water levels in the delta zone would be necessary to accurately estimate the contribution, in terms of freshwater discharge, of the small

tributaries of the main river branches in the delta zone. This is out of the scape of our study as as stated by the reviewer, this does not affect the pattern of the results, i.e. the significant trend of increasing SPM concentration thus SPM flux at the river mouth.

2. Any satellite measurement of suspended solid concentration will be in a surface layer which the satellite can 'see'. In a turbid estuary, this layer may be less than a metre thick. Suspended sediment concentrations tend to increase towards the bed, so the surface concentration measured from space is likely to be an under-estimate of the depth-mean concentration which is needed for the flux calculation. This limitation, like that in point 1 above, will lead to an under-estimate of flux. The extent of the under-estimate is tantalising: it will depend on the vertical profile of sediment concentration and on the depth to which the satellite sees. These two quantities will be related and it would be interesting to explore what reflectance measurements tell us about depth-mean sediment concentrations. An interesting problem for a future paper. I should think these two points could be dealt with by appropriate remarks added at the right place in the text.

Answer. Thank you for this interesting comment. As already discussed in the text, we know that ocean-colour satellite observations in turbid coastal waters are indeed limited to the surface layer (typically the one-meter thick layer below the air-water interface, and possibly as low as the 50 to 10 cm thick layer in the case of highly turbid waters). This is even more true when using near-infrared spectral bands (here we are using the MODIS 748-nm band) where light absorption by pure water is higher than in the visible spectral region. The SPM concentration is expected to increase with water depth, being higher close to the bottom in estuaries where both advection but also resuspension of bottom sediments contribute to maintain particles in suspension. In such a case satellite observations will typically lead to an underestimation of the mean SPM concentration along the water column.

In the text we argue that the Mackenzie River mouth is very shallow (1- to 5-m depths) and the high river flow during the summer period is able to maintain particles in suspension in a well-mixed water column. These assumptions are supported by the field measurements carried out in 2004 during the CASES experiment (S. Bélanger, pers. comm.). Frames equipped with temperature, density and bio-optical sensors were profiled from surface to bottom and the vertical profiles of particulate attenuation and backscattering, two proxies of the SPM concentrations, were observed to be almost constant as a function of water depth. Currents were strong enough to maintain a well-mixed water column and sustain particles in suspension homogeneously as a function of water depth. These measurements were carried out in June-July, periods of high river discharge. During a period of lower river discharge thus weaker currents at the river mouth (September), variations of SPM concentration along the water column can be expected with a more turbid layer close to the bottom. However field measurements are currently not available to confirm it. We agree: an interesting study for a future paper will be to document (if possible model) the vertical profile of SPM at the river mouth as a function of current velocities and/or river discharge.

The text was modified accordingly to highlight this issue:

“”

Some smaller points:

a) The title is good, but the word ‘amount’ is ambiguous. Amount of particles could mean number, volume or some other quantity. The authors mean mass, so I suggest replacing ‘amount’ with ‘mass’ here, and elsewhere in the text (including the abstract) where the 50% increase in export is mentioned.

Answer. We agree with this comment, we mean ‘mass’. The word ‘amount’ was therefore replaced by ‘mass’ in the title, abstract and along the text when appropriate.

b) The word ‘precipitations’ is sometimes used. I think the correct English is always to use the singular ‘precipitation’.

Answer. This is correct. We replaced ‘precipitations’ by ‘precipitation’ in the text.

c) Top of page 308, I don’t understand the need for ‘for SPM’ after Doxaran et al., 2009.

Answer. We agree and the useless ‘for SPM’ was removed.

d) On page 320, substitute ‘remember’ for ‘remind’: : :’It is also important to remember: : :’

Answer. We agree and the word ‘remind’ was replaced by ‘remember’.

e) In figure 10, the units on the y-axis need attention, I think. A flux is usually expressed in units of mass/time. In figures 10a) and 10b) we are shown the mass in one month, which is OK, but in figure 10c) I’m not sure what the time scale is. Is it still mass per month?

Answer. No the time scale in Figure 10c) is not mass per month, it is mass. It is actually the estimated mass (and not flux we agree) of SPM delivered by the Mackenzie River into the Beaufort Sea over the June to September period, i.e. over four months. The legend of Figure 10c) has been changed accordingly:

“Total estimated mass (in g) of SPM delivered by the Mackenzie River into the Beaufort Sea during the summer period (June to September) from 2003 to 2013 (c).”

f) What does figure 9a show exactly? The caption says SPM concentration, but the axis label says SPM flux (but gives units of concentration).

Answer. Sorry there was a mistake in the legend of Figure 9a) (y-axis label). It is SPM concentration and the axis label was changed into: ‘SPM concentration (unit of concentration) at river mouth.’

g) Figure 5 caption mentions June to July, but the figures cover the period June to August.

Answer. No we think Figure 5 caption is correct as it says: ‘maps obtained over the study area in selected days in June, July and August 2004.’.

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.

Now we agree a great deal of additional information could be obtained using the MODIS high resolution bands. The two bands are associated to a spatial resolution of 250 m are in the red (645 nm) and near-infrared (859 nm) spectral regions 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 such a spatial resolution would provide a better understanding of the dynamics 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’.

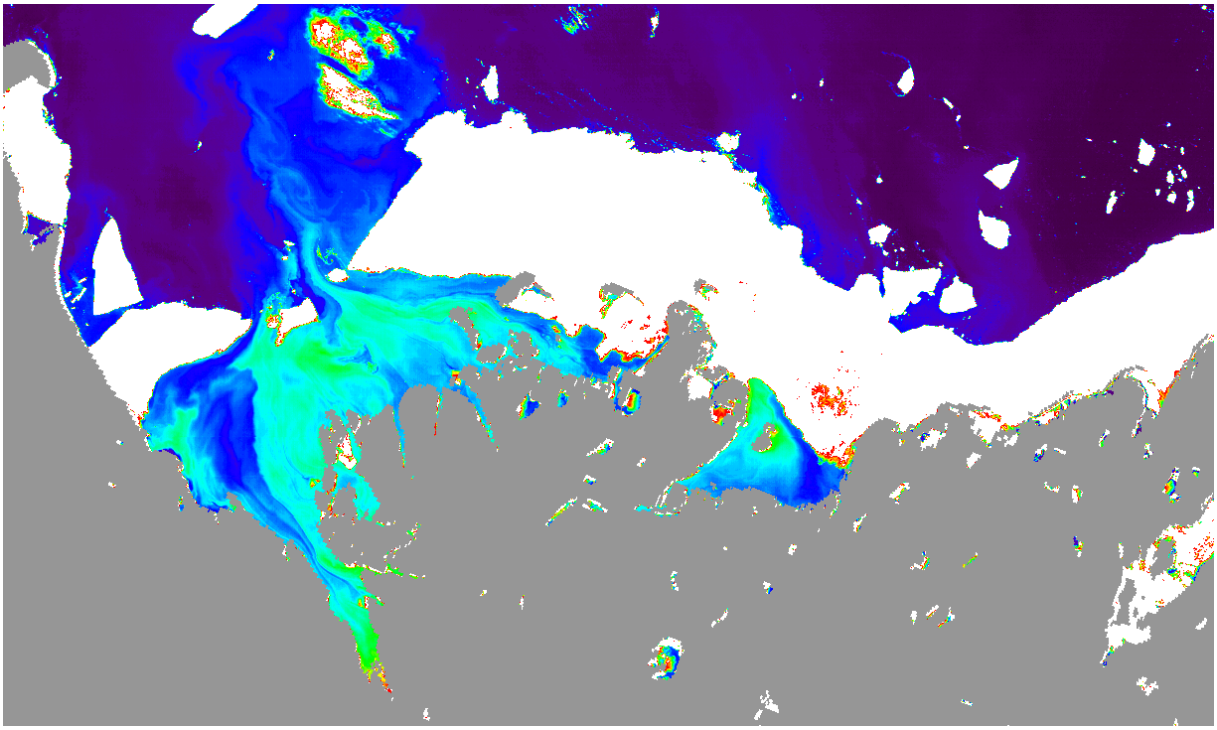

Figure 1. Radiance recorded at the top of the atmosphere (MODIS-Aqua, band 2: 859 nm, 24 June 2004) at a spatial resolution of 250 m: zoom on the Mackenzie River mouth (delta zone and stamukha).

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 would have affected their optical properties (i.e., their mass-specific light absorption and backscattering coefficients). Now 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. This near-infrared (748 nm) to green (555) spectral band ratio is quite similar to the one developed by Doxaran et al. (2002, 2006 and 2009) for the Gironde estuary. These

authors have demonstrated that such a spectral band ratio allows establishing a robust relationship with the SPM concentration 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 fornightly daily cycles as well as over seasonal cycles (river discharges). Despites these strong variations, single relationships have beed established between a near-infrared to red (or green) spectral band ration of seawater reflectance and the SPM concentration. For that reason, as explained in the text, we believe 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 be used to identify any changes over time in the composition and size distribution of SPM 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 ùmeasured on water samples collected from surface waters which are viewed and sensed by ocean colour satellite data.

4. Where was the freshwater discharge measured?

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.