

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.

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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 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 scope of our study 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 truer when near-infrared spectral bands are used (here we are using the MODIS 748-nm band) since light absorption by pure sea-water is much higher than in the visible spectral region. The SPM concentration is expected to increase with depth, being higher close to the bottom in estuaries where both advection and 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 profiled the water column from surface to bottom. Vertical profiles of particulate attenuation and backscattering coefficients, two proxies of SPM concentrations, were observed to be almost constant with depth. Currents were strong enough to maintain a well-mixed water column and sustain particles in suspension homogeneously as a function of depth. These measurements were carried out in June-July, periods of high river discharge. During periods of low river discharge and weak currents at the river mouth (September), increase of SPM concentration at the bottom of the water column can be expected. However field measurements are currently not available to confirm if this is the case or not. We agree that an interesting study for a future paper will be to document (and if possible model) the vertical profile of SPM at the river mouth as a function of current velocities and/or river discharge.

The text (section 4. SDiscussion') was modified accordingly:

“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. The satellite-derived SPM concentrations are therefore well representative of the depth-averaged SPM concentration, as field measurements during the CASES 2004 (S. Bélanger, pers. comm.) and MALINA 2009 experiments showed inherent optical properties constant with depth at the very shallow river mouth. However the presence of a bottom nepheloid layer (BNL) cannot be detected by satellite data. The BNL is...”

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.'