Reply to comments, Referee 2

'Ocean Colour remote sensing in the Southern Laptev Sea: Evaluation and Applications' by Heim et al.

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REFEREE 2: The authors present results from comparing ship measurements from the two expeditions in August and September 2010 to the southern Laptev Sea with MERIS satellite derived chlorophyll, suspended material and CDOM estimates. In common with other studies in the Arctic, they find that satellite estimates of chlorophyll are high by about a factor 10. Estimates of TSM seem more reasonable. CDOM does not seem to be evaluated. The authors also discuss hydrodynamical patterns, seen in satellite images, but seem to come to few clear conclusions. The paper needs major revision. The English is poor, making it hard to understand the paper. The paper badly needs editing for language and grammar. The paper needs to be made much clearer. The conclusions on quantitative estimates of water constituents and on hydrodynamical patterns could be separated. In several places, the paper summarizes results from other studies, tending to make this partly a review paper. The authors should focus on their results, commenting only on agreements or disagreements with others.

We thank Referee 2 for providing helpful comments to improve and clarify the text: the text was generally revised and restructured. The chapters 'methods', 'results' and 'discussions' were structured into more subchapters to improve the readability of the text. The conclusions on quantitative estimates of water constituents and on hydrodynamical patterns were like this separated. The flow in the text was improved by further editing.

Commenting agreements or disagreements with others was done in the new subsection in 'discussions' 5.1. Value and validity of Ocean Colour applications for the Siberian shelf (see below and also new references). The other new subchapters in discussions '5.2 Widespread lateral surface advection in the sea ice-free season', '5.3 Resuspension zones above shallows'.

See also main points made by Referee 1 and main editorial changes made by the authors:

the C2R evaluation discussion chapter has been moved and merged within 'results'. Also, the methods of the C2R evaluation, such as how the in-situ data have been handled [e.g. which depths, depth of the upper mixing layer, time delay between match-ups etc.] have been moved out of the chapter 'results' to a new subchapter C2R evaluation in 'methods' because several comments of referees 1 and 2 had asked for this information that had been in the manuscript text already in 'results' but obviously was not well readable and detectable. In detail:

i) moved to 'methods', new subchapter: 3.3. Match-up analyses with MERIS C2R parameters

The MERIS acquisitions on Jul 31, Aug 3-6, and Aug 10, 2010 show low cloud coverage and are close in time to the L10 ship expedition in Buor Khaya Bay that took place from Jul 29 to Aug 7, 2010. A MERIS acquisition on Sep 7, 2010 is the cloud-free acquisition closest in time to the TRANSDRIFT-XVII expedition that took part from Sep 9-20, 2010. The next usable MERIS acquisitions on Sep 18 and 20, 2010, have higher cloud coverage.

The in-situ data taken for the evaluation of the MERIS C2R parameters are averaged over the first 2 m water layer for transmissivity, cDOM, SPM and Chl-a. CTD data from L10 and the TRANSDRIFT-XVII expedition show a homogenous, mixed layer in any case within this depth. Stratification due to the riverine freshwater occurred in the Buor Khaya Bay with a sharp halocline below 5 to 8 meter in August 2010 during L10 (Kraberg et al., this volume), and below 10 m in September 2010 during TRANSDRIFT-XVII (Kassens et al. 2010).

Exact match-up analyses take the remote sensing value from the pixel location on the same day of the ship-based in-situ measurement. For the Laptev Sea region this is not feasible due to frequent cloud coverage. Match-up analyses using spatial averages of pixels could be a technical solution. However, for the Laptev Sea, the high-spatial and high-temporal horizontal heterogeneity confounds the spatially averaged match-up analyses.

Figures 2 a-c show the high spatial- and temporal variability of MERIS C2R_Z90 on Aug 3, 4, 5, 2010. For example, the L10 sampling stations 1 to 3 and 25 are of the turbid water-type with values of C2R_Z90 ~1 m on Aug 3, 2010, changing to more transparency with values of C2R_Z90 ~2 m only within 1 to 2 days due to frontal changes. The best matching coordinate pairs in time from L10 (table 2) and the TRANSDRIFT-XVII expedition (table 3) were selected for the match-up analyses.

ii) text was moved from 'discussion' to 'results', into subchapter 4.2. Evaluation of MERIS C2R parameters. The new subchapter 4.2 with the merged text sections:

The analyses of matching pairs of cloud-free pixels and L10 data covered a range of values of the optical parameters connected to turbidity within the Buor Khaya Bay, but no types of highly transparent waters such as the water types of the outer shelf system. The matching of pairs of cloud-free pixels and TRANSDRIFT-XVII expedition data cover a larger variety of optical surface water types including transparent water types of the outer shelf. The match-up analyses using SPM data show a close relationship between the optical C2R parameters connected to suspended matter (e.g., $C2R\_k_{min}$, C2R_b_tsm (scattering of TSM), C2R_Z90, C2R_TSM) although there is a temporal difference of 2 to 11 days between the in-situ sampling and the MERIS acquisition on Sep 7, 2010. Fig. 5 shows the relationship TRANSDRIFT-XVII SPM versus C2R_TSM (Sep 7, 2010).

The match-up analyses for cDOM and SPM versus C2R_kmin and C2R_Z90 show for near-coast on-shore waters that the major direct relationship exists between transmissivity and SPM. This optimal relationship (e.g., Fig. 4a, C2R_Z90 versus SPM) indicates that the turbidity/particulate matter is the dominating Ocean Colour producing aquatic component in the water-leaving spectral reflectances. The relationship C2R_Z90 versus cDOM (e.g., Fig. 4b) shows that cDOM influences the transparency parameters (C2R_kmin, C2R_Z90), but is not as dominating as SPM (Fig. 4a).

C2R_Chl-a values show a minimum of ten-fold overestimation that is the order of one magnitude. In general, calculated C2R_Chl-a concentrations in Buor Khaya Bay during the ice-free season show up to 20 to 30 $\mu g\ l^{-1}$ C2R_Chl-a for all the years 2006 to 2011. A minimum of ten-fold Chl-a overestimation that represents the order of one magnitude is also characteristic to the global standard NASA SeaWiFS and MODIS Chl-a products. As an example, we also included the match-ups of the MODIS Level3 binned Chl-a averaged product for September 2010 (9 km spatial pixel resolution) versus the TRANSDRIFT-XVII Chl-a data (Fig. 6). Fig. 7 indicates how the magnitude of cDOM concentration correspondingly influences the calculated values of MERIS C2R_Chl-a.

cDOM is underestimated as C2R_a_gelbstoff. (new figure) but we know from L8, L10 and TRANSDRIFT-XVII expedition data that high cDOM concentrations are widespread in coastal waters and on the inner shelf (table 1). The strong absorption in the visible wavelength range that occurs due to the high cDOM concentrations is operationally attributed towards high Chl-a concentration. The over-estimation of Chl-a occurs with all standard NASA and ESA processing algorithms because the standard assumption in all operational Ocean Colour algorithms contributes the main share of absorption towards the phytoplankton absorption.

iii) Referee 1 suggested adding more discussion about the Chl-a overestimation in Arctic coastal waters, therefore we merged the final general discussion statements on the evaluation and the discussion on Chl-a evaluation to a new subchapter in 'discussions': 5.1. Value and validity of Ocean Colour applications for the Siberian shelf

Ocean Colour remote sensing provides new hydrodynamic information for the shallow Siberian inner shelf waters and coastal waters. The synoptic information on re-suspension events, meandering and filamenting cannot be made visible from sampling from shipborne platforms because high-sea Arctic ship expeditions are forced to stay in deeper waters due to their draft. Even with grid sampling from shallow-water going ships it would be difficult to capture these spatial features as sampling cannot logistically be done on a small enough spatial scale. Deployment of drifting sensors could provide measurements on fronts, meanders, eddies, and filaments, but it would need several weeks for them to map the area of the Southern Laptev Sea. The highly dynamically changing spatial patterns could also not be mapped as temporal snapshots such as it is the case for successful cloud-free satellite acquisitions.

The first evaluation experiments show that the optical C2R parameters such as C2R_Z90 and concentration parameters such as C2R_TSM can be used reliably to trace the surface hydrodynamics of the Laptev Sea region. However, care must be taken when using operational Chl-a products for the Siberian inner shelf regions, the Laptev Sea and the Siberian Sea. Bio-optical measurements from Örek et al., (submitted, this volume) in the organic-rich Lena River waters in 2011 show that the specific phytoplankton absorption coefficient is around 3 times higher and more effective than the global mean. The authors discuss the difficulty of the calculation of phytoplankton from the water-leaving reflectances because phytoplankton absorption contributed < 10 % to the overall absorption. We incorporated the enhanced phytoplankton absorption capacity in the C2R processing (equation 1), however the elevated cDOM background concentrations of the innershelf still lead to a ten-fold Chl-a overestimation, We assume that due to elevated cDOM background concentrations and a very effective phytoplankton absorption due to dark waters all global ESA and NASA Chl-a products show Chl-a concentrations that are overestimated by at least a factor of 10. This regional overestimation is the hightest reported to date for Arctic coastal waters, but also the cDOM background concentrations are the highest reported for Arctic coastal waters.

Vetrov et al. (2008) reported an overestimation factor of around 5 for the Laptev Sea, however described large difficulties of match-ups in the inner-shelf due to cloudiness. It remains unclear how many and which samples were used to estimate the factor. Matsuoka et al. (2007, 2012) report that Ocean Colour Chl-a retrievals for the western Beaufort and Chukchi seas were within 25% and 30% accuracy, Wang and Cota (2003) report an overestimation factor of 1.5 for this region. For the southeastern Beaufort Sea cDOM background concentrations are higher on the inner shelf, Mustapha et al. (212) evaluated operational Chl-a products of various Ocean Colour sensors with the large in-situ data set of the Canadian Arctic Shelf Exchange Study (CASES) reporting an overestimation by a factor of three to five, the highest overestimation based on match-up analyses they found for coastal waters under a freshwater influence. Hessen et al. (2010) describe Chl-concentrations of an order of magnitude too high for Levenberg-Marquadt based processed MODIS products from summer 2003 (Pozdnyakov et al., 2005) covering the southern Kara Sea with the Ob estuary. That may technically also be due to the high concentrations of dissolved organic matter for the coastal Kara Sea waters with reported in-situ concentrations of > 5 mg l^{-1} DOC. Mustapha et al. (2012) in their study of the south-eastern Beaufort Sea also assume that the widespread higher particle background in Beaufort Sea coastal waters increase the backscattering and potentially contributes to the large overestimation of operational Chl-a products.

The focus of our application is therefore not to use the absolute parameter values but to analyse the Ocean Colour data qualitatively. In the following sections we discuss the value of the Ocean Colour visualization for several applications: i) the hydrographic pattern of meanders, eddies and filaments that indicate a wide-spread lateral advection in the sea-ice free season and ii) re-suspension zones that potentially indicate vertical transport pathways of nutrients, carbon, sediments and heat.

The new discussion sub-chapters follow: '5.2 Widespread lateral surface advection in the sea ice-free season'. The text here has not been changed and is the same as in the original manuscript, only being put separately as sub-chapter.

Wegner et al. (this volume) discuss how the freshwater from the Lena River and other Siberian rivers is wide-spread on the Laptev Sea shelf. The authors describe a SPM-enriched fresh water surface layer up to latitude of 76.8° N north of the Lena River Delta and 77.8° N on the eastern shelf due to dominating offshore winds, in September 2008, a non-normal year of anti-cyclonic atmospheric circulation pattern. Even in September 2007, in a quasi-normal year of cyclonic atmospheric circulation pattern, with dominating onshore winds and eastward, non cross-shelf transport of the riverine freshwater, the authors describe that SPM-enriched fresh water was measured up to latitude of 75° N. The authors showed that this contrasting fresh-water transport could also be made visible in the mapped MERIS C2R-parameters: In 2008, the outer shelf areas showed less transmissivity (higher $C2R\_k_{min}$, lower C2R_Z90) compared to more transparent waters on the outer shelf in 2007 (Wegner et al., this volume).

We did not observe a well-defined Lena River plume in the distribution of C2R_a_gelbstoff and C2R_TSM ore related turbidity parameters (C2R_k_{min}, C2r_Z90). Multi-year expedition data show that the southern Laptev Sea is characterised by a wide-spread high freshwater signal and background cDOM concentrations (e.g., $a443_{cDOM}$ range in Buor Khaya Bay is 2 to 2.5 m^{-1}) and that the cDOM concentration of the Lena River in August is of the same magnitude as in the surface waters around the Lena River Delta and in Buor Khaya Bay in the August and September months. That the magnitude of concentrations is of the same order or higher in Buor Khaya Bay is also a finding related to POC, nutrients (NO3, PO4) pCO2 and oxygen saturation from multi-year expedition data (Semiletov et al., this volume, submitted).

Due to continuous cloud coverage north of 75° N at a longitude of 130° E and westwards of it, the most transparent, lowest cDOM and SPM-water type is only visible within a few small cloud-free patches in the MERIS time series. Regularly, the high gradient between high-cDOM freshwater-influenced surface waters to low-cDOM marine-background waters seems to lie northwards of the cloud-free mapped areas. However, what is still visible even under these limited conditions is that the MERIS snapshots of the outer shelf system indicate that the spatial pattern of the transparent waters and the different types of less transparent waters do outline a coastal turbid meandering zone of several 100 km. Only in the year of prevailing anti-cyclonic atmospheric circulation in 2008, this spatial pattern was partly hidden due to higher diffuse turbidity of surface waters on the outer shelf.

The horizontal meander fields and filament-fields in the Southern Laptev Sea suggest that a high frontal instability is continuously being generated. The frontal instability may be shed from the Lena River inflow and from unstable coastal currents. Meanders, filaments and eddies horizontally transport material in the surface water layer due to hydrodynamical equilibrium forces. Hydrodynamical model simulations and mooring current measurements show that these horizontal structures also provide vertical motion and indicate the vertical mixing of a surface layer (e.g., Chao and Shaw, 2002, Ralph 2002, Sutherland et al., 2011, Fong et al., 2002). Kraberg et al. (this volume) show a well-mixed fresh-water influenced upper layer of 5 to 8 m depth in the Buor Khaya Bay. The rich hydrographic spatio-temporal pattern of filament fields, meander fields and eddies suggests that they carry chemical and biological fields and could trigger a high patchiness of phytoplankton and zooplankton in the Laptev See region. Kraberg et al (this volume) discuss a high spatial heterogeneity in phytoplankton composition in August 2010 in the Buor Khaya Bay probably resulting from the out-flushing from the Lena River.

‘5.3 Resuspension zones above shallows’. The text here has not been changed or has been improved in respect to the flow of the text.

The visualisation of resuspension events in the mapped MERIS C2R parameters highlights vertical mixing events down to the sea bottom of shallow banks in the southern Laptev Sea region. A turbidity belt around the Lena River delta is always visible. Reimnitz (2000) describes the high-latitudinal specific shallow bank around the Lena River Delta and other Arctic deltas that is most probably generated by bottom-fast ice cover. Eicken et al. (2005) describe that the presence of the wide shallow bank around the Lena River Delta is in line with the mostly extensional sea-ice regime in this area.

Several shallow banks are delineated by the 5 m, 10 m and 15 m isobaths (State Geological Map of Russian Federation, 1999) on the Laptev Sea shelf and in the western part of the East Siberian Sea shelf. Gavrilov et al. (2003) discuss that the present-day shallow banks represent former Ice-Complex islands that have been destroyed by coastal thermal erosion and thermal abrasion during the last thousand years. Gavrilov et al. (2003) cite observations made on Russian seismic expeditions during the summer months that described the local turbidity on these shallow banks (in Lisitsin et al., 2000; Dmitrenko et al., 2001).

Charkin et al. (2011) discuss that for the shallow Laptev Sea, the impacted zone by resuspension events should be on average down to the 10 m bathymetry (with an estimation of average wave height of 1 m), accounting for the only short durability of strong waves. They describe how the dominating sand to sandy silt fraction that they found on the shallows and on the shallow bank around the Lena River Delta supports the theory of vertical mixing events that bring velocity currents down to these bathymetric depths. Vonk et al. (2012) confine a potential sedimentational regime to the shelf areas below 30 m depth, thereby excluding half of the shelf area of the Laptev Sea and Eastern Siberian shelf. Wegner et al. (this volume) discuss that sediment entrainment due to resuspension at depths around 30 m take place mainly after storm events. Their data are based on current speeds of the ANABAR mooring station (74° 30' N, 127° 20' E) in the Laptev Sea.

These findings on the depth of the mixing events should be revisited and analysed in the context what resuspension events made be visible by Ocean Colour remote sensing show in terms of the depth of the mixing layer. Analysing the resuspension events related to wind strength and directions may allow to spatially distinguishing between the submarine depths of regular submarine seabed erosion and entrainment and the submarine depths where abrasion occurs only caused by strong storm events.

Referee#2

Specific comments:

I would expect to see plots in the paper comparing satellite estimates and surface measurements of the three parameters, with a clear indication of time differences imposed by cloud and other factors.

and We need to know at what depths water samples were collected. Section 4.2 states that in-situ data are averaged over the top 2 m of the water column. Does this mean that water samples were somehow collected to be averages over this depth, or does it mean that samples were collected at several depths, and the average value for the top 2 m was computed.

The methods of the C2R evaluation, such as how the in-situ data have been handled [e.g. which depths, depth of the upper mixing layer, time delay between match-ups etc.] have been moved out of the chapter 'results' to a new subchapter C2R evaluation in 'methods' because several comments of referees 1 and 2 had asked for this information that had been in the manuscript text already in 'results' but obviously was not well readable and detectable.

3.3. Match-up analyses with MERIS C2R parameters (see above)

Plots of match-ups of Chl-a (Figure 6) and SPM (Figure 5) have been shown in the discussion paper. cDOM has been evaluated in the original text as being considerably underestimated, but has not been shown as figure. A new figure showing match-ups of cDOM is added. The time differences have been shown in the original text but were hidden within a too large subsection in results. Now : 'The MERIS acquisitions on Jul 31, Aug 3-6, and Aug 10, 2010 show low cloud coverage and are close in time to the L10 ship expedition in Buor Khaya Bay that took place from Jul 29 to Aug 7, 2010. A MERIS acquisition on Sep 7, 2010 is the cloud-free acquisition closest in time to the TRANSDRIFT-XVII expedition that took part from Sep 9-20, 2010. The next usable MERIS acquisitions on Sep 18 and 20, 2010, have higher cloud coverage.' **Tables 2 (former table 1) and 3 (former table 2) show the dates of the samples used.**

Figures 4a and 4b do not seem useful.

The relevance of Figures 4 a and b was discussed in the original text (see below). Due to the new structure in subchapters end edits to the flow of the text the manuscript is easier to follow and these findings do not get submerged.

'The match-up analyses for cDOM and SPM versus C2R kmin and C2R Z90 show for near-coast on-shore waters that the major direct relationship exists between transmissivity and SPM. This optimal relationship (e.g. Fig. 4a, C2R Z90 versus SPM) indicates that the turbidity/particulate matter is the dominating Ocean Colour producing aquatic component in the water-leaving spectral reflectances. The relationship C2R Z90 versus cDOM (e.g. Fig. 4b) shows that cDOM influences the transparency parameters (C2R kmin, C2R Z90), but is not as dominating as SPM (Fig. 4a).'

Figure 1b plots positions from an additional expedition in 2008. It is not clear how this fits in the paper and

The authors note that high SPM occurs at all salinities due to resuspension as well as river discharge. It is not clear whether they observe low SPM at all salinities, implying some fresh water sources with low SPM. I suspect low SPM only occurs in offshore water.

The results from the LENA2008 expeditions have been discussed in the chapter 'results' subsection 4.1. 'Ranges of optically visible water parameters in the Southern Laptev Sea' but were obviously hidden within a too large subsection (see new editing in sub-chapters, above).

New table 1: 'LENA2008, 2010, TRANSDRIFT-XVII: characterisation of water types in the southern Laptev Sea, value ranges of surface water layer' is added showing that high SPM occurs with a large ranges of salinities in nearshore and onshore waters, but also medium concentrations occur in onshore and offshore waters of Buorkhaya Bay with low salinities due to the large fresh-water influence of the Lena River freshwater discharge. Yes, low SPM occurs in pelagic offshore waters.

New references, revised manuscript:

Kattner, G., Lobbes, J.M., Fitznar, H.P., Engbroth, R., Nöthig, E.-M., Lara, R.J., 1999. Tracing dissolved organic substances and nutrients from the Lena River through the Laptev Sea, Arctic. Mar. Chem. 65, 25-39.

Matsuoka, A., Huot, Y., Shimada, K., Saitoh, S., and Babin, M., 2007. Bio-optical characteristics of the Western Arctic Ocean: implications for ocean color algorithms, Can. J. Remote Sen., 33, 503–518.

Matsuoka, A., Bricaud, A., Benner, R., Para, J., Sempere, R., Prieur, L., Belanger, S., and Babin, M., 2012. Tracing the transport of colored dissolved organic matter in water masses of the Southern Beaufort Sea: relationship with hydrographic characteristics, Biogeosciences, 9, 925–940.

Matsuoka, A., Huot, Y., Shimada, K., Saitoh, S., and Babin, M. 2012. Bio-optical characteristics of the Western Arctic Ocean: Implications for ocean color algorithms, Can. J. Remote Sen., 33, 503–518.

Mustapha, S.B., Belanger, S. and Larouche, P., 2012. Evaluation of ocean color algorithms in the southeastern Beaufort Sea, Canadian Arctic: New parameterization using SeaWiFS, MODIS, and MERIS spectral bands. Can. J. Remote Sen., 38, 5, 535- 556.

Vetrov, E.A., Romankevich, E.A., and Belyaev, N.A., 2008. Chlorophyll, primary production, fluxes, and balance of organic carbon in the Laptev Sea. Geochemistry International, 46, 1055- 1063.

Wang, J. and G.F. Cota, 2003. Remote sensing reflectance in the Beaufort and Chukchi Seas: Observations and models. Appl. Optics, 42, 2754-2765.