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## Reply on RC2

Emilia Trudnowska et al.

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Author comment on "Cells of matter and life – towards understanding the structuring of particles and plankton patchiness in the Arctic fjords" by Emilia Trudnowska et al.,  
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Trudnowska et al. present a study of the distribution of particles using high-resolution datasets from two arctic fjords. They analyze how the distribution of particle patches changes over environmental gradients and time. This is an exciting dataset that has the potential to provide new insight into fine-scale patches, how they vary, and what causes the variation. I also found the attempt to quantify the shape of patches intriguing. While I feel this study has great potential, I have some serious concerns with the current manuscript.

REPLY: We would like to thank the reviewer for appreciation of the potential of our study and for pointing out several issues for improvements. Below we refer to the specific concerns raised by the reviewer.

Major comments:

- While I agree with the authors that heterogeneity in particle distributions is poorly understood, especially on the scales quantified by this dataset, in general I found the manuscript was poorly motivated. The introduction should be reworked to better formulate the primary questions, provide the broader context, and articulate why we need to understand the fine-scale distribution of patches. A description of why these sites were selected for this study would also be helpful.

REPLY: The clear formulation of the motivation of the studies that are mostly of scientific interest, but have not any direct commercial value, is in general tricky, even in the case of such fascinating phenomenon as finding a patterns in on art of a distribution of 'cells of matter and life' : patchiness. We agree that this could be better emphasized, especially by the sentences that clearly refer to the significance of this particular study, such as e.g.,:

Broader context : "*Distribution of particles and plankton in the oceans is highly patchy. Those 'clouds of matter' are fundamental 'cells' for trophic interactions and organic carbon cycling (Benoit-Bird et al., 2011; Brentnall et al., 2003; Godø et al., 2012; Priyadarshi et al., 2019), by as their distribution is structuring the further elements of marine ecosystems, e.g., the hotspots of fisheries and other marine harvesting initiatives, or the massive vectors of carbon pump vs. the recycling of matter within the upper water layers*"

Primary questions:

*"The possibility to document and observe the patchiness has opened just recently, thanks to the high resolution automatic instruments such as underwater cameras, laser counters and acoustic methods (Davis et al., 2005; Geoffroy et al., 2017; Möller et al., 2012; Trudnowska et al., 2012, 2016). However, in most cases the patches of only one type or fraction of particles or plankton could be studied, mostly due to the methodological constraints, as every single method is limited to specific type/size of objects (Martin, 2003; Woodson et al., 2007). The simultaneous application of the combination of various instruments, dedicated to different size fractions of particles and plankton, opens up the possibility of traceability of the full composition of those 'cells of matter and life' (Forest et al., 2012; Lombard et al., 2019; Stemmann et al., 2008; Szeligowska et al., 2020; Trudnowska et al., 2018). Moreover, such an approach gives an unique possibility to check, if those patches are multi-fractioned or rather composed of monospecific size fractions. The studies of existence of mono- vs. multi-fraction patches may assist the exploration, if those are randomly or physically gathered objects, or rather the biologically rich hotspots that accumulated together in an active way."*

*"The goal of this study was to answer a few crucial questions: 1) Does the distribution of particles and plankton patches differ over time and space? 2) How many percent of the water column is occupied by the patches of particles and plankton? 3) Are patches of various size fractions of particles and plankton co-occurring, and if yes - why? 4) Does the internal structure of particles and plankton patches differ?"*

Why: there are a few sentences pointing out the knowledge gaps with regard to the issues raised in the article, e.g.:

*"Although patches of particles and plankton are very common in marine systems, we know very little about their size, composition and internal structure (Currie et al., 1998; Kotliar and Wiens, 1990)."*

*"Despite those numerous studies still the mechanisms favouring generation of patches, and the processes underlying plankton distribution within patches, need further recognition (Menden-Deuer, 2012; Nayak et al., 2021)."*

*"To date, empirical measurements of particles and plankton patch structures are still challenging, as they require in-depth exploration with various dedicated techniques and sophisticated approaches. Also the modelling of plankton patchiness even though is more than a half-century old, is still in its infancy (McGillcuddy and Franks, 2019)."*

*"This study addresses a recognized requirement for new insight studies at the interactions between ocean physics and ecology in structuring marine ecosystems (Borja et al., 2020; Lévy et al., 2018)"*

Why the Arctic fjords: *"Those processes are especially complicated and dynamic in the Arctic fjord systems, where the advected warm, saline and biologically rich Atlantic waters collide with the outflow of cold, fresh and turbid waters from the melting glaciers (Halbach et al., 2019; Trudnowska et al., 2014, 2020a). Such strong hydrographical gradients set a perfect scene for both horizontal and vertical partitioning of water by both plankton and particles. It results in high spatial variability in distribution patterns of particles and plankton and thus in spatial gradients in primary and secondary production (Piwoz et al., 2009; Trudnowska et al., 2014). The inter-annual variability of the intensity of water advection is also an important driving force, as it can even surpass the effect of local processes (Szeligowska et al., 2020). Indeed, the progressing "Atlantification" of west Spitsbergen fjords is highly modifying the community compositions of protists (Kubiszyn et al., 2014; Smoła et al., 2017) and zooplankton (Gluchowska et al., 2016; Trudnowska*

*et al., 2020b), influencing finally the overall food web interactions in the fjords (Csapó et al., 2021; Vihtakari et al., 2018; Węśławski et al., 2017)."*

- While the authors presented a nice summary of the data, the manuscript lacked an in depth analysis and discussion of potential mechanisms driving the observed distributions. It appears that there were recurring patches along the transect, what determined the location of these patches? An analysis of density differences (rather than temperature and salinity separately), light profiles (even just estimates based on surface PAR and in situ chlorophyll), and nutrient concentrations (was this collected?) could have provided critical mechanistic insight.

REPLY: We refer to those analyses as follows:

*"We analysed the cross correlations between patch characteristics (depth range, horizontal length, area, size spectrum), environmental settings (temperature, salinity, chlorophyll), 110 spatial heterogeneity indices (logarithms of variance/mean ratio, Lloyd's crowding and patchiness indices), and concentrations of particular size fractions of particles and plankton (log<sub>10</sub>()). In the dbRDA model we divided the explanatory variables into three groups: i) spatial (depth and horizontal part), ii) environmental (temperature, salinity, chlorophyll), and iii) size (vertical extension and area)."*

*"We also tested over which ranges of those explanatory variables specific types of patches emerged by a density function of their occurrence." But as this approach was criticized by the other reviewer, we decided to take it out from the article.*

However, none of the applied analyses ended up with a straightforward conclusion, as the studied fjords are probably too dynamic, with too many possible forces structuring the water column. Therefore in Discussion we rather speculate and try to link the observed trends with the existing knowledge from other studies and from this particular region, e.g.,:

*"Even though we extended our comprehension of patchiness phenomenon by analysing thoroughly 94 patches of various size fractions of particles and plankton that existed in comparable environmental conditions (two Arctic fjords) over several years of the study, it still remains an ambiguous matter when, why, and which of the mechanisms (physical vs. biological) prevails in shaping the patterns of particles and plankton distribution. Since no explicit conclusions could be made, this study rather opens up new perspectives for further research by providing a proposition how to categorize the types of structuring of those 'cells of matter and life' in a water column as a potentially additional aspect to be considered for understanding their short term and local variability."*

*"Whereas melting glaciers were clearly recognized as the dominating local process, resulting in the recurring high particles and plankton accumulations in the innermost glacial bays, which is typical for the summer melting period (D'Angelo et al., 2018; Kanna et al., 2018; Meire et al., 2017; Szeligowska et al., 2020; Trudnowska et al., 2020a)."*

*"However, as only half of the variation was explained by the studied explanatory variables, the considered relations turned out to be much weaker than intuitively expected, pointing towards the interference of some other driving forces. Those were either mechanistic constraints that could not be detected by hydrographic measurements, or some ecological interactions that are in general immeasurable."*

*"the development and persistence of patches was not strictly associated with the existence of strong environmental spatial gradients observed in both fjords. The determined by us environmental cues (temperature, salinity, chlorophyll), explained only 20-30% of overall studied variation."*

*"The fact that a distribution of particles and plankton was not reflecting the hydrographical structure of the water column indicates that they are not purely dye-like passive tracers of advection and/or local hydrographical water structuring. Moreover, as shown by differences in the correlations strengths and directions between the two studied regions, it is important to note that the correlations may have only short term and local validity."*

*"Because only the concentrations of the Large size fraction correlated significantly with chlorophyll just in Isfjorden, this indicates that in general the concentration hotspots of smaller size fractions did not consist of actively fluorescent particles or plankton, and that rather large sized phytoplankton or fluorescent aggregates (Timmerman et al., 2014), or alternatively the relationship between herbivorous grazers (as the Large fraction is mostly represented by Calanus copepods (Balazy et al., 2018, 2019)) and food availability (expressed as high chlorophyll levels) could be observed."*

Unfortunately we do not have the corresponding measurements of light and nutrients. At some point we were considering to analyse density, but as it is a function of temperature and salinity, it is co-correlated with them.

I really liked the size-spectra calculations as a way to assess the patches, but it was not clear to me how these were made - how did the authors deal with differences over depth? I would have loved to have seen a size-spectra analysis per particle patch! That would have been a truly novel insight that I have not seen previously. Analyzing the patches as a unit rather than analyzing each separately by particle size would have been a lot easier to follow.

REPLY: First of all, we would like to thank a reviewer for pointing this out and enthusiasm about the analysis we have done.

The size spectra were calculated over the patch, so all the data points that fall in a patch were used to build the concentrations for a spectra, regardless of the depth, because we decided that if depth was not a parameter limiting a patch formation, than we should not treat it as such.

The separation of patches between the size fractions was dictated by the fact, that if we selected only the data points of the highest total abundances, then those would represent only the patches of the Pico- fraction, which is the most numerous (e.g. concentrations per  $e+8$ ), while we wanted to present the patches that are representing the elevated concentrations of also other size fractions, which are by definition much less abundant (e.g. Nano fraction - concentrations expressed in  $e+7$ , Medium in  $e+4$ , Large in  $e+3$ ).

- The study aimed to compare the two fjords but only presented minimal data from Isfjord. It would have been helpful to have had a complementary figure to Figure 2 for this site. In addition, the authors recently published a paper on the dataset from Isfjord, but it was not clear how the results from that paper integrated into this study - what was new in this study that was not done in the previous study?

REPLY: Because such basic, background section plots were presented in a previous study (Szeligowska et. al 2020, figure presented in a supplementary material to this review), we decided we should not double them, especially that it is not the crucial part of our article, rather something like setting a scene for reasoning about patches.

This previous paper did not analyse patches et all. This article was focused on the inter-annual variability and horizontal gradient of plankton taxonomic composition (sampled traditionally via nets and bottles) in relation to environmental settings, including particles and plankton concentrations assessed via laser counters (LISST & LOPC).

Minor comments:

- There are many terms which are used in the introduction but poorly defined and not integrated into rest of the manuscript e.g. 'clouds of matter', 'cells of matter and life'

REPLY: We used those terms to 'sketch' the studied phenomenon in order to 'visualize' what the patches in the oceans actually are – something really important. We will incorporate this concept better in the revised version.

The methods section lacked critical details:

- How was the background separated from the patches?

REPLY: For each individual transect we analysed the threshold for the patch (mean+sd), so anything below this value was regarded as 'background' and above this threshold as 'patch'. Therefore, we did not subtract the 'background'. Now we realize that we should not use the word 'background' as it may be misleading. In a revised version it will be described as follows: "*Data points assigned as 'patches' were the ones that had higher concentrations than a threshold (mean abundance + sd), which was defined separately for each transect. Therefore, the patch threshold is fjord- and year-specific.*"

- How was Llyod's index calculated, please provide the formula

REPLY: Those parameters are calculated basing on the formulas using mean (m) and variance ( $s^2$ ). We took the formulas from the article of Pinel-Allou, 1995 (presented in a supplementary material to this review)

We can incorporate them into the methodology of the article.

- What were the background variables that were collected?

REPLY: You mean environmental factors? It is indicated in Methods as: "*....supplemented by a conductivity-temperature-depth (CTD, SBE 911plus, Seabird Electronics Inc., United States) and a fluorometer (Seapoint Sensors Inc., United States) sensors.*"

*"In the dbRDA model we divided the explanatory variables into three groups: i) spatial (depth and horizontal location), ii) environmental (temperature, salinity, chlorophyll), and iii) size (vertical extension and area)."*

- Several of the figures were confusing - e.g. Figure 6, 7, and 9 (why not show the RDA?). In Figure 2, why were only 3 years shown when 6 years are mentioned in the methods.

REPLY: Fig. 6 will be modified according the suggestions raised by the Reviewer 1. Figure 7 will be removed from the article. Figure 9 will be supplemented by the RDA plot.

We decided that showing all the years will make the Figure2 too busy and the panels too small. The other years are presented in Supplementary material, as this is just a 'background', not a clue of this article.

Moreover, we plan to change Figure 4 in order to better show the selected patches as exemplified in a supplementary material to this review.

Please also note the supplement to this comment:

<https://bg.copernicus.org/preprints/bg-2021-98/bg-2021-98-AC2-supplement.pdf>