Response to comments on the submitted manuscript: Greaves et al. - *The Southern Annular Mode (SAM) influences phytoplankton communities in the seasonal ice zone of the Southern Ocean*

23 December 2019

We thank the reviewer for their valuable feedback on this manuscript. These have identified several areas for improvement of the manuscript, which we have addressed below:

RC2 - Damiano Righettim, 21 November 2019

(i) Key concepts (SAM or SAM index) are not clearly defined. The SAM definition leaves it open to the reader, how the sign of the SAM index is calculated, and whether atmospheric pressure or water pressure constitutes the SAM index.

- SAM is calculated by NOAA (USA), as already stated in the Methods section: "*Daily estimates of SAM were obtained from the US NWS Climate Prediction Center's website and are the NOAA Antarctic Oscillation Index values based on 700-hPa geopotential height anomalies (NOAA, 2017)*." (line 140) – the description wording is as specified by NOAA. We will clarify the definition of SAM and the SAM index (line 58 onwards): "*The Southern Annular Mode (SAM, also called the High-Latitude Mode or the Antarctic Oscillation) is the principal mode of atmospheric variability over the Southern Ocean (Gong andWang, 1999; Marshall, 2003), characterised by large-scale movement of air mass between high and mid latitudes. Importantly for this study, it determines the strength and latitudinal variation of the westerly wind belt. There are various definitions and indices for SAM (Ho et al, 2012) - it has been defined as the difference in normalised zonal mean atmospheric sea-level pressure between 40°S and 65°S (Gong and Wang, 1999; Marshall, 2003), however we have used the NOAA Antarctic Oscillation Index values, which are based on 700-hPa geopotential height anomalies (NOAA, 2017). More positive values of the SAM index lead to stronger westerly winds in high latitudes, including the study area (Hall and Visbeck 2002; Lovenduski and Gruber 2005; Arblaster and Meehl, 2006)*".
- The SAM is an atmospheric index, we will clarify by adding the word "*atmospheric*" to the Introduction paragraph of section 1.2 (as underlined here): "*The Southern Annular Mode (SAM), which is also variously also called the High-Latitude Mode and the Antarctic Oscillation, has been defined as the difference in normalised zonal mean atmospheric sea-level pressure between 40°S and 65°S (Gong andWang, 1999; Marshall, 2003)*." (line 58)
- We will include "*SAM index (hereafter referred to as SAM)*" in line 58 to clarify any confusion, and include the previously observed range in SAM (in the order of *"-3 to +3*") in the text to improve clarity.

There is a problem with clarity of statements and consistency of word use (e.g., different expressions are used for the same thing), and a lack of clear correspondence between hypothesis, methods, and key results. I provide detailed examples on clarity below.

- These will be checked for consistency

(ii) My main conceptual critique point is that the impact of the time-averaged SAM signal in autumn on phytoplankton community composition in spring to summer has not been firmly tested by the data shown.

- The relationship between time-averaged SAM signal in autumn on phytoplankton community composition was apparent in the analysis, and reasonable (being the time ice was forming) but otherwise untestable. However:
- Correlations with the empirically defined SAM range in the autumn and the relative abundances of 12 of the 22 taxa supported the conclusion. Further:
- The peak of SAM influence in the preceding autumn was also detected in response surfaces for NASA satellite total chlorophyll (correlation between SAM in autumn and NASA total chlorophyll is 0.5) and nutrient levels (correlation between SAM in autumn and [PO_4] was -0.64 for all samples, and -0.84 for the later-in-season half of the samples) – these response surfaces will be included in the extra material (as drafted below). NASA satellite total chlorophyll and [PO_4] are observationally independent of the taxonomic counts, so similar prior-autumn maxima for the correlation with SAM and these traits are supportive of our finding that "*time-averaged SAM signal in autumn influences phytoplankton community composition in spring to summer*"
- Two Supplementary material figures to be included:

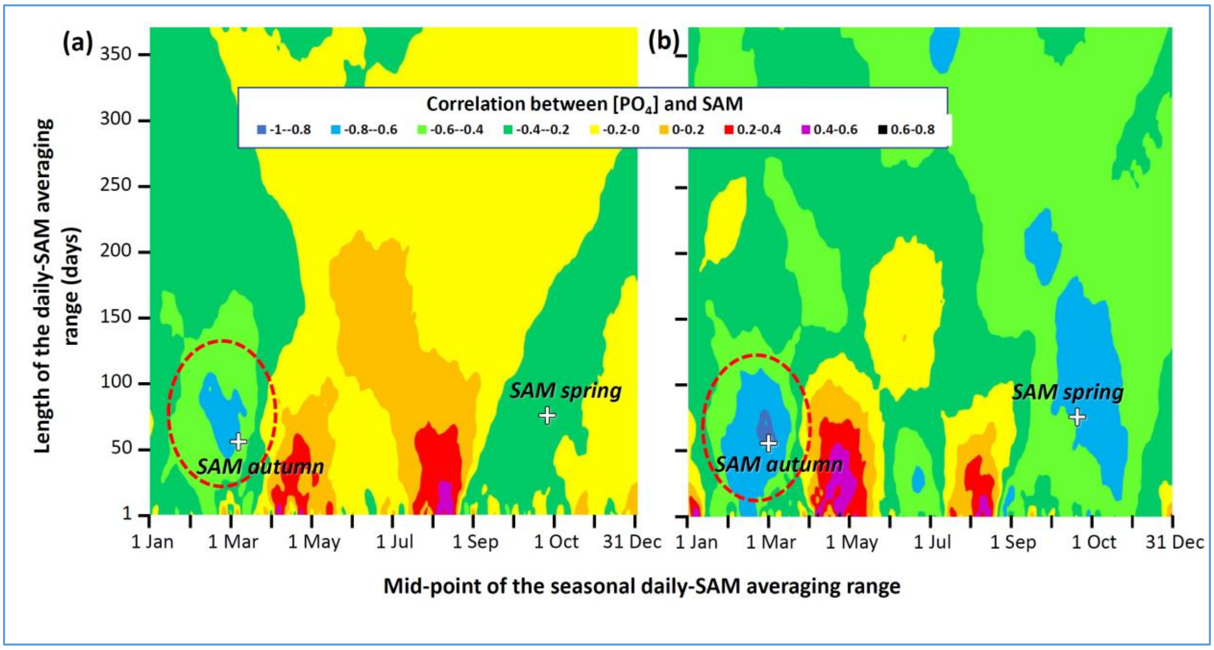

Figure [Supplementary material]: Response surfaces of the correlation between [PO_4] and the averaged SAM, versus timing and length of the daily-SAM averaging range, i.e. the calendar date of the mid-point of the date range (horizontal axis), and the number of days over which those indices were averaged (vertical axis), respectively. The SAM maxima identified in Figure 3 are shown (SAM autumn, SAM spring). Evident maxima in autumn are indicated with red broken line loops. (a) Analysis includes all available data (n=51), (b) analysis includes only half of the samples, being those collected later in the spring-summer productive season (n=26).

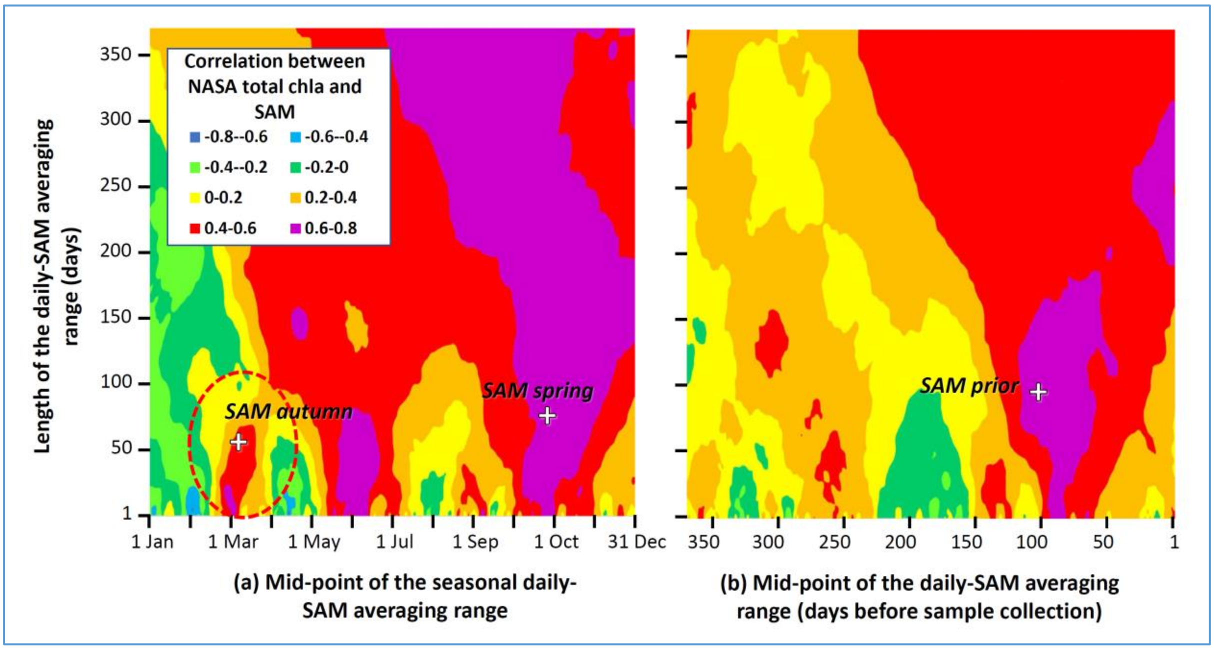

Figure [Supplementary material]: Response surfaces of the correlation between NASA satellite total chlorophyll and the averaged SAM, versus timing and length of the SAM period. The SAM period is the number of days of daily-SAM averaged (vertical axis) and the timing of the range of averaged daily-SAM (horizontal axis). The SAM maxima identified in Figure 3 are shown (SAM autumn, SAM spring). Evident maxima in autumn are indicated with red broken line loops. (a) Analysis includes all available data (n=51), (b) analysis includes only half of the samples, being those collected later in the spring-summer productive season (n=26).

The study demonstrates that it is possible to average the daily SAM index in a way that a significant part of the variation in community composition can be explained in next spring/summer, yet it is unclear why microbial species that live on timescales from days to weeks, would respond to the SAM signal with a time-lag of several months.

- We will include in the discussion "*Phytoplankton taxa must survive the six months of darkness and ice-cover between the middle of the Austral autumn and mid-spring by variously hibernating and/or producing resting spores (see manuscript, as described from line 290) so their metabolic condition in autumn is likely to determine their viability and relative vigour in spring.*"

I suggest that relationships between a more positive state of SAM in autumn and temperature, wind speed, mixed-layer depths, and nutrient levels in spring to summer—factors that may directly shape phytoplankton composition—shall be evaluated, to support the paper's message.

- "**relationships between a more positive state of SAM in autumn and temperature, wind speed, mixed-layer depths, and nutrient levels in spring to summer**" are beyond the scope of this paper – others have made observations/predictions of the influence of the SAM on wind-speed and mixed-layer-depths as cited: "*More positive SAM has been associated with lower atmospheric pressure at sea level and increased storminess (Kwok and Comiso, 2002; Hall and Visbeck, 2002; Marshall, 2007). These changes are particularly marked south of 60°S in the atmospheric Southern Circumpolar Trough (Hines et al., 2000; Mackintosh et al., 2017), a region characterised by strong winds with variable direction (Taljaard, 1967). Stronger winds may result in increased transport of surface water northward from the*

Antarctic Divergence by Ekman drift (Lovenduski and Gruber, 2005; DiFiore et al., 2006), potentially driving increased upwelling of nutrient- and carbon-rich deep ocean water at the Antarctic Divergence (Hall and Visbeck, 2002). More positive SAM is also associated with reduced near-surface air temperature over the SIZ due to an increased frequency of strong southerly winds and increased cloud cover (Lefebvre et al., 2004; Sen Gupta and England, 2006)."

- We don't have wind-speed and mixed-layer-depth for each sample, and we would require this information daily for the location of each sample for the year preceding each sample, and arguably for a range of locations around each sample (since the surface water is migrating horizontally at speeds up to 15 cm s^{-1}, as discussed from line 397). Whilst this would be an interesting analysis, it is far beyond the scope of this paper, which was to determine if an effect of the SAM could be detected in the taxonomic composition of phytoplankton (as stated in our hypothesis)
- Nutrients are replete at the start of spring, assumed to be unaffected by SAM the previous autumn
- It is possible that SAM in the autumn influences SAM in the following spring – we did not identify a significant correlation between SAM in the autumn and SAM in the following spring (Table 2 of the submitted manuscript)

In section 4 ('Other relationships'), there are several relationships presented between predictors, yet the results are not presented in a structured way to support the hypothesis that SAM-induced changes in temperature, wind-speed, mixed-layer depth or nutrient concentrations affect community composition.

- These other relationships are worthy of inclusion – some introductory text will be added to the section to make this more clear
- We did not hypothesise that "**SAM-induced changes in temperature, wind-speed, mixed-layer depth or nutrient concentrations affect community composition**", our hypothesis was: "*Based on the predicted and observed positive relationships between the SAM and phytoplankton productivity and biomass in the SIZ of the SO, we hypothesised that changes in the SAM could also elicit changes in the composition and abundance of the phytoplankton community*." (line 93)

The current association between the SAM signal (or "SAM modes") described and community composition may not be causal. In the context of fast-lived organisms it seems crucial to test if the link between summer community composition and (preceding) SAM is plausible.

- Sure, may not be causal – but it is plausible, as discussed above. Without conducting a series of overwintering experiments, there is no way to check for sure.
- We would expect SAM prior to sampling (***SAM prior*** and ***SAM spring***) would influence phytoplankton composition, as we would expect SAM in the winter to have a lesser influence because the surface-ocean is insulated from the atmospheric conditions by sea-ice. These expected influences were observed (Figure 3). The influence of SAM the previous autumn was not expected, but is considered a real influence as it is the time when sea-ice is forming and thus a critical time for phytoplankton preparing to hibernate the six-months of ice-cover.
- Further, the empirically defined SAM autumn showed pairwise correlations with 12 of the 22 taxa identified.

- Further, SAM maxima were apparent in similar response surface analysis of the correlation between SAM and (a) NASA satellite total chlorophyll, and (b) [PO_4] in all samples, and (c) as a stronger correlation with [PO_4] when only the later-in-the-season half of samples were considered (analysis not included in original manuscript, but now to be included with response surface figures in Supplementary Material – as indicated above)

Recommendations

I suggest that the manuscript is thoroughly screened for clarity.

- We will carefully review and improve the manuscript for clarity

Second, besides further testing the associations of the SAM signal of autumn with physicochemical factors known to affect phytoplankton composition (and whether these associations are in line with expectation), I suggest splitting the 22 taxa into ecological test groups, which are expected to respond differently to changing mixing-, wind-, and nutrient patterns under a more positive SAM state. These expectations can be presented as specific hypotheses in the introduction.

- We do not believe that we have enough information about enough of the identified taxa to be able to sensibly break the identified taxa into groups that will lead to a sensible group-based analysis of responses to SAM. Not a great deal is known about many identified Southern Ocean polar hard-shelled phytoplankton Supplementary taxa, which have previously largely been to only identified at the genera level, and we have identified significant differences in the behaviour of taxa within single genera.

Such a biological approach has been partly implemented by comparing small diatoms (presumably better adapted to stable waters) with large diatoms (presumably better adapted to strong mixing). Yet the results of this test lack a graphical presentation in the manuscript, across all taxa.

- We will interpret the observed results with reference to organism size and shape to infer any influence
- However, size is not necessarily a useful parameter upon which to aggregate taxa, as whilst some taxa are always small, others have been identified as both large and small taxa.

Species may be grouped further into warm, temperate, or polar species, depending on their global distributions (e.g. using observations from OBIS and GIBF; Righetti et al., 2019) and their responses may differ under SAM-induced warming/cooling.

- We will endeavour to associate "warm, temperate, or polar" to each taxon after OBIS and GIBF; Righetti et al., (2019) to ascertain if such grouping supports the observed taxa responses to the environmental variables

Similarly, R-strategist (fast growing, light stress tolerant species) and S-strategists (slow growing, nutrient stress tolerant species) may be grouped together (Brun et al., 2015), as they may respond oppositely to changing nutrient levels.

- Brun et al (2015) reproduces the *R-S-strategist* classification of organisms from Reynolds (2006): of the 22 taxa in our study, only 4 were classified (as *R-strategists*), and 5 were classified as "*unclassified*", with 15 not included in Brun et al (2015)'s reproduction of Reynolds (2006) classification [we haven't as yet been able to access Reynolds, C.S., 2006. *The ecology of phytoplankton*. Book: Cambridge University Press]. Given the paucity of *R-S-*

strategist classifications (4 out 22 taxa with classifications) it would be inappropriate to specifically overlay the *R-S-strategist* framework on the taxonomic data we have collected.

- We propose to include discussion of the *R-S-strategist* classification in our re-worked discussion.

Additionally, species with large vs. small cells may show opposite responses to changing turbulence and wind regimes (Margalef, 1997, 1978).

- We propose to include in our re-worked discussion more discussion of size and shape (after Margalef 1997) of the taxa that showed influence of SAM

Finally, predicting the response of siliceous vs. calcareous taxa to SAM constitutes an exciting hypothesis: these groups have shown opposite responses to deeper mixing or nutrient entrainment (Cermeño et al., 2008).

- The area studied was the Seasonal Ice Zone (SIZ) which is situated over the ocean upwelling zone of the Antarctic Divergence – nutrients in the surface waters of the SIZ are replenished over the six months when the sea surface is ice-covered and when there is almost no productivity (or consumption of nutrients). It is considered a high-nutrient, low-chlorophyll zone. In this region of annual winter nutrient replenishment, the influence of mixed-layer depth is less than most other areas of the world's ocean. The area falls outside the analysis of Cermeño et al., (2008), whose sampled area extended southward to only well north of the Antarctic Divergence, and would not be expected to conform to the trends observed by Cermeño et al., (2008) due to the replenishment of nutrients every winter in the area of our study.

With respect to the clustering techniques used to describe communities I cannot give detailed recommendations, as the metrics used are beyond my expertise.

Detailed comments

There are too many comments to be listed. I therefore give examples for selected paragraphs, with comments on clarity, for each:

Abstract:

- Line 3: How many variables were tested?

- We will amend the text to include

- Line 6: How many species (genera, higher taxa) were included among the 22 taxa?

- We will amend the text to include

- Line 7: I do not understand 'CAP'. This term has not been introduced.

- We will amend the text to include the full name of the CAP procedure

- Lines 8, 9, 11, 17: The following terms are used: taxonomic community composition, taxa composition, phytoplankton community structure, taxonomic composition of phytoplankton. While I understand that the authors strive to include stylistic variation, the reader is confused by the multiple expressions. Do they denote the same thing or not? I recommend using use the same expression for the same thing. Else, once an expression is clear, an abbreviation of the latter may be used therein, as long as it denotes the same thing.

- We will amend the text to make the terms consistent

- Line 10: Unclear to me, if the correlation is significant or not.

- We will amend the text to clarify

- Line 13: Unclear to me, if "response" means a response of abundance or not.

- We will amend the text to clarify

- Line 15: Before, the expression "SAM index" was used, not "higher SAM". Does "higher SAM" refer to a more positive state of the SAM index?

- We will amend the text to clarify

- Line 17: Confusing, as taxonomic composition of phytoplankton is not the same thing as a standing stock (or a "pasture") of biomass of phytoplankton.

- We will amend the text to clarify

- Line 16: It is unclear to me, if the expression "pelagic ecosystem" is suitable in the context of a sea ice transition zone.

- We will remove the word "*pelagic*" to avoid confusion

- Line 16: It is unclear, how many of the total species that were studied, responded significantly to SAM. Thus, it is unclear, if this result is important or general.

- We will amend the text to clarify

- Line 10 ff: It is surprising that 'day of sampling' explains more variation in community composition than any other locally sampled environmental factor (SST, nutrients, etc). An interpretation on why this is the case would help the reader to assess the plausibility or importance of this result.

- The seasonal ice zone has been previously observed and reported to have a winter period (around 6 months) with little or no phytoplankton productivity when the sea-surface is frozen, and a well-characterised bloom and systematic taxonomic succession through the spring-summer months as sea-ice melts – we will include this point in the abstract (it is already in the introduction and in the discussion)

Introduction:

- Line 21-23: The first two sentences are partially repetitive.

- We will improve the text

- Line 21 ff: The paragraph wants to establish the importance of phytoplankton productivity in the study area for global phytoplankton productivity. While the reader understands that a larger fraction (~30%) of carbon fixed by phytoplankton is exported in the study region, relative to the global average (~ 20% exported) it remains unclear, if the study region is globally important. What is the area-weighted contribution of the study region to global phytoplankton C-export?

- We will include statement to this effect indicating the fraction of global C-export attributed to the SIZ of the Southern Ocean.

1.2 The Southern Annular Mode

- Line 58 ff: Clarify the definition of SAM (see above). The reader cannot grasp how the sign of SAM is calculated or linked to changing pressure gradients, and thus how it is associated with physicochemical changes in the study system.

- The calculation of SAM is beyond the scope of this paper, except in the most general terms – the SAM index used was calculated by NOAA (USA) and the wording of the description is as NOAA wants it reported.
- We will endeavour to craft a further, greatly simplified, single-sentence description of the SAM for inclusion around line 58.

- Line 64 ff: SAM vs. SAM index vs. SAM state vs. SAM mode. Please use consistent expressions throughout the manuscript. …… and the use of "mode" in both the context of SAM and community composition may confuse the reader

- We will remove all references to SAM maxima as MODES to remove confusion with <u>MODE</u>=MAXIMA and SOUTHERN ANNULAR <u>MODE</u>, that is, we will just define the terms ***SAM spring*** and ***SAM autumn*** and refer to them by name without using the term "*mode*".

In addition, "taxon" could always refer to both a species and a group of species.

- *Taxon* is singular, *taxa* is plural – we have used "*taxon*" to refer to a single taxa-group, whether it is a single taxon or a group of taxa, and we have used "*taxa*" – we will carefully consider each usage of "*taxa*" and "*taxon*" for consistency

2.1 Phytoplankton composition and abundance

- Line 116: One reads as if the abundance of phytoplankton communities was sampled. As much as I understand, the abundance of species or taxa was sampled. (Then, an abundance-weighted community composition was calculated?).

- Improve text to remove any suggestion that "**abundance of phytoplankton communities was sampled**"

2.3 Statistical analysis

- Line 151 ff: The methods section needs clarification, structurally and through editing. In this section, I have difficulties to understand whether three or more sets of analyses were performed based on the phytoplankton field data, and which of these analyses is most important to test the key hypothesis of the paper,

- We will edit methods to improve clarity

….. and at what temporal resolution the analyses were performed.

- Temporal resolution is specified (line 147-): "*These were derived by evaluating separate CAP analyses (described below) based on daily SAM averaged across a range of days {1, 3, 5, . . . 365 <u>days</u>} centred on (i) each calendar day individually (1 Jan – 31 Dec) through the year associated with each sample; and (ii) lagged from 1 to 365 days prior to each sample collection date.*" – We consider this description to be succinct, but we will craft a more descriptive and wordy description for readers who may be unable to interpret the existing description.

- We will add "*Heat maps were used to display the variance explained from individual CAP analyses according to the number of days and mid-point (or lagged mid-point) used for each derived SAM average, thereby allowing an investigation of the derived SAM index showing greatest correlation with community structure*."

- Line 152: Has "community structure" really been correlated to "environmental covariates"? If I understand correctly, the abundance data was related to possible environmental drivers, per species. In this case, please specify: e.g. …and species abundance between samples

- The correlation between the community structure (as determined from the ordination) and each environmental covariate was calculated according the procedure outlined in ter Braak (1995) and attributed to Dargie (1984) – we will include more explanation of CAP analysis for greater ease of interpretation for readers not familiar with CAP analysis.

- Line 151 ff: It is not clearly motivated, why clustering of community-level samples is suitable to identify the effect of SAM on community composition. To me, the number of 52 samples seems rather low already, and each degree of freedom may be valuable.

- Clustering shows that there are significant differences between the community composition of the samples. Clustering does not identify an effect of SAM, at least not directly, since environmental covariates are not included in the cluster analysis. The group structure determined by cluster analysis is displayed in the CAP ordination (using colour) to demonstrate that samples that clustered together are indeed close to one another in the 2D ordination. This lends confidence that the 2D ordination is a reasonable approximation to the full, high-dimensional structure. As we know the values for the environmental covariates for each sample, it is possible to determine the correlation between the 2D CAP solution and each environmental covariate. We display this correlation as a projected vector (arrow) where direction indicates the sign and length indicates strength. For example, Figure 6 shows that group 5 (dark blue points) are positively correlated with Long.E, but negatively correlated with DaysAfter1Oct (at least up to the approximation afforded by the first two canonical axes).

3. Results

- The first results presented to the reader are abundance-distributions of taxa across samples. Yet, the reader might expect that the most important piece of evidence to elucidate the role of SAM for phytoplankton composition is first presented.

- The logic behind the analysis and presentation of the data in relation to the hypothesis will be explained in the first paragraph of the *Results* section
- We will re-arrange the *Results* section to put abundance information later, i.e. Section 3.1 "*Observed abundance*" will become Section 3.2, with Section 3.1 becoming "*CAP analysis and pair-wise relationships*"

- Line 206 ff. Can P, n, and R2-values be provided for the correlations?

- The text will be modified to include specification of n and p with all in-text correlations
- P-values are not tabulated - currently reported correlations in tables are formatted to indicate when $p<0.05$ and when $p<0.05/20$ for Bonferroni correction

- Table 1: I do not understand, why nutrients are excluded in this table.

- We will include text to explain that nutrient levels are an effect of phytoplankton, not a cause, in this high-nutrient-low-chlorophyll environment that is nutrient-replenished through the winter – i.e. more growth through the productive spring-summer leads to less nutrition at the end of the summer

- Figure 5. The caption remains vague. What are the "several underlying assumptions" of linear regression? Relevant to be discussed in the caption?

- We agree that the caption should be improved and we will remove the words "*though clearly several underlying assumptions of linear regression would not be met*" from the caption

Overall, the manuscript requires a clear structure in order to show to what degree the SAM signals may matter to community composition, based on (ecological) hypotheses tested and data. The support in the data for this message, and the evaluation of the manuscript are complicated at current and warrant further attention.

- We will reconsider the structure for the manuscript.