

We really appreciate the anonymous referee for your very positive and constructive comments. All suggestions have been accepted as described below.

RC = Referee's comments; AR = Authors' Response (written in blue); RS = Reconstructed sentences (written in green)

General Comments

RC1: The cluster 3, dominated by haptophytes, only occurred in September 2008 in the Canadian Basin. Coupel et al observed that this area was dominated by prasinophytes in August 2008. This means that the longer growing season of 2008 permits the appearance of a phytoplankton community that usually do not dominate under a normal ice season. This new community structure occurred at the very end of the productive season (September) when incident light has already decline very much. It is not clear in the current version of the paper what the authors mean by a shift in phytoplankton community structure. It seems to be a seasonal (temporal) shift since prasinophytes still the dominant specie in earlier in season (in August). In other words, haptophytes probably dominate only for a few weeks in late season. The implications may be important, may be not so important.

AR1: Thank for the insightful comment. We would like to reveal that haptophytes appeared in the nutrient depleted northern water but well warmed due to earlier ice retreat (i.e. longer ice-free period). As you pointed out, Coupel et al. (2012) have reported the prasinophytes dominated communities in the same region during August of 2008. We also found the domination of prasinophytes in northern part of the Chukchi Sea (~75°N, 160–180°W, Fig. 4a) in 2008, where observed usual ice retreat timing. Therefore, we accepted your recommendation and we would like to emphasize “the change of seasonal succession of phytoplankton community structure” rather than “shift of the phytoplankton community”. Section 4.3 was reconstructed as follows (including revisions for other comments).

RS1: Cluster 3 dominated by haptophytes was observed only in 2008 in the

eastern Chukchi Sea, where prasinophytes were dominant in the other two years. To understand the reason for this difference among the years, we focused on the inter-annual variability of open water area and the temporal variability of the onset date of sea ice melt. As indicated in Figs 7a–e, there were significant differences in the onset date among the three years. In particular, an earlier onset of 1 to 2 months was observed in the eastern Chukchi Sea in 2008 (Figs 7d and e). We hypothesize that this earlier sea ice melt and longer ice-free periods reduced the ice albedo in 2008, and warm water ($\sim 5^{\circ}\text{C}$) consequently distributed in the eastern Chukchi Sea. The locations of haptophyte-dominated samples showed good agreement with early open water and warm water (Figs 4a and 7a, d and e). Such relatively warm and oligotrophic water conditions should be favorable for haptophytes (Figs 6a, e and f). In contrast, Coupel et al. (2012) reported the high abundance of prasinophytes in the same region but one month earlier and much colder ($< 0^{\circ}\text{C}$) than our observation in 2008. Haptophytes are known as mixotrophic organisms and can survive in nutrient-depleted waters by grazing bacteria or mixotrophic nanoflagellates (Estep et al., 1986; Porter, 1988). In addition, an earlier sea ice retreat might release phytoplankton from light limitation. Under light-limited conditions, phytoplankton tend to synthesize *chl b* and *chl a* to increase their photosynthesis efficiency (Giesks and Kraay, 1986). In the Arctic Ocean, phytoplankton often experience light limitation due to the presence of sea ice (e.g., Sakshaug, 2004; Hill et al., 2005). Therefore, prasinophytes, which contain more *chl b* due to low-light acclimation, are distributed widely in the Arctic. However, the longer ice-free period of 2008 may have triggered the appearance of unusual phytoplankton community that domination by haptophytes due to improved light conditions. Thus, we suggest that the dominance of haptophytes observed only in 2008 was due to the spread of warm, nutrient-depleted water and/or changing light conditions, all of which likely follow an early sea ice retreat.

Lovejoy et al. (2007) reported that, during late summer, the Arctic marine food web is supported by low temperature, low light and

oligotrophic-adapted prasinophytes. Our results, however, revealed an appearance of the different community composition in area of earlier sea ice retreat; such changes in phytoplankton communities have the potential to trigger the dramatic changes in the Arctic marine food web. Reduction in sea ice is expected to increase in the future (Perovich and Richter-Menge, 2009). We note that the earlier and broader distribution of open water areas can result in a larger area in which alternation of phytoplankton community structure, from prasinophytes to haptophytes, may occur during late summer. Few studies exist showing that phytoplankton community shifts actually affect biogeochemical cycles or higher trophic levels in the western Arctic. However, a high-resolution time series observation conducted in Svalbard revealed that changes in phytoplankton community composition alter food quality for copepods (Søreide et al., 2010; Leu et al., 2011). Leu et al. (2011) revealed that phytoplankton bloom dominated by diatoms contains higher quality of polyunsaturated fatty acids (PUFAs) than other flagellates. On the other hand, it has been reported that diatoms can reduce their nutritional quality in lower nutrient conditions (Ban et al., 1997). Leu et al. (2011) also reported the importance of temporal matching between primary and secondary producers. The change of seasonal succession of phytoplankton communities due to the change of sea ice retreat timing includes risks in reproduction and growth for secondary producers. It is not yet understood what will happen if the switching of dominant algal groups from prasinophytes to haptophytes occurs in a large temporal and spatial scale. As Leu et al. (2011) have noted, process studies are the only way to determine how the spatiotemporal variability of sea ice affects lower trophic levels. However we suggest that the ecosystem can be more heterotrophic, reproductive and such season can be longer along with the appearance of mixotrophic haptophytes due to the reduction of sea ice and warming temperature in the future western Arctic. Moreover, change of community structure during late summer can co-occur with earlier phytoplankton bloom during spring because the bloom timing in the Arctic Ocean very likely to follow the timing of sea ice retreat (Kahru et al., 2010,

Ji et al., 2012). Therefore, further studies are required to assess the biogeochemical and ecological impacts of the alternation of summer phytoplankton community composition in the western Arctic.

RC2: At the end of the summer in the oligotrophic waters of the deep Arctic basin, most of the primary production occurs in the subsurface chlorophyll maximum (SCM) between 40 to 60 meter depth (Hill et al., Prog. Oceanogr. 2013; Ardyna et al., BG 2013). The species composition actually differ in the SCM relative to the surface (Coupel et al., 2012). So future studies should considered the whole water column to evaluate the impact of species sift or succession community structure on the marine ecosystems. The authors must discuss this limitation.

AR2: Thank you for the valuable comment. We addressed the limitation of omitting SCM in the strongly stratified Arctic adding a paragraph at the end of section 4.3 as RS2.

RS2: One of the limitations of present study is that we only focused on the interannual variability of surface phytoplankton communities. However, recent environmental changes of the Arctic Ocean likely to affect upper layer phytoplankton communities directly; sea-ice shrinking, rinsing temperature (Steele et al., 2008; Perovich and Richter-Menge, 2009), increase of river discharge (Peterson et al., 2002, Yamamoto-Kawai et al., 2009). It thus should be pointed out the importance of favorable environment of surface phytoplankton communities. On the other hand, several studies revealed that the importance of subsurface chlorophyll-a maxima (SCM) in the stratified Arctic Ocean which generally co-occur with nutricline (e.g., Tremblay et al., 2008; Martin et al., 2010; Ardyna et al., 2011). SCM contributes up to 90% of water column integrated primary production in the highly stratified and oligotrophic Arctic (Hill et al., 2013). Phytoplankton community composition is also known to be different between the two layers; pico-sized communities generally dominated at surface but larger phytoplankton dominated at SCM in contrast (Sukhanova et al., 2009; Joo et al., 2012; Coupel et al., 2012). Thus, the ecological impact of changes of phytoplankton community and its

production at the SCM is seemed to be larger than those at the surface. However, since our finding suggests that surface phytoplankton community structure can change due to the rinsing of sea surface temperature consequence of early sea ice retreat, it is likely that surface phytoplankton communities are more responsive to the temporal and spatial variability of sea ice distribution than that of SCM.

Specific Comments

P15155, L6–13:

AR: The sentences were corrected as suggested

RS: Corresponding to a deepening nutricline, induced by increasing volumes of low-density water, a predominance of small phytoplankton groups and reduced primary productivity can be expected in the Beaufort Sea (Li et al., 2009; McLaughlin and Carmack, 2010). On the other hand, it has been reported that a thinning or/and shrinking of sea ice enhanced underwater light availability, which stimulated higher primary productivity, where phytoplankton were not strongly limited by nutrient availability (Lee and Whitledge, 2005; Nishino et al., 2011; Arrigo et al., 2012).

P15155, L23–25:

AR: The sentences were corrected as suggested

RS: The main objective was to understand how the spatial variability of sea ice distribution can affect phytoplankton community composition.

P15157, L11–12: Did you filter the water sample in series? For example, is the chlorophyll-a measured on the 0.7 micron is the fraction between 0.7 and 2 micron? If not, then the filtration on 0.7 micron is the total chlorophyll-a concentration. This is not clear.

Why not keeping the four size classes in the analysis?

AR: Size fractionated filtration was conducted in series. One of the reasons why we did not consider much about size fractionated chla to infer phytoplankton groups is because of the lack of the sample during the cruise of 2008, which cluster 3 mainly observed. Therefore sample number is different from the other variables. Another reason is that several studies used 5 μ m as a criterion to divide phytoplankton size into two groups in the Arctic, (Gosselin et al., 1997, Hill et al., 2005, Ardyna et al., 2011, Ferland et al., 2011). However, as the refrees pointed out, if we can use them, it will really improve the inferring of dominant phytoplankton groups. We calculated means and standard deviations of %chla for the size classes for

each cluster (Table R1 and Table 1 of the revised manuscript) with the notice that number of samples is different from HPLC pigment data. These mean community size compositions were considered to infer dominant phytoplankton groups. The paragraph begins from P15157, L3 were reconstructed as follows

RS: Size-fractionated *chl a* concentrations were measured using a fluorometric method with a Turner Designs 10-AU fluorometer (Welshmeyer et al., 1994) during the 2009 and 2010 cruises. The sample water was passed through Whatman Nuclepore and GF/F filters with pore sizes of 10, 5, 2, and 0.7 μm , respectively. Percent contributions of size-fractionated *chl a* detected from the each mesh size to total *chl a* were determined; %*chl a*_{>10 μm} , %*chl a*_{5–10 μm} , %*chl a*_{2–5 μm} , %*chl a*_{<2 μm} , respectively. In particular, we use sum of %*chl a*_{>10 μm} and % *chl a*_{5–10 μm} called F_L in Fujiwara et al. (2011) for statistical analysis (section 2.3) as a quantitative index of phytoplankton size structure, which is widely used as a criterion to divide phytoplankton size into two classes in the Arctic Ocean (Gosselin et al., 1997; Hill et al., 2005; Ardyna et al., 2011; Ferland et al., 2011).

P15157, L14–P15158, L12: Here you mention that MRA and CA determine the predominant phytoplankton group, while four lines later you mention that MRA cannot discriminate taxonomic group. This is confusing.

It was not clear to me what is used in the multiple regression analysis (i.e. input versus output of the MRA) until I saw eq 2 in section 3.1.2. I think the authors can better explained the MRA.

AR: I agree. More detailed description was added. The sentences were reconstructed as bellow.

RS: Multiple regression analysis (MRA) was applied to the phytoplankton pigment data to determine the most predominant phytoplankton group at each sampling station. MRA can assess the contributions of accessory pigment to *chl a* levels (Wright and Jeffrey, 2006) and does not require any assumptions about the pigment ratios of each algal group, as does Chemical Taxonomy (CHEMTAX) (Mackey et al., 1996). Although MRA cannot discriminate among taxonomic groups that have diagnostic

pigments in common (e.g., prasinophytes and chlorophytes both contain *chl**b***), it is sufficient to infer important phytoplankton groups fully comparing with previous studies in the same region (e.g. Booth and Horner, 1997, Vidussi et al., 2004, Hill et al., 2005, Sukhanova et al., 2009, Joo et al., 2012, Coupel et al., 2012). In this study, MRA was conducted twice using the following method: the first MRA included all pigment data, then several pigments with large standard errors (>1.0) or unrealistic partial regression coefficients when compared to previous studies (e.g., Suzuki et al., 2002; Vidussi et al., 2004) were excluded and a second MRA was performed on the confined dataset. On the other hand, cluster analysis (CA) was performed to divide sampling sites into groups that have similar pigment composition, with Ward's linkage method using Euclidean distance. The same pigments used for CHEMTAX analysis for Baffin Bay, in the Arctic Ocean, by Vidussi et al. (2004) were chosen for CA because similar algal groups are expected to appear in our study region—*chl**c**3*, *peri*, *but*, *fuco*, *prasi*, *hex*, *allo*, *zea*, *lut* and *chl**b***. The ratios of these pigments were calculated and used for CA. Then, we inferred the areas contain similar taxonomic composition combination with MRA results.

P15158, L7: It is still not clear to me how the MRA and CA are linked. Do the coefficients of equation 2 use to transform the pigment concentrations into ratios of accessory pigment to chl a. The CA is thus apply on those pigments ratios, not on pigment concentration right? I think the text can be improve to make things clearer.

AR: We agree. More detailed description about CA was described together with MRA (see RS above).

P15158, L20: You calculate the open water area for which region exactly? Did you use the same limits as the one used in Fig. 4? Please indicate the boundary of the region of interest.

AR: We apologize for unintelligible description. We did not calculate open water “area”. We would like to mean the whether a pixel was ice-free or not. The sentences were reconstructed as follows

RS: A given pixel was defined as ice-free which SIC pixel values were less than 10%, following Arrigo et al. (2008) and then the onset date of the sea ice retreat was defined as the first day that became ice-free.

P15159, L12: bathymetry? To me, "increase with depth" is for vertical profile.

AR: The word "depth" was changed to "bathymetry"

P15159, L15&L18: for all three cruises? please specify. any difference among cruises?

AR: Yes, it is for all three cruises. The sentences were reconstructed as follows

RS: Surface chl_a concentration of the three cruises were successfully expressed from MRA (Eq. 1), which included six accessory pigments:

$$\text{chl}_a = 1.49[\text{peri}] + 1.85[\text{fuco}] + 1.74[\text{hex}] + 5.88[\text{allo}] + 3.54[\text{zea}] + 1.31[\text{chl}_b] + 0.02$$

(1)

where the adjusted R² was 0.99, and all partial regression coefficients of Eq. 1 were statistically significant (p<0.001 by t-test and p<0.001 by F-test).

P15159, L20: add space

AR: The words "pigment/chl aratio" were corrected to "pigment/chl_a ratio"

P15162, L10–L20: Do you mean dominated communities or dominating communities? It is not clear.

AR: The paragraph begins from P15162-L11 was reconstructed as follows. We apologize for misdescription. We meant "eastern Chukchi Sea" not "western". On the other hand, we would like to keep the sentence "Although clusters 1 and 3 showed a similar surface distribution pattern, most of cluster 3 was sampled in 2008 (Fig 4a)", because one sampling site in 2010 was divided into cluster 3, where located at southernmost site (Bering Strait). Since we visited the same site for two times during the cruise, cluster 2 has been plotted over cluster 3. Figures 4c and 7c were reconstructed colored in half and half (see Fig R1 and R2). The sentences

were reconstructed as follows

RS: Prasinophytes dominated the algal communities (cluster 1) mainly in the basin area of the northern Chukchi Sea and partly near the ice edge around Barrow Canyon. Diatoms and dinoflagellates, which dominated cluster 2 and 4 respectively, exhibited similar horizontal distribution patterns. These clusters tended to occur in waters that extended from the shelf region of the Bering Strait to Chukchi shelf break. The most distinct interannual difference in the distribution patterns was observed in the eastern Chukchi Sea. Although clusters 1 and 3 showed a similar surface distribution pattern, most of cluster 3 was sampled in 2008 (Fig 4a).

P15163, L23–25: The phrase is incomplete or not clear.

AR: The sentences begin from L23 to 27 were reconstructed as follows

RS: The statistical difference of the timing of sea ice retreat observed by satellite remote sensing was also examined (Fig 6i). We found significantly later ice retreat at the stations where the cluster 1 appeared. Note that advection of sea surface water was omitted for this analysis.

P15164, L13:

AR: The words “in the deep basin” were added

P15164, L23–25: Please refer to Coupel et al BG 2012 who examined the performance of CHEMTAX.

AR: Thank you for the comment. The sentences were added as follows

RS: Coupel et al. (2012) is perhaps the first study that applied CHEMTAX to the western Arctic Ocean. Since they applied CHEMTAX without optimization of initial pigment matrix, they also reported the problems of overestimation of diatoms and underestimation of nanophytoplankton biomass. They attributed this result to the presence of fuco-containing dinoflagellates and nano-sized flagellates. Unfortunately, a quantitative relationship between phytoplankton pigment composition and the microscopically identified has not been established, and in addition, such data were unavailable either in this study.

P15167, L2–4, L9, L13–14: Coupel found one month earlier in 2008 that prasinophyte was the dominant algal species in the Canadian Basin, which is the area dominated by Cluster 1. Therefore, the presence of haptophytes later relative to the ice season may be better interpreted as a seasonal succession of species rather than a "shift" in plankton communities. So the longer growing season results in the appearances of species that usually cannot develop. I suggest to rephrase your text to reflect this interpretation.

AR: We agree. Reply of this comment was described in AR1.

P15167, L11: It is not clear to me whether or not the appearance of a haptophytes community at the end of the summer will have dramatic change on the Arctic marine food web since the productivity may be just earlier in season. The timing of the productive period may be even more important.

AR: The sentences were added to 2nd paragraph of section 4.3 that refer to the importance of timing when the important phytoplankton species for secondary producers appear (Leu et al., 2011). We also noted that change of community structure during late summer can co-occur with earlier phytoplankton bloom during spring because the bloom timing in the Arctic Ocean very likely to follow the timing of sea ice retreat (Kahru et al., 2010, Rubao et al., 2012). We would like to emphasize that potential influence of the appearance of unusual phytoplankton community on upper trophic level organisms or biogeochemical cycles. Please see AR1 and RS1.

P15167, L27: You have to consider the temporal species succession. Here you give the impression that haptophyte will take over the place of prasinophyte. There is no such evidence in your data of you consider what was present earlier in season (Coupel et al 2012). In other words, prasinophyte will probably not decrease in importance in the future, but occur earlier in season. Interestingly, the "extra" growing season favored by the reduction of sea ice and warming temperature will be likely as you described, i.e. a more heterotrophic and reproductive along with increase of mixotrophic conditions.

AR: Thank you for the comment. We accepted and section 4.3 was reconstructed (please see AR1)

P15168: You need to have at least a paragraph about the vertical distribution of species. At the end of the summer, in the oligotrophic waters of the deep Arctic basin, most of the primary production occurs in the subsurface chlorophyll maximum (SCM) between 40 to 60 meter depth. The species composition actually differ in the SCM relative to the surface (Coupel et al., 2012). So future studies should considered the whole water column to evaluate the impact of species sift or succession on the marine ecosystems.

AR: Thank you for the comments. We added a paragraph at the end of section 4.3 (please see AR2).

P15177, Fig. 4: I would think that the SST map is a composite of several images because such clear sky is extremely rare in the Arctic in September.

AR: We apologize for the misdescription. SST images were composited to 9-days mean centered on September 1. Figure caption was corrected as follows

RS: SST data were collected by MODIS and composited to 9-days average centered on September 1 of each year.

Table R1. Means and standard deviations of pigment/chla and pigment/pigment ratios and percent contribution of size fractionated chla to the total that were used in this study to determine the dominant phytoplankton groups in each cluster. Standard deviations are shown in parentheses. Note that since we obtained only one size fractionated chla sample that classified into cluster 3, standard deviations are not shown for cluster 3.

Pigment	Cluster 1	Cluster 2	Cluster 3	Cluster 4
peri/chla	0.023 (0.025)	0.060 (0.025)	0.041 (0.036)	0.249 (0.105)
but/chla	0.030 (0.011)	0.016 (0.018)	0.029 (0.017)	0.011 (0.003)
fuco/chla	0.125 (0.034)	0.25 (0.072)	0.122 (0.037)	0.096 (0.022)
hex/chla	0.060 (0.022)	0.025 (0.026)	0.129 (0.060)	0.014 (0.006)
prasi/chla	0.065 (0.019)	0.022 (0.007)	0.040 (0.012)	0.026 (0.011)
zea/chla	0.011 (0.009)	0.011 (0.006)	0.012 (0.013)	0.009 (0.005)
lut/chla	0.001 (0.002)	0.001 (0.001)	0.001 (0.002)	0.001 (0.001)
chlb/chla	0.293 (0.064)	0.105 (0.039)	0.097 (0.067)	0.118 (0.039)
pras/chlb	0.227 (0.076)	0.222 (0.086)	0.296 (0.065)	0.210 (0.042)
fuco/hex	2.37 (1.24)	19.4 (22.5)	1.30 (0.965)	7.79 (3.93)
fuco/but	4.76 (2.50)	24.8 (24.3)	5.03 (3.28)	9.73 (3.84)
%chla _{>10μm}	14.9 (8.71)	38.5 (20.27)	11.0 (-)	46.4 (19.33)
%chla _{5-10μm}	6.31 (4.98)	16.8 (7.10)	7.07 (-)	7.50 (4.32)
%chla _{2-5μm}	15.6 (6.11)	17.7 (6.79)	17.2 (-)	12.5 (5.35)
%chla _{<2μm}	63.1 (14.96)	27.4 (9.78)	64.7 (-)	33.6 (12.07)

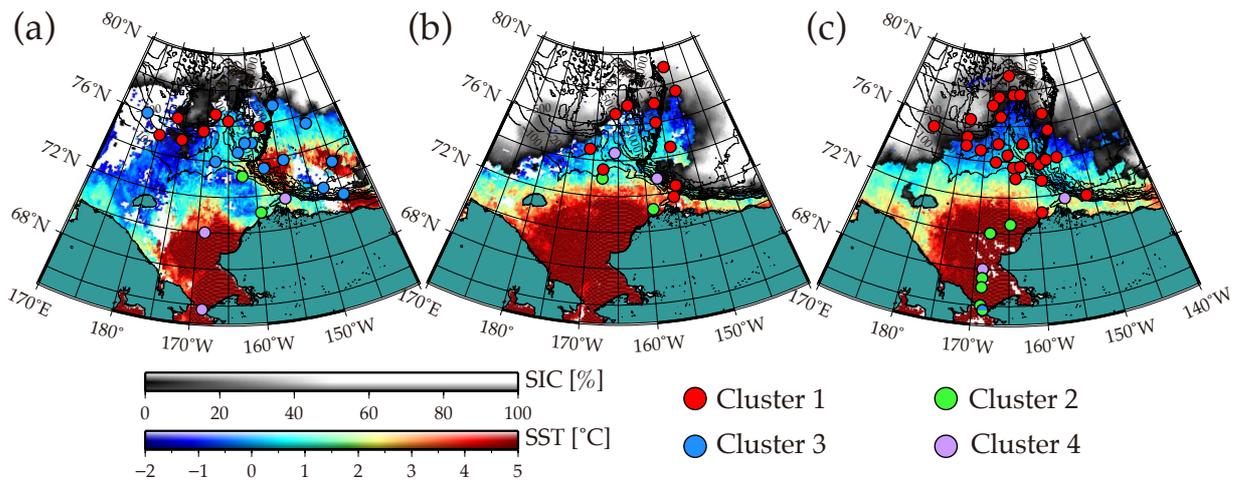


Fig. R1. Distribution of dominant phytoplankton groups at the surface layer in (a) 2008, (b) 2009 and (c) 2010. Clusters were identified by cluster analysis. SIC data were collected by AMSR-E on September 1; SST data were collected by MODIS and composited to 9-days average centered on September 1 of each year. Depth contours indicate 100-, 200-, 500-, 1000-, 1500-, and 2000-m intervals, respectively.

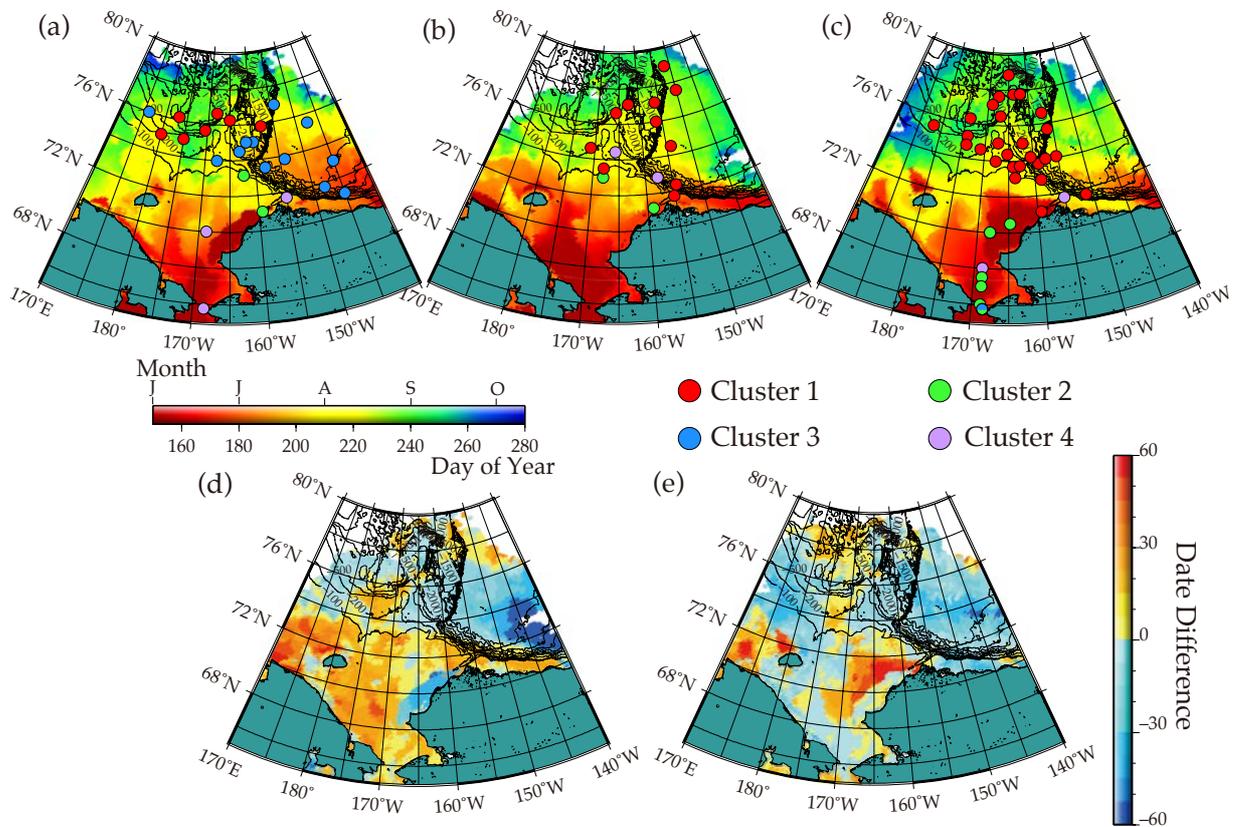


Fig. R2. Distribution of the clusters across Julian day when the area became open water in (a) 2008, (b) 2009 and (c) 2010. Clusters were identified by cluster analysis. White indicates areas where no open water appeared during the entire year. Differences of sea ice retreat timing between (d) 2008 and 2009, and between (e) 2008 and 2010 were also calculated subtracting Figure 7b and c from Figure 7a. Depth contours indicate 100-, 200-, 500-, 1000-, 1500-, and 2000-m intervals, respectively.

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