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Interactive comment on "Seasonality of sea ice controls interannual variability of summertime Ω_A at the ice shelf in the Eastern Weddell Sea – an ocean acidification sensitivity study" *by* A. Weeber et al.

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Biogeosciences Discuss., 12, C1193–C1195, 2015 www.biogeosciences-discuss.net/12/C1193/2015/ © Author(s) 2015. This work is distributed under the Creative Commons Attribute 3.0 License. Open Access Biogeosciences Discussions Interactive comment on "Seasonality of sea ice controls interannual variability of summertime âĎęA at the ice shelf in the Eastern Weddell Sea – an ocean acidification sensitivity study" by A. Weeber et al.

Response to Referee: N. Bednarsek (Referee) nina.bednarsek@noaa.gov Received and published: 14 April 2015

Thank you for the time and effort that you spent on our paper, as well as for the valuable comments that you have made. Please note that due to the recommendations of a referee, we have removed Figure 3, and thus Figure 4 becomes Figure 3, Figure 5 becomes Figure 4, Figure 6 becomes Figure 5, Figure 7 becomes Figure 6 and Figure 8 becomes Figure 7.

Due to the predicted impacts of OA on the Southern Ocean, this is a very interesting paper that illuminates the dynamics of the seasonality and inter-annual variability. It describes the effects of the physical changes (rate of thawing, changes in mixing related density etc.) on chemical processes (aragonite saturation state) through the sensitivity type of analyses. It is teasing out and constraining some of the factors as the drivers with the major impact on the chemical process, the mechanism that is much needed for future understanding of OA. It also concurs with the findings from other studies C1193 BGD 12, C1193–C1195, 2015 Interactive Comment Full Screen / Esc Printer-friendly Version Interactive Discussion Discussion Paper and puts it in the perspective of concurrent observations. This is a good first draft of interesting study but it needs quite a lot of further improvements, in three directions: Firstly: it needs to describe processes in the more quantitative, statically-correlated way (I am referring to the text more specifically below). Secondly: The biological section is its weakest part . It is very loosely delineated and needs much more details in order to be relevant and make use of the chemical observations for the biology implications. Authors need to explain when in the season and how the chemical changes relate to the life cycle of pteropods (which is something that is known). Relating chemical dynamics and vital bio processes, authors could identify the main stressors and bottlenecks for pteropod population. This sections needs to be expanded, more detailed and put into perspective. Thank you for this comment, we agree that this section is weak and needs work and thus we appreciate the time we have had to engage in this with you. Thank you for your contributions to the manuscript. Thirdly: writing style is too loose, unstructured and repetitive. It really needs some restructuring for the sake of reader's clarity and understanding. Grammatical errors need to be reduced. Abstract also does not capture the content of the manuscript and should be rewritten in the next rounds. In general (and I will be explicit where further in my comments), I have noticed that the author first brings the conclusion or even cites the other study without first presenting her own results - on this basis, it does not create a credible statement for the reader to follow, understand and support the argument. This needs work in this manuscript and should be rechecked at the next round of revisions (see e.g. page 1661, line 15-25). We agree with these comments, and have worked on the grammar and structure accordingly. We have also re-written the abstract so that it now reads: "As anthropogenic CO2 increases, surface water aragonite saturation state (âĎęA) decreases, negatively affecting calcifying Euthecosome pteropods and the wider Antarctic ecosystem. However, the seasonal and interannual variability of the physical (stratification and mixing) and biological (photosynthesis) processes in this vulnerable Antarctic ecosystem are poorly understood. We collected surface water âĎęA data over four consecutive summers from the Eastern Weddell Gyre (EWG) ice shelf region, and investigated the drivers of (âĎęA) variability and the role played by the seasonal cycle of physical and biological processes in the interannual variability of âĎęA. Interannual variability in the timing and the rate of the summer ice thaw were the primary factors explaining interannual variability in surface water âĎęA. During the summers of 2008/2009 and 2010/2011, sea ice thaw was initiated in late November/early December, and the summertime increase in âĎęA was 1.02, while in 2009/2010 and 2011/2012 when sea ice thaw was delayed until late December, the summer increase in âĎęA was 0.46 and 0.59 respectively. We propose that two critical climate (physical-biogeochemical) sensitivities for ΩA are the timing and the rate of sea ice thaw, which play an important role in summertime surface water stratification due to the influx of fresh sea-ice melt water and hence in the resulting onset, magnitude and persistence of phytoplankton blooms. The strength of summertime carbonate saturation depends on seasonal characteristics of sea ice,

stratification and primary production. The sensitivity of surface water biogeochemistry to interannual changes in mixed layer - sea ice processes in this region suggests that future trends in climate and the seasonal cycle of sea ice, combined with increasing anthropogenic CO2 may negatively affect the Antarctic ice shelf ecosystem within the next few decades. Our results suggest that any future reductions in primary production due to changes in stratification dynamics, combined with increasing anthropogenic CO2, may culminate in the emergence of EWG summertime surface water aragonite undersaturation by the middle of this century."

I also noticed interchanged use of seasonal vs interaannual. Thank you, we agree that we have interchanged these words throughout the manuscript, which is incorrect and can be very confusing. The interchanged use of seasonal and interannual has been corrected throughout the manuscript. 1655: line 28: Limacina helicina in italics Thank you, this has been corrected. 1656: line 8-15: make comparisons with the other vulnerable regions, e.g. Arctic and upwelling Thank you, we agree that this is important to do, and we have thus included a sentence comparing this region to the arctic and upwelling regions. "Other vulnerable regions such as the Arctic Ocean and some upwelling regions are predicted to experience periodic aragonite undersaturation within the next decade (Steinacher et al., 2009) and possible permanent aragonite undersaturation by the middle of this century (Gruber et al., 2012; Hauri et al., 2013)."

line 22: expand from here, provide results. Thank you, we have expanded this section and provided results so that it now reads: "Seasonal phytoplankton blooms assimilate CO2 in the euphotic zone, resulting in an increase in âĎęA (Orr et al., 2005).The seasonal cycle of phytoplankton blooms in the SO is mediated by light availability, sea ice, water column stability and nutrient supply and how the timing of these processes interact with the phenology of the ecosystem (Arrigo et al., 2008; Thomalla et al., 2011). Thomalla et al (2011; supplementary material) suggest that the optimal bloom initiation period in the SO Marginal Ice Zone is 1-15th December. An understanding of the links between the drivers of mixed layer physics such as sea ice thaw, buoyancy and wind-induced mixing are of key importance to understanding the climate sensitivity of surface water âĎęA and the ecosystem in the 21st century. Interannual variability in the magnitude of the seasonal cycle of âĎęA also highlights the importance of regional studies, particularly at the ice shelf ocean domain around Antarctica, which has one of the highest sensitivities in the global ocean for ocean acidification. The intraseasonal and seasonal scales of the analysis also help provide an understanding of how the progression of OA is modulated by surface layer physics which itself is linked to climate: it makes the carbon – climate links explicit."

1659: lines 1-25: in all this text it is unclear to me it this is referring only to the surface? int he same paragraph: describe in which papers the same methods have been described and accepted before? This is not novel, provide evidence that the use of the C1194 BGD 12, C1193–C1195, 2015 Interactive Comment Full Screen / Esc Printer-friendly Version Interactive Discussion Discussion Paper method here has been used before and is acceptable. Thank you, we agree that this was unclear. We have changed the paragraph to read: "2.3 Empirical data Underway sea surface temperature (SST) and sea surface salinity (SSS) data were used as proxy variables to calculate an empirical surface water TA dataset, using the equations of Lee et al (2006) for the SO region as done in Jones et al (2010). To determine the magnitude of local anomalies in the calculated TA, we compared the calculated values to in situ surface water CTD and measured TA from the VINDTA potentiometric titration. The January 2011 CTD casts were used for this comparison, as these CTDs were the only ones for which surface TA was measured. Data points were chosen by matching the underway station times to surface water CTD samples in the EWG, as per Jones et al (2010). Empirically calculated TA compared well to the measured surface TA (r2 = 0.66;). In the study region (68-71°S), the mean measured TA anomaly was -3μmol.kg-1, which suggests that the empirical equations may slightly overestimate TA here. The precision of the measured DIC and TA data corresponds to a maximum uncertainty of $\pm$ 0.05μmol.kg-1 in âĎęA. This error contributes approximately 6% of the mean seasonal $\triangle$âĎęA amplitude ($\triangle$âĎęA $\sim$ 0.77). fCO2, TA, SST and SSS were used to calculate DIC and âĎęA

using the CO2Sys code (Lewis and Wallace, 1998). To estimate possible surface water âĎęA for the middle and end of this century, the CO2Sys program was used, with fCO2 increased by 160μatm and with fCO2 doubled relative to a contemporary reference value of 390μatm, while TA, SST and SSS were unchanged from their present values. This estimation does not take into account that with increased CO2, pH will decrease and thus there will likely be more CaCO3 dissolution resulting in higher TA, but the complexities of this dynamic system are not well understood. 2.4 Satellite-derived sea ice concentration and surface wind stress Sea ice concentration (daily percent area coverage by ice) at a resolution of 25km was obtained from the National Snow and Ice Data Centre (NSIDC). The data was averaged over the ice shelf study area (68-71°S 0-10°W) to obtain mean daily sea ice concentrations. Surface wind stress observations (τ, N m-2 referenced to 10m above sea level) were obtained from the Seawinds blended product on a 25km grid at a 6 hourly resolution (Zhang, 2006). The 6 hourly estimates were averaged to daily wind fields."

1660: lines 6: to the surface? We agree that this section was not clear. We have changed it to clarify that the minimum âĎęA of 1.3 was for the upper 200m of the water column. "The four-year data set obtained from the ice shelf in the EWG shows a strong seasonal mode of aragonite carbonate saturation (âĎęA), (Fig. 3a-d). There is also strong interannual variability in the summertime maximum âĎęA, with a summer âĎęA maximum of 2.32 in 2009 and in 2010/2011 and 1.76 and 1.89 in 2010 and 2012 respectively (Fig. 3a-d, Table 1). Within the upper 200m, âĎęA reaches a sub-surface minimum ($\sim$ 1.3), (Fig. 2b) in winter. Previous research suggests that this sub-surface minimum in âĎęA is due to a combination of: convective mixing, the entrainment of CO2-rich Weddell Sea Deep Water (WSDW), brine rejection associated with the formation of WW (Mosby, 1934; Carmack and Foster, 1975; Carmack and Foster 1977) and winter light limitation of ocean primary productivity (Arrigo et al., 2008; McNeil and Matear, 2008; Thomalla et al., 2011), with the entrainment of WW being the dominant contributor to the winter minimum in âĎęA."

1660: lines 5-10: quantify this! Thank you, we agree that this section needed to have more values in it. We have corrected it and we hope that this answers your question (see section above). 1661: first paragraph does not belong to the results section. next paragraph: I would like the author to demonstrate which is it, the magnitude or phasing that will have more impact and carry-over effects on the biology. Thank you, we agree that this paragraph does not belong to the results. Due to recommendations of other reviewers this paragraph has been moved to the end of the introduction. To address the comment on the magnitude and phasing of omega we have rewritten the fourth paragraph in our Results and Discussions (see below). The direct impact on the biology is driven by the magnitude of omega but the seasonal magnitude of the delta omega is influenced by the phasing of the sea ice thaw and its impact on the spring-summer phytoplankton blooms. "Our data showed coherence in the response of âĎęA (mean summer increase in âĎęA $\sim$ 0.77) to variability in buoyancy (temperature and salinity) and wind stress forcing (Fig. 3, 5, 6). Temperature (Fig. 3i-l) and salinity (Fig. 3e-h) reflect an expected seasonal cycle of decreasing salinity, with sea-ice thaw forming a shallow mixed layer, which enhances the associated warming rates and strengthens stratification (see conceptual model, Fig. 6). It is well known that the summer increase in carbonate at the ice shelf ocean domain around Antarctica is highly correlated to the response of primary production to summer surface boundary layer dynamics (Roden et al., 2013; Shadwick et al., 2013, Taylor et al., 2013; Mattsdotter Björk et al., 2014). Our results are consistent with these studies and highlight the importance of summer primary production (Fig. 4) in the EWG as a key element to creating a more suitable habitat for calcifiers by reducing surface water pCO2 resulting in an increase in surface water pH and âĎęA. The direct impact on the biology is driven by the magnitude of omega but the seasonal magnitude of the delta omega is influenced by the phasing of the sea ice thaw and its impact on the spring-summer phytoplankton blooms."

line 10-25: this sections needs much more explanation of details a coherent though in this section lacking- rewrite can you include magnitude difference for Temp, salinity in Table1? Thank you, we agree that this section is not clear. We feel that there

was a lot of repetition and we have addresses this by rewriting the section. We hope that this addresses your comment. "Our data showed coherence in the response of âĎęA (mean summer increase in âĎęA $\sim$ 0.77) to variability in buoyancy (temperature and salinity) and wind stress forcing (Fig. 3, 5, 6). Temperature (Fig. 3i-l) and salinity (Fig. 3e-h) reflect an expected seasonal cycle of decreasing salinity, with sea-ice thaw forming a shallow mixed layer, which enhances the associated warming rates and further strengthens stratification (see conceptual model, Fig. 6). It is well known that the summer increase in carbonate at the ice shelf ocean domain around Antarctica is highly correlated to the response of primary production to summer surface boundary layer dynamics (Roden et al., 2013; Shadwick et al., 2013, Taylor et al., 2013; Mattsdotter Björk et al., 2014). Our results are consistent with these studies and highlight the importance of summer primary production (Fig. 4) in the EWG as a key element to creating a more suitable habitat for calcifiers by reducing surface water pCO2 resulting in an increase in surface water pH and âĎęA. The direct impact on the biology is driven by the magnitude of omega but the seasonal magnitude of the delta omega is influenced by the phasing of the sea ice thaw and its impact on the spring-summer phytoplankton blooms. What is remarkable in our data set are the contrasting magnitudes of both seasonal and intraseasonal variability in surface water temperature, salinity and âĎęA observed during the four year period. Arrigo et al (2008) show how seasonal modulation of stratification and the mixed layer depth through the entrainment of denser WW reflects variability in the relative magnitudes of buoyancy and mixing. We propose through our conceptual model (Fig. 6) that the two key drivers of this variability in seasonal cycles are: the rate of sea ice thaw, which is the primary driver of surface water density (buoyancy forcing) and stratification through its impact on salinity (Fig. 3e-h, 6a-d), and wind stress (Fig. 5e-h), which regulates the mixing fluxes."

line 20: where is this seen in figure 4g, h? We agree that in Figure 4 (now Fig. 3)g and h, the summer increase/decrease in SST and SSS is not as much as in the other two years. This said we do feel that there is still a seasonal decrease in SSS and increase in SST but it is just less than in other years. Salinity decreases in both Fig 3g and Fig

3h as summer progresses. The decrease is less than in the previous two years but there is still a decrease. We hope that this addresses your comment.

1663: lines 10-25: please, constrain how biological processes impact saturation state. Thank you, we agree that this is important. The impact of biological processes on saturation state is approximately 0.7, which is double that of the physics. This has been added to the manuscript. "During our four summers of data collection, the extremes of the temperature and salinity properties of the surface boundary layer temperature ranged from supercooled temperatures of -2oC and 0.5 oC and high salinities of 34.1 – 34.3 in WW, to a relatively warmer (T$\sim$0.5 °C) and fresher (S$\sim$33.2 – 33.9) Summer Surface Layer (SSL) (Fig. 3). These physical constraints support the view that the maximum contribution from seasonal temperature and salinity changes to ∆âĎęA at the EWG ice shelf is about $\sim$ 0.15, which is about 50% of what is observed for years in which ∆âĎęA remains low (2009/2010 and 2011/2012, Table 1). WW outcrops with a mean pCO2 of 410-415μatm, indicating that outgassing to atmospheric equilibrium could also play a role in the adjustment of seasonal âĎęA. Assuming that atmospheric pCO2 was 394μatm, degassing would contribute to a ∆âĎęA $\sim$ 0.14. Thus, collectively all non-biological processes could result in a seasonal ∆âĎęA $\sim$ 0.3, which compares closely to the observed ∆âĎęA in the low âĎęA summer periods of 2010 (∆âĎęA $\sim$0.46) and 2012 (∆âĎęA $\sim$ 0.59), (Table 1). We can thus estimate the biological contribution to ∆âĎęA $\sim$ 0.7, more than double that of the non-biological processes. This suggests that in years of low primary production, the contribution of biology, degassing and temperature are approximately equal, whereas in years where primary production is relatively high, the contribution from biological processes is approximately double that of physical processes. The differences among these low (2009/2010 and 2011/2012) and high (2008/2009 and 2010/2011) primary production years are thought to reflect the impact of the late thaw of sea-ice cover (Fig. 5), which reduced the impact of degassing on ∆âĎęA during the summers of 2009/2010 and 2011/2012."

1664, line 1-5: provide some quantification If we are reading this comment correctly

you are asking us to quantify the contribution of physical and biological processes to changes in ∆âĎęA, this has been dome earlier in the section (see above). line 15-20: where are this data corroborated? This data is corroborated in Figs 5 and 6 and this has been added to the manuscript. "During all years, the extent of summer blooms (Fig 5) seemed to be reliant on the complex interaction between the timing and rate of sea ice thaw (Fig 6), its impact on stratification dynamics, the regulation of the supply of nutrients, including dFe (Geibert et al., 2010; Taylor et al., 2013) and alleviation of light limitation (Thomalla et al., 2011)." 1665, line 7-20 (25): provide more detailed quantification Thank you, we agree that this section could be more quantitative and we have addresses this by adding values for Chl-a and omega.

"Among the four summer periods we investigated, we found two "optimal" scenarios where sea ice thaw was initiated in late November resulting in higher âĎęA (summer maximum âĎęA > 2), (Fig. 3a,c) and two extreme low âĎęA scenarios when sea ice thaw was initiated later, in early December (summer maximum âĎęA < 1.7), (Fig. 3b,d). The optimal summer scenarios both had a ∆ $\sim$ 0.4 during the bloom period (Fig. 3 and 5). The extreme low âĎęA seasonal states showed ∆ < 0.4 and ∆ > 0.4. The two "optimal" austral summer periods of 2008/2009 and 2010/2011, when sea ice thaw began in late November, closely phased with critical seasonal PAR (Thomalla et al., 2011), resulted in elevated early summer (December) phytoplankton biomass (chl-a > 4μg.l-1) and âĎęA (âĎęA > 1.6). The corresponding seasonal periods in 2009/2010 and 2011/2012 when sea ice thaw only began in mid-late December - early January (Fig. 5b,c) resulted in low chl-a (chl-a < 2μg.l-1) and we assume a low early summer âĎęA (Fig. 3b, d). Therefore, we propose that the two primary factors influencing the magnitude of summertime primary production and hence the summer increase in surface water âĎęA are the timing of sea ice thaw and the variability of the forcing (buoyancy and mixing) controlling stratification and MLD."

1666, line 3: what about year 2011? Thank you for this comment. We first discuss the two late thaw years (2009/2010 and 2011/2012) and then we discuss the two "optimal" thaw years. Year 2011/2012 is discussed below the year 2009/2010 in the following paragraph (1666, lines 20-29 and 1667, lines 1-4). “The second seasonal extreme low ΔâĎęA scenario was observed during the summer of 2011/2012 (Fig. 3d). Delayed sea-ice thaw (> 60% cover in early January 2012) and its associated weak buoyancy forcing, linked with elevated wind stress (τ > 0.5Nm-2), (Fig. 5d, h) resulted in persistence of deep mixed layers (Fig. 4d) typical of winter and reflected by the elevated salinities and low temperatures (Fig. 3h,l). During most of the summer Δ < 0.4, suggesting that the water column stability was not sufficient to facilitate a significant summer bloom, despite relatively rapid sea ice thaw rates in January (mean monthly loss of $\sim$ 1.5% cover per day). There was, however, a three day period where $\Delta \sim$ 0.4 which coincided with a rapid increase in Chla (Fig. 4e) and thus in âĎęA (Fig. 3d). In the SO, where light can be a limiting factor for photosynthesis, a deep (MLD > 45m), well mixed water column results in mixing phytoplankton below the 1% light level creating a light limited seasonal regime (Fig. 6). We suggest that this explains the decreased biomass that resulted in the observed high mean summer surface water fCO2 of 322.9$\pm$38μatm and low mean summer âĎęA of 1.51$\pm$0.13.”

line 20-30: where is the rate of thawing explicitly quantified? elaborate on this. Thank you, we have addressed this by quantifying the rate of ice thaw in the manuscript (see above). It is also quantified in Figure 5a, b, c and d.

1667: lines 5-25: define error and variability extent of the changes in density. Thank you. We have calculated the error in density to be < 0.01, using the instrument precision for SST and SSS. We have addressed this by added a sentence into our methods that defines the variability in SST, SSS and . We hope that this addresses your comment. “The error of < 0.01kg.m-3 for is linked to the precision of the instrumentation for SSS (0.012) and of SST (0.002°C).” 1668: bio effects: needs to be stressed out that this is all on surface, sub-surface undersaturation states will have even more impact on biology Thank you, we have stressed that this is all on the surface. “As proposed by our conceptual model (Fig. 6) there seems to be a threshold density anomaly Δ of around

0.4 kg.m-3, when surface water stratification supported an amplified response of primary productivity as reflected by large biomass and âĎęA anomalies. Two aspects of these seasonal dynamics are notable: firstly, the sensitivity of the seasonal bloom to the phasing of the onset of sea-ice thaw and light flux control, and secondly, the sensitivity of the bloom to the intraseasonal characteristics of the MLD. As discussed earlier, in these systems sea-ice thaw is the primary buoyancy driver, with warming from solar heating as a secondary factor which amplifies the primary freshwater flux-driven stratification. Under optimal seasonal phasing, melting sea ice injects buoyancy into the residual WW in the surface layer during late November/early December when the seasonal light availability is high enough to trigger photosynthesis (Thomalla et al., 2011). Variability in âĎęA can be further understood by looking at the influences of photosynthesis and dilution on surface water TA and DIC. Surface water âĎęA is influenced by fresh water fluxes, largely through dilution of TA and by primary production, mainly through uptake of DIC (Fig. 7). The vector plot (Fig. 7) shows the contribution made by dilution and primary production to the residual evolution of surface water âĎęA during an ‘optimal’ summer (2010/2011) and during a low âĎęA summer (2012). During the ‘optimal’ summer, early sea ice thaw and strong surface stratification resulted in increased photosynthesis and thus in ΩA which increased by approximately 0.8 from its winter value (Fig. 7). During January 2012 when summer sea ice thaw was relatively late and the stratified summer period very short, primary production was much lower, which limited the summer ΩA increase to approximately 0.4 (Fig. 7). This highlights the importance of sustained summer phytoplankton blooms in increasing surface water ΩA for creating pteropod habitats where âĎęA increases from its winter minimum. Potential impacts of interannual seasonal variability on the sensitivity of the system to increasing anthropogenic CO2 are now examined.“

1669, line 17-18: what about anthropogenic CO2? Thank you, we forgot to include this. Anthropogenic CO2 has been added. 1670: line 20 and below: compare to the studies that are showing increase in phyoplankton production Thank you, we have added this: “Contrastingly, Greene and Pershing (2007) show that with increased stratification in polar regions, primary production has been observed to increase, highlighting the complexity of these predictions."

1671: line 13: repeated text Thank you, this repeated text has been removed line 25: where is omega value of 1.5 coming from? here define how will feeding impact pteropods, see Seibel et al., 2012 study, compare the years for pteropods. We approximated "low" omega a to be around 1.5 but we see that this is not an accurate estimate. We have rewritten this section on ecosystem implications and we hope that this will address your comments around the weakness of this section, thank you. "4 Implication of near-future carbonate trends on pteropods in the Weddell Sea ecosystem.

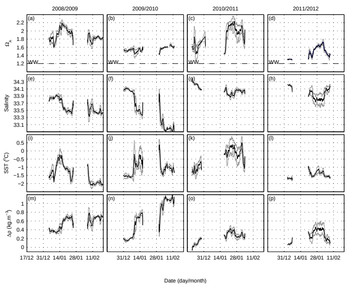
With their thin aragonite shells that start to dissolve with the onset of corrosive waters (âĎę≤1), pteropods are considered to be one of the early warning indicators (Orr et al., 2005) for observing, understanding and constraining the biological effects of ocean acidification on a seasonal and interannual time scales in the Southern Ocean. Pteropods are regionally significant components of the Southern Ocean pelagic ecosystem. With high ingestion rates (Bernard and Froneman, 2009) and a large contribution to total grazing, pteropods play an important role in vertical carbon fluxes (Manno et al., 2010; Accornero et al., 2003) and energy transfer to higher trophic levels as a diet component of various zooplankton groups, pelagic and demersal fish and birds (Hunt et al., 2008). In the Weddell Sea pteropods are an important component of macrozooplankton community, contributing up to 17% of the zooplankton biomass (Boysen-Ennen and Piatkowski, 1991). In the northern Weddell Sea, Clio pyramidata is a characteristic species of the oceanic community, while in the southern Weddell Sea Limacina helicina dominates zooplankton community with more neritic distribution (Boysen Ennen and Piatkowski, 1991). Based on the reported length size of Limacina helicina in the Weddel Sea (Hunt et al., 2008), 2-3 year life cycle can be assumed, with juveniles dominating the population up to 98% in the austral summer (Bednaršek et al., 2012). Juveniles, with the lipid content of around two to three times higher than in the later stages (Gannefors et al., 2005), depend on phytoplankton

blooms to gain enough energy to favor their survivorship during winter (Siebel, 2000), particularly in the environments characterized by extreme spatial and temporal food patchiness (Kattner et al. 1998, Phleger et al. 1998). Thus, phytoplankton blooms to a large extent determine spatial and temporal variability in pteropod abundances and also the timing of the spawning (Comiso et al., 1993; Seibel and Dierssen, 2003). Low food availability ($\sim$ < 1 mg m-3) during the growth can have severe consequences with reduced metabolic rates followed by metabolic suppression, delayed spawning and failed reproduction (Maas et al., 2011, et al., 2013),) in the population with high natural mortality rates of 98 % (Bednaršek et al., 2012). In addition to food deprivation, ocean acidification is another stressor that can impact the same vital biological processes. At the aragonite saturation states predicted in the natural environment of Weddell Sea by 2050, increased effect of ocean acidification can contribute to reduced metabolic scope (Seibel et al., 2013), ceased shell calcification (Comeau et al., 2010), reduced shell growth (Lischka et al., 2011) and increased shell dissolution (Bednaršek et al., 2012; 2014) Moreover, OA is not only decreasing thermodynamic favorability for calcification but might also increase the 'costs' for other vital biological processes that can ultimately impact survival (Wood et al., 2008). While food deprivation predominantly impact seasonal recruitment and mortality, OA imposes chronic stress on long-term pteropod standing stock. This makes pteropods increasingly dependent on sufficient phytoplankton production to offset the cost of the biological trade-offs.

Ocean acidification will have indelible effect on pteropod population but we can predict the impacts with much more certainty if we take combined effect of ocean acidification and food deprivation into consideration as a base to construct 'optimal' scenarios for pteropod population. Currently, at no time in the course of this four year data set was the system close to values where the negative effects of ocean acidification occurred, however low food availability during the late thaw season in 2010 and 2012 was within the range to suppress metabolic scope and impose physiological stress on the juvenile pteropods. However, by 2050 the extent of ocean acidification in the unfavorable late thaw years with reduced food availability (as observed in 2010 and 2012) might create seasonally imminent habitat loss, the extent of it being depended on the growing trend of stronger than expected interannual variability in the seasonal cycle of aragonite saturation state. Pteropods will become increasingly more vulnerable due to prolonged (3-4 months) exposure of near-saturation state (âĎę∼1), where severe shell dissolution becomes predominant process and calcification decline by 50-60% (Comeau et al., 2010) cannot offset dissolution (Bednaršek et al., 2014). Combined with low energy supply from phytoplankton biomass in the years with too much or too little freshwater fluxes, reduced energy budget might potentially not allow for sufficient recruitment or trade-offs of increased costs. These years could be the tipping points resulting in lower abundances in the following years. These changes will also have biogeochemical implications with reduced sinking fluxes and decreased carbonate sequestration to the ocean depth (Bednaršek et al., 2014). Given their 2-year life cycle before reaching their maximum reproductive effort, they have 45-50 generations by 2100 to adapt to the changes, allowing for limited capacity for adaptation but with possible changes in acclimatization scope or migration. On the other hand, given sufficient frequency of the 'optimal' years with early thaws this might offset the effects of late thaw years and allow for the sustainability of pteropod population. The Weddell Sea might seasonally become a 'refugia' for Southern Ocean pteropods under increasing ocean acidification by 2100 where pteropods can be considered an indicator of good health of the ecosystem (Seibel and Dierssen, 2003). These data suggest that inter and intra seasonal variability in the physics and biogeochemistry of the surface boundary layer may not only be key factors in ecosystem forcing but may also reflect an additional sensitivity to long term CO2 forcing of these high latitude systems. Moreover, it creates the framework for understanding how the ecosystem vulnerability depends on the seasonal and long term dynamics of both the climate-related bottom-up physics forcing, which this paper is advancing and the top-down anthropogenic CO2 that drives OA. However, other accompanying stressors, such as an increased freshening and warming in the Weddell Sea (Smedsrud et al., 2005; Hellmer et al., 2011) that are known to directly impact survival of shelled pteropods have to be taken into consideration when consid-

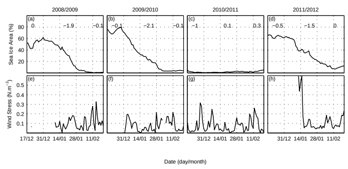
ering ecological and biogeochemical implications."

Interactive comment on Biogeosciences Discuss., 12, 1653, 2015.



Student Version of MATLAB

Fig. 1.



Student Version of MATLAB

Fig. 2.