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

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BGD 12, C827–C829, 2015 Interactive Comment Full Screen / Esc Printer-friendly Version Interactive Discussion Discussion Paper Biogeosciences Discuss., 12, C827–C829, 2015 www.biogeosciences-discuss.net/12/C827/2015/ © 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.



Anonymous Referee #1 Received and published: 26 March 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.

The submitted manuscript deals with variability in the saturation state of aragonite (ÎRar) in an Antarctic shelf region. The drivers of summertime Î ′ Rar are physics and ′ biology, with the latter being driven by physics through the timing of the melting of seaice and hence light availability. Also nutrient availability and supply play key roles (incl. Fe). Observations of carbonate chemistry variability have been made by other authors for both Arctic and Antarctic regions. The quality of the data is fine, with a somewhat high value for the precision of the DIC measurements. It is unclear whether nutrient concentrations were taken into account for the TA calculation. C827 BGD 12, C827–C829, 2015 Interactive Comment Full Screen / Esc Printer-friendly Version Interactive Discussion Discussion Paper Overall, the work is interesting but the draft of the manuscript should have gone through quite a couple of more cycles of internal reviews by the authors. There are many spelling errors, repeats and a weak structure. It is very hard to follow the storyline in the paper, as issues are repeated and key processes are not very clearly presented. The manuscript is too long. The paper lacks from a clear statistical approach in the data interpretation. Are there significant relationships between the observed variables? The shelf region of the Antarctic continent is an important region for study of variations in carbonate chemistry under climate change conditions. The topic of the manuscript is important. The contribution by this paper, in its current form, is however insufficiently strong to make a good impact. P 1654 Abstract. The abstract is very hard to read, with poor sentence phrasing and lack of quantification. The reasoning is hard to follow. Line 2: its???? What is its? line 4/5: seasonal cycle of what? Variability of what? Which ecosystem? In case seasonal cycles are unclear, then this study will not address this through summer sampling. Line

7: drivers of what? Seasonal cycle of what? How can a seasonal cycle play a role in saturation state variability: cycle of what? Line 8: what is seasonal phasing? Line 10: how can a summer be optimal Line 12: what actually was the value of the saturation state Line 15: what impact on the mixed layer? Line 23: why would primary production decrease in future P 1655 Line 12: I am not sure what is depicted as the Revelle Factor. The definition here is unconventional. Line 13: what does sensitive mean here? Line 1 and 15: is meant here: atmospheric anthropogenic CO2? Line 18: undersaturation also results in corrosion of shells. Line 23: there is also plenty of literature that indicates no effects of high CO2 on calcification processes, or even enhanced calcification! P 1656 Line 17: PAR should be light availability P 1657. GPS: spell out Section 2.1: this is confusing. Read again carefully and explain carefully what was measured where, and using which instruments. Line 20: confusing to have this statement here in technique section. P 1658. Line 6. What is a 50% HgCl solution? 50% of what? Line 9: what CRM was analysed? Were nutrients analysed for the TA C828 BGD 12, C827–C829, 2015 Interactive Comment Full Screen / Esc Printer-friendly Version Interactive Discussion Discussion Paper calculation? Line 13: should be: van Heuven How was chl a analysed? P 1659: sea ice concentration. This is an awkward phrase. Fig. 1: the cruise was actually between the S Sandwich Islands and the continent. It is not clear from the text where samples were collected over the years, on what cruises, at what depth and with what approaches. Fig is difficult to read, with black dots on grey background and overlapping coloured dots. Fig. 2: I am not sure what fig. 2a shows. It seems to be T, but the caption mentions omega? What are the black numbers? Fig. 3. The Lee TA calculation has its limitation, which has been shown in a number of publications. I am not sure whether Fig 3 adds anything to the message of the manuscript. P 1661: Line 12-13: why? Many calcifiers appear to grow happy under low saturation states. P 1662: line 10. The paper has many CTD sections. Why are these not used? P 1664. Start of section 3 contains many repeats of previous statements p 1665. Line 6. Is there data on nutrient supply? P 1667, line 13: is there sea ice cover or not for the bloom to proceed. This is unclear. P 1669, line 5. It is better to use the recent IPCC



projections for CO2. Line 20. I am not sure what is meant by:' they increased. . ...' Was this a model or observational study. How was SS and ST increased. Unclear. P 1670 Line 3 It is not clear to me how the authors' model operates. Interactive comment on Biogeosciences Discuss., 12, 1653, 2015. C829

Response to: Anonymous Referee #1 Received and published: 26 March 2015 1. It is unclear whether nutrient concentrations were taken into account for the TA calculation Thank you, we agree that this was unclear in our methods. Nutrient concentrations were taken into account for the TA calculations and we have explained this in the manuscript. TA was corrected for NO3 uptake. "In January 2011 we completed a CTD and Underway CTD (UCTD) transect (64 stations), extending between South Georgia Island and the Antarctic ice shelf (70-58°S 9-25°W), using a nominal spatial resolution of 20 nautical miles. Niskin bottle water samples (24 per CTD cast) were collected from relevant depths to ensure that specific features were captured: surface, thermocline, chlorophyll a (chl-a) maximum, bottom of chl-a maximum and export depth. Thus, each CTD cast sampled water at different depths from the surface to 300m in order to measure chl-a , DIC, Total Alkalinity (TA) and nutrients (nitrate, silicate and phosphate). In addition, 48 CTD profiles were conducted at two locations at the Antarctic ice shelf edge (cyan circles in Fig. 1) over the austral summers of 2009, 2010, 2011 and 2012 to assess physical and biogeochemical processes and related interannual variability (Fig. 4). Chl-a was measured by vacuum filtering 250ml of water through Whatman GF/F filters. Chi-a was extracted with 8ml acetone for 12-24 hours. Raw fluorescence was read using a Turner design trilogy laboratory fluorometer, calibrated onshore before the voyage. The chl-a concentration ($\mu$g.l-1) was derived using the slope of a calibration curve of known chl-a concentrations. To measure DIC and TA, ship based analysis samples were stored in 500ml bottles spiked with 200 $\mu$L of 50% diluted HgCl2 (Mercuric Chloride) solution. These samples were analysed in situ using the Marianda Versatile Instrument to determine total inorganic carbon and titration alkalinity (VINDTA 3C),). Certified Reference Materials (CRM),from the Marine Physical laboratory, Scrips Institute of Oceanography, San Diego were run before and after each batch and every fifth sample was run as a duplicate to determine the accuracy and the reproducibility of the VINDTA. Raw TA and DIC data were post-calibrated and corrected for nutrient uptake using nutrient data from the CTD casts and the MATLAB script (VINDTA_CALCALK) by van Heuven. The precision of the DIC and TA data was determined by analysis of CRM's (Dickson and Goyet, 1994) and was found to be 3.10$\mu$mol.kg-1 and 2.60$\mu$mol.kg-1, respectively."

2. Spelling errors, repeats and a weak structure Thank you, we have taken note of this and have corrected the spelling errors and have improved the structure of the paper. The abstract was difficult to follow and we have addressed this by rewriting it: "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 $\Omega$A 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." We also felt that the ecosystem implications needed to be improved and we have thus rewritten section 4: "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$\leq$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 (∼ < 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 considering ecological and biogeochemical implications." We have improved the overall structure of the manuscript and corrected the spelling errors. We hope that this addresses your comment.

3. Are there significant relationships between the observed variables? Thank you for this valuable comment. We have calculated the relationship between omega and delta rho and in all four years, $p < 0.001$. The R2 values for omega and delta density for each year are: 2008/2009 R2 = 0.253 2009/2010 R2 = 0.208 2010/2011 R2 = 0.668 2011/2012 R2 = 0.436 Although these values are all significant, the relationship between omega and delta rho is not linear, rather it is a threshold problem. It has linear ranges above and below the delta omega value of 0.4 above and below which omega decreases. Due to this non-linear relationship, we think that adding these linear statistical metrics unnecessary. Our conceptual model is an attempt to explain the threshold response between these two variables. We hope that this answers your question. 3. The abstract is very hard to read, with poor sentence phrasing and lack of quantification. The reasoning is hard to follow. Thank you, we have addressed this comment by rewriting the abstract (see above). Line 2: its???? What is its? We agree that this sentence did not make sense, thank you. “Its” is referring to (âĎęA) and we have changed the sentence to: “As anthropogenic $CO_2$ increases, surface water aragonite saturation state (âĎęA) decreases, negatively affecting calcifying Euthecosome pteropods and the wider Antarctic ecosystem.” line 4/5: seasonal cycle of what? Thank you, we agree that we were not clear here. The seasonal cycle is referring to the seasonal cycle of the physical (sea ice thaw and wind-induced mixing) and biological (photosynthesis) processes. This sentence has been changed to: “However, our understanding of the seasonal cycle and interannual variability of the physical (density and mixing) and biological (photosynthesis) marine processes in this vulnerable Antarctic ecosystem remains limited.” Variability of what? Thank you, we agree that this was not clear. The variability was referring to the variability of âĎęA and we have changed the relevant sentence to include this. “This study examines surface water âĎęA from four consecutive summers in the Eastern Weddell Gyre (EWG) ice shelf region, and investigates the drivers of (âĎęA) variability and the role played by the seasonal cycle of physical



(sea ice thaw and wind-induced mixing) and biological (photosynthesis) processes in the interannual variability of âĎęA.” Which ecosystem? Thank you, we were not being explicit here. We were referring to the Antarctic ecosystem. This has been added (see above). In case seasonal cycles are unclear, then this study will not address this through summer sampling. We agree with this comment as this study was conducted over four summer periods. When we refer to the seasonal cycle we are making the assumption that during winter, sea ice covers this region and thus we can estimate the winter surface water conditions. Line 7: drivers of what? Thank you, we were referring to the drivers of âĎęA variability. This has been made clearer in the manuscript (see above). Seasonal cycle of what? How can a seasonal cycle play a role in saturation state variability: cycle of what? Thank you, we agree that this was unclear. We were referring to the seasonal cycle of physical (sea ice thaw and wind-induced mixing) and biological (photosynthesis) processes. This has been corrected in the manuscript (see above). Line 8: what is seasonal phasing? Thank you, are aware that this may be confusing and that the use of seasonal phasing here is not clear. We used seasonal phasing to mean the timing of the variability in the seasonal cycle, but we agree that this should be changed in this sentence. We have corrected the sentence to: “Interannual variability in the timing and the rate of the summer ice thaw were the primary factors explaining interannual variability in surface water âĎęA.” Line 10: how can a summer be optimal In this study we have defined “optimal” summers as the summers when the timing of sea ice thaw was in phase with the initiation of summertime phytoplankton blooms and resulted in a large increase in omega. As we only explain this later on in the paper, we agree that it does not make sense here in the Abstract. We have changed the sentence to: “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.” Line 12: what actually was the value of the saturation state Thank you, we agree that we should have added more values to our abstract. The summer increase in saturation state in the two summers when sea ice thaw was delayed to late December (2009/2010 and 2011/2012), was 0.46 in 2009/2010 and 0.59 and 2011/2012. This has been added to the abstract (see above). Line 15: what impact on the mixed layer? Thank you, we agree that it was not clear what the impact on the mixed layer was. We found the timing and the rate of sea ice thaw to impact the depth of the mixed layer. We have changed the sentence to read: "We propose that two critical climate (physical-biogeochemical) sensitivities for $\Omega$A 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." Line 23: why would primary production decrease in future? From the studies that we have read, it seems as if, with an increase in surface water temperature and thus stratification, there will be a decrease in nutrients to the euphotic zone and thus a decrease in primary production. We did not make this clear in our manuscript and we have changed the last sentence to: "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 $CO_2$ 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 $CO_2$, may culminate in the emergence of EWG summertime surface water aragonite undersaturation by the middle of this century."

P 1655 Line 12: I am not sure what is depicted as the Revelle Factor. The definition here is unconventional. Thank you, we agree that this was not the most accurate formula to use for Revelle factor. The Revelle Factor definition has been changed to: $(\partial \ln[CO_2]/\partial \ln DIC)$. "The high Revelle Factors $(\partial pCO_2/\partial DIC)*DIC/pCO_2$, where DIC is Dissolved Inorganic Carbon) and cold water temperatures in Polar Regions, make aragonite saturation state (âĎęA) in these areas more sensitive to increases in $CO_2$ (Sabine et al., 2004; Egleston et al., 2010)." Line 13: what does sensitive mean here? Thank you, we have taken note that we did not specify what the sensitivity was referring



to. Sensitive is referring to the sensitivity of aragonite saturation state. We have added this to the manuscript so that the sentence now reads:

"The high Revelle Factors $(\partial pCO_2/\partial DIC)*DIC/pCO_2$, where DIC is Dissolved Inorganic Carbon) and cold water temperatures in Polar Regions, make aragonite saturation state (âĎęA) in these areas more sensitive to increases in $CO_2$ (Sabine et al., 2004; Egleston et al., 2010)."

Line 1 and 15: is meant here: atmospheric anthropogenic $CO_2$? Thank you, we agree that this was not clear. We did mean anthropogenic $CO_2$ in the atmosphere and we have corrected this in the manuscript. "Rising atmospheric, anthropogenic $CO_2$ is increasing surface water [$CO_2$], which decreases ocean pH as well as the carbonate saturation level (âĎęA), a process called ocean acidification (Caldeira and Wickett, 2003; Doney et al., 2009). Changes in temperature and salinity can, through their impact on the equilibrium constants of $CaCO_3$, also have an indirect influence on the relative variability of pH and âĎęA (Zeebe and Wolf-Gladrow, 2001; Millero et al., 2006). Ocean acidification is threatening global marine ecosystems by modifying fundamental chemical and biological processes (Fabry et al., 2008). Oceans have absorbed approximately a third of the atmospheric anthropogenic $CO_2$ (Sabine et al., 2004), moderating the effects of climate change (Solomon et al., 2009). This oceanic $CO_2$ sink is not without consequence – having already caused a 0.1 decrease in surface ocean pH and a shoaling of the calcite and aragonite saturation horizons (Orr et al., 2005). Oceans demonstrate variable sensitivities to increases in $pCO_2$, which depend on regional buffering capacity (Egleston et al., 2010). The high Revelle Factors $(\partial pCO_2/\partial DIC)*DIC/pCO_2$ , where DIC is Dissolved Inorganic Carbon) and cold water temperatures in Polar Regions, make aragonite saturation state (âĎęA) in these areas more sensitive to increases in $CO_2$ (Sabine et al., 2004; Egleston et al., 2010)."

Line 18: undersaturation also results in corrosion of shells. Thank you, we agree that this should have been included and we have added this to the manuscript. "Marine calcifying organisms such as coccolithophores, pteropods, molluscs and corals rely on carbonate supersaturated state > 1 waters to minimize energy costs for the formation of their shells and skeletons (Fabry et al., 2008). Under natural and experimental conditions, elevated seawater pCO2 has a variety of detrimental effects on marine calcifiers, including decreases in respiration rates (Hennige et al., 2014), shell corrosion and reductions in calcification rates (Crook et al., 2013) and reductions in growth rates and development (Kroeker et al., 2013)." Line 23: there is also plenty of literature that indicates no effects of high CO2 on calcification processes, or even enhanced calcification! Thank you, we have taken note of this and have added three references in to demonstrate this important point. "However, there have also been many studies demonstrating varied responses in marine calcifying species to increases in pCO2 (Ries et al., 2009; Maas et al., 2012; Roberts et al., 2014). These studies highlight the complexities and the sensitivity of many calcifying species, and hence ecosystems, to ocean acidification."

P 1656 Line 17: PAR should be light availability This has been changed, thank you. P 1657. GPS: spell out This has been spelled out, thank you. Section 2.1: this is confusing. Read again carefully and explain carefully what was measured where, and using which instruments. Thank you, we agree that this section was unclear and confusing. We have made corrections so that the instruments and sampling procedures are more clearly explained. "2.1 Underway Data The partial pressure of CO2 (pCO2) was determined quasi-continuously in surface water and in the marine atmosphere. This was done using an underway, General Oceanics equibrator-based system with a Li-COR LI-7000 infra-red gas analyser, designed after Wanninkhof and Thoning (1993) and described by Pierrot et al (2009). Four reference gases of known pCO2 (pCO2: 0.00, 357.32, 377.8 and 427.83ppm), provided and cross-calibrated to international standards by the GAW station at Cape Point, were used during the cruise to calibrate the instrument. Fugacity of carbon dioxide (fCO2) was calculated from pCO2, sea surface temperature (SST) and salinity (SSS). Ancillary instruments logged onto the underway pCO2 analyser include a Global Positioning System device, an atmospheric pressure probe situated 5m above the equilibrator in a deck housing, a thermometer



to measure intake temperature (the inlet pipe was situated near the keel at 5m depth), a Fluke digital thermometer and a differential barometer to measure the equilibrator temperature, and pressure relative to atmospheric pressure, a Turner 10-AU fluorometer, and an Idronaut multisensor that measures the sea surface temperature (SST) and salinity (SSS). Surface water density () was calculated from SST and SSS. 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).2.2 Conductivity-Temperature-Depth (CTD) data In January 2011 we completed a CTD and Underway CTD (UCTD) transect (64 stations), extending between South Georgia Island and the Antarctic ice shelf (70-58°S 9-25°W), using a nominal spatial resolution of 20 nautical miles. Niskin bottle water samples (24 per CTD cast) were collected from relevant depths to ensure that specific features were captured: surface, thermocline, chlorophyll a (chl-a) maximum, bottom of chl-a maximum and export depth. Thus, each CTD cast sampled water at different depths from the surface to 300m in order to measure chl-a , DIC, Total Alkalinity (TA) and nutrients (nitrate, silicate and phosphate). In addition, 48 CTD profiles were conducted at two locations at the Antarctic ice shelf edge (cyan circles in Fig. 1) over the austral summers of 2009, 2010, 2011 and 2012 to assess physical and biogeochemical processes and related interannual variability (Fig. 4). Chl-a was measured by vacuum filtering 250ml of water through Whatman GF/F filters. Chi-a was extracted with 8ml acetone for 12-24 hours. Raw fluorescence was read using a Turner design trilogy laboratory fluorometer, calibrated onshore before the voyage. The chl-a concentration ($\mu$g.l-1) was derived using the slope of a calibration curve of known chl-a concentrations. To measure DIC and TA, ship based analysis samples were stored in 500ml bottles spiked with 200 $\mu$L of 50% diluted HgCl2 (Mercuric Chloride) solution. These samples were analysed in situ using the Marianda Versatile Instrument to determine total inorganic carbon and titration alkalinity (VINDTA 3C),). Certified Reference Materials (CRM), from the Marine Physical laboratory, Scrips Institute of Oceanography, San Diego were run before and after each batch and every fifth sample was run as a duplicate to determine the accuracy and the reproducibility of the VINDTA. Raw TA and DIC data were post-calibrated and corrected for nutrient uptake using nutrient data from the CTD casts and the MATLAB script (VINDTA_CALCALK) by van Heuven. The precision of the DIC and TA data was determined by analysis of CRM's (Dickson and Goyet, 1994) and was found to be 3.10$\mu$mol.kg-1 and 2.60$\mu$mol.kg-1, respectively."

Line 20: confusing to have this statement here in technique section. Thank you, we agree that this statement is confusing here and we have thus moved this statement to the end of section 2.3 as this section deals with the calculation of winter water.

"2.3 Characterisation of Winter Water (WW) Residual WW is defined by a potential temperature ($\theta$) minimum in the winter mixed layer (WML), following Jones et al (2010) and Geibert et al (2010) and found between 55-110m depth (Fig 2a). WW âĎęA was derived from the mean TA and DIC concentrations in the WML using the CO2Sys code (Lewis and Wallace, 1998). Following the definition of the WML and calculating the WW based on the mean TA and DIC therein, gave a WW âĎęA of 1.3 (Fig. 2a). A contour of âĎęA from the ice shelf to 61.5°S was plotted using the bottle CTD data (Fig. 2b). The change in density ($\Delta$) from WW (WW$\sim$ 1027.61 kg.m-3) to summer surface water was calculated."

P 1658. Line 6. What is a 50% HgCl solution? 50% of what? Thank you, we agree that this is not clear. The 50% HgCl2 (Mercuric chloride) solution was made up by diluting saturated HgCl2, by 50%. We have added this into the manuscript to clarify this, (see section 2.1 above) Line 9: what CRM was analysed? The Certified Reference Material (CRM) for TA and DIC were from the Marine Physical laboratory, Scrips Institute of Oceanography, San Diego. We have added this to the manuscript, thank you. See section 2.1 above. Were nutrients analysed for the TA C828 BGD 12, C827–C829, 2015 Interactive Comment Full Screen / Esc Printer-friendly Version Interactive Discussion Discussion Paper calculation? Thank you, this follows on from your initial comment about whether nutrient concentrations were used for TA corrections. There is nutrient data for the CTD stations where TA and DIC were analysed and we have added a sentence to the methods to clarify this. "Thus each CTD cast sampled water at different



depths from the surface to 300m in order to measure Chlorophyll a (chl-a), DIC, Total Alkalinity (TA) and nutrients (nitrate, silicate and phosphate)." Line 13: should be: van Heuven Thank you, van Heuven has been corrected. How was chl a analysed? Thank you very much for drawing our attention to this important detail. The methods for the analysis of chl-a have been added to the methods (see section 2.1 above). P 1659: sea ice concentration. This is an awkward phrase. Thank you, we agree that this is an awkward phrase, and the sentence has been changed to: "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)." Fig. 1: the cruise was actually between the S Sandwich Islands and the continent. It is not clear from the text where samples were collected over the years, on what cruises, at what depth and with what approaches. Fig is difficult to read, with black dots on grey background and overlapping coloured dots. Thank you, we agree that this figure is not easy to read. Unfortunately we are not able to show all the detail on one map. We tried a few different ways of representing the data but none of them were clearer than this map. The different symbols and colours represent the different methods of data collection as we felt that this was of more importance than showing the different cruises. We have changed the caption in the hope that the figure will be easier to read. "Figure 1. Map showing stations for all years: underway sampling region (black dots), 48 repeat ice shelf CTD stations (two small groups of cyan circles) and the January 2011 CTD (red dots) UCTD (green triangles) stations. The mean locations of the southern ACC front (SACCF) and the southern boundary of the ACC (SBdy), as determined from satellite altimetry (Swart et al., 2010), are depicted with magenta lines. The regional bathymetry (ETOPO2) is overlaid (m below sea level)."

Fig. 2: I am not sure what fig. 2a shows. It seems to be T, but the caption mentions omega? What are the black numbers? Thank you, we agree that this caption was not clear. The profiles are of temperature. The black dots and black numbers are the overlaid aragonite saturation state at the depth where temperature is at a minimum. We have changed the caption to read:

" Figure 2. (a) Potential temperature profiles with aragonite saturation state (âĎęA) overlaid at the depths where potential temperature is at a minimum for each profile, between South Georgia and the Antarctic ice shelf. CTD stations are indicted with grey lines. (b) Aragonite saturation state (âĎęA) from bottle data, CTD stations where TA and DIC were sampled are indicted with grey lines."

Fig. 3. The Lee TA calculation has its limitation, which has been shown in a number of publications. I am not sure whether Fig 3 adds anything to the message of the manuscript. ... Thank you, we agree with this comment and have removed Fig 3. P 1661: Line 12-13: why? Many calcifiers appear to grow happy under low saturation states. Thank you, we agree that it was not clear in this line that increased primary production results in decreased CO2 and thus in increased omega. Due to recommendations of other reviewers we have rewritten this paragraph, 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."



P 1662: line 10. The paper has many CTD sections. Why are these not used? We are not sure exactly what is meant by this comment as the CTD sections are used in Figs 2 and 5. The CTD sections have been used to show the variability of âĎęA with depth, to calculate an estimate for Winter Water and to take note of the extent of the subsurface chlorophyll a. P 1664. Start of section 3 contains many repeats of previous statements Thank you for pointing this out, we have removed the repeated sections and 3.1 now reads: "3.1 The characteristics of âĎęA variability 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. âĎęA increased throughout the summer months of December, January and February but the magnitude and phasing of the observed seasonal cycle showed a strong interannual variability (Fig. 3a-d). The magnitude of the seasonal summertime increase in âĎęA ($\Delta$âĎęA= maximum âĎęA – Winter Water âĎęA) was found to be relatively low during the summers of 2010 and 2012, 0.46 and 0.59 respectively, while during the summers of 2009 and 2010/2011, $\Delta$âĎęA doubled to 1.02 (Table 1). The phasing of the seasonal maxima also showed a significant interannual variability with the peak being as early as mid-January in 2009, to late January - early February in 2011 and 2012 and as late as the 10th February in 2010 (Fig. 3a-d). There are relatively few data sets characterizing the seasonal variability of the carbonate system at the ice shelf ocean domain around Antarctica (Roden et al., 2013, Shadwick et al., 2013; Mattsdotter BjÓğrk et al., 2014). Here the mean △âĎęA calculated was 0.77, similar to the results of Roden et al (2013), where they found âĎęA at a coastal site in East Antarctica to vary seasonally from 1.19 in winter to 1.92 in summer. Shadwick et al. (2013) studied the annual cycle of âĎęA in Prydz Bay, East Antarctica, from 1993-1995, and found a seasonal increase in âĎęA of almost 3. They attributed the large summer increase in âĎęA to increased summer biological production and high levels of nutrient availability in the bay. 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. These variable physical-biogeochemical characteristics indicate that optimal summer primary production is very sensitive to the balance between buoyancy forcing and mixing, which determine the MLD and the magnitude of stratification. Previous studies have related the thaw of sea ice to both buoyancy forcing as well as to changes in iron (dFe) fluxes, and hence primary production (Smith and Nelson, 1986; Sedwick and DiTullio, 1997; Leventer, 2003; Taylor et al., 2013). Hence, we propose the following conceptual model (Fig. 6), which links the three stratification states, primary production and âĎęA. We used a mixed layer stratification proxy, $\Delta$, to connect water column dynamics to biogeochemistry, as other physical data were limited. $\Delta$ is the change in density between WW ( $\approx$ 1027.61 kg.m-3) and the summer surface layer (Fig. 3m-p). In the absence of comparable CTD sections, we found $\Delta$ to be a useful index of the seasonal evolution of the balance between buoyancy and mixing, as well as to calculate the MLD assuming that freshwater was the only source of buoyancy flux. We found that $\Delta$ variability in the four year dataset fitted into three categories or states that reflect MLD, mixing dynamics and stratification. These three states of $\Delta$ are synthesised in the conceptual model (Fig. 6). Phytoplankton production and âĎęA (âĎęA> 1.7) peak when $\Delta$ is approximately 0.4 (i.e. moderately stratified). When $\Delta$ < 0.4, indicating weak buoyancy forcing from delayed or slow sea-ice thaw and/or strong wind stress, or $\Delta$ > 0.4 indicating strong buoyancy forcing from sea-ice thaw and/or weak wind stress, phytoplankton production and summer âĎęA (âĎęA < 1.6) are at varying minimum magnitudes (1.3 – 1.7), (Fig. 3 and 5). We propose that contemporary variability in the timing, rate and extent of sea-ice thaw, coupled with the wind stress and seasonal solar radiation drive variability in MLD and in primary production (Fig. 4), are the major drivers of seasonal and intra-seasonal variability in surface water âĎęA (Fig. 3, 5, 6). Thus, we examine these mechanisms in greater detail."

p 1665. Line 6. Is there data on nutrient supply? There are profiles of nitrate and silicate but we do not have iron data. Due to this we did not feel that we could calculate nutrient supply. P 1667, line 13: is there sea ice cover or not for the bloom to proceed.

This is unclear. Thank you for this comment, we agree that this sentence is unclear. The assumption of a 1m thick sea-ice layer is referring to the winter sea ice, we propose that the primary summer buoyancy forcing comes from the thaw of a 1m-thick layer of annual sea ice. We have changed the text to clarify this. “Based on an assumption that the summer buoyancy forcing comes from the thawing of a 1m thick winter sea-ice layer and a salinity decrease of 0.3 (34.2 to 33.9) it is estimated that the MLD was about 40m deep and therefore within the euphotic zone, creating an optimal bloom environment with sufficient light and nutrients (Fig. 6).”

P 1669, line 5. It is better to use the recent IPCC projections for CO2. Line 20. I am not sure what is meant by:' they increased. . ...' Was this a model or observational study. How was SS and ST increased. Unclear. Line 5: Thank you, we have taken note of this and have corrected our reference to IPCC 2013. Line 20: We agree that this was very unclear. “They” was referring to the study by Mattsdotter BjÓğrk., et al (2014), and this has been clarified in the manuscript. This was an observational study and then they used the same simplified model as we did to predict future aragonite undersaturation. They did not increase TA, SST or SSS in their model, but they increased DIC at a rate of 10 $\mu$mol.kg-1. decade-1. We have added a sentence to the manuscript to clarify this. “In their study, Mattsdotter BjÓğrk., et al (2014) used their measured SST, SSS and TA data and increased DIC by 10$\mu$mol.kg-1. decade-1.” P 1670 Line 3 It is not clear to me how the authors' model operates. Thank you, we agree that this was not made clear here. There is a short section in the results that explains our simplified model: “To estimate possible surface water âĎęA for the middle and end of this century, the CO2Sys program was used, with fCO2 increased by 160$\mu$atm and with fCO2 doubled relative to a contemporary reference value of 390$\mu$atm, 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.”



We have changed the results and discussion section to read: “Our estimates of surface water âĎęA for the middle and end of this century suggest that during both the 'optimal' summer scenario (data from 2010/2011) and the late ice thaw summer scenario (data from 2011/2012), surface waters at the EWG ice shelf are not likely to experience summertime $\Omega$A undersaturation before the year 2050 (Table 2), in agreement with Orr et al (2005). During years when the timing of sea ice thaw is 'optimal', we predict that mean summer surface water $\Omega$A $\sim$ 1.25$\pm$0.1 by the year 2050 and 1.04$\pm$0.13 by the year 2100 (Table 2), depending on the accuracy of future anthropogenic CO2 trajectories. This suggests that if there are sufficient 'optimal' summers, the EWG ice shelf region could remain interannually supersaturated with aragonite until the end of this century. Alternatively, during summers when sea ice thaw is out of phase with ecosystem phenology, (either before November or late December/ January), surface water $\Omega$A $\sim$ 1.07$\pm$0.05 by the year 2050 and 0.82$\pm$0.07 by the year 2100 (Table 2). Thus, given an increasing number of summers where the timing of sea ice thaw is not 'optimal', surface water $\Omega$A $\sim$ 1 by the middle of this century.”

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