Clim. Past Discuss., 9, C3122–C3130, 2014
www.clim-past-discuss.net/9/C3122/2014/

Climate of the Past Discussions
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Interactive comment on "Seasonal changes in glacial polynya activity inferred from Weddell Sea varves" *by* D. Sprenk et al.

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Received and published: 15 January 2014

Thank you very much for your comments and advises. We have addressed each reviewer comment below: "Sprenk et al. present a series of physical and geochemical analyses of a Weddell Sea core, PS1795, to support the hypothesis that winter polynya formation led to enhanced Antarctic-region bottom water formation during the Last Glacial Maximum. The authors describe extensive new data for their core, including wet-bulk density, magnetic susceptibility, total corbon/nitrogen/sulfur, biogenic opal, IRD counts, thin section descriptions, a suite of XRF elemental concentrations, and 14C dates. They also use a few interesting image processing tools to identify particle sizes and laminations. These data greatly improve the description of core sediment and the character of late glacial period varves that have been previously reported. The

authors go on to explain a proposed mechanism of varve formation, seasonal variations in water velocity due to changes in the volumes of brine formed during the closing of polynyas and to further describe katabatic winds and polynya formation." "The authors have clearly gone through a great deal of effort to gather new physical and geochemical data on core PS1795. What is the importance of this data, and how does it influence the interpretation of varve formation, polynya activity, and bottom water formation? It really is a nice dataset, but it is difficult for me to see the importance of the data with regards to the discussion and conclusions. Much of the material in the discussion has been examined previously- Weber et al., 2010 and 2011 give good evidence that the laminations are seasonal varves, and several papers (e.g., Weber et al., 1994; Smith et al., 2010; Weber et al., 2010) discuss polynya activity generating bottom water. The authors therefore need to specify the contribution of their data to their interpretations. Does the new data remove some uncertainties regarding the mechanism of varve formation." "The introduction and discussion cover very similar ideas. It is not clear how interpretations from this study differ from interpretations in previous work. The authors need to be more explicit about what ideas are their own (and new), and what ideas have already been published. What does this study bring to the field?"

Reply: The introduction and discussion have now been improved in the revised version. In this study, sediment-physical data from sediment core PS1795 are presented. This sediment core was opened in 2011 and results thereof have not been published before. For the first time ever, we present thin sections and consequently high-resolution images of the varved sediment from the channel-ridge system in the SE Weddell Sea. Furthermore, we include high-resolution X-ray fluorescence (XRF) analysis and grain-size measurements with the RADIUS tool (Seelos and Sirocko, 2005) using thin sections to characterize the two seasonal components of the varves at sub-mm resolution to distinguish the seasonal components of the varves. Therefore, this study provides for the first time insight into the composition of the varved sediment and the elemental and mineral composition changes between the lighter coarser-grained layers and the darker finer-grained layers. Our results reveal seasonal changes in grain size and related changes in element and mineral composition. Lighter coarser-grained layers contain higher amounts of silt-sized particles, mostly quartz grains, which is also shown by maxima in Si counts. Additionally, the lighter coarser-grained layers are also enriched in Zr, reveal coarser grain sizes and show higher densities as indicated by less darkening of the X-ray film. Darker finer-grained layers contain mainly clay-sized particles as well as maxima in K, Fe, Ti, and Rb, i.e. typical trace elements for clay minerals such as chlorite and illite as well as mica such as biotite. Additionally, we expand the existing discussion about the sedimentation process in the channel-ridge system and the reason of the varvation. Therefore, we additionally discuss recently published literature about the SE Weddell Sea and especially coastal polynya activity in that area during the LGM.

"I agree with the first reviewer in their comment regarding the deposition of IRD during winter months.

Reply: See explanation given for referee #1.

How do the authors reconcile winter IRD deposition with the explanation that faster bottom waters deposited the silt-rich layers? If there was iceberg rafting of sands, there was likely iceberg rafting of silts. Can the varves be explained simply by invoking seasonal IRD deposition, and without appealing to bottom water velocities? Given that there really is only a slight increase in the percentage of silt-sized particles within the light layers, any input of silt to the core should be considered relevant." Reply: The varves cannot be explained by variable IRD deposition. Detailed grain-size investigation (e.g., Weber et al., 1994, Figs. 10 and 13) showed that, although not conducted on specific laminae, higher silt content also revealed better sorting coefficients and more negative skewness of the silt, which is a clear indication of current transport, whereas IRD delivery of the silt fraction would yield a wide range of unsorted grain sizes.

"The authors mention a few studies (e.g., Renfrew et al., 2002; Justino and Peltier, 2006) to support seasonal polynya activity, which is central to the authors' interpretation

of varve formation. But, there are two issues stemming from this: how seasonal is polynya activity, and how seasonal are the local katabatic winds? Renfrew et al. show some polynya ice production all throughout the years of their study, with the exception of during the very peak of summer. I suspect (although I could be wrong), that with the more expansive sea ice of the LGM, polynya formation and closure could persist throughout the summer. The LGM sea ice extent estimated by Gersonde et al., 2005 would support this, I think. The authors might also benefit from referring to seasons as “warmer” and “colder”, to get around the definitions of “winter” and “summer”."

Reply: We don't believe that colder and warmer would adequate to differentiate the seasons during the LGM (see also comment to referee #1). Instead, windier and less windy would be more appropriate and more decisive for the processes of varve formation. We explained already the polynya activity today and also discussed LGM reconstructions in chapter 5.2 “Modern and LGM polynyas and their relation to bottom-water production in the SE Weddell Sea. Haid and Timmermann (2013) identified the Brunt Ice Shelf, which is close to the core sites (Fig. 1), together with the Ronne Ice Shelf (e.g. Hollands et al., 2013) and southern regions of Antarctic Peninsula as important polynya areas and highlighted that ice production is 9 – 14 times higher in these areas compared to neighbouring regions with the highest mean heat flux during the winter months July and August. Today, coastal polynyas are pervasive around Antarctica during winter (Kern, 2009) and considered as the areas of highest ice production in winter (Morales Maqueda et al., 2004). Tamura et al. (2008) estimated that 10 % of all sea ice in the Southern Ocean and about 6 % in the Weddell Sea (Renfrew et al., 2002) is produced in Antarctic coastal polynyas. In the Weddell Sea, investigations showed that years with large coastal polynya areas are in accordance with maxima in total ice extent (Comiso and Gordon, 1998). Renfrew et al. (2002) highlighted that the interannual variations in coastal polynya activity and area seem to be related to katabatic winds, cyclones, as well as barrier winds. Heinemann et al. (2013) studied coastal polynyas in the Weddell Sea area and showed that especially in the area of Coats Land, in front of the Brunt Ice Shelf (Fig. 1), the offshore winds are mainly driven by katabatic winds, due to the steepness and length of the slope in that area. However, for glacial conditions, there is still little knowledge on katabatic winds and coastal polynya activity as well as their seasonal changes in the southeastern Weddell Sea. Due to the fact that ice sheets covered the continental shelf in the Weddell Sea, the bottom-water formation must have deviated from today, where dense bottom waters are formed on the continental shelf under the ice shelves (e.g. Haid and Timmermann, 2013). LGM simulations by Shin et al. (2003) showed that around 80 % of the AABW could have been formed by increased brine release in the sea-ice production zones in the Southern Ocean. Coastal polynyas in front of the grounded ice sheet above the continental slope might have played a major role in the bottom water formation during the LGM. In the coastal polynya areas there don't even need to be a large open water area as it is also explained in Refrew et al. (2002) and it might also be a region with a thin ice cover.

"While it is likely, judging from the Justino and Pelier (2006) modeling study and from modern observations of katabatic winds on Antarctica, that LGM katabatic winds exhibited some seasonality, I do not think that they entirely ceased for the summer. Katabatic winds during the modern summer are less frequent and less intense than during winter (see Nylen et al., 2004, JGR, figure 4), but they do occur throughout the year. How would this impact the authors' interpretation of the varves? Additionally, there are influences on katabatic winds beyond simple seasonal temperature changes. Yasunari and Kodama (1993, JGR) demonstrate that E. Antarctic katabatic wind strength increased with a weakening in upper level westerlies, and Nylen et al. describe synoptic scale forcings on katabatic wind strength. An explanation of the atmospheric dynamics here is well beyond my expertise, but I'd suggest that the authors consider these influences when making their interpretations. Overall, a stronger case needs to be made for a very seasonal katabatic cycle."

Reply: In our other manuscript (under review at Quaternary Science Review), we include Southern Hemisphere ocean and atmospheric model simulations for the LGM.

Although complicated in its interactions (and we will not refer to these results here, following the advise of referee #1), these forcings likely effected for lower frequency, decadal- to centennial-scale variability documented in varve thickness.

"What happens to the clay-sized particles during the deposition of the light-colored layers? Are they winnowed away due to the swifter currents, do they settle out farther downstream from the core site, or are they present in the light layers but diluted by the coarser particles? A brief discussion of this would be helpful to understanding varve formation mechanisms."

Reply: The clay-sized particles are possibly also originating from the Bottom Nepheloid Layer, i.e. a layer of water directly above the ocean floor contain a significant amount of suspended material. The overspilling thermohaline current possibly also disperses fine-grained clayey particles, which settle down after the deposition of the coarser grains. The clay-sized particles are diluted by the coarser particles. The darker finer-grained layer though consist also of fine silt particles.

"Why use a 20-63μm definition for silt size? A brief discussion of this would be helpful, particularly because clay-sized particles (<2μm or <4μm) aren't really produced by subglacial abrasion (which I assume is the source of most of the core sediment). If the "clayey" layers in the manuscript are actually fine silts, this should be mentioned."

Reply: The 20-63 μm was not used as definition for silt size. The 20-63 μm fraction was defined by the RADIUS tool developers (Seelos & Sirocko, 2005) and only occurs in the RADIUS tool chapter 4.3.3, where it is described as medium to coarse silt and in Figure 6. The "clayey" layers are now called darker finer-grained layers throughout the manuscript.

"I would like to see a description of the thickness of layers (in particular, is there a difference between average thickness of clay-rich layers and silt-rich layers?)"

Reply: In our Sprenk et al. (in review for QSR) manuscript we investigated varved sediment cores PS1599, PS1789, and PS1791, in all varved sections we identified that overall the thickness variation of the lighter coarser-grained layers and the darker finer-grained layers seems to be related, but the darker finer-grained layers are as well often minimal thicker than the lighter coarser-grained layers. This is also true for the varved sections of PS1795. Strong thickness variations can be noticed both in the darker finer-grained layers and the lighter coarser-grained layers (Fig. 3), with thicknesses of only few hundred μm up to 3 mm. The darker finer-grained layers are often thicker than the lighter coarser-grained layers.

"Is there IRD being deposited within modern polynyas? I know that this information may not exist, but if it does, it would be interesting to discuss as a comparison to your varve mechanism.“

Reply: As noticeable on Figure 2 (Parameter A) ice-rafted debris are also deposited during the recent Interglacial. Although due to the fact, that the ice sheets are retreated from the shelf edge and sea ice was reduced, the velocity of the thermohaline current is strongly decreased, leading to significantly lower linear sedimentation rates and thus accumulation of bioturbated hemipelagic mud in the core site area.

"Would you predict any downstream (away from the coast) effect of repeated and frequent polynya formation? For instance, would you develop freshwater lenses at the margin of the sea ice resulting from the increased ice flux to the area of melt? There's no need to incorporate this into the manuscript, but it might be interesting to think about.“

Reply: In our reply to referee #1, we already stated that our model involves coastal polynyas rather than open ocean polynyas further away from the coast. Therefore, we would assume decline of polynya intensity away from the coast, also because katabatic winds have the strongest effect immediately in front of the ice shelf.

"I'm a bit unclear as to how the orientation of the channels, and the process of overspilling, affect your interpretations. I think this could be expanded on, and incorporated

more into your interpretation of varve formation mechanism.“

Reply: Thermohaline water masses reworked sediment and drained into the channels, depositing the material mainly northwest of each channel because of the Coriolis force, building natural levees (Michels et al., 2002). Depending on seasonal velocity changes of the thermohaline current, the transporting sediment grain size changed, leading to varved sedimentation with alternating silty-rich and more clayey layers. Bioturbated hemipelagic mud was deposited during times when the ice sheet is retreated from the shelf edge and sea ice was reduced. The velocity of the thermohaline current is strongly decreased, leading to significantly lower linear sedimentation rates.

"I understand the desire for cautious writing, but you need to finish your discussion and conclusion sections on strong notes, otherwise the reader will disregard what you have said. I would, in fact, remove your final conclusions paragraph.“

Reply: The final conclusions paragraph has been removed now.

"I agree with the first reviewer that a more uniform name needs to be given to the sediment layers, and that the writing needs to be cleaned up a bit (it's not bad, but there are some grammar errors).“ Reply: Agreed. The two layers are now consistently named lighter coarser-grained and darker finer-grained layers.

"5134, 25: Why aren't the varves horizontal? Is this an artifact of the coring process?"

Reply: The varves aren't horizontal, because of the sedimentation process on the ridges. The sediment is transported by a thermohaline current down the continental slope and into the channels of the channel-ridge system in the SE Weddell Sea. If the volume of the current is high enough the current overspill the channel, depositing the material mainly northwest of each channel because of the Coriolis force, building natural levees (Weber et al., 1994).

"5135, 8-20: Why is the origin and distribution of Si important to this study? Expand on your discussion."

Reply: The main purpose of this study was to investigate the elemental and mineral composition of the lighter coarser-grained and the darker finer-grained layers of the varved sediment and discuss the transportation and deposition of the material.

Interactive comment on Clim. Past Discuss., 9, 5123, 2013.