4 Discussion

With this study we wanted to identify to what extent the higher surface water productivity in a fjord with a MTG is reflected in carbon burial potential of the deep water sediments. We therefore expected higher OC content and OCBRs in sediments of Nuup Kangerlua compared to Ameralik, as MTGs present in Nuup Kangerlua increase nutrient upwelling, allowing primary productivity to extend over longer periods. Indeed, earlier studies by Stuart-Lee et al. (2023) and Meire et al. (2023) noted comparable primary productivity in Nuup Kangerlua and Ameralik at the start of the productive season (April, May). Yet, with increasing meltwater discharge, a summer bloom was observed in Nuup Kangerlua which led to a greater overall phytoplankton biomass compared to Ameralik (Stuart-Lee et al., 2023; Meire et al., 2023). However, in this study, we found a higher OC content in sediments of outer and mid fjord stations AM5 and AM8 in Ameralik compared to Nuup Kangerlua. These findings are supported by observations from a gravity core sampled nearby station AM5, which also revealed similar elevated carbon content in the sediment (Møller et al., 2006). Our results therefore do not support the hypothesis of higher carbon burial potential of MTG fjords compared to LTG driven systems.

4.1 Surface sediment OC content

The OC content in the sediments of Nuup Kangerlua and Ameralik is representative for (sub-) Arctic fjord sediments (Fig. 5A). In terms of fresh organic matter, we found an average Chl-a content in Nuup Kangerlua's sediments which was slightly below the typical range observed in other North Atlantic fjords (Włodarska-Kowalczuk et al., 2019). In contrast, Ameralik exhibited an average Chl-a content nearly three times higher than the maximum values reported for Svalbard fjords (Włodarska-Kowalczuk et al., 2019). This elevated average is largely driven by the exceptionally high Chl-a content observed at station AM5.

So far, studies comparing MTG and LTG fjord systems are limited (Koziorowska et al., 2015; Laufer-Meiser et al., 2021). These studies suggest that MTG fjords tend to exhibit higher OC accumulation, as indicated by elevated OC content in surface sediments. However, when comparing the LTG system Ameralik and the MTG system Nuup Kangerlua with datasets from other fjords (Smith et al., 2002; Thamdrup et al., 2007; Koziorowska et al., 2015; Cui et al., 2016; Faust and Knies, 2019; Włodarska-Kowalczuk et al., 2019; Laufer-Meiser et al., 2021), we observed that surface sediment OC content in LTG and even non-glaciated fjords can be comparable to that of MTG systems across the (sub-)Arctic region (Fig. 5A). Nevertheless, it is important to note that LTG fjords are underrepresented in current datasets, and low-glacial-activity MTG systems may bias comparative interpretations.

These observations suggest that factors beyond glacial influence play a significant role in controlling the degree of benthic-pelagic coupling. Specifically, the presence of MTGs does not inherently result in higher OC accumulation within sediments compared to systems without subglacial upwelling. However, elevated MARs may dilute OC content with inorganic material, potentially skewing these observations. Additionally, higher TOC content in surface sediments does not automatically equate to more efficient OC burial.

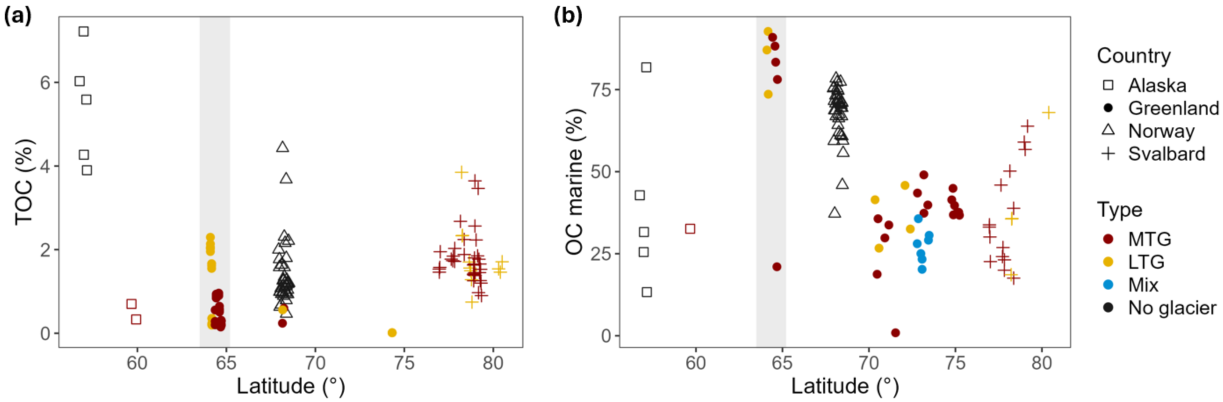

Figure 5: (a) TOC content of surface sediments along latitude. Data compiled from Smith et al. (2002), Thamdrup et al. (2007), Koziorowska et al. (2015), Cui et al. (2016a); Faust and Knies (2019), Włodarska-Kowalczuk et al. (2019), Laufer-Meiser et al. (2021) and this study. **(b)** Fraction of TOC of marine origin along latitude. Data compiled from Koziorowska et al. (2015), Faust and Knies (2019) and this study. Both figures display data from fjords located in high latitude countries: Alaska, Greenland, Norway and Svalbard. The grey band constraints the Greenland fjords investigated in this study. Data indicated in red and yellow represent Marine terminating-glacier (MTG) and land terminating-glacier (LTG)-influenced fjord systems, respectively. The mixed type represents fjords where the dominance of MTG(s) vs LTG(s) on the fjord's hydrology could not be differentiated from literature or satellite images are depicted in blue. Non-glacial fjords are represented in black. Both graphs were created following and updating the example of Faust and Knies (2019).

4.2.1 OC origin

An important clue in resolving the observed patterns can be found in the deepest part of Ameralik's basin. There, specifically at station AM5, we measured a 5 times higher Chl-a content combined with 1.7 times higher Chl-a:CPE ratios compared to the maximum values in sediments of Nuup Kangerlua, which points to an enhanced preservation of fresh organic matter (i.e. more labile OC) within these sediments. The Chl-a content remained elevated throughout the entire 10 cm sediment profile and was consistent between spring and summer data. A difference in timing of the onset of the phytoplankton bloom between the two fjords, as previously observed (Stuart-Lee et al., 2023), could have led to an earlier build-up of pigments at the seafloor of Ameralik compared to Nuup Kangerlua at the time of sampling. However, the relatively elevated values throughout the 10 cm sediment profiles and the consistency between spring and summer data exclude such sampling time bias. In Svalbard, Koziorowska et al. (2015) also observed higher OC content in the surface sediments of a LTG-influenced fjord versus a MTG-impacted fjord. The LTG-fed fjord appeared to receive a higher fraction of terrestrial OC, which tends to be more resistant against degradation compared to marine OC (Wakeham and Canuel; 2006; Koziorowska et al., 2015). Yet, in our case, the sediment stable isotope composition and C:N ratios of both fjords reflect OC of predominantly marine origin in both fjords, likely due to the limited vegetation and a catchment geology consisting of orthogneisses, granodiorites and granites rather than organic-rich sedimentary rocks (Næraa et al., 2014) (Fig. 4; Fig. 5B). An exception is inner station NK13 in Nuup Kangerlua, which displayed $\delta^{15}N$ of marine signature, though depleted $\delta^{13}C$ values which combined with C:N values indicated a freshwater provenance (Fig. 4b). Since elevated $\delta^{15}N$ values can also be caused by degradation (Dai et al., 2005), this station may contain OM more of terrestrial origin. In contrast, the stable isotope composition found at the head of Ameralik, in front of the land-terminating glacier, does not indicate a dominant terrestrial input.

So in general, the higher OC content in Ameralik sediments is not related to increased terrestrial input in the LTG fjord compared to the MTG-dominated fjord. In fact, sediments from both fjords receive OM from predominantly marine origin.

4.2 Organic carbon burial rates

Despite the higher OC content observed in the outer and mid part of the LTG-fed fjord, OCBRs were similar in both fjords due to the relatively higher MARs in Nuup Kangerlua. The higher MARs in Nuup Kangerlua result from the substantially higher discharge that three MTGs and three LTGs generate compared to the input of a single LTG in Ameralik. The average OCBR in Nuup Kangerlua was only on average slightly higher (18.0 ± 1.6 g OC m^{-2} yr^{-1}), but not significantly, compared to Ameralik (16.2 ± 1.7 g OC m^{-2} yr^{-1}). However, it must be noted that glacial run-off induced lithogenic dilution of OC can lead to an underestimation of OCBR in Nuup Kangerlua. Nevertheless, the observed values fall within the range of sub-Arctic fjords and Arctic fjords impacted by active glaciers (Włodarska-Kowalczuk et al., 2019).

On the local scale, Meire et al. (2023) estimated that annual pelagic primary production in 2016 was approximately three times higher in a head station of Nuup Kangerlua (~90 g C m^{-2} yr^{-1} at NK10) than in a head station of Ameralik (~30 g C m^{-2} yr^{-1} at AM10). Similarly, our results show that the OCBR at this very same station NK10 was about three times higher than at AM10. However, at basin scale, carbon burial remains similar in both fjords. These findings underscore the complexity of carbon burial dynamics in glacial fjords, highlighting that surface productivity and glacier type alone are not reliable predictors of OC burial.

4.3 Pelagic and geomorphological influence on OC burial

OC burial in fjord sediments is shaped not only by surface productivity but also by complex interactions between water column processes, fjord morphology, and bottom water conditions. There are several processes potentially at work leading to a decoupling of OC production in the water column and OC burial in the fjord sediments as discussed further and summarized in Fig 6.

4.3.1 OC preservation conditions

Since most of the OC deposited in both fjords is of marine origin, any differences in organic matter preservation between them are likely driven by environmental conditions rather than by differences in the nature of the organic material itself. The distinct geomorphology of Ameralik and Nuup Kangerlua, particularly their differing sill depths, likely shapes bottom water temperatures and may influence organic matter preservation within the fjords. Both fjords have no anoxic deep water masses and bottom water renewal occurs every one to two years (Mortensen, 2011; Stuart-Lee et al., 2021), but bottom water temperature differs. Ameralik's shallower sill depth (~110 m) compared to Nuup Kangerlua (~200 m) restricts the inflow of warmer, saltier coastal waters (Stuart-Lee et al., 2021). Consequently, during field sampling, bottom water temperatures in Nuup Kangerlua were consistently warmer than in Ameralik, particularly in spring, with average values of 1.33 °C and 0.53 °C, respectively. The lower bottom water temperatures in Ameralik may explain the observed higher pigment and OC preservation in AM5 by reducing microbial degradation and slowing remineralization processes compared to sediments at the mouth of Nuup Kangerlua under influence of warmer waters. A comparative study of several Svalbard fjords suggested that relatively higher pigment content in sediments may be linked to lower bottom water temperatures (Krajewska et al., 2020). However, this hypothesis warrants further investigation, as Arctic microbial communities are well adapted to low temperatures, and mineralization rates below 10 °C appear to differ only minimally (Thamdrup et al., 2007; Scholze et al., 2020).

4.3.2 Transport dynamics

Besides potential differences in organic matter preservation, lateral transport may also influence the spatial distribution of OC across the seafloor. In Nuup Kangerlua, weak along-fjord gradients in sediment TOC, TN, and Chl-a content suggest dynamic currents that may redistribute OC. Estuarine and subglacial circulations, most active during melt season, can enhance OC export from inner to outer fjord (Mortensen et al., 2011; 2014; Juul-Pedersen et al., 2015).

At both fjord mouths, tidal mixing over sills drives baroclinic circulation, reintroducing nutrients into surface waters, promoting outer fjord surface productivity (Stuart-Lee et al., 2021, 2023). This aligns with higher TOC and pigment content as well as higher Chl-a:CPE ratios in Ameralik's outer fjord sediments. In contrast, Nuup Kangerlua sediments show no similar increase in TOC and pigment content in sediments of NK6 and NK7.

Sørensen et al. (2015) proposed that high POC export in Kobbefjord, a nearby glacier-free fjord, may result from OC input from Nuup Kangerlua. A similar OC transfer might explain a higher TOC and Chl-a content in the sediments toward Ameralik's mouth. While both fjords have estuarine and baroclinic circulation, stronger subglacial upwelling in Nuup Kangerlua likely enhances OC transport efficiency towards the fjord mouth. Ameralik may thus receive OC from outside, with deep basin retention supporting OC preservation (Fig. 6). The slightly coarser grain size at Ameralik's mid and outer stations, despite their distance from glacial input, may indeed reflect input from the entrance sill. Furthermore, the topography of Ameralik with the deep depression behind the sill can promote downslope transport and sediment accumulation, resulting in the relative higher TOC and pigment content at AM5 (Hargrave and Nielsen, 1976; Wassmann et al, 1984; Erlandsson, 2008). Therefore, hydrodynamics, downslope transport, or a combination of both can decouple surface productivity from local sediment deposition.

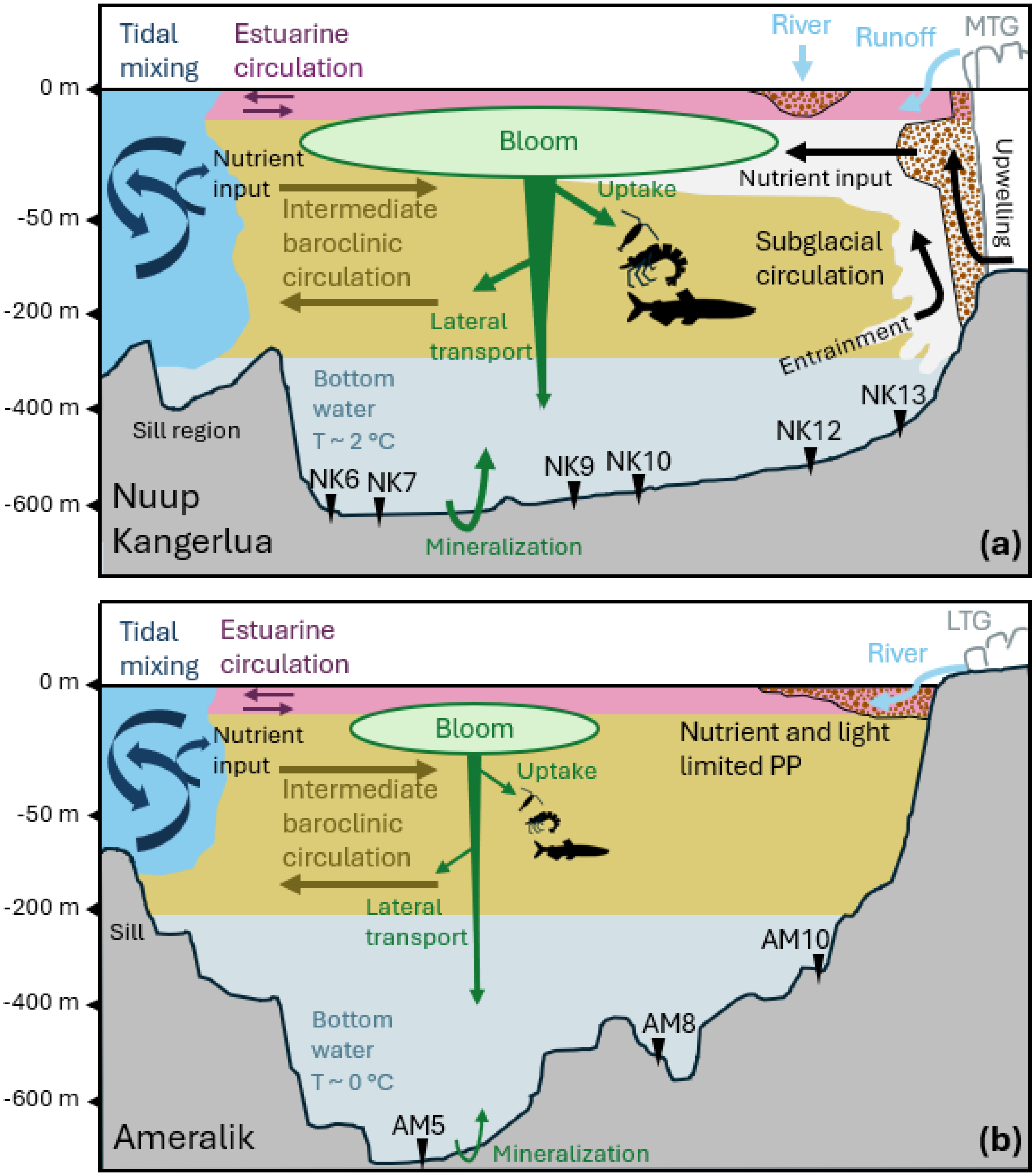

Figure 6: Schematic cross-sectional view of current regime and possible ways of phytoplankton or OC flow during summer in Nuup Kangerlua (**A**) and Ameralik (**B**) fjord systems. Tidal mixing above the sill area, estuarine circulation and intermediate baroclinic circulation occurs in both fjord systems, while the presence of MTGs in Nuup Kangerlua drives subglacial circulation through subglacial discharge. Nutrients are brought to the euphotic zone via tidal mixing and subglacial circulation. Turbid plumes, indicative of suspended sediment and organic matter input from glacier discharge and river runoff, are represented by the brown dotted pattern. Green arrows represent phytoplankton or OC transport and remineralization of organic carbon at the sediment-water

interface. A larger arrow points to higher expected flows. Station locations are marked along the fjords. The current dynamics illustrated for Nuup Kangerlua are based on Mortensen et al. (2018) and Stuart-Lee et al. (2023), while those for Ameralik are derived from Stuart-Lee et al. (2021; 2023).

4.3.3 Food web OC uptake

As both fjords exhibit a high contribution of marine-derived OC compared to other Arctic fjord systems (Fig. 5B), the unexpectedly higher sediment OC content in Ameralik's basin may reflect differences in carbon cycling pathways, both within sediments (stronger temperature-driven preservation, see 4.3.1) and in the overlying water column. In Nuup Kangerlua, greater phytoplankton biomass and a larger size class may support a more complex and efficient food web compared to Ameralik (Meire et al., 2023; Stuart-Lee et al., 2023), resulting in more OC being consumed or remineralized before it reaches the seafloor (Fig. 6). This is further supported by differences in zooplankton composition: Nuup Kangerlua hosts a higher proportion of large herbivorous copepods during the summer bloom, while smaller omnivorous taxa dominate in Ameralik (Stuart-Lee et al., 2024). However, despite these community differences, total zooplankton biomass did not differ significantly between fjords, possibly due to elevated predation pressure on larger zooplankton in Nuup Kangerlua (Stuart-Lee et al., 2024).

Elevated halibut landings in MTG-influenced fjords (Meire et al., 2017), combined with the known role of MTG fronts as productive foraging zones in Svalbard (Lydersen et al., 2014; Urbanski et al., 2017; Vacquié-Garcia et al., 2018; Hamilton et al., 2019), lend further support to the hypothesis that OC transfer through higher trophic levels is intensified in Nuup Kangerlua. This enhanced trophic transfer likely reduces vertical OC export, contributing to the lower sediment OC content observed despite higher pelagic productivity.

4.4 Recommendations for future research

The expected link between elevated surface primary production in MTG-influenced fjords and OCBR was not observed. Future studies should therefore examine the mechanisms controlling this mismatch between pelagic productivity and sediment burial. In addition, our results imply that glacial influence is not necessarily the most important factor steering OCBR, which means that more Greenland fjord systems should be studied to better understand the effect of retreating MTGs on OC burial. Based on our results we identified the following avenues for future research:

1. Mass accumulation rates and OCBRs need to be studied in Greenlandic and other Arctic fjords, ideally applying the CRS method, for standardized comparisons. As not all of our MARs could be determined by the CRS method, these estimates should be verified in the future.

2. Accurate carbon budget construction requires integrated knowledge of primary production, zooplankton grazing, pelagic and benthic biomass as well as pelagic and benthic mineralization rates (Spilling et al.,

2019), which are currently limited or lacking for these fjord systems. These parameters help quantify the mismatch between OC production and burial, which may arise from lateral transport processes or from OC incorporation into higher trophic levels. To address this, a more comprehensive understanding of food web dynamics and carbon flow in both fjords is essential.

3. An understanding of benthic OC cycling is important for quantifying carbon turnover at the sediment-water interface, potentially revealing processes that drive differences in OC burial efficiency in different fjord systems.

5 Conclusion

This study provides new insights into carbon burial processes in two southwest Greenland fjords with a different type of glacier influence. Our findings point to complex processes at work regarding carbon burial as our data revealed a different pattern than generally assumed in literature (Hopwood et al., 2020). Our data show that primary production generates most of the organic matter ending up at the seabed sediments in two sub-Arctic fjords with similar metamorphic and igneous catchment geology. Despite the upwelling mechanism in place sustaining more primary production, this process does not seem to induce a higher OC burial in the seabed sediments of a MTG-impacted fjord compared to a LTG-fed fjord. In contrast, this upwelling could be responsible for an export of carbon out the fjord or promoting the transfer of carbon through a more extensive food-web. In that case, MTGs could function as carbon pumps where an important part of the produced OC is stored beyond the fjord basin sediments. However, differences in geomorphology or bottom water characteristics between the two fjords can also override the importance of the subglacial nutrient supply and lead to a higher preservation of the OC in the fjord sediments.

Our findings highlight the importance of investigating both the pelagic as benthic compartment of Greenland fjord systems, which are understudied and underrepresented in global carbon budgets compared to other regions. Although this study advances our understanding of the carbon dynamics in Greenland fjords, several unresolved questions remain. For example, the role of physical circulation patterns in redistributing OC as well as differences in diagenetic processes between MTG- and LTG-influenced fjords, require further investigation. Additionally, the potential for complex food webs and more intense trophic interactions in MTG fjords to influence carbon sequestration deserves more attention.

Understanding the driving mechanisms of OCBR in fjord systems is essential to predict the impact of climate change on OC sequestration as MTGs evolve to LTGs. The similar OCBR observed between systems suggests that the retreat of MTGs from fjords may not necessarily reduce carbon burial, as new conditions influencing OCBR will emerge. Nevertheless, when assessing the impact of climate change on OC burial budgets, it is crucial to consider the fate of OC produced within the fjord.