Anonymous Referee #1

The manuscript of Pados and co-authors on ‘Oxygen and carbon isotope composition of modern planktic foraminifera and near-surface waters in the Fram Strait (Arctic Ocean) – a case-study’ is well written and presents new data on a region rather intensely studied since the 1980s. Most of the conclusions hence read quite familiar, although the absolute numbers may slightly differ from those published before.

1. Comment:

In addition some of the results presented in the manuscript repeat those just published by the same authors (Pados and Spielhagen, 2014, Polar Research). For example, figure 2 of the present manuscript resembles figure 2 in Pados and Spielhagen (2014) [idem Table 1]. The data (standing stocks) presented in figures 5 and 6 of Pados and Spielhagen (2014) are exactly the same as in the present manuscript. The authors may want to present the data (T, S, and standing stocks) in a more synthetic way, though, and add a new perspective to the same story. However, despite all redundancies and duplications, the manuscript may still merit publication, to make sure that the precious new data are not getting lost.

Authors' general response:

As mentioned in line 12-14 on page 8638, we analyzed in the above-mentioned two manuscripts (Pados and Spielhagen, 2014 and present manuscript) the same samples taken during cruise ARKXXVI/1. However, the aims of the two studies are completely different and they were meant to give a detailed description of planktic foraminiferal fauna in the sampled area from two different perspectives. Pados and Spielhagen, 2014 focuses on the ecology (faunal composition and depth distribution) of planktic foraminifera, while the present manuscript reports on the stable isotope composition of the tests and aims at discussing the effects of environmental factors on the oxygen and carbon isotope composition of the shells.

Our specific response to:

[...] some of the results presented in the manuscript repeat those just published by the same authors (Pados and Spielhagen, 2014, Polar Research). For example, figure 2 of the present manuscript resembles figure 2 in Pados and Spielhagen (2014).

As the two papers are associated, the data presented in Pados and Spielhagen, 2014 holds important background information for present study as well. However, not every reader of present paper may want/will be able to download and read the other manuscript only to get an overview over the research area. Therefore, in chapter 4.2 we shortly summarized the results of Pados and Spielhagen, 2014. Moreover, we consider it absolutely necessary to give an overview of oceanic conditions (T, S) during sampling (Figure 2 in both manuscripts) since these data are crucial for understanding the isotope data presented and discussed.

Our specific response to:

[...]*The data (standing stocks) presented in figures 5 and 6 of Pados and Spielhagen (2014) are exactly the same as in the present manuscript.*

Since figures 5 and 6 in the Polar Research manuscript are not shown in the BGD manuscript (and nothing similar either) we assume the reviewer means that figures 3 and 4 in the Polar Research manuscript resemble figures 5 and 6 in the BGD manuscript. However, while the first two show the species composition and the relative abundances in the samples, the latter two show standing stocks for the two species (calculation is explained in chapter 3 Materials and Methods). These figures 5 and 6 in the present manuscript aim to show the calculated calcification depths of the two species. This calcification depth is calculated from the standing stock, which therefore is important information in the present paper. Neither standing stocks nor calcification depths were shown or discussed in the Polar Research paper and thus they are new data when shown in the BDG manuscript.

2. Comment:

On the scientific level, I have some concerns about the use of name and species concept of Neogloboquadrina pachyderma. The species concept is discussed in detail by Darling et al. (2006, Paleoceanography), and coiling direction may not be used to distinguish N. pachyderma (more left than right coiling) from N. incompta (more right than left coiling)[the authors may just skip ‘(sin.)’ after ‘N. pachyderma’].

Authors' response:

The reviewer is right, from the genetical point of view it is not correct to use "*Neogloboquadrina pachyderma* (sin.)" for describing a species. We are aware of the problem, however we did not have the possibility to genetically analyze our samples, we could only visually differentiate the species. Therefore we follow the suggestion of the reviewer. In the revised manuscript we have added a sentence explaining that we use the term "*Neogloboquadrina pachyderma*" (with no addition of "sin."). However, we also state that for isotopical analyses we have used left-coiling specimens only, which may genetically be (to a very minor amount) *N. incompta*. Considering the fact that each isotopic measurement was performed on a sample of several left-coiling specimens, we think it is still justified to use "*Neogloboquadrina pachyderma*" when discussing the results.

Changes in the manuscript:

We have deleted "sin." after "*N. pachyderma*" and in the "Material and Methods" we have added a sentence explaining that we follow the species concept of Darling et al. (2006). Moreover we clarified that we used only left coiling specimens for the stable isotope analysis.

3. Comment:

T. quinqueloba may or may not contain symbionts (page 8645, line 26 to page 8646, line 1), and which would affect the interpretation of the stable isotope signal (Hemleben et al. 1989, Ortiz et al. 1995). I would suspect that T. quinqueloba do not harbor symbionts at the high latitudes sample here.

Authors' response:
The reviewer is right, Ortiz et al., 1995 describes *T. quiqueloba* collected in the California Current as asymbiotic. However, all studies conducted in high latitudes that we are aware of describe *T. quinqueloba* as symbiotic species (Schiebel and Hemleben, 2005, Palaeont. Zeitschr.; Simstich, 2003; Jensen, 1988, Ber. SFB 313; Hemleben et al., 1989; Be, 1977). We therefore assume that the observations of Ortiz et al. (1995) represent more the exception than the rule.

Changes in the manuscript:
None.

4. Comment:
I don't see how increasing river discharges at quite remote places would affect the stable isotope of the foraminifers sampled in the Fram Strait (page 8648, lines 17-23). Please explain.

Authors' response:
Increasing river discharges (e.g., Peterson et al., 2002) in the last 8 decades have significantly changed the freshwater budget of the Arctic Ocean (Morison et al., 2012, Nature) and resulted in a net storage of freshwater here. Accordingly, model results (e.g., Holland et al., 2006, J. Clim.) indicate an increased freshwater export through Fram Strait in the 20th and 21st century. Since this export occurs in near-surface water masses inhabited by the planktic foraminifers, the isotopic composition of waters and contained foraminifers should have changed accordingly, resulting in a reduction of δ^{18}O values.

Changes in the manuscript:
We have added one sentence that explains this chain of arguments in more detail (page 12, line 27-30)

5. Comment:
Chapter 5.3 on Carbon isotope values of DIC and foraminifera finally gives no answer on the question asked here. The idea of discussing the affect of the carbonate ion effect on the 13C signal of the foraminifer test analyzed here is good, but the data are possibly not suited for an in-depth discussion. The chapter hence ends with the unsatisfactory remark that offsets might be caused by differences in age (which might be true, but does not answer the question initially asked). I would suggest reorganize and shorten the chapter.

Authors' response:
The reviewer is right, indeed we cannot discuss the carbonate ion effect (CIE) very detailed because as we mention in the manuscript we did not measure the carbonate ion concentration. However, since other factors can be excluded (at least to a certain degree), we consider it appropriate to propose a possible effect of the carbonate ion concentration on the carbon isotope composition of the shells. This may help to encourage interested colleagues to investigate this effect in the working area in more detail. Moreover, we

included in the discussion (as suggested by the short comment of Lukas Jonkers) the evaluation of carbonate ion concentrations in the area extracted from databases, and the possibility of temperature effect on $\delta^{13}C$.

Changes in the manuscript:

We have added an evaluation of vertical carbonate ion distribution in the area and that of the possible temperature effect (page 15-16). Regarding the $\delta^{13}C$ differences between fossil and modern foraminifera, we have shortened the discussion here and concentrate on a hint to the Suess effect.

6. Comment:

Why not discussing differences with older data from the same region, to show an increasing (or not) effect of carbonate ion concentration on calcification at high latitudes over the past 20 years or so.

Authors' response:

Criticism accepted.

Changes in the manuscript:

Assuming the validity of the hypothesis on the effect of increased carbonate ion concentration through high primary production, we included a comparison of vital effects in $\delta^{13}C$ incorporation with the results of Volkmann and Mensch (2001) and Stangeew (2001) (page 16, line 4-12).

Anonymous Referee #2

Pados et al. present a set of measurements from the Farm Strait, which includes d18O and d13C of two foraminifera species in the water column and in the sediment as well as the corresponding isotope measurements of the water d18O and DIC -d13C. As such, the results are interesting for calibration of the wide use of foraminifera in paleoceanographic studies.

1. Comment:
I have two major concerns, which are of a general nature: 1. what is the degree of the overlap between this paper and the Pados and Spielhagen (in press) paper? I did not see the later and cannot comment on that.

Authors' response:
As mentioned in line 12-14 on page 8638, we analysed in the above-mentioned two manuscripts (Pados and Spielhagen, 2014 and present manuscript) the same samples taken during cruise ARKXXVI/1. However, the aims of the two studies are completely different and they were meant to give a detailed description of planktic foraminiferal fauna in the sampled area from two different perspectives. Pados and Spielhagen, 2014 focuses on the ecology (faunal composition and depth distribution) of planktic foraminifera, while the present manuscript reports on the stable isotope composition of the tests and aims at discussing the effects of environmental factors on the oxygen and carbon isotope composition of the shells. As the two papers are associated, the data presented in Pados and Spielhagen, 2014 holds important background information for present study as well. However, not every reader of present paper may want/will be able to download and read the other manuscript only to get an overview over the research area. Therefore, in chapter 4.2 we shortly summarized the results of Pados and Spielhagen, 2014.

2. Comment:
2. Overall, when isotopic differences are discussed (between water column and sediment or between water column foram and calculated equilibrium) the rigorous Standard deviation should be presented. I also suggest to put the differences in a graphic presentation to make it clear to the reader.

Authors' response:
The reviewer is right, we have added the standard deviation in the adequate places. However, the reviewer's request for a graphic presentation of the differences "between water column and sediment or between water column foram and calculated equilibrium" leaves us a bit puzzled. These data are presented as red, blue and dashed green lines in Fig. 7 (note: Fig7. changed to Fig. 5 in the revised manuscript), and we think that the differences can easily be picked visually from the horizontal offsets between the lines. Of course we could add another figure and display the offsets as horizontal bars of different length plotted on the red dots (data points) in the red lines. However, we do not think that this would make the differences more obvious that they already are from current Figure 7.

Changes in the manuscript:
We have added the standard deviations in the adequate places.

Other comments:

1. page 2 line9-10: why do you ignore temperature?

Authors' response:
We regret that we had forgotten to mention the kinetic effect that temperature exhibits on the $\delta^{18}O$ -variability of foraminifera.

Changes in the manuscript:
We have added this information in the third sentence of the Introduction chapter (page 2, lines 8-11).

2. Page 2 line 22: is it carbon or oxygen or both?

Authors' response and changes in the manuscript:
Both carbon and oxygen isotope ratios of the calcite shell decrease with increasing seawater carbonate ion concentration (Spero et al., 1997). We added this information to the sentence (page 2, line 23).

3. Page 3 line 8: what are the disciplines?

Authors' response and changes in the manuscript:
The reviewer is right. We have changed ""results from a multidisciplinary approach" to a more appropriate "results from isotopic analyses" (page 3, line 8).

4. Page 5 line 23: please add oC to T.

Authors' response and changes in the manuscript:
Agreed. We have changed "T" to "T(°C)" (page 5, line 30).

5. Page 6 Figure 4: axis of isotopes are missing from the graphs

Authors' response and changes in the manuscript:
In Figure 4 the lower x-axis represents the axis for both temperature and isotopes, while the upper x-axis is for the salinity. We added this the information to the figure caption.

6. Page 6: what is the slope of d18O/salinity

Authors' response and changes in the manuscript:
We have added a regression line and the corresponding equation to Fig. 3.

7. Page 7: Fig 7 appears before Fig. 5-6 8.

Authors' response and changes in the manuscript:
The reviewer is right. We have corrected the order of figures and have changed the figure references in the text accordingly.

8. Page 7 line 27: please add STDEV to all numbers

Authors' response and changes in the manuscript:
We added the STDEV to all numbers (page 8, line 8).

9. Page 8 line 7: please put numbers + STDEV on highest and lowest

Authors' response and changes in the manuscript:
We put the numbers but as they are row values we cannot provide any standard deviations (page 8, lines 18-19).

10. Page 9 line 3: this is not a theoretical equation. It is an empirical calibration

Authors' response and changes in the manuscript:
We have changed "theoretical d18O value" to "potential d18O value" (page 9, line 17).

11. Page 9 line 20-26: please provide numbers

Authors' response and changes in the manuscript:
We added the numbers where appropriate (page 10, line 10).

12. Page 10 line 5: needs a better explanation although rejected later

Authors' response and changes in the manuscript:
Here we refer to the theory of Volkmann & Mensch (2001). Similar to us, they observed greater offsets between the equilibrium calcite values and the oxygen isotope composition of tests under the sea ice. They conclude that unfavourable conditions here make the individuals grow faster (i.e., increase their metabolism). However this statement it is not explained furthermore in their paper, among other things, this is why we cannot agree with it. Nevertheless, we followed the suggestion of the reviewer and added the above explanation to the text (page 10, lines 23-26).

13. Page 10 line 12: do you numbers to support the claim of high Primary Production? The d13C does not show it.

Authors' response: In Pados and Spielhagen, 2014 we reported on a major increase in absolute abundances of planktic foraminifera at the sea ice margin, probably caused by enhanced phytoplankton biomass. The ice margin offers increased food supply for the foraminifera with higher primary production caused by diatoms that are the major food source for *N. pachyderma* (Hemleben et al. 1989). Diatoms typically do not develop well under permanent ice cover due to the light limitation, but they prefer seasonally stratified water conditions that occur in the marginal ice zone (Smith et al. 1987; Williams 1993). Ice melting increases stratification and consequently the stability of the water column, which triggers phytoplankton blooms (Alexander 1980).

Changes in the manuscript: We added a sentence with three references (Alexander 1980; Carstens et al. 1997; Pados & Spielhagen 2014) to support the hypothesis of high primary production (page 11, lines 1-3).

14. Page 12 line 9: please change throughout the text to either station numbers or longitude.

Authors' response and changes in the manuscript:
We changed throughout the text the station numbers to longitude or provided both information.

15. page 13 line 20: needs STDEV

Authors' response and changes in the manuscript:
We have added the standard deviations to the manuscript (page 14, lines 12-15).

16. Page 14 line 1-2: not clear

Authors' response and changes in the manuscript:
We have rephrased the sentence for a better understanding (page 14, lines 25-26).

17. Page 14 +STDEV

Authors' response and changes in the manuscript:
We provided the standard deviations (page 14, line 28, page 15, line 2).

18. Page 14 Line 6-13: this is a place where the differences should be graphically presented.

Authors' response and changes in the manuscript:
As explained above (response to reviewer's major comment no. 2), we do not think that an additional figure would make the differences more obvious than they are in Figs. 7 and 8. Instead, we have slightly expanded the text discussing the results displayed in Figs. 7 and 8 to lead the reader to the important points (page 15, lines 4-6).
(Note: in the revised manuscript Fig. 7 changed to Fig. 5, and Fig. 8 to Fig. 9).

19. Page 15 line 1-5: this contradicts the conclusion of oxygen difference between sediment and water column. If the Suess effect is the explanation it is restricted to 250 years and not 1-3Ka.

Authors' response:
We do not fully understand this comment. We believe that we have explained in sufficient detail that there is a significant age difference between the living foraminifera from the water column and the dead specimens from the sediment surface samples (the latter having an average age of ca. 1 ky). The significance of this age difference lies in the developments that have occurred

in the last ca. 100 years: A freshening of the Arctic Ocean near-surface waters (resulting in lower $\delta^{18}O$) and the intrusion of low-$\delta^{13}C$ carbon dioxide (Suess effect). Since the foraminifera from the water column have both lower $\delta^{13}C$ and $\delta^{18}O$ than those from the surface sediments, we propose that the differences observed can be explained by the two effects explained above and in the manuscript (see also conclusion no. 6).

Changes in the manuscript:
We have slightly modified the last paragraph of the discussion to make the point more obvious to the reader. We have also slightly changed conclusion no. 6 which summarizes the findings (page 16, lines 25-26; page 17, lines 17-18).

Lukas Jonkers

1. Comment:

My main concern is with the discussion on the offset between $\delta^{13}C_{calcite}$ and $\delta^{13}C_{DIC}$. Pados et al. discuss several reasons for this offset and suggest that the $[CO_3^{-2}]$ may be an important parameter. However, they ignore the possibility of a temperature effect on the $\Delta\delta^{13}C$, which has been observed in culture studies (Bemis et al., 2000) and potentially also in field studies on *N. pachyderma* (Jonkers et al., 2013b). It would be a significant improvement to the study if the authors attempted to quantify both effects on the $\delta^{13}C_{calcite}$. A temperature effect can readily be evaluated and since no carbonate system data exists for the ARK XXVI/1 cruise I suggest the authors make use of data that is available in the CARINA and GLODAP databases (some is also accessible through ODV) to obtain first order estimate.

Author´s response and changes in the manuscript:
We thank Lukas Jonkers for his valuable suggestion, which also in our opinion would improve the manuscript. Therefore, we have included the evaluation of the temperature effect on the offset between $\delta^{13}C_{calcite}$ and $\delta^{13}C_{DIC}$ and also evaluated the vertical carbonate ion distribution in the area, by extracting data from the CARINA database (page 15-16).

2. Comment:

It would also be valuable if the comparison with previous studies in the Fram Strait was more extensive. Perhaps add a figure comparing the different studies. And an additional reference that could be used for this purpose is Stangeew (2001).

Author´s response and changes in the manuscript:
We have picked up Jonker' suggestion and included an additional figure comparing our results to those of Volkmann and Mensch (2001) and Stangeew (2001), showing $\delta^{18}O$ of *N. pachyderma* (sin.) from the water column and the equilibrium calcite values in the upper water column (Fig. 10). In the manuscript text we have made reference to this figure in the appropriate places. Moreover, we have added a short paragraph to the discussion of $\delta^{13}C$, discussing the different vital effects reported by Volkmann and Mensch (2001) and Stangeew (2001) from the same area (page 15, lines 4-12).

3. Comment:

Vital effect: the offset from equilibrium $\delta^{18}O$ of course depends on the paleotemperature equation that is used to calculate $\delta^{18}O_{eq}$. This needs to be highlighted and also means that the estimate of the vital effect derived by Jonkers et al. (2010), which is based on the Kim & O`Neil (1997), needs to be adjusted before it can be compared to the other estimates (see also Jonkers et al., (2013a)).

Author´s response and changes in the manuscript:

Jonkers is right. However, in this case, the adjustment does not change the validity of the respective sentence (that the offsets reported in Jonkers et al., 2010 are smaller than in our study). Nevertheless, we have changed the reference to Jonkers et al., 2013 where the authors mention the same vital effect calculated with the paleotemperature equation of Shackleton (1974) modified after O´Neil (1969) (page 10, line 5).

4. Comment:

T. quinqueloba data: it is worthy showing these if they are potentially unreliable due to low amounts of calcite? At the very least, this major caveat needs to be stressed again in the discussion of $\delta^{13}C$.

Author´s response and changes in the manuscript:

We try to be honest when we state that the scatter observed in the *T. quinqueloba* data may at least partly result from the low amounts of calcite in the samples and not always represent natural variation of the $\delta^{13}C$ and $\delta^{18}O$ values. Nevertheless, we think the data should be documented, if only for a comparison with future studies. Unless the editor suggests to remove the figure (Fig. 8 in the original manuscript, Fig. 9 in the revised version) we prefer to keep it in the paper and mention the described inaccuracy again in the discussion chapter (page 15, lines 3-4).

5. Comment:

Seasonality: both *N. pachyderma* and *T. quinqueloba* have a growing season that is significantly longer than a month in summer (Jensen, 1998; Jonkers et al., 2010, Kohfeld et al., 1996). The fossil signal will therefore not only reflect maximum temperatures during summer, but integrate the entire growing season and hence incorporate lower temperatures as well. This could also help to explain the difference between the (snap)shot plankton tow data and the sediment data.

Author´s response and changes in the manuscript:

To our knowledge, the timing and length of the growing seasons of *N. pachyderma* and *T. quinqueloba* in ice-covered and seasonally open waters are still somewhat elusive. Kohfeld et al. (1996) report on maximum fluxes in a 2 week-long bloom event at the beginning of August (in the Northeast Water Polynya). Similar observations were made by Wolfteich (1994) on the Iceland Plateau. On the other hand, in the Irminger Sea the growing season seems to be much longer (Jonkers et al., 2010). One may speculate that seasonally and interannually variable factors (ice drift, arrival of the ice margin at the particular stations, remaining coverage by patchy sea ice) play an important role, and from our limited database it seems impossible to draw conclusions in the length of the growing season (it would also go beyond the scope of our manuscript). Nevertheless, we thank Jonkers for his comment, which we gratefully pick up and mention the length of the growing season as one of the unknowns in our manuscript (page 12, lines 3-4). In the end, however, we can only stick with a comparison of what we have: data from the water column and from the sea floor...

6. Comment:

Effect of eddies and temporal temperature variability: how sensible is it to compare shell chemistry to snapshots of hydrography when foraminifera reflect ambient water conditions over their entire life span? Part of the offsets between water column and test $\delta^{18}O$ and $\delta^{13}C$ could potentially be explained by mesoscale variability (which is visible in Fig. 2). In addition the estimates of advection distance (Von Gyldenfeldt et al., 2000) represent only the sinking phase (i.e. after death of the foram). During its life stage, a test can be advected over greater lengths.

Author´s response and changes in the manuscript:
Lukas Jonkers' comment touches a weakness of all studies so far using plankton tows and water samplers: both instruments always reveal the situation only at the time of sampling. Ideally (to get full insight into the system), samples should be obtained every two weeks or so at exactly the same positions along a transect, again and again over a time period of several months – an effort that is so demanding on shiptime that has not been performed in the Fram Strait or other places in the Nordic Seas, at least to our knowledge. For the moment, we have to live with snapshot data of foraminifers and can compare them to water data from the same day and to what we know about intraseasonal variability. We agree that such mesoscale variability might also influence the offset between the isotope values of the water column and the foraminifera samples. However, the temperature anomalies that are revealed from Figure 2 are not reflected in the offsets found at the same locations. Mesoscale variability may thus play a role but this is hard to estimate based on the available data. Nevertheless, we have included mesoscale variability as a potential factor in the revised version of the manuscript (page 9, lines 23-25).
Regarding the possible transport of foraminifers over long distances, we cannot exclude this possibility. However, if transport would play a large role, we would then expect a more or less systematic offset of foraminifer and equilibrium calcite $\delta^{18}O$ along our transect, in particular for *T. quinqueloba,* which is more likely to be advected from the south than the polar *N. pachyderma* (which actually shows such a systematic offset, although for other reasons, as discussed in the text). One would expect that in the east *T.q*. and equilibrium calcite values are less different from each other than in the west where waters are much colder and accordingly the offset should be larger if the *T.q*. had spent a large part of their lifespan in warm Atlantic waters. In fact, there is no such systematic offset visible from Fig. 8 and thus, we refrain from considering long-range transport of foraminifers an important factor. Nevertheless, we have rephrased the text slightly so that transport effects are not fully excluded (page 12, lines 12-15).

7. Comment:
For comparison with the sediment data it would be useful to also plot the weighted mean isotope data in Fig 7 and 8.

Author´s response and changes in the manuscript:
We thank Jonkers for this suggestion, which we gladly pick up. However, we think that additional data points in figs. 7 and 8 (Fig. 5 and 9 in the revised version of the manuscript) will not improve the clarity of these figures. Instead,

we prefer to add one more figure (Fig. 8 in the revised version), which compares the data from the surface samples and the weighted means of foraminifer isotope values from the water column. In the manuscript text we have made reference to this figure in the appropriate places.

8. Comment:

Sea ice and vial effect: the observation of a variable vital effect is very interesting and deserves more attention, as this crucial information for paleoceanographers. While I cannot offer an explanation for this variability I would like to point out that the highest concentration of *N. pachyderma* (or of planktonic foraminifera, for that matter) was found in sea ice: up to 320 #/L! (Spindler and Dieckmann, 1986). Perhaps sea ice does therefore not represent unfavourable conditions.

Author´s response:

We are aware of the results of Spindler and Dieckmann (1986), but to our knowledge *N. pachyderma* has never been found in Arctic sea ice in significant amounts. We thus refrain from far-reaching speculations here. Instead we stick to own observations (Pados & Spielhagen, 2014) and those of others working in the area that in the Fram Strait the absolute abundances of planktic foraminifera in the upper water column decrease significantly under the sea ice compared to the conditions at the sea ice margin. Even if we do not know the ultimate reason for this, we simply conclude from this observation that the water column under sea ice cover represents favourable conditions.

Oxygen and carbon isotope composition of modern planktic foraminifera and near-surface waters in the Fram Strait (Arctic Ocean) – A case-study

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Abstract

The upper 500 m of the water column and the sediment surface along an E-W transect in the Fram Strait were sampled for recent planktic foraminifera. The $\delta^{18}O$ and $\delta^{13}C$ values of the tests are compared to the stable isotope composition of the water samples taken from the same depths, and related to the characteristics of the water column. The polar species *Neogloboquadrina pachyderma* clearly dominates the species assemblage in the Fram Strait in the early summer, while the subpolar *Turborotalita quinqueloba* accounts only for 5-23%. In this area the average depth of calcification of *N. pachyderma* lies between 70-150 m water depth, *T. quinqueloba* shows a similar range with 50-120 m water depth. The $\delta^{18}O$ values of *N. pachyderma* show an average vital effect of about −1.5‰ compared to calculated equilibrium calcite values. Except for the upper ~75 m, the vertical profiles of $\delta^{13}C$ of the net-sampled shells are nearly parallel to the values measured in the water column with an average offset of −1.6‰ and −3.6‰ for *N. pachyderma* and *T. quinqueloba*, respectively. The discrepancy found in the upper ~75 m might indicate an influence of the 'carbonate ion effect' on the carbon isotope incorporation in the tests. Oxygen and carbon isotopes from the sediment surface yield higher values than those from the water column for both species. This

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may be because specimens from the water column reflect a modern snapshot only, while tests from surface sediments record environmental parameters from the past ~1000 years.

1 Introduction

The stable isotope composition of foraminiferal shells from sediment cores is often used in palaeoceanographic studies to reconstruct past oceanic environments. Planktic foraminifera precipitate their calcite tests from the surrounding seawater. Thus, variations in the stable oxygen ($^{18}O/^{16}O$, $\delta^{18}O$) ratios of shell carbonate are controlled by the ratio in the seawater and the calcification temperature, while the stable carbon ($^{13}C/^{12}C$, $\delta^{13}C$) isotope ratios are a function of the ratio of dissolved inorganic carbon. The stable isotope ratios of seawater, on the other hand, are determined by the interplay of various factors (e.g., evaporation, sea-ice formation, productivity). Therefore, $\delta^{18}O$ values of fossil planktic foraminiferal shells have been widely used to estimate sea surface temperatures (e.g., Kellogg et al., 1978; Erez and Luz, 1983), salinity (e.g., Duplessy et al. 1992), and ocean stratification (Simstich et al., 2003). Planktic $\delta^{13}C$ records are generally assumed to reflect changes in paleoproductivity and ventilation of surface and near-surface waters (Duplessy, 1978). Several studies of living planktic foraminifera showed that these protozoa do not calcify in equilibrium with the ambient sea water (Shackleton et al., 1973; Vergnaud Grazzini, 1976; Kahn, 1979; Kohfeld et al., 1996; Bauch et al., 1997; Volkmann and Mensch, 2001) and that the stable isotope composition of their tests is influenced not only by regional effects but also by numerous other chemical (e.g., pH, carbonate ion concentration) and biological (e.g., symbiont photosynthesis, metabolic activity, test weight) factors. Increasing pH and carbonate ion concentrations are known to decrease both carbon and oxygen stable isotope ratios (Spero et al., 1997; Bauch et al., 2002), while the presence of symbionts causes depletion in ^{18}O and an increase in $\delta^{13}C$ values of the shells (Spero and Deniro, 1987). A higher metabolic rate, characteristic for earlier ontogenetic stages (Hemleben et al., 1989), is associated with a discrimination against heavy isotopes (McConnaughey, 1989). Furthermore, planktic foraminifera are assumed to migrate in the water column during ontogeny (Berberich, 1996; Schiebel and Hemleben, 2005) and form their secondary calcite crust while descending into deeper layers (Simstich et al., 2003). Heavier, encrusted individuals are reported to have higher $\delta^{18}O$ and lower $\delta^{13}C$ values (Kohfeld et al., 1996; Bauch et al., 1997; Volkmann and Mensch, 2001; Simstich et al., 2003). Combinations of these and other factors make the fossil record difficult to interpret. For example, while both increasing temperature and symbiont activity tend to decrease the $\delta^{18}O$ value, at the same time both of them can increase the test weight (Hecht, 1976; Spero, 1992), and thereby also indirectly increase the $^{18}O/^{16}O$ ratio. Thus, it is essential for an improved interpretation of isotopic records from sediment cores to have detailed knowledge on how modern environmental parameters influence the stable isotope composition of living foraminifera and to which degree the isotopic composition of their shells reflects the composition of the ambient sea water.

Here we report on results from isotopic analyses to investigate the effects of environmental factors on the isotopic composition of polar planktic foraminifera. Our study was performed in the Fram Strait that connects the Arctic and North Atlantic Oceans and comprises strong oceanographic contrasts (Fig. 1). On an E-W transect between the Svalbard and Greenland margins, the upper water column and sediment surface were sampled for planktic foraminifera species *Neogloboquadrina pachyderma* (Ehrenberg, 1861) and *Turburotalita quinqueloba* (Natland, 1983). The stable oxygen and carbon isotope compositions of net-sampled tests are compared to the isotope data of ambient seawater and to that of tests from sediment surface samples. Possible reasons for the revealed discrepancies are discussed. Findings about the species assemblage and depth distribution of foraminifera from the same samples are discussed in Pados and Spielhagen (2014).

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2 Hydrographical setting

The Fram Strait is the only deep passage between the Arctic Ocean and the rest of the world ocean, supplying the Arctic Ocean with waters of North Atlantic origin. The oceanography is dominated by two major surface current systems: the northward flowing West Spitsbergen Current (WSC) carries warm and saline water masses, while in the East Greenland Current (EGC) cold and fresh Polar waters exit the Arctic Ocean (Johannessen, 1986). The upper 500 m of the WSC are dominated by Atlantic Water (Rudels et al., 1999), characterized by temperatures higher than 0.5°C and salinities above 34.5 (Jones, 2001). In the western part of the strait the upper 200 m are characterized by temperatures below 0°C and salinities between 32 and 34. In the summer, as a result of ice melt, the surface waters have even lower salinities (below 32). A well-developed halocline separates the Polar waters from the Atlantic Layer found between 200 and 500 m (Rudels et al., 2000). The interaction between these two water masses controls the sea-ice coverage in the strait. In summer the ice cover usually extends from Greenland to the East Greenland shelf edge but it can intrude also into the eastern part of the strait in the case of extremely cold winter/spring conditions (Dickson et al., 2000).

The oceanographic system is highly variable and the surface distribution of Polar waters can change on a daily timescale (e.g. Beszczynska-Möller et al., 2011). Oceanographic measurements during cruise ARK XXVI/1 (Beszczynska-Möller and Wisotzki, 2012) provide a detailed profile across the Fram Strait at the time of sampling (Fig. 2). The upper 500 m of the WSC were characterized by salinities near 35 and temperatures between 4°C and 2°C. At the surface an approx. 100 m thick, warm layer was observed, with temperatures up to 7-8°C. During the time of sampling, at 2°E and 4°E (stations 39 and 35), cold and fresh water masses intruded into the upper 50-100 m of this layer. After one week these water masses were not present anymore at the same locations (see water column properties at 3°E (station 87) that was sampled 8 days later), in agreement with high variability of oceanic fluxes in this region (Beszczynska-Möller et al., 2011). In the western part of the strait and in the EGC, the Polar waters extended down to ~200 m water depth and had salinities around 33 and an average temperature of −1.5°C at the time of the sampling (Fig. 2). Here, on the very surface low salinities (~30) were found that is probably caused by melt water. The Polar waters were mainly ice-covered. Below ~200 m water depth submerged warmer and salty Atlantic waters were found. The sea-ice margin over the position of the transect was located at ~2°W during the sampling period.

3 Material and methods

Plankton tow, sediment surface and water samples used in this study were obtained during expedition ARK XXVI/1 with research vessel Polarstern in June/July 2011 in the Fram Strait. Samples were collected at 10 stations along a transect at 78°50'N across the Fram Strait (Fig. 1, Table 1). Plankton samples were collected by a MultiNet sampler (net opening 0.5 m^2, Hydro-Bios, Kiel, Germany); the nets of 63 µm mesh size were towed vertically on regular depth intervals (500-300 m, 300-200 m, 200-100 m, 100-50 m, 50-0 m). Sediment surface samples were obtained from multicorer deployments at the same stations. Sample collection and handling procedures are described in detail by Pados and Spielhagen (2014).

For stable isotope analysis 10-25 specimens of *Neogloboquadrina pachyderma* and 10 specimens of *Turborotalita quinqueloba* were picked from the >100 µm fraction (plankton

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samples) and from the 100-250 µm fraction (sediment samples). The number of picked tests was restricted by the number of available, same-sized and clearly identifiable shells. In case of *N. pachyderma* we follow the species concept of Darling et al. (2006) and we differentiate between *N. pachyderma* and *N. incompta* by coiling direction. However, we have to emphasise that we did not genetically analyse the samples, and for isotopical analyses we have used left-coiling specimens only. Thus, according to Darling et al. (2006) the picked tests may genetically be to a very minor amount *N. incompta*. The oxygen and carbon isotope analysis of foraminiferal calcite was performed at the GEOMAR Stable Isotope Lab using a Finnigan-MAT 253 mass spectrometer system connected to a Kiel IV Carbonate Preparation Device.

Temperature and salinity of the water column were measured by a conductivity-temperature-depth (CTD) profiler (Beszczynska-Möller and Wisotzki, 2012), immediately before the deployment of plankton tows. Data of ice coverage were obtained by shipboard observations. Water samples for stable isotope analyses were taken from the rosette sampler, immediately after arriving on the deck to minimize the exchange of contained CO_2 with the atmosphere. Water samples for $\delta^{13}C$ analysis (100 ml) were drafted carefully into glass bottles without sputtering and thus avoiding bubbles. Samples were immediately poisoned with $HgCl_2$ (0.2 ml) to stop biochemical reactions, which may alter the carbon isotopic composition of CO_2, and bottles were then sealed by aluminium caps with high-density butyl-rubber plugs. Water samples for $\delta^{18}O$ analysis (50 ml) were filled into glass bottles and sealed by plastic screw-on caps. The oxygen and carbon isotope mass ratios of the water samples were measured in the stable isotope laboratories of AWI Potsdam with a Finnigan-MAT Delta-S mass spectrometer with two coupled equilibration units ($\delta^{18}O$) and of MARUM (Bremen) using a Gasbench coupled to a MAT 252 mass spectrometer ($\delta^{13}C_{DIC}$), with a precision and accuracy of at least ±0.1‰ and ±0.15‰ for $\delta^{18}O$ (Meyer et al., 2000) and $\delta^{13}C_{DIC}$, respectively.

"Equilibrium calcite values" (δ_c) were calculated for the water samples between sea surface and 500 m water depth from actual $\delta^{18}O$ (δ_w) and temperature (T) measurements according to the so called "palaeotemperature equation" of O'Neil et al. (1969):

$$T(°C) = 16.9 - 4.38(\delta_c - \delta_w) + 0.1(\delta_c - \delta_w)^2 \qquad (1)$$

where δ_c and δ_w are the stable oxygen isotope values of the calcite and the water on the PDB scale, respectively. Isotope measurements of water are presented using SMOW as a standard. $\delta^{18}O$ (SMOW) was converted to $\delta^{18}O$ (PDB) for the palaeotemperature equation according to Bemis et al. (1998):

$$\delta^{18}O\ (PDB) = 0.9998\ \delta^{18}O(SMOW) - 0.2‰. \qquad (2)$$

Weighted averages of the stable isotope results for each station were calculated using the standing stock (sum of isotope values for each interval multiplied with the concentration of foraminifera in depth interval/sum concentrations in all intervals; see Bauch et al., 1997). Carbonate ion concentrations from our sampling area in Fram Strait at about 78.5°N were extracted from the hydrographic database CARINA (CARbon dioxide IN the Atlantic Ocean; http://cdiac.ornl.gov/oceans/CARINA/) from expeditions on RV Hudson and RV Knorr in 1982 and 2002, respectively.

4 Results

4.1 Water column properties

4.1.1 Stable isotopes in the upper water column

In general, oxygen isotope composition of water is roughly linearly correlated to salinity (Fig. 3). Both change along the transect with lowest values at the surface and are continuously increasing with depth. Surface $\delta^{18}O$ and salinity are lowest in the west and highest in the east (Fig. 4). The vertical $\delta^{18}O$ profiles of the two westernmost stations show strong similarities with the vertical profiles of stations 35 and 39 (4°E and 2°E, respectively) where during the time of sampling cold and fresh water masses intruded into the warm surface waters. At these four stations extremely low salinity and $\delta^{18}O$ values mark Polar waters at the surface that are reaching from the surface down to ~200 m water depth at stations 75 and 71 (4°W and 5°W, respectively) and to ~100 m water depth at stations 39 and 35 (2°E and 4°E, respectively). Below the surface layers the Atlantic waters are characterized by relatively high and constant $\delta^{18}O$ values of about +0.3‰ (Fig. 4). The remaining six stations reveal more scatter: we found a slight increase from the surface to 25 m water depth, then a decrease to 75-100 m depth, followed by invariant $\delta^{18}O$ values of the Atlantic Layer (Table 2). When evaluating average values over the upper 500 m of the water column, the two westernmost stations (75 and 71) yield the lowest average values (−0.41‰±0.94‰ and −0.84‰±1.16‰, respectively) while the highest average value (+0.34‰±0.03‰) is observed at 3°E at station 87.

The vertical variation of the carbon isotope composition of the dissolved inorganic carbon (DIC) in the upper 500 m of the water column is rather small. The $\delta^{13}C_{DIC}$ values have an average value of about +1.04‰ with a standard deviation of 0.24. Surface waters always yield heavier values, decreasing down to ~100 m water depth followed by relatively constant values down to 500 m water depth (Fig. 4, Table 2).

4.1.2 Equilibrium calcite values

The equilibrium calcite values calculated from $\delta^{18}O$ and temperature of seawater increase constantly with depth in the eastern part of the strait, while at the stations at 4°W and 5°W, in the western part of the strait, a stronger increase is observed from the surface down to 150 m water depth, followed by a slight decrease. A similar pattern, though in a narrower range, can be found at 4°E and 2°E, in the middle of the strait, where near the surface unusually low temperatures of the water were recorded during the sampling period (Fig. 5, Table 2).

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4.2 Species distribution of planktic foraminifera

In the Fram Strait the planktic foraminiferal fauna is dominated by polar *N. pachyderma* and subpolar symbiont-bearing *Turborotalita quinqueloba* (Volkmann, 2000; Simstich et al., 2003; Pados and Spielhagen, 2014). *N. pachyderma* clearly prevails in our samples contributing to the total assemblages with 73-92% compared to the the subpolar *T. quinqueloba*, contributing with 23-5%. The proportion of *N. pachyderma* shows an increasing trend towards the west while *T. quinqueloba* follows an exactly reverse tendency. Both species have maximum absolute abundances between 0-100 m water depth with a shallower maximum under the ice cover than in the open ocean (Fig. 6, 7). The species assemblage found in the sediment surface was found to correlate best with the living fauna caught between 50-100 m water depth (Pados and Spielhagen, 2014).

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4.3 Stable isotope composition of foraminifera

4.3.1 *Neogloboquadrina pachyderma* (sin.)

The oxygen isotope composition of *N. pachyderma* from sediment surface samples shows lowest values at the three easternmost stations (stations 127, 25, 19; at 8°E-6°E). The highest value is found in the western part at station 75, at 4°W. The sediment surface samples have an average δ^{18}O value of +3.2‰±0.3‰ (Table 3). The plankton samples generally have a lower oxygen isotope composition than the sediment surface samples. The weighted average δ^{18}O values at each station are ranging from −0.7‰±1.7‰ to +3.3‰±0.2‰ over the whole transect. There is no clear east-west difference and the stations in the middle of the strait (at 4°E, 2°E and at 2°W) yield the highest values (Fig. 8). The vertical distribution of δ^{18}O does not show a well-pronounced trend. The only clearly recognisable pattern is that values in the depth interval of 0-50 m are usually lower than those from the interval 50-100 m (an exception is station 54 where the surface waters yielded slightly heavier δ^{18}O values) (Fig. 5, Table 4).

The δ^{13}C values of *N. pachyderma* from sediment surface samples are relatively constant and have an average value of +0.5‰±0.2‰. The lateral distribution of the δ^{13}C values from the sediments shows a trend similar to the δ^{18}O results: the easternmost stations have the lowest values (+0.09‰, +0.15‰ and +0.4‰ at 8°E, 7°E and 6°E, respectively) while the highest (+0.7‰) is found in the western part of the section, at the sea ice margin at 2°W (Table 3). The carbon isotope composition of *N. pachyderma* from plankton tows shows lower values at each station than the δ^{13}C values from sediments. The δ^{13}C values of plankton samples have a mean of −0.8‰±0.7‰ of weighted averages over the whole transect. The plankton samples do not follow the E-W trend found in the core top samples and both the lowest and the highest values are found at stations in the middle of the transect (at 3°E and 2°E, respectively) (Fig. 8). Vertical δ^{13}C profiles of the plankton samples show increasing values from the sea surface down to the depth interval of 100-200 m (exceptions are the stations at 8°E, 3°E and 5°W where maximum values lie in the depth interval of 50-100 m), followed by a slight decrease to 300-500 m (Fig. 5, Table 4).

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4.3.2 *Turborotalita quinqueloba*

Both oxygen and carbon isotope compositions of *T. quinqueloba* from sediment surface samples show increasing values from east to west; averaging over the transect −0.1‰±0.2‰ and +2.7‰±0.3‰, respectively (Table 3).

The weighted average of the δ^{18}O and δ^{13}C values of net sampled specimens scatter along the stations and do not show any pronounced east-west difference (Fig. 8). The vertical profiles of both parameters show extremely low values near the surface compared to all other depth intervals. The vertical variation of the δ^{18}O and δ^{13}C values in *T. quinqueloba* is much bigger than the variation found in *N. pachyderma* (sin.) (Fig. 9, Table 4). However, it has to be taken into account that the number of specimens available for isotope analysis (on average ten tests) was rather low and possibly not sufficient to yield reliable results for this thin-walled species. We cannot exclude that the differences in variation are due to a non-systematic error in the isotope measurements of *T. quinqueloba*.

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5 Discussion

5.1 Oxygen isotope values of water samples and foraminifera

The calculated equilibrium calcite isotope composition represents the potential δ^{18}O value of inorganic calcite precipitated in isotopic equilibrium with the surrounding seawater. The offset found between the equilibrium calcite value and the measured δ^{18}O value of foraminiferal tests is commonly described as 'vital effect' related to differential isotopic uptake in carbonate organisms compared to equilibrium conditions. The δ^{18}O values of living foraminifera in our work area during early summer were consistently lower than the calculated equilibrium calcite values. Part of this offset may certainly result from mesoscale oceanic variability, i.e., short-term changes of salinity and/or temperature due to, e.g., sea ice formation/melting or local vertical convection. The mean offsets were −1.5‰±1.3‰ in *N. pachyderma* and −3.7‰±1.7‰ in *T. quinqueloba*. Based on previously published results, the magnitude of the vital effect in *N. pachyderma* appears to vary regionally. Bauch et al. (1997) reported a consistent offset of −1.0‰ between equilibrium calcite values and δ^{18}O data of net-sampled *N. pachyderma* (sin.) in the Nansen Basin. Volkmann and Mensch (2001) found an average vital effect of −1.3‰ in the Laptev Sea for *N. pachyderma* and −1.6‰ and −1.3‰ in

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the Fram Strait for *N. pachyderma* and for *T. quinqueloba*, respectively. Plankton tows from various hydrographic regimes in the Nordic Seas revealed vital offsets of −1.0‰ and −1.1‰ for *N. pachyderma* and *T.quinqueloba*, respectively (Simstich et al., 2003). Significantly smaller offsets were reported from the western subpolar North Atlantic, calculated from shells collected with sediment traps (Jonkers et al., 2013). Even studies conducted in the Fram Strait reveal slightly different values (see Stangeew, 2001; Volkmann and Mensch, 2001). Figure 10 comprises results on $\delta^{18}O_{N.p.}$ and equilibrium calcite values in the upper water column reported from the Fram Strait.

In our study *T. quinqueloba* shows larger offsets between the equilibrium calcite values and the measured $\delta^{18}O$ values than *N. pachyderma* (on average −3.7‰ and −1.5‰, respectively). Earlier works (e.g., Fairbanks et al., 1980; Lončarić et al., 2006) also recorded a larger negative offset in spinose species compared to nonspinose species. Moreover, symbiont-bearing species, like *T. quinqueloba*, are known to be more depleted in ^{18}O as a consequence of higher CO_2 fixation caused by photosynthesis (Bijma et al., 1990; Spero et al., 1997). In *N. pachyderma* we found a clear east-west difference in the magnitude of the vital effect along the transect, similar to observations by Volkmann and Mensch (2001). In their study the eastern and western part of the strait yielded significantly different offsets, with highest deviations from the equilibrium calcite values in the west. They concluded that ice coverage increases the magnitude of the vital effect. In our samples in *N. pachyderma* the strongest disequilibrium was indeed found at the two ice-covered stations (−4.0‰ and −1.8‰, at 4°W and 5°W, respectively) and at station 87 (−3.9‰, at 4°E). These results are also in line with observations of Bauch et al. (1997) who found slightly increasing isotopic differences between water and plankton samples with decreasing salinity and temperature. Similar to these results, Volkmann & Mensch (2001) observed greater vital offset in the cold and less saline waters of the western Fram Strait. They concluded that unfavourable conditions here make the individuals grow faster (i.e., increase their calcification rate). An increased calcification rate decreases the $\delta^{18}O$ of tests (McConnaughey, 1989) and may thus increase the disequilibrium. While this hypothesis can explain high offsets at increased calcification rates, the validity of the hypothesis seems rather unlikely as unfavourable conditions generally lead to lower metabolism and thus, decreased calcification rates. Moreover, lower temperatures decrease metabolic rates in all organisms (Hemmingsen, 1960; Gillooly et al., 2001). The abrupt increase in the offset close to the sea-ice margin may rather be explained by

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increased primary production, associated with the ice margin where ice melting increases stratification and consequently the stability of the water column, which triggers phytoplankton blooms (cf. Alexander, 1980; Carstens et al., 1997; Pados and Spielhagen, 2014). During biological production dissolved inorganic carbon is consumed. This considerably increases pH and consequently the carbonate ion concentration ($[CO_3^{2-}]$) of the water (Chierchi and Franson, 2009). Spero et al. (1997) showed that increasing seawater $[CO_3^{2-}]$ decreases the $^{18}O/^{16}O$ ratios of the shells of foraminifera and may thus simultaneously increase the vital effect. Still, the effect of carbonate ion concentrations alone cannot explain the high deviation from equilibrium calcite found at the station at 4°E where no increased primary production is expected. A possible reason for the increased vital effect at the stations at 5°W, 4°W and 4°E might also be a sampling during different ontogenetic stages. *N. pachyderma* is known to reproduce on a synodic lunar cycle (Bijma et al., 1990; Schiebel and Hemleben, 2005) and as these three stations were sampled in sequence in the second half of the cruise, it is possible that in the respective samples there were more specimens in early life stages compared to the stations sampled 7-10 days before. Early ontogenetic stages are associated with higher respiration and calcification rates (Hemleben et al., 1989). Rapidly growing skeletons tend to show depletion in both ^{13}C and ^{18}O (McConnaughey, 1989), which could account for the increased vital effect observed at the respective stations.

In contrast to *N. pachyderma*, the offsets found between equilibrium calcite values and the $\delta^{18}O$ values of *T. quinqueloba* do not follow a clear trend along the transect and show great scatter (Fig. 9). However, the low numbers of specimens found in the samples at most of the stations did not allow us to determine $\delta^{18}O$ over the whole water column sampled. Moreover, as a consequence, lower numbers of tests (on average ten) were used for stable isotope analysis than in *N. pachyderma* (25), which might also account for the scatter in both $\delta^{13}C$ and $\delta^{18}O$ values in *T. quinqueloba*. We therefore refrain from discussing the vital effect in *T. quinqueloba*.

Our analysis shows that recent specimens of planktic foraminifera from the water column have a lower oxygen isotopic value than fossils on the sediment surface (Fig. 5, 9). This is in agreement with a number of studies conducted in different regions of the world (e.g., Duplessy et al., 1981; Schmidt and Mulitza, 2002). Berger (1970) suggested in his hypothesis on intraspecific selective dissolution that within one species preferentially the thin-shelled

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individuals are dissolved during deposition. These tests are secreted during the warmest period of the year and thus, their dissolution increases the average $\delta^{18}O$ value of the species in the core top samples. Even though the length of growing season of planktic foraminifera in the Fram Strait is unknown, it has been shown that in the Nordic Seas the production maximum of planktic foraminifera occurs during summer (Kohfeld et al., 1996; Jonkers et al., 2010), with almost zero production during other seasons. This means that the majority of the specimens calcifies the shells under similar conditions. Accordingly, differences in the thickness of tests are not to be expected. Therefore the hypothesis of Berger (1970) cannot explain the isotopic differences between plankton and sediment surface samples in our study area. Lateral transport of the shells during deposition is another effect that could explain the discrepancies. However, mean transport distances in the Fram Strait are only 25-50 km for *N. pachyderma* and 50-100 km for *T. quinqueloba* (von Gyldenfeldt et al., 2000). Even if we consider that specimens may also be carried a similar range during their lifespan, these distances appear too short to transport isotopic signatures from water masses with significantly different temperature/salinity signatures into the sediments. The offset found in the $\delta^{18}O$ values between plankton and sediment surface samples can be rather attributed to the age difference between living plankton and sediment surface samples. Core top samples are assumed to represent modern conditions in palaeoceanographic reconstructions. Nevertheless, depending on sedimentation rates and bioturbation intensity, their average age can vary in a great range (in the Fram Strait a few decades to 3 ky, on average 1 ky, see Simstich et al., 2003) while net-sampled foraminifera reflect a snapshot of actual modern conditions. Discrepancies found between isotopic composition of shells collected on the sediment surface and in the water column may therefore be related to changes in the oceanographic parameters between the early summer of 2011 and average conditions during the period represented by sediment surface samples. To explain the lower modern $\delta^{18}O$ values, the water mass in the calcification depth interval of the foraminifera must have become warmer and/or the $\delta^{18}O_{water}$ must have decreased and thus, the salinity signature must have changed significantly. It has been shown indeed that due to increasing river discharges (e.g., Peterson et al., 2002) the freshwater budget of the Arctic Ocean significantly changed in the last in the last 8 decades (Morison et al., 2012), which resulted in increased freshwater export through the Fram Strait. Moreover, rising temperatures have been documented for the last decades in the Arctic as well (e.g., Zhang et al., 1998; Serreze et al., 2000; Spielhagen et al., 2011). The mean offset found between the $\delta^{18}O$ values of net-sampled foraminifera and the tests from the sediment surface

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along the transect is ~1.3‰. Assuming that the oxygen isotope composition of the water remained constant over the time, this difference would correspond to a change in water temperature of about 5°C. Neglecting the two extremely high offsets found at 4°W and 3°E, the mean offset would decrease to ~0.6‰, corresponding to a temperature change of ~2.4°C. A temperature change of 2.4°C is similar to the reconstructed temperature increase of Atlantic Water during the last 200 years (Spielhagen et al., 2011). However, a temperature change of 5°C during the last millennia over the whole Fram Strait area seems much too large and clearly, water temperature changes may not solely account for the differences found in the isotopic composition between modern and fossil foraminifera. The results nevertheless suggest the combined effect of temperature rise and $\delta^{18}O_{water}$-change, possible dissolution and transport effects during the last ~1000 years.

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5.2 Calcification depth

With currently available methods we cannot directly determine the actual calcification depth of planktic foraminifera in the water column. Therefore we assume that planktic foraminifera build their shells at the depth where they are most abundant. The average depth of calcification (calculated from the standing stock) of *N. pachyderma* in the Fram Strait lies between 70-150 m water depth. *T. quinqueloba* shows a similar calcification range at 50-120 m water depth (Fig. 6, 7). Both species show deepest average calcification depth at the easternmost station. Our results are in accordance with Simstich et al. (2003) who calculated an apparent calcification depth for *N. pachyderma* of 70-130 m and 70-250 m in the EGC and off Norway, respectively. From the Nansen Basin (eastern Arctic Ocean), Bauch et al. (1997) reported a deeper average calcification depth for *N. pachyderma*. However, in the northern regime of the Nansen Basin, where the water column properties are similar to those in the western Fram Strait, *N. pachyderma* prefers shallower waters than in the southern Nansen Basin where the water column is strongly influenced by the subsurface inflow of Atlantic Waters (Bauch et al., 1997). This trend observed by Bauch et al. (1997) coincides with our results. The difference found in calcification depths in the Nansen Basin and in the Fram Strait might be caused by the different habitats that these locations represent. The northern Nansen Basin is covered by sea ice throughout the year and thus represents a different habitat for planktic foraminifera than the narrow Fram Strait. Here, the interannual W-E variability in the position of the average summer sea ice margin is high and the ice-covered stations sampled in this study might therefore be ice-free in another summer. It has been shown that

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the depth habitat of planktic foraminifera in the Fram Strait in the early summer is predominantly controlled by the position of the deep chlorophyll maximum (Pados and Spielhagen, 2014). The permanent ice cover in the Nansen Basin may alter the factors controlling the depth habitat of foraminifera and may consequently cause a different depth habitat (and calcification depth) than in the Fram Strait.

Calculating the vital effect from differences between water and plankton samples at each depth level assumes that foraminifera calcified their tests at the depth interval where they were caught. This might not be true, as foraminifera are known to migrate in the water column during their life cycle. Alternatively we may assume that the main encrustation process of foraminifera indeed happened solely at the average calcification depth that is derived in our study from the standing stock. When calculating the average offset between water and foraminifera for the calcification depth only, a vital effect of −0.9‰±0.5‰ in *N. pachyderma* and −3.1‰±2.9‰ in *T. quinqueloba* is determined. These vital effects are significantly smaller than those determined over the whole water column, which are −1.5‰±1.3‰ and −3.7‰±1.7‰ for *N. pachyderma* and *T. quinqueloba*, respectively. In general, we have to take into account that both calcification-scenarios represent extreme cases and the actual vital effect may be between these two extremes.

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5.3 Carbon isotope values of DIC and foraminifera

The interpretation of the carbon isotope composition of foraminiferal shells is quite complicated as several factors can influence the carbon isotope incorporation. The gas exchange between sea and atmosphere, the biological production, the community respiration and species dependent incorporations of carbon isotopes are the main processes that can affect the $^{13}C/^{12}C$ ratio in calcite tests. A number of studies reported on a consistent offset between $\delta^{13}C$ of calcite shells and the $\delta^{13}C_{DIC}$ measured within the water column (e.g., Bauch et al., 2000; Volkmann and Mensch, 2001). According to Romanek et al. (1992) the $\delta^{13}C$ of inorganic calcite that precipitates in equilibrium with seawater is 1‰ higher than $\delta^{13}C_{DIC}$. In our study area below 75 m water depth the $\delta^{13}C$ values of *N. pachyderma* run relatively parallel to the $\delta^{13}C_{DIC}$, but with an average offset of −1.6‰±0.7‰. This reveals a vital effect of about −2.6‰. Kohfeld et al. (1996) reported from the Northeast Water Polynya on the Greenland shelf a vital effect of −1‰ while another study in the Nansin Basin (Bauch et al., 2000) revealed a vital effect of −2‰. The discrepancies found here may suggest the influence

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of oceanographic variability on the vital effect in δ^{13}C of *N. pachyderma*. The δ^{13}C of *T. quinqueloba* shows a stronger vertical scatter with an average vital effect of $-4.6‰ \pm 1.5‰$. Again we emphasise that in case of *T. quinqueloba* the low amounts of calcite analysed might have also influenced the results. Nevertheless, in the upper 75-100 m of the water column for both species the $\delta^{13}C_{DIC}$ and the δ^{13}C of shells show an exactly reverse tendency (Fig. 5, 9): the $\delta^{13}C_{DIC}$ is increasing towards sea surface while the δ^{13}C of the tests is decreasing. The high $\delta^{13}C_{DIC}$ values found close to the sea surface are assumed to be caused by high primary production, resulting in enrichment in ^{13}C (Fogel and Cifuentes, 1993): as ^{12}C is taken for photosynthesis, the water becomes enriched in ^{13}C. However, if no other processes would affect the incorporation of carbon into the calcite shells, the tests should also show the enrichment in ^{13}C. One possible explanation for the deviation in the upper ~75 m could be the effect of high (near-surface) temperatures on the carbon isotope incorporation of the tests. Laboratory (Bemis et al., 2000) and field experiments (Jonkers et al., 2013) have shown that foraminiferal δ^{13}C linearly decreases with increasing temperatures. However, in our data set the offsets measured between $\delta^{13}C_{DIC}$ and $\delta^{13}C_{foraminifera}$ have no correlation with *in-situ* water temperatures. Therefore this hypothesis cannot explain in our case the greater vital effect found in near-surface waters.

Another explanation for the deviation might be an increased carbonate ion concentration ($[CO^{2-}_3]$) as a consequence of strong biological production in the upper water column (Chierchi and Franson, 2009). Both culturing (Spero et al., 1997) and field experiments (Bauch et al., 2002) have shown that the carbon isotope composition of foraminifera is correlated to the carbonate ion concentration of the water. The "carbonate ion effect" (CIE) describes that increasing seawater $[CO^{2-}_3]$ causes depletion in ^{13}C of the foraminiferal tests. The CIE could therefore explain our observed low δ^{13}C values of shells living in ^{13}C-enriched waters. A direct interpretation of this effect is not possible as during cruise ARKXXVI/1 the concentration of $[CO^{2-}_3]$ or the parameters needed to calculate $[CO^{2-}_3]$ (e.g. pH and total alkalinity of the water samples) were not determined. However, vertical profiles of $[CO^{2-}_3]$ measured in the area (CARINA database, 2015) show in the upper 500 m of the water column a quite uniform $[CO^{2-}_3]$ distribution, with values of 100-120 µmol/kg. Only at the surface in the WSC (upper 50 m) values are higher (up to 160 µmol/kg). Applying the observed effect on *Globigerina bulloides* ($-1.3‰$ in $\delta^{13}C_{foraminifera}$/ 100µmol/kg in $[CO^{2-}_3]$; Spero et al., 1997) the range of about 50 µmol/kg in $[CO^{2-}_3]$ implies a potential effect of $-0.65‰$ on the δ^{13}C

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values of foraminifera, and thus might explain the lower values found in the surface waters in the east. However, we cannot see this difference between east and west in the offsets measured between $\delta^{13}C_{DIC}$ and $\delta^{13}C_{N.p.}$ which points to the fact that other processes are responsible for the deviation found in near-surface waters as well. Nevertheless, assuming that the vital effect in $\delta^{13}C$ close to the sea surface is influenced by increased carbonate ion concentrations induced through high primary production, the smaller average vital effects reported by Volkmann and Mensch (2001; −2.15‰) and Stangeew (2001; −2‰) from the Fram Strait more than 10 years earlier may point to an increase in bioproductivity during the last decades in the area. Datasets of $[CO^{2-}_3]$ recorded between 1982 and 2002 in the Fram Strait (CARINA database, 2015) however do not show respective changes, which may indicate a significant shift only after 2002. We also have to consider that bioproductivity may vary interannually and within the summer season.

As also discussed with respect to the offset in $\delta^{18}O$ between coretop and living foraminifera, the age of core top samples can vary in a great range (between modern to 3 ky, with an average of ~1 ky, Simstich et al., 2003). Accordingly, they may reflect significantly older environments than the plankton samples. The negative offset in $\delta^{13}C$ between the sediment and plankton samples may thus be explained by the surface ocean Suess effect: during the last 100 years the carbon isotope composition of the atmosphere has changed due to the increased anthropogenic combustion of fossil carbon which is extremely negative in $\delta^{13}C$. The $\delta^{13}C$ values of the atmospheric CO_2 have decreased by about 1.4‰ (Friedli et al., 1986; Francey et al., 1999) and the concurrent shift in the stable carbon isotope composition of ocean surface water is reflected in the decrease of $\delta^{13}C$ of recent foraminiferal shells (Bauch et al., 2000). The offset of roughly −1‰ in $\delta^{13}C$ between the sediment and plankton samples observed both in this study and in that of Bauch et al. (2000) may therefore be explained by the different ages of the carbonate in both sample sets and the developments that have occurred in the last ca. 100 years.

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6 Conclusions

(1) The polar species *Neogloboquadrina pachyderma* clearly dominates the foraminiferal species assemblage in the Fram Strait in the early summer. Subpolar *Turborotalita quinqueloba* accounts for only 5-25%.

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(2) In the study area both species dwell shallower under the ice cover than in the open ocean. The average depth of calcification of *N. pachyderma* lies between 70-150 m water depth, *T. quinqueloba* shows a similar range with 50-120 m water depth.

(3) When calculating the average vital effect in the oxygen isotope composition for the whole sampled water column, *N. pachyderma* and *T. quinqueloba* show an average offset of about −1.5‰ and −3.7‰ (respectively) compared to calculated equilibrium calcite values. These vital effects are higher than those determined at the calcification depth only where it is −0.9‰ for *N. pachyderma* and −3.1‰ for *T. quinqueloba*.

(4) The $\delta^{13}C_{DIC}$ and the $\delta^{13}C$ values of the net-sampled shells show an average offset of −1.6‰ and −3.6‰ for *N. pachyderma* and *T. quinqueloba*, respectively. The discrepancies with earlier published results may suggest the influence of regional variability on the vital effect in $\delta^{13}C$.

(5) In the upper ~75 m of the water column the $\delta^{13}C_{DIC}$ and the $\delta^{13}C$ of shells of both species show an exactly reverse tendency that might relate to the influence of the 'carbonate ion effect' on the carbon isotope incorporation in the tests.

(6) The shells of both species collected from the water column yield lower $\delta^{18}O$ and $\delta^{13}C$ values than those from the sediment surface, suggesting a significant change of the stable isotope ratios in the recent past (last centuries, likely the last 100-150 years only). The negative offset in $\delta^{18}O$ between the sediment and plankton samples suggests a combined effect of temperature rise and $\delta^{18}O_{water}$-change, while the offset in $\delta^{13}C$ may be explained by the surface ocean Suess effect.

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during the process. Lukas Jonkers and two anonymous reviewers gave important comments that significantly helped to improve the manuscript. This research was conducted with funding of the European Community's 7th Framework Programme FP7 2007/2013, Marie-Curie Actions, under Grant Agreement No. 238111 – CASE ITN. R.F.S. acknowledges the financial support through the "Akademienprogramm" by the Academy of Sciences, Humanities, and Literature Mainz.

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Table 1. List of the stations sampled during cruise ARKXXVI/1 in June/July 2011.

Station	Latitude	Longitude	Water depth	Date	Ice cover
PS78-19	78°49.84´N	6°0.69´E	2464 m	25.06.11	no
PS78-25	78°49.962´N	7°0.077´E	1465 m	26.06.11	no
PS78-35	78°49.772´N	3°58.380´E	2335 m	28.06.11	no
PS78-39	78°50.09´N	1°54.56´E	2554 m	28.06.11	no
PS78-44	78°49.972´N	0°4.630´E	2636 m	29.06.11	no
PS78-54	78°50.02´N	2°0.21´W	2714 m	01.07.11	ice margin
PS78-71	78°49.66´N	5°20.99´W	684 m	04.07.11	ice covered
PS78-75	78°49.74´N	3°55.44´W	1978 m	04.07.11	ice covered
PS78-87	78°50.44´N	3°0.19´E	2454 m	06.07.11	no
PS78-127	78°49.84´N	8°1.33´E	1019 m	10.07.11	no

Table 2. $\delta^{18}O$, $\delta^{13}C$ and equilibrium calcite values in the upper 500 m of the water column.

Station	Depth (m)	$\delta^{18}O$ (‰ SMOW)	$\delta^{13}C$ (‰ PDB)	Equ.calc.
PS78-19	0	0.29	1.63	2.90
	25	0.38	1.71	3.01
	50	0.4	1.39	3.32
	75	0.34	0.92	3.44
	100	0.21	0.66	3.33
	125		0.95	
	150	0.28	1.06	3.49
	200	0.31	0.84	3.55
	250	0.21		3.50
	300	0.31	0.95	3.66
	400	0.23	1.10	3.77
	500	0.27	1.06	3.91
PS78-25	0	0.32	0.89	2.70
	25	0.37	0.92	2.73
	50	0.33	0.96	3.24
	75	0.3	0.98	3.29
	100	0.31	0.86	3.36
	125	0.3	0.83	3.44
	150	0.28	0.97	3.47
	200	0.29	0.90	3.50
	250			
	300	0.26	0.95	3.53
	400	0.25	0.99	3.70
	500	0.25	0.94	3.94
PS78-35	0	-0.98	1.30	3.06
	25	-0.46	1.30	3.99
	50	0.09	1.03	4.26
	75	0.23	0.96	3.62
	100	0.29	0.70	3.53
	125	0.37	0.73	3.65
	150	0.29	0.99	3.63
	200	0.33	1.05	3.82
	250			
	300	0.33	1.01	3.81
	400	0.23	1.07	3.82
	500	0.29	1.01	4.00
PS78-39	0	-0.29	1.50	3.92
	25	-0.25	1.31	4.27
	50	0.06	1.21	4.64
	75	0.14	1.11	3.99
	100	0.17	0.97	4.02
	125	0.22	1.05	3.82
	150	0.25	1.13	3.67
	200	0.36	1.01	3.87
	250			
	300	0.28	0.82	3.76
	400	0.29	0.79	3.71
	500	0.28	1.09	3.80
PS78-44	0	0.25	1.39	2.73
	25	0.38	1.16	3.03
	50	0.38	1.01	3.14
	75	0.3	0.88	3.19
	100	0.37	0.89	3.40
	125	0.38	0.98	3.48
	150	0.31	0.96	3.45
	200	0.29	1.19	3.47
	250			
	300	0.28	0.88	3.60

	400	0.35	0.98	3.79
	500	0.28	1.14	3.89
PS78-54	0	0.33	1.68	4.41
	25	0.41	1.61	4.69
	50	0.37	0.94	3.06
	75	0.32	0.95	3.21
	100	0.37	1.06	3.38
	125	0.36	0.94	3.44
	150	0.36	1.10	3.49
	200	0.25	1.09	3.46
	250			
	300	0.21	0.90	3.49
	400	0.36	1.04	3.72
	500	0.3	0.87	3.77
PS78-71	0	-2.63	1.49	1.67
	25	-2.4	1.50	2.15
	50	-2.18	1.23	2.38
	75	-1.41	1.12	3.13
	100	-1	1.11	3.49
	125	-0.52	1.02	3.98
	150	-0.25	1.09	4.24
	200	0.04	1.13	4.15
	250			
	300	0.36	0.94	4.13
	400	0.37	0.95	4.07
	500	0.4	1.18	4.34
PS78-75	0	-2.2	1.34	2.31
	25	-1.85	0.96	2.70
	50	-1.2	1.15	3.34
	75	-0.51	1.10	3.94
	100	-0.27	1.11	4.05
	125	-0.09	0.91	4.16
	150	0.21	0.86	4.24
	200	0.36	0.91	3.34
	250			
	300	0.37	1.01	3.46
	400	0.34	0.87	3.56
	500	0.36	0.99	4.19
PS78-87	0	0.31	1.54	2.58
	25	0.38	1.20	2.51
	50	0.35	1.08	2.94
	75	0.3	1.02	3.02
	100	0.36	0.64	3.19
	125	0.35	0.70	3.27
	150	0.37	0.69	3.38
	200	0.29	0.86	3.46
	250			
	300	0.36	0.79	3.67
	400	0.33	0.64	3.74
	500	0.37	0.87	3.87
PS78-127	0	0.34	1.64	2.60
	25	0.49	1.31	2.64
	50	0.4	0.95	2.91
	75	0.21	0.85	2.76
	100	0.38	0.87	2.96
	125	0.32	0.93	2.94
	150	0.36	0.88	3.03
	200	0.34	0.94	3.07
	250			
	300	0.28	0.96	3.22
	400	0.32	1.00	3.40
	500	0.3	1.02	3.49

Table 3. $\delta^{18}O$ and $\delta^{13}C$ values of *N. pachyderma* (*N. p.*) and *T. quinqueloba* (*T. q.*) from sediment surface samples.

	$\delta^{18}O$ (‰ PDB)		$\delta^{13}C$ (‰ PDB)	
Station	*N. p.*	*T. q.*	*N. p.*	*T. q.*
PS78-19	3.17	2.56	0.44	-1.10
PS78-25	2.84	2.05	0.15	-1.28
PS78-35	3.36	2.70	0.66	-1.05
PS78-39	3.31	2.53	0.61	-1.20
PS78-44	3.35	2.98	0.49	-1.09
PS78-54	3.44	3.08	0.75	-0.59
PS78-71	3.32		0.50	
PS78-75	3.57	3.00	0.72	-0.67
PS78-87	3.36	2.75	0.58	-1.02
PS78-127	2.71		0.09	

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Table 4. $\delta^{18}O$ and $\delta^{13}C$ values of *N. pachyderma* (*N. p.*) and *T. quinqueloba* (*T. q.*) from plankton tows.

		$\delta^{18}O$ (‰ PDB)		$\delta^{13}C$ (‰ PDB)	
Station	Depth (m)	*N. p.*	*T. q.*	*N. p.*	*T. q.*
PS78-19	0-50	2.38		-0.99	
	50-100	2.69	1.96	-0.40	-1.64
	100-200	2.82	1.81	-0.38	-1.88
	200-300	2.36		-0.74	
	300-500	2.67		-0.78	
PS78-25	0-50	2.40		-0.78	
	50-100	2.55	-2.85	-0.37	-4.25
	100-200	2.51	1.64	-0.10	-1.72
	200-300	1.98		-1.40	
	300-500	2.56	0.31	-0.43	-2.50
PS78-35	0-50	2.32	-5.54	-0.89	-6.13
	50-100	3.08	-5.57	-0.28	-6.03
	100-200	3.00	2.25	-0.15	-1.68
	200-300	2.95		-0.16	
	300-500	2.88		-0.44	
PS78-39	0-50	3.25	-4.99	-0.19	-5.79
	50-100	3.25	-1.36	-0.13	-3.61
	100-200	3.34	1.57	0.08	-1.99
	200-300	3.34		0.03	
	300-500	2.32		-0.75	
PS78-44	0-50	2.58	-7.35	-0.60	-7.86
	50-100	2.64		-0.44	
	100-200	3.01	2.13	-0.10	-1.44
	200-300	2.86	0.41	-0.25	-2.46
	300-500	2.65	-0.51	-0.83	-5.78
PS78-54	0-50	2.77	-0.86	-0.62	-5.96
	50-100	2.75	2.46	-0.21	-1.22
	100-200	2.83	2.20	-0.21	-1.56
	200-300	2.69	1.59	-0.24	-2.57
	300-500	2.61	2.18	-0.28	-1.52
PS78-71	0-50	0.99		-0.63	
	50-100	1.86	1.72	-0.14	-1.78
	100-200	1.80	-1.93	-1.04	-3.84
	200-300	2.89	0.85	-0.15	-2.30
	300-500	2.12		-0.50	
PS78-75	0-50	-2.94		-4.14	
	50-100	1.36	-2.72	-0.79	-4.00
	100-200	0.93		-0.69	
	200-300	0.56		-1.38	
	300-500				
PS78-87	0-50	-1.54		-2.14	
	50-100	1.87	0.25	-0.43	-3.54
	100-200	1.89	0.25	-1.37	-2.22
	200-300	0.23		-1.88	
	300-500	-2.56		-4.38	
PS78-127	0-50	1.07	-5.01	-2.59	-7.79
	50-100	2.80	1.99	-0.48	-1.72
	100-200	2.06	2.39	-0.98	-1.51
	200-300	2.08	2.42	-1.02	-1.54
	300-500	2.16	1.90	-1.06	-1.76

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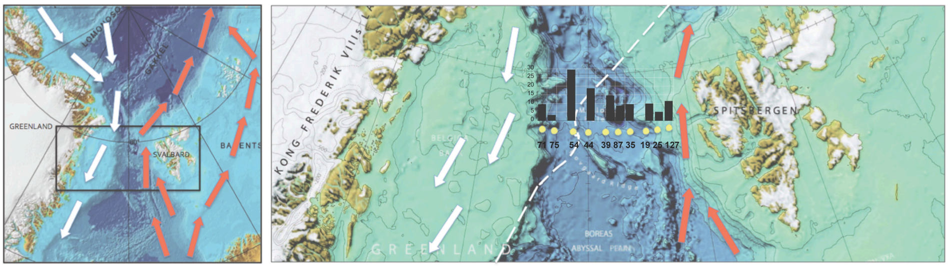

Figure 1. Map and schematic surface ocean circulation of the study area (red arrows: West Spitsbergen Current, white arrows: East Greenland Current). The enlarged part shows the sampled stations (yellow dots). Bars represent absolute abundances (ind./m^3 water) of planktic foraminifera in the upper 500 m of the water column along the transect at 78°50'N across the Fram Strait. The white dashed line shows the position of the sea ice margin at the position of the transect during the sampling period (shipboard observation and satellite data from the US National Oceanic and Atmospheric Administration). Map source: the International Bathymetric Chart of the Southern Ocean (Jakobsson et al., 2012).

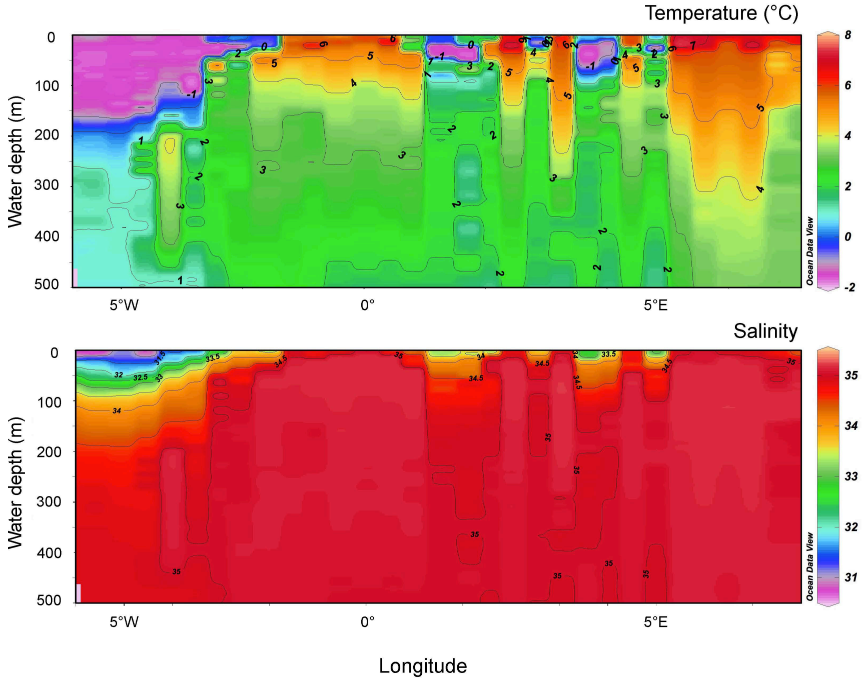

Figure 2. Temperature and salinity of the water column in the upper 500 m along a transect at 78°50'N across the Fram Strait. Data obtained by conductivity-temperature-density (CTD) measurements during the expedition ARK XXVI/1 (Beszczynska-Möller and Wisotzki, 2012). The figure comprises data obtained from 30 CTD stations, equally distributed along the transect.

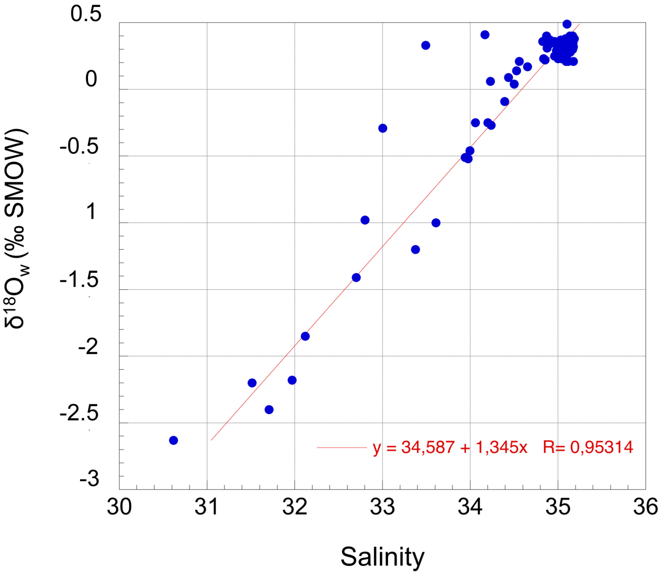

Figure 3. δ^{18}O (‰ SMOW) values of the upper 500 m of the water column vs. salinities (PSU) for the sampled transect at 78°50'N across the Fram Strait.

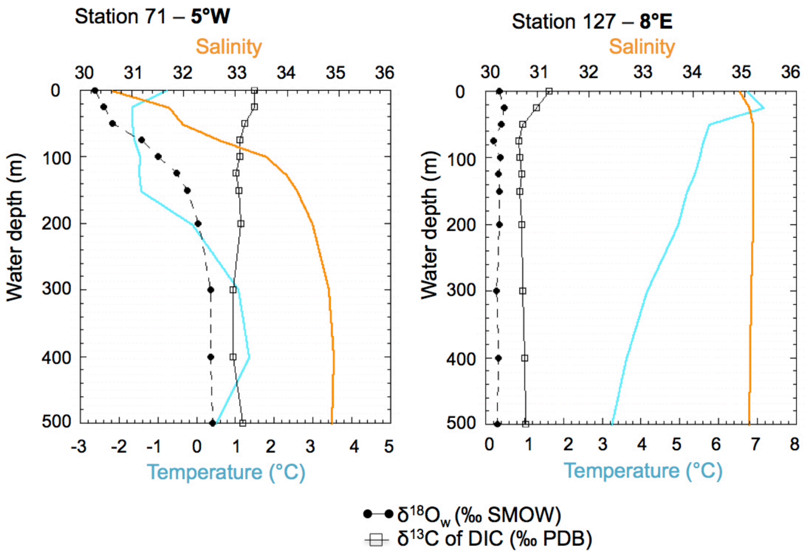

Figure 4. Salinity, temperature, $\delta^{18}O$ (‰ SMOW) and $\delta^{13}C_{DIC}$ (‰ PDB) profiles of the upper 500 m of the water column from the westernmost and easternmost stations sampled along a transect at 78°50'N across the Fram Strait. The lower x-axis represents the axis for both temperatures and isotope values.

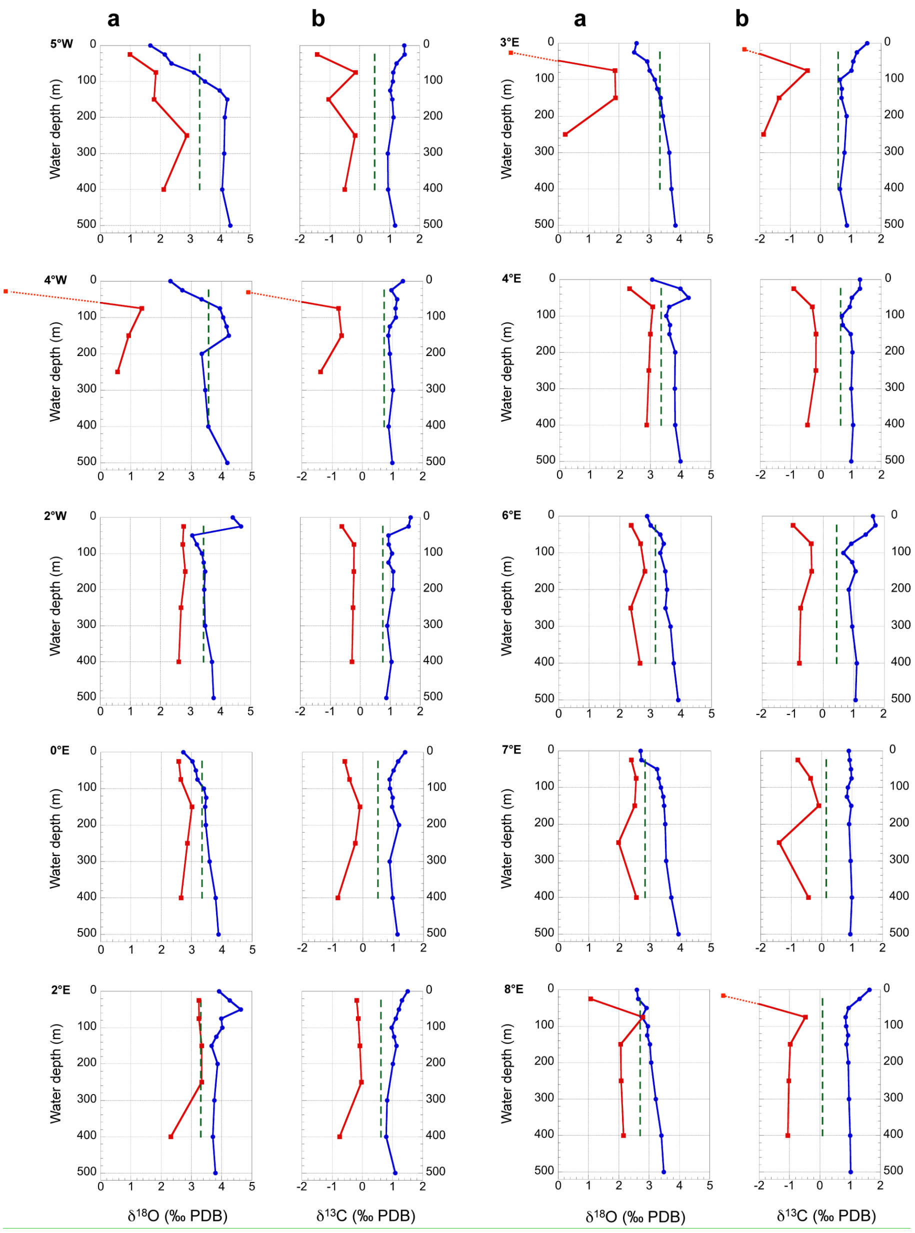

Figure 5. (a) δ^{18}O and (b) δ^{13}C values of *N. pachyderma* from the water column (red squares) and from the sediment surface (green dashed line). The blue dots indicate (a) the equilibrium calcite and (b) the $\delta^{13}C_{DIC}$ profile of the water column.

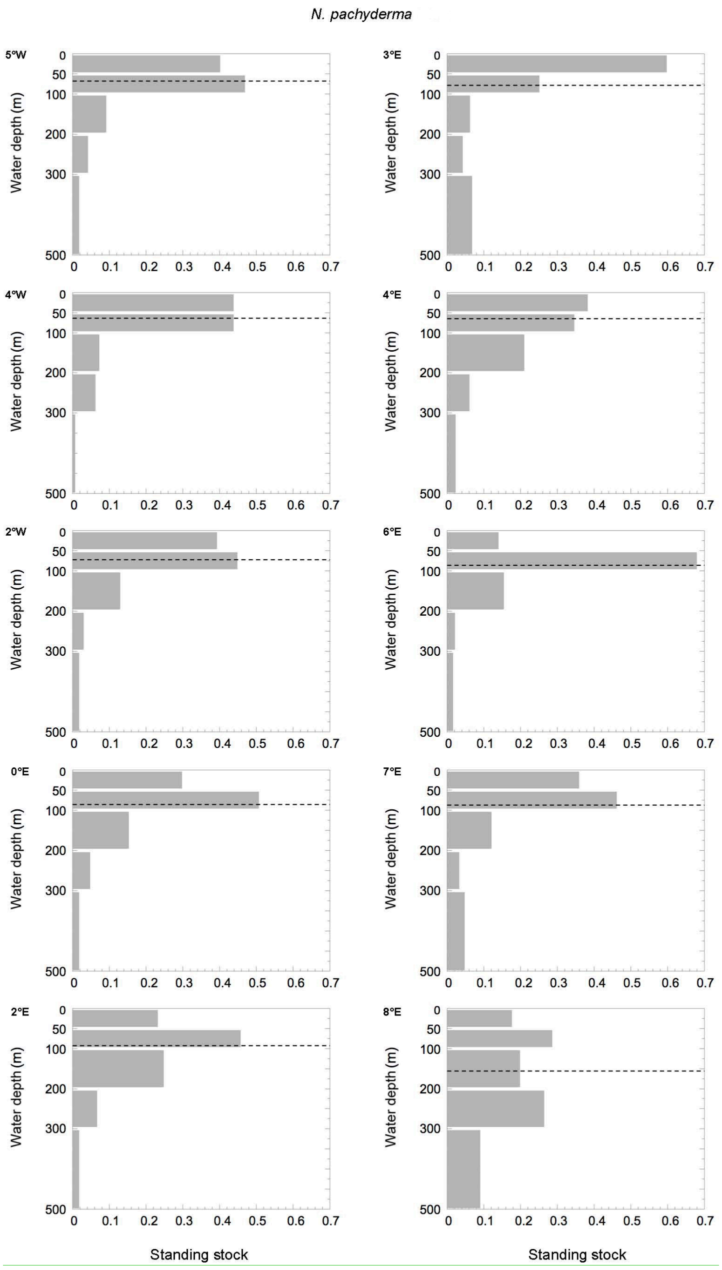

Figure 6. Standing stock of *N. pachyderma* for each sampling interval. The black dashed line indicates the average depth of calcification (calculated from the standing stock).

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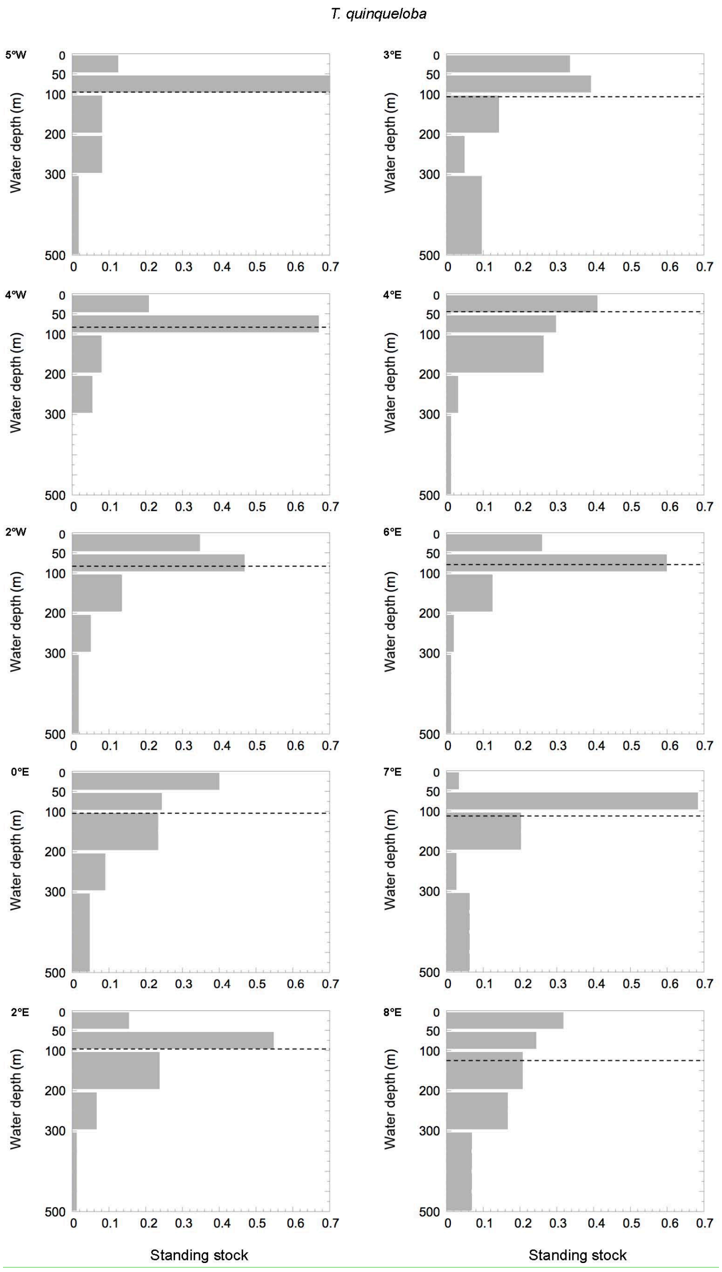

Figure 7. Standing stock of *T. quinqueloba* for each sampling interval. The black dashed line indicates the average depth of calcification (calculated from the standing stock).

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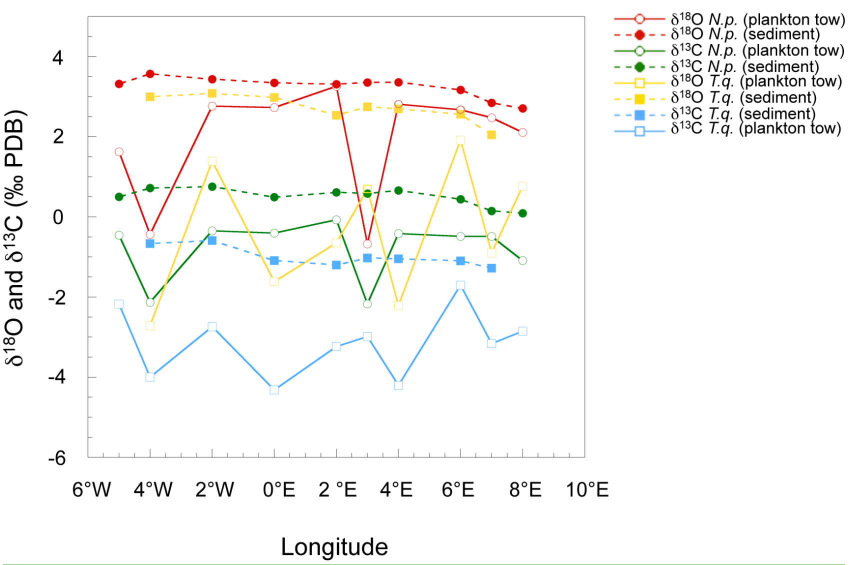

Figure 8. δ^{18}O and δ^{13}C of *N. pachyderma* (circles) and *T. quinqueloba* (squares) from the water column (weighted average over the upper 500 m of the water column; non-filled symbols) and from the sediment surface (filled symbols) along a transect at 78°50'N across the Fram Strait.

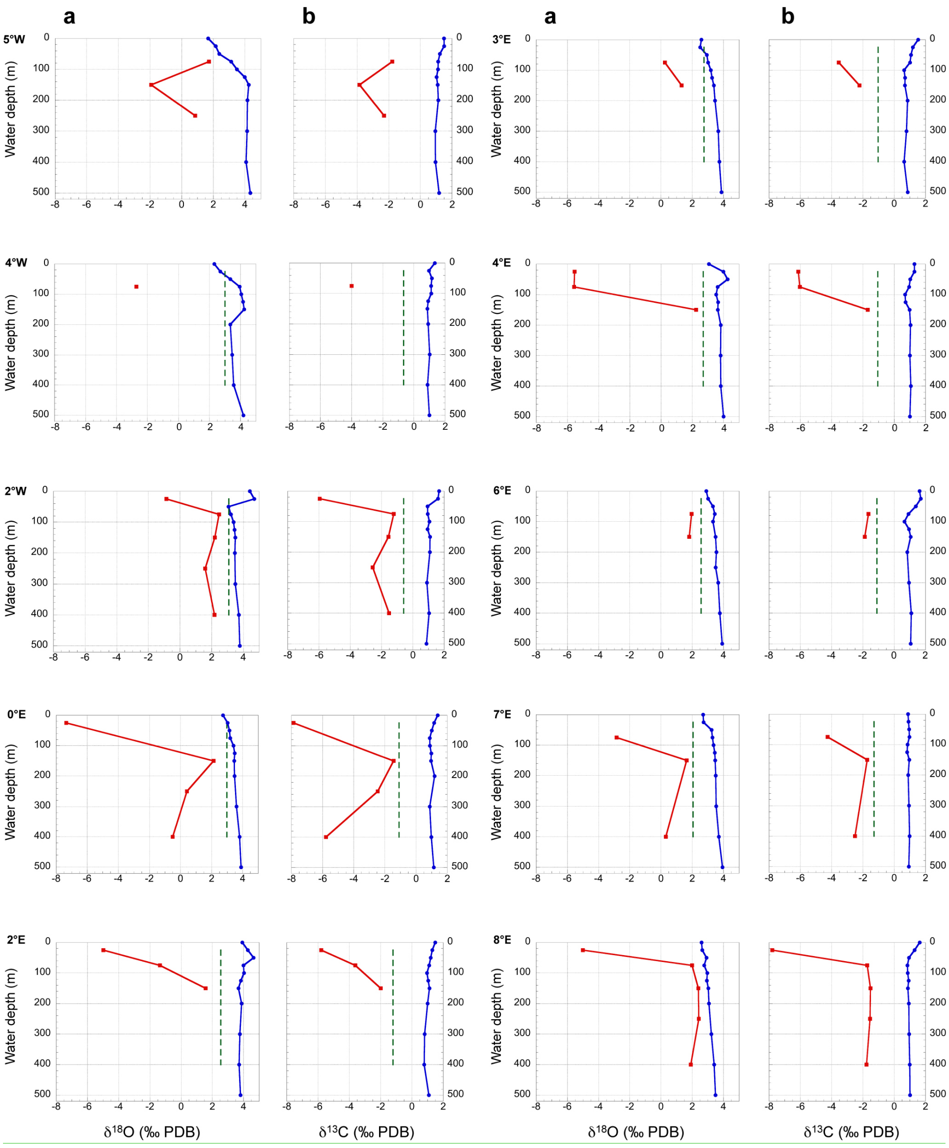

Figure 9. (a) $\delta^{18}O$ and (b) $\delta^{13}C$ values of *T. quinqueloba* from the water column (red squares) and from the sediment surface (green dashed line). The blue dots indicate (a) the equilibrium calcite and (b) the $\delta^{13}C_{DIC}$ profile of the water column.

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Deleted: Figure 7. (a) $\delta^{18}O$ and (b) $\delta^{13}C$ values of *N. pachyderma* (sin.) from the water column (red squares) and from the sediment surface (green dashed line). The blue dots indicate (a) the equilibrium calcite and (b) the $\delta^{13}C_{DIC}$ profile of the water column. ... [1]

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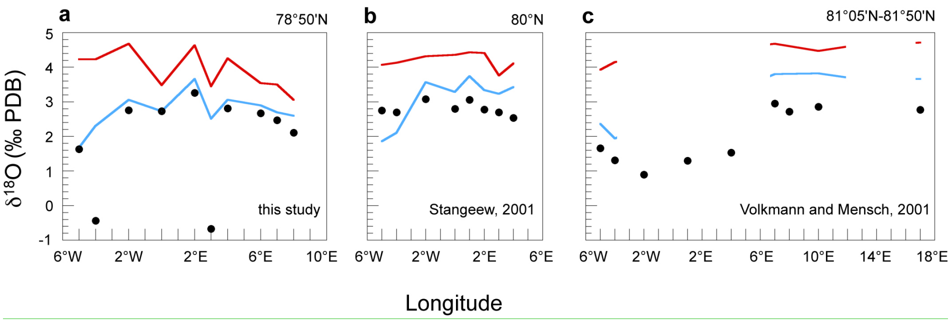

Figure 10. δ^{18}O of *N. pachyderma* from the water column (weighted average; black dots) with the range of equilibrium calcite values in the upper 200 m (blue line: minimum, red line: maximum) along three parallel E-W transects between 78°50'N and 81°50'N in the Fram Strait: (a) this study, (b) Stangeew, 2001; Bauch (unpubl. data), (c) Volkmann and Mensch, 2001.