



RESEARCH ARTICLE

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Benthic foraminiferal growth seasons implied from Mg/Ca-temperature correlations for three Arctic species

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Key Points:

- Mg/Ca-temperature correlation plots for three species of Arctic benthic foraminifera are presented
- The data set indicates season-specific growth periods for the three species, which can be linked to specific events within the seasons
- Mg/Ca temperature reconstructions on these species represent seasonal temperatures rather than annual average temperatures in this area

Supporting Information:

- Supporting Information S1
- Data Set S1
- Data Set S2

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Abstract Core-top sediment samples from Kongsfjorden, Svalbard, and adjacent fjord and shelf areas were collected in order to investigate a potential relationship between Mg/Ca-ratios of Arctic benthic foraminifera and the ambient bottom water temperatures (BWT). The area is influenced by large seasonal variation in factors such as light and temperature, which is further strengthened by oceanographic shifts, including inflow of relatively warm Atlantic water. Four hydrological seasons have been defined. The studied samples were collected during the years 2005–2010 and comprise data from three hydrological seasons: spring, summer, and autumn. Five common species of cold-water benthic foraminifera were investigated: *Islandiella helenae/norcrossi*, *Buccella frigida*, *Nonionellina labradorica*, *Elphidium clavatum*, and *Cassidulina reniforme*. For *E. clavatum* and *C. reniforme*, the investigations failed. For the remaining three species, the Mg/Ca-temperature correlations initially appeared stochastic holding correlation coefficients between 0.01 and 0.15. However, grouping the data based on seasons gave stronger Mg/Ca-temperature correlations, indicating specific growing seasons for the three species. The equations represent a starting point for a discussion on seasonality rather than robust, “ready-to-use” equations. *I. helenae/norcrossi* seems to reproduce and grow during summer (July/August) in outer Kongsfjorden. For *B. frigida*, a Mg/Ca-temperature correlation is seen both in summer (July/August) and autumn (October/November) samples, indicative of a continuous reproduction/growth-season lasting from July to November. *N. labradorica* appears to reproduce and grow during autumn (October/November). The results indicate that temperature reconstructions based on these benthic foraminifera reproduce seasonal temperatures rather than annual average temperatures.

1. Introduction

Incorporation of magnesium (Mg) into carbonates is an endothermic reaction favored at warmer temperatures [Lea, 2003]. A correlation between content of Mg in biogenic carbonates and temperature of ambient seawater was observed and discussed throughout the last century [Clarke and Wheeler, 1922; Chave, 1954; Blackmon and Todd, 1959; Dodd, 1965; Schopf and Manheim, 1967]. These initial studies focused on variations between Mg content between different genera and species of several groups of marine organisms, including bryozoans, crinoids, brachiopods, mollusks, corals, and foraminifera [Clarke and Wheeler, 1922; Chave, 1954; Todd and Blackmon, 1956; Dodd, 1965].

Benthic foraminifera, due to their high abundances and presence in most marine environments, are considered ideal objects for marine paleoreconstructions [Barbieri et al., 2006]. Throughout the 1990s and the 2000s, several species and family specific Mg/Ca-temperature calibrations were made for benthic foraminifera [Rosenthal et al., 1997; Toyofuku et al., 2000; Lear et al., 2002; Martin et al., 2002; Marchitto and deMenocal, 2003; Marchitto et al., 2007; Izuka, 1988]. However, few studies on cold-water environments have been carried out [Kristjándóttir et al., 2007; Healey et al., 2008; Quillmann et al., 2012]. Nevertheless, there is a need to get a better grasp on the paleoclimatic development for the cold Arctic region, as it may play an important role in the climate system: the presently changing climate appears to be amplified in Arctic regions, where the predicted temperature increase is double the global average [IPCC, 2013]. Existing temperature proxies, particularly for the benthic environment, are however sparse and ambiguous for Arctic areas.

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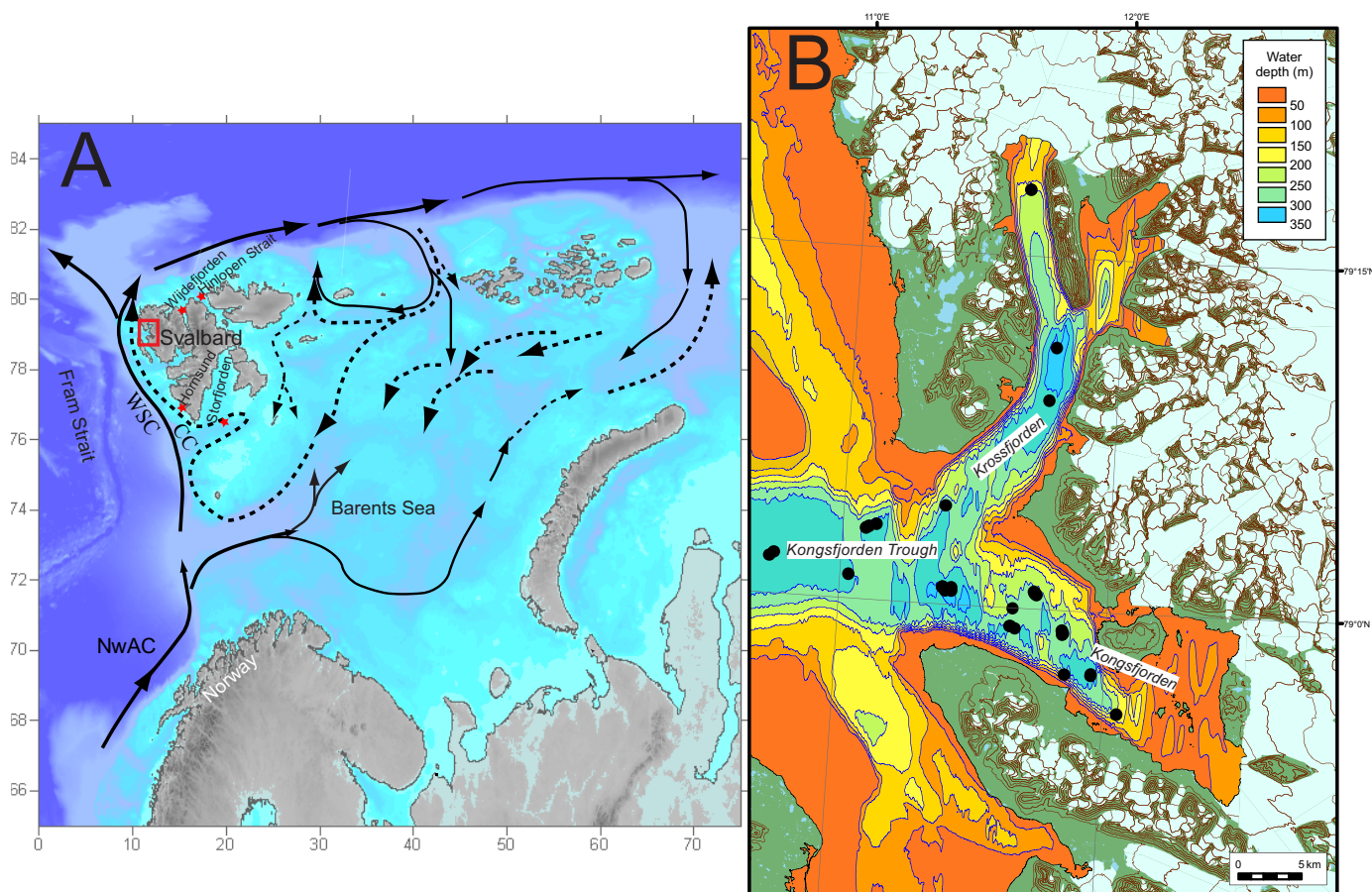


Figure 1. Location maps showing (a) Oceanography of Svalbard and Barents Sea area. Full lines indicate Atlantic Water Masses (NwAC: Norwegian Atlantic Current; WSC: West Spitsbergen Current.) Dashed lines indicate Arctic Water Masses (CC: Coastal Current). Red dots indicate core locations outside the Kongsfjorden-Krossfjorden system. (b) Detailed map from the Kongsfjorden-Krossfjorden system, showing the bathymetry of the fjords and their continuation out on the shelf; the Kongsfjorden Trough. Core locations are indicated with black circles. The circles are largely overlapping as the same locations have been sampled systematically in the period between 2005 and 2010. (Modified from *Klitgaard-Kristensen et al.* [2013]).

Studies based on Mg coordination in foraminiferal calcite support incorporation of Mg to be a thermodynamic process and hence, strongly related to temperature of ambient seawater [Branson *et al.*, 2013]. However, as the method has developed, difficulties and weak aspects have been encountered. Some of these are related directly to Mg-incorporation to foraminiferal tests, like size fractionation [Tisserand *et al.*, 2013], carbonate ion concentration [Elderfield *et al.*, 2006; Rosenthal *et al.*, 2006], and salinity effect [Dissard *et al.*, 2010], while others are a result of secondary influences like calcite dissolution [McCorkle *et al.*, 1995] or diagenetic overgrowths [Barker *et al.*, 2003]. These potential sources of error must be considered for the individual data sets being investigated when working with Mg/Ca-thermometry.

This study is carried out using surface sediment samples mainly from the Arctic fjord Kongsfjorden, Western Spitsbergen, in addition to a few samples from Krossfjorden, Hornsund, Wijdefjorden, Storfjorden, and Hinlopen Strait (Svalbard area; Figure 1 and Table 1). The same data set has previously been used to study foraminiferal assemblages in a seasonal perspective. Although the area experience large seasonal variations (see below), no clear indications on seasonal preferences were observed in the fauna [Jernas, 2012]. This will be further investigated here, using geochemical methods. The purpose is to evaluate the present relationship between bottom water temperature (BWT) and the Mg/Ca-ratio of five common species of benthic foraminifera living in Arctic shelf and fjord environments, and to use these data to investigate if these species have any preferential growing seasons. The overall aim is to improve the Mg/Ca-method for cold-water environments. The species under investigation are *Islandiella helenae/norcrossi*, *Buccella frigida*, *Nonionellina labradorica*, *Elphidium clavatum*, and *Cassidulina reniforme*. These species are all major constituents in modern fjord and shelf faunas both in Kongsfjorden [Jernas, 2012] and adjacent Arctic and sub-Arctic shelves and

Table 1. Logistic Information From Core Top Stations^a

Core	Date	Hydrol. Season	Water Depth (m)	Location	Latitude (°N)	Longitude (°E)	BWT, °C	BWS
NP05-11-5MC	8/9/2005	Summer	336	Kongsfjorden Inner Central	78 57,30	11 57,10	1.88	34.8
NP05-11-8MC	8/9/2005	Summer	250	Kongsfjorden Central	79 00,70	11 44, 00	1.88	34.8
NP05-11-14MC	8/11/2005	Summer	305	Kongsfjorden Outer	79 04,20	11 22,70	2.06	34.8
NP05-11-20MC	8/12/2005	Summer	319	Kongsfjorden Trough	79 01,60	10 44,00	2.68	34.9
NP05-11-35MC	8/15/2005	Summer	439	Hinlopen Trough	80 12,70	16 57,00	3.27	35.0
NP06-16-12MC	8/25/2006	Summer	377	Kongsfjorden Outer	79 00,74	11 23,01	1.64	34.8
NP06-16-30MC	8/26/2006	Summer	311	Kongsfjorden Central	78 59,13	11 50,19	1.76	34.8
NP06-16-37MC	8/15/2005	Summer	287	Kongsfjorden Central	78 59,99	11 38,99	1.72	34.8
NP06-16-39MC	8/27/2006	Summer	195	Kongsfjorden Inner Central	78 55,72	12 03,25	3.74	34.9
NP06-16-43MC	8/28/2006	Summer	315	Kongsfjorden Mouth	79 01,03	11 01,93	1.54	34.8
NP06-16-53MC	8/29/2006	Summer	199	Krossfjorden Inner	79 17,83	11 37,78	2.25	34.7
NP07-13-16MC	9/3/2007	Summer	374	Krossfjorden Central	79 11,17	11 45,67	0.71	35.0
NP07-13-42MC	9/6/2007	Summer	319	Kongsfjorden Central	78 59,17	11 50,22	2.07	35.0
NP07-13-44MC	9/6/2007	Summer	285	Kongsfjorden Central	79 00,71	11 43,54	2.17	35.0
NP07-13-53MC	9/7/2007	Summer	278	Kongsfjorden Central	78 59,17	11 39,45	2.17	35.0
NP07-13-55MC	9/7/2007	Summer	340	Krossfjorden Outer	79 08,91	11 44,62	0.94	35.0
JM08-kb0MC	4/18/2008	Spring	336	Kongsfjorden Mouth	79 03,12	11 05,80	0.01	35.0
NP08-16-30MC	8/20/2008	Summer	330	Kongsfjorden Mouth	79 03,05	11 05,17	1.12	34.9
NP08-16-33MC	8/20/2008	Summer	328	Kongsfjorden Trough	79 01,75	10 44,96	0.96	34.9
NP08-16-37MC	8/21/2008	Summer	342	Kongsfjorden Inner Central	78 57,37	11 57,14	1.07	34.9
NP08-16-40MC	8/21/2008	Summer	319	Kongsfjorden Central	78 59,17	11 50,22	1.28	34.9
NP08-16-44MC	8/22/2008	Summer	278	Kongsfjorden Central	78 59,17	11 39,45	1.33	34.9
JM08-704-57MC	27/10/2008	Autumn	357	Kongsfjorden Outer	79 00,74	11 24,99	2.37	34.9
JM08-704-58MC	27/10/2008	Autumn	280	Kongsfjorden Central	78 59,24	11 38,75	2.72	34.9
JM08-704-59MC	27/10/2008	Autumn	293	Kongsfjorden Inner Central	78 59,05	11 50,46	2.91	34.9
JM08-704-60MC	27/10/2008	Autumn	286	Kongsfjorden Central	79 00,62	11 44,12	2.95	34.9
JM08-704-61MC	27/10/2008	Autumn	324	Kongsfjorden Mouth	79 03,24	11 07,53	2.64	34.9
JM09-05/un0MC	5/10/2009	Spring	336	Kongsfjorden Mouth	79 03,12	11 05,80	1.62	34.8
JM09-05/un1MC	5/10/2009	Spring	386	Kongsfjorden Outer	79 00,60	11 23,70	1.74	34.8
JM09-05/un3MC	5/10/2009	Spring	236	Kongsfjorden Inner Central	78 57,30	11 51,20	0.68	34.8
JM09-05/un4MC	5/10/2009	Spring	285	Kongsfjorden Central	79 00,71	11 43,54	1.28	34.8
JM09-nov02MC	10/27/2009	Autumn	378	Kongsfjorden Outer	79 00, 75	11 23, 07	3.50	35.0
JM09-nov03MC	10/27/2009	Autumn	274	Kongsfjorden Central	78 59, 15	11 39, 73	3.38	34.9
JM09-nov05MC	10/27/2009	Autumn	284	Kongsfjorden Central	79 00, 67	11 43, 76	3.16	34.9
JM09-nov07BC	11/2/2009	Autumn	141	Vidjefjorden Outer	79 43, 96	15 22, 96	3.90	34.9
JM09-H-01BC	11/5/2009	Autumn	131	Hornsund Outer	76 57, 23	15 41, 78	2.84	34.7
JM09-019BC	11/5/2009	Autumn	252	Storfjorden Outer	76 19, 33	19 40, 38	0.78	34.9
JM10-180 MC	4/28/2010	Spring	369	Kongsfjorden Outer	79 00,60	11 25,05	0.52	34.7
JM10-181 MC	4/29/2010	Spring	286	Kongsfjorden Central	78 59,24	11 38,53	0.53	34.7
JM10-182 MC	4/29/2010	Spring	301	Kongsfjorden Inner Central	78 59,00	11 50,33	0.46	34.7
JM10-183 MC	4/29/2010	Spring	273	Kongsfjorden Central	79 00,75	11 43,53	0.00	34.7

^aHydrological seasons are defined as Spring (April–June); Summer (June–September); Autumn (September–December).

fjords [Hald and Steinsund, 1992; Hunt and Corliss, 1993; Jennings and Helgadottir, 1994; Newton and Rowe, 1995; Hald and Korsun, 1997; Korsun and Hald, 1998, 2000; Polyak et al., 2002; Jennings et al., 2004; Lloyd, 2006]. The species are also frequent in glaciomarine paleorecords from the northern hemisphere during the Weichselian and the Holocene [Hald and Vorren, 1987; Hald et al., 1989, 1999; Osterman and Nelson, 1989; Eiriksson et al., 1997, 2000; Jennings et al., 2000; Klitgaard-Kristensen et al., 2001; Ślubowska et al., 2005; Rasmussen et al., 2007; Ślubowska-Woldengen et al., 2007, 2008]. Our data set includes samples from different seasons for the years 2005–2010 (Table 1). By investigating samples from different seasons, we try to evaluate whether benthic foraminifera from this area represent proxies for annual average temperatures or seasonal temperatures. Hence, this paper attempts to push forward our understanding of Arctic benthic foraminifera as monitors for Arctic paleoclimate.

2. Physical Setting

Kongsfjorden is an east-west oriented fjord located on western Spitsbergen at approximately 79° north and 11° east (Figure 1a). The fjord is 20 km long and 4–10 km wide. Kongsfjorden consists of several basins with a depth range between 50 and 400 m (Figure 1b). It has four tidewater glaciers draining into the inner part of the fjord and one draining into the northern side. On the shelf Kongsfjorden and the neighboring fjord

Krossfjorden, merge into the Kongsfjorden Trough (200–350 m depth; Figure 1b). At the fjord mouth, a shallow sill (~250 m depth) divides two deep basins [Elverhøi *et al.*, 1983; Ottesen *et al.*, 2007]. The sill is less pronounced on the southern side of the fjord allowing inflow of shelf waters to the fjord [Svendsen *et al.*, 2002]. The coast off western/northern Svalbard is mainly dominated by two water masses (Figure 1); cool Arctic Water transported northward by the Coastal Current (CC) and, west of this, relatively warm and saline Atlantic Water masses moving northward as the West Spitsbergen Current (WSC), a continuation of the Norwegian Atlantic Current (NwAC) [Johannessen, 1986; Svendsen *et al.*, 2002]. At approximately 78°N, the Atlantic Water of the WSC reaches a density level allowing it to subduct below the Arctic Water, and continue northward as a subsurface current [Aagaard and Greisman, 1975]. The Atlantic derived water masses entering Kongsfjorden are referred to as Transformed Atlantic Water (TAW). In addition to the two shelf water masses, a variety of mixed and local water masses exist; fjord surface water, local fjord water, intermediate water, and winter cooled water [Cottier *et al.*, 2005], causing a complex hydrological system [Svendsen *et al.*, 2002]. Krossfjorden, Hornsund, Wijdefjorden, Storfjorden, and Hinlopen are also influenced by Atlantic Water, Arctic Water, and discharge from glaciers, sea-ice, and rivers.

3. Hydrological Seasons

The high-latitude setting of Spitsbergen experience large seasonal variations throughout the year. Distinct shifts between Arctic Water and Atlantic Water domination have a strong influence on the hydrology in Kongsfjorden, also in a seasonal perspective. In the following, four hydrological seasons characteristic of Kongsfjorden are described: Spring (April–June); summer (June–September); autumn (September–December); and winter (December–April).

3.1. Hydrological Winter, December–April

The hydrological winter is defined by cooled homogenized water masses, typically lasting from December to April. Bottom water temperatures and salinities are usually between -1 to 1°C and ~ 35 , and a ~ 0.7 m thick sea ice occupies the inner part of the fjord [Gerland *et al.*, 1999]. A strong barotropic front is normally formed at the fjord mouth inhibiting shelf water inflow [Cottier *et al.*, 2005]. However, there have been observations in recent years showing intrusions of Atlantic Water occurring as early as February [Hegseth and Tverberg, 2013]. Due to the polar night, no primary producers are present. However, new studies from Kongsfjorden indicate higher biological activity during the polar night than previously thought, and potential sources of foraminiferal food are available also during hydrological winter [Berge *et al.*, 2015].

3.2. Hydrological Spring, April–June

Hydrological spring is the period when water stratification builds up in Kongsfjorden, mainly by the formation of an upper pycnocline. During May, the upper water column begins to stratify because of melt water input and sequential warming of this surface layer [Svendsen *et al.*, 2002]. The establishing phase of the pycnocline is characteristic for hydrological spring onset [Korsun and Hald, 2000], and runoff season normally lasts until September [Hop *et al.*, 2002; Svendsen *et al.*, 2002]. Spring bloom typically contributes to a large portion of the annual primary production in Arctic seas [Sakshaug, 2004]. It starts as the sea ice begins to melt, i.e., in the transition between hydrological winter and spring, and is the only predictable bloom in Kongsfjorden [Hop *et al.*, 2002].

3.3. Hydrological Summer, June–September

As the meltwater pycnocline builds up, subsurface intrusions of warmer, Atlantic Water masses is initiated. By June/July, Atlantic Water typically propagates from the shelf into the fjord, topographically steered, as the strong density field created in winter weakens. The key factors contributing to this intrusion are northerly winds creating instabilities along the Arctic Front, subsequently allowing the AW to intrude the shelf areas [Saloranta and Svendsen, 2001]. In addition, there is a weakening of the winter density field in the fjord, initially by stratification and secondly by upfjord winds [Cottier *et al.*, 2005]. By September, the inflow of Atlantic Water to Kongsfjorden stabilizes.

3.4. Hydrological Autumn, September–December

Hydrological autumn is defined as the period when a stable warm core of AW is present in the fjord, usually lasting from September to November. The thermal optimum of Atlantic Water in Kongsfjorden is in

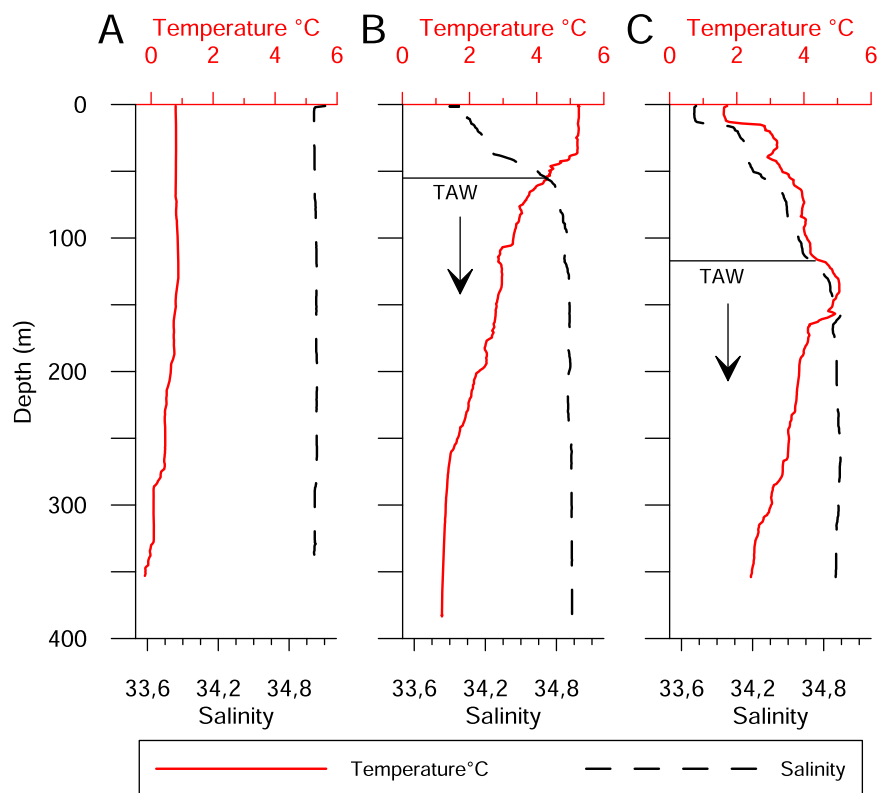


Figure 2. CTD profiles showing temperature and salinity through the water column in outer Kongsfjorden in 2008 (a) spring, (b) summer, and (c) autumn. The area of transformed Atlantic Water (TAW: Temperature > 1°C and salinity > 34.7) is indicated for summer and autumn.

October/November, similar to observations from the sub-Arctic Malangen fjord, northern Norway [Hald *et al.*, 2011]. The distinct AW core present during the hydrological autumn has temperatures reaching up to 5–6°C [Rokkan Iversen and Seuthe, 2011; Jernas, 2012]. CTD data from the present study shows that high bottom water temperatures were still present in early November (Figure 2). No studies have recorded the termination of the shelf-fjord advection but in December the water masses again reach a homogenized state [Rokkan Iversen and Seuthe, 2011], characteristic for hydrological winter.

Looking at the annual temperature evolution, the hydrological seasons are delayed compared to the seasons on land. However, for simplicity, we use the season terms corresponding to the season on land, instead of redefining them based on the temperature evolution in the marine environment. It should be noted that the timing of the hydrological seasons might vary on an interannual basis, depending on factors like insolation, ice-coverage, AW-inflow, and temperature of the AW. During recent years, large interannual changes has occurred regarding sea ice-cover [Gerland *et al.*, 1999], WSC temperature [Schlichtholz and Goszczko, 2006; Walczowski and Piechura, 2006], degree of AW influence [Hop *et al.*, 2006], timing of AW inflow and positioning of the AW in the water column [Hegseth and Tverberg, 2013].

4. Materials and Methods

Surface sediment samples were collected using multicorer and box corer during cruises with R/V Jan Mayen and R/V Lance. A total of 41 core top samples from Kongsfjorden (34) and other Svalbard fjords (7) were obtained (Table 1). The samples were collected in August/September 2005–2008 and April/May and October/November 2008–2010. CTD measurements were carried out concurrently at all locations. The CTD-instrument (SBE 911 plus), measuring conductivity, temperature, and depth of the entire water column, was ideally lowered down to 5–10 m above the seafloor. In situations of bad weather, it was stopped further above the sea floor to avoid damage of instrument. Depth of stations varied between 141 and 386 m. Surface samples consisting of the fluffy layer, a loose water saturated layer of recently settled material, typically

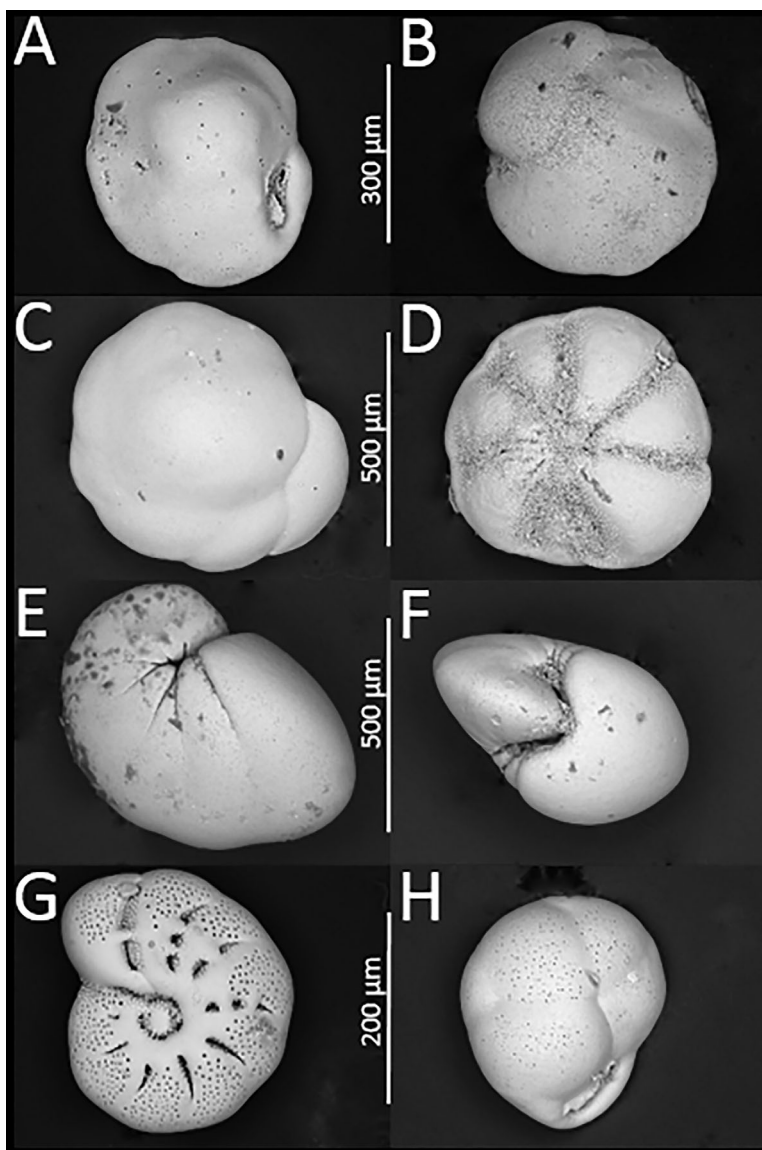


Figure 3. Scanning electron microscope images of (a and b) *Islandiella helenae*; (c and d) *Buccella frigida*; (e and f) *Nonionellina labradorica*; (g) *Elphidium clavatum*; and (h) *Cassidulina reniforme*.

high in organic matter, were immediately sampled, stained using a Rose Bengal solution (1 g RB/1 l ethanol), and stored in a cooling room. For some stations, the centimeter below were sampled and treated in the same manner. Rose Bengal stain any protoplasm in a sample, and enables detection of specimens of living foraminifera [Walton, 1952]. However, recently deceased organisms may also appear living, and in cold-water environments protoplasm may retain in the shell 4 weeks, or longer [Bernhard, 1988]. To optimize the use of this method, only fully stained specimens were chosen. The samples were sieved through mesh sizes 63, 100, and 1000 μm . A total of 130 samples from the 100–1000 μm fraction were used for the analysis, distributed between five species of benthic foraminifera; *N. labradorica*, *B. frigida*, *I. helenae/norcrossi*, *C. reniforme*, and *E. clavatum* (Figure 3). *Islandiella helenae* and *I. norcrossi* were mixed to attain sufficient sample sizes, but *I. helenae* generally dominates. As a precaution to reduced control on living individuals, due to the use of Rose Bengal stain, 50 specimens from the fluffy layer were ideally picked for analysis, in order to avoid time averaging. However, because of limitations in the material, samples containing as few as 15 specimens were included in the data set (Table 2). For some samples, material from the centimeter below (referred to as 1–2 cm) was also added (Table 2), and in a few cases separate samples were picked from the fluffy layer and the 1–2 cm layer. Only samples entirely made out of large, uniformly sized specimens

Table 2. List of Samples Analyzed for *I. helenae/norcrossi*, *B. frigida*, and *N. labradorica*, Including Information on Location, Hydrological Season, Bottom Water Temperature, Sediment Depth, Mg/Ca-Ratio, and Number of Foraminifera in the Analyzed Sample^a

Core-site	Hydrological Season	Locality	BWT °C	Season	Sed. Depth (cm)	Mg/Ca (mmol/mol)	# Forams Ran
				Corrected BWT (°C)			
<i>Islandiella helenae</i>							
NP05-11-20MC	Summer	Kongsfjorden Trough	2.68		0-2	1.295	65
NP05-11-35MC	Summer	Hinlopen Trough	3.27		0-2	1.216	25
NP06-16-30MC	Summer	Kongsfjorden Central	1.76		0-2	1.250	60
NP06-16-37MC	Summer	Kongsfjorden Central	1.72		0-2	1.244	35
NP06-16-39MC	Summer	Kongsfjorden Inner Central	3.74		0-2	1.151	27
NP06-16-53MC	Summer	Krossfjorden Inner	2.25		0-2	1.372	15
NP07-13-16MC	Summer	Krossfjorden Central	0.71		0-1	1.229	18
NP07-13-42MC	Summer	Kongsfjorden Inner	2.07		0-1,5	1.204	39
NP07-13-44MC	Summer	Kongsfjorden Central	2.17		0-2	1.210	38
NP07-13-53MC	Summer	Kongsfjorden Central	2.17		0-1	1.259	34
NP08-16-33MC	Summer	Kongsfjorden Trough	0.96		0-1	1.129	43
NP08-16-37MC	Summer	Kongsfjorden Inner Central	1.07		0-1	1.392	18
NP08-16-44MC	Summer	Kongsfjorden Central	1.33		0-1	1.203	93
NP08-16-44MC	Summer	Kongsfjorden Central	1.33		0-1	1.186	93
JM08-704-58MC	Autumn (Summer)	Kongsfjorden Central	2.72	1.45	0-2	1.198	37
JM08-704-59MC	Autumn	Kongsfjorden Inner Central	2.91		0-2	1.187	43
JM08-704-60MC	Autumn (Summer)	Kongsfjorden Central	2.95	1.32	0-2	1.195	56
JM08-704-61MC	Autumn (Summer)	Kongsfjorden Mouth	2.64		0-2	1.285	16
JM09-unis3MC	Spring	Kongsfjorden Inner Central	0.68		0-1	1.610	43
JM09-unis3MC	Spring	Kongsfjorden Inner Central	0.68		1-2	1.200	29
JM09-unis4MC	Spring	Kongsfjorden Central	1.28		0-1	1.238	54
JM09-H-01BC	Autumn	Hornsund Outer	2.84		0-1	0.912	43
JM09-H-01BC	Autumn	Hornsund Outer	2.84		0-1	0.979	43
JM09-nov02MC	Autumn	Kongsfjorden Outer	3.50		0-2	1.150	22
JM09-nov03MC	Autumn	Kongsfjorden Central	3.38		0-2	1.154	29
JM09-nov05MC	Autumn	Kongsfjorden Central	3.16		0-1	1.101	31
JM09-nov07BC	Autumn	Vidjefjorden Outer	3.90		0-1	1.175	60
JM09-019BC	Autumn	Storfjorden Outer	0.78		0-1	1.039	49
JM10-180MC	Spring	Kongsfjorden Outer	0.52		0-2	1.197	25
JM10-182MC	Spring	Kongsfjorden Inner	0.46		0-1	1.231	38
JM10-183MC	Spring	Kongsfjorden Central	0.00		0-1	1.240	25
<i>Nonionella labradorica</i>							
NP05-11-05MC	Summer	Kongsfjorden Inner Central	1.88		0-2	1.618	60
NP05-11-08MC	Summer	Kongsfjorden Central	1.88		0-2	1.652	51
NP05-11-14MC	Summer	Kongsfjorden Outer	2.06		0-2	1.430	113
NP05-11-20MC	Summer	Kongsfjorden Trough	2.68		0-2	1.686	51
NP05-11-35MC	Summer	Hinlopen Trough	3.27		0-2	1.447	31
NP05-11-35MC	Summer	Hinlopen Trough	3.27		0-2	1.649	49
NP06-16-12MC	Summer	Kongsfjorden outer	1.64		0-2	1.588	52
NP06-16-30MC	Summer	Kongsfjorden Central	1.76		0-1	1.749	48
NP06-16-37MC	Summer	Kongsfjorden Central	1.72		0-2	1.646	54
NP06-16-39MC	Summer	Kongsfjorden Inner Central	3.74		0-2	1.556	33
NP06-16-43MC	Summer	Kongsfjorddjupet	1.54		0-2	1.616	58
NP07-13-16MC	Summer	Krossfjorden (central)	0.71		0-2	1.616	48
NP07-13-16MC	Summer	Krossfjorden (central)	0.71		0-2	1.591	48
NP07-13-42MC	Summer	Kongsfjorden Inner central	2.07		1,5-2	1.694	55
NP07-13-55MC	Summer	Krossfjorden Outer	0.94		0-1	1.659	38
JM08-kb0MC	Spring	Kongsfjorden Mouth	0.01		0-1	1.530	45
NP08-16-30MC	Summer	Kongsfjorden Mouth	1.12		0-1	1.504	54
NP08-16-33MC	Summer	Kongsfjorden Trough	0.96		0-1	1.497	28
NP08-16-37MC	Summer	Kongsfjorden Inner Central	1.07		0-1	1.815	45
NP08-16-40MC	Summer	Kongsfjorden Central	1.28		1-1,5	1.608	56
NP08-16-44MC	Summer	Kongsfjorden Central	1.33		0-1	2.401	52
JM08-704-57MC	Autumn	Kongsfjorden Outer	2.37		0-2	1.582	58
JM08-704-59MC	Autumn	Kongsfjorden Inner Central	2.91		0-1	1.692	48
JM08-704-60MC	Autumn	Kongsfjorden Central	2.95		0-1	1.569	33
JM08-704-60MC	Autumn	Kongsfjorden Central	2.95		1-2	1.712	53
JM08-704-61MC	Autumn	Kongsfjorden Mouth	2.64		0-2	1.672	56
JM09-05/unis0MC	Spring	Kongsfjorden Mouth	1.62		0-2	1.616	47
JM09-05/unis1MC	Spring	Kongsfjorden Outer	1.74		0-2	1.557	18
JM09-05/unis3MC	Spring (Autumn)	Kongsfjorden Inner Central	0.68	3.5	0-1	1.619	50
JM09-05/unis4MC	Spring	Kongsfjorden Central	1.38		1-2	1.476	52
JM09-05/unis4MC	Spring (Autumn)	Kongsfjorden Central	1.38	2.95	0-1	1.618	43
JM09-nov02MC	Autumn	Kongsfjorden Outer	3.50		0-1	1.690	48

Table 2. (continued)

Core-site	Hydrological Season	Locality	BWT °C	Season Corrected BWT (°C)	Sed. Depth (cm)	Mg/Ca (mmol/mol)	# Forams Ran
JM09-nov02MC	Autumn	Kongsfjorden Outer	3.50		1-2	1.480	44
JM09-nov03MC	Autumn	Kongsfjorden Central	3.38		0-2	1.658	34
JM09-nov05MC	Autumn	Kongsfjorden Central	3.16		0-1	1.588	42
JM09-nov07BC	Autumn	Vidjefjorden Outer	3.90		0-1	1.694	28
JM09-H-01BC	Autumn	Hornsund Outer	2.84		0-2	1.543	47
JM09-019BC	Autumn	Storfjorden Outer	0.78		0-1	1.359	23
JM10-181MC	Spring	Kongsfjorden Central	0.53		0-1	1.583	47
JM10-181MC	Spring	Kongsfjorden Central	0.53		0-1	1.638	47
JM10-182MC	Spring	Kongsfjorden Inner Central	0.46		0-1	1.551	42
<i>Buccella frigida</i>							
NP05-11-35MC	Summer	Hinlopen Trough	3.27		0-2	0.851	37
JM06-16-43MC	Summer	Kongsfjorden Mouth	1.54		0-1	0.733	22
JM06-16-43MC	Summer	Kongsfjorden Mouth	1.54		0-1	0.709	22
NP08-16-33MC	Summer	Kongsfjorden Trough	0.96		0-2	0.695	31
JM08-16-44MC	Summer	Kongsfjorden Central	1.33		0-1	0.812	34
JM08-704-57MC	Autumn	Kongsfjorden Outer	2.37		0-2	0.760	17
JM08-704-58MC	Autumn	Kongsfjorden Central	2.72		0-2	0.817	19
JM08-704-60MC	Autumn	Kongsfjorden Central	2.95		0-1	0.832	54
JM08-704-60MC	Autumn	Kongsfjorden Central	2.95		1-2	0.850	26
JM08-704-61MC	Autumn	Kongsfjorden Mouth	2.78		0-2	0.799	17
JM09-unis0MC	Spring (Autumn)	Kongsfjorden Mouth	1.62	2.57	0-2	0.812	22
JM09-unis3MC	Spring (Autumn)	Kongsfjorden Inner Central	0.68		1-2	0.821	25
JM09-unis3MC	Spring (Autumn)	Kongsfjorden Inner Central	0.68	3.5	0	0.886	88
JM09-unis3MC	Spring (Autumn)	Kongsfjorden Inner Central	0.68	3.5	0-1	0.872	88
JM09-nov03MC	Autumn	Kongsfjorden Central	3.38		0-2	0.788	19
JM09-nov05MC	Autumn	Kongsfjorden Central	3.16		0-1	0.784	19
JM09-nov07BC	Autumn	Vidjefjorden Outer	3.90		0-2	0.858	22
JM09-019BC	Autumn	Storfjorden Outer	0.78		0-1	0.744	22
JM10-180MC	Spring (Autumn)	Kongsfjorden Outer	0.52	3.5	0-2	0.821	23
JM10-182MC	Spring	Kongsfjorden Inner	0.46		0-2	0.732	8
JM10-183MC	Spring (Autumn)	Kongsfjorden Central	0.00	3.16	0-1	0.834	31

^aSeason corrected BWT refers to samples which has been correlated to CTD measurements from the same area collected in the previous season (shown in parenthesis). Bold rows refer to samples used in equations (1)–(3).

(interpreted as fully grown) were used. High-resolution images of foraminiferal tests were taken using a Hitachi TM3030 Tabletop Scanning Electron Microscope at the University of Tromsø.

The samples were crushed between glass plates to crack open all test chambers before cleaning, transferred into acid-leached plastic tubes, and then cleaned in a four-step procedure. Sample crushing was carried out under a microscope, and only pristine looking specimens were chosen. In the initial step, the samples were soaked in commercial bleach (5.25% sodium hypochlorite, further diluted 10:1 with ultrapure water), in order to remove the Rose Bengal staining. The samples were kept in diluted bleach overnight and rinsed six or more times with ultrapure water. Subsequently they were cleaned following full cleaning procedures including a clay removal step, a reductive step, and an oxidative step as initially described by *Boyle and Keigwin* [1985] and later modified [*Boyle and Rosenthal*, 1996; *Martin and Lea*, 2002]. The samples were analyzed for Mg/Ca-ratios on an ICP-MS (Thermo Finnigan Element 2) located at INSTAAR, University of Colorado at Boulder, holding an analytical precision of 0.5% over a wide range of sample sizes [*Marchitto*, 2006]. The ICP-MS analysis also provided Mn/Ca, Fe/Ca, Zn/Ca-ratios, which is used to evaluate contamination levels.

5. Results

5.1. CTD-Measurements

The CTD-measurements typically indicate the temperature 5–10 m or more above the sea floor (Table 2). Thus, the values measured by the CTD might not reflect accurate bottom water temperature, and this discrepancy in depth can be a potential source of error. To correct for this, the temperature evolution down the water column was evaluated. Where the slope of the temperature change was high toward the bottom, the bottom water temperature was recalculated from this slope, instead of using the lowermost measurement of the CTD-record (Table 2). Oceanographic surveys from the fjord indicate consistent temperature

values in the lower 50 m of the water column in the outer fjord, whether it is occupied by Local Water or Atlantic Water masses [Svendsen *et al.*, 2002; Cottier *et al.*, 2005]. Influence of brine formation in the basins of Kongsfjorden could be a potential source of error for the temperature data set. However, this has only been observed in the inner fjord glacier proximal basins in Kongsfjorden [Svendsen *et al.*, 2002]. The data set has a temperature range of 0–3.9°C. All utilized temperatures fit within the known seasonal temperature variations in Svalbard fjords and WSC in general [Hegseth and Tverberg, 2013; Hopkins, 1991; Svendsen *et al.*, 2002; Hop *et al.*, 2006; Schlichtholz and Goszczko, 2006; Jernas, 2012].

5.2. Mg/Ca-Measurements

In all, 130 samples were measured for Mg/Ca ratios. Samples that showed indications of low CaCO₃-mass (<5 µg) were omitted from the data set if the Fe/Ca and Al/Ca-ratios showed signs of contamination, indicated by offset values. High values of Mn/Ca and Fe/Ca can indicate high amounts of Mn-CaCO₃ and/or Mn-Fe-oxide coatings due to diagenetic overgrowth [Boyle, 1983; Barker *et al.*, 2003]. For *I. helenae/norcrossi* and *B. frigida*, the Mn/Ca and Fe/Ca values were below 100 µmol/mol. Conversely, *N. labradorica* showed extremely high Mn/Ca and Fe/Ca values, with an average of 1229 and 1348 µmol/mol, respectively. However, due to the consistency of these high values throughout the data set, they are investigated further in the following.

For *C. reniforme* and *E. clavatum*, the Mg/Ca-data were rejected as most of them showed values exceeding the other species by several orders of magnitude. The results showed CaCO₃-mass <5 µg for all of these measurement, likely due to loss of material during cleaning procedures. Both *C. reniforme* and *E. clavatum* are small-sized foraminifera, particularly the ones found in Arctic environments. Crushing their chambers leaves behind very small fragments that are more exposed to dissipation during the cleaning procedures. The loss of CaCO₃ mass for *C. reniforme* and *E. clavatum* can likely be attributed to this. Thus, only results for *I. helenae/norcrossi*, *N. labradorica*, and *B. frigida* are presented in the following.

5.3. Mg/Ca-Temperature Calibration Data Set: Seasonal Implications

Figure 4 shows plots of Mg/Ca-ratios versus CTD bottom water temperatures for each of the three species *I. helenae/norcrossi*, *N. labradorica*, and *B. frigida*. The data points for each species clusters together in the plot. Yet no correlation between Mg/Ca and temperature is seen for *B. frigida*, *N. labradorica*, and *I. helenae/norcrossi*. In the following, we investigate the material focusing on seasonal preferences of the three species.

5.3.1. *Islandiella Helenae/Norcrossi*

The surface sediment samples used for this species have CTD bottom water temperatures varying between 0 and 3.9°C while the Mg/Ca-ratios vary between 0.91 and 1.61 µmol/mol (Table 2). The samples were grouped based on seasons, and the equations and corresponding correlation coefficients are shown in Figure 5a. The autumn group gave the highest correlation coefficient ($r^2 = 0.21$). There were some obvious outliers in samples from other fjords (low values) and inner fjords (high values) (Figure 4 and Table 2). Hence, data limited to outer-Kongsfjorden summer (July/August) samples, were also tested as a group. This gave a correlation coefficient of 0.75, indicating a correlation between Mg/Ca-ratio and BWT (Figure 5a). Due to seasonal sample collection, this correlation is based on eight measurements.

5.3.2. *Buccella Frigida*

The *B. frigida* data set had CTD-temperatures varying between 0 and 3.9°C and Mg/Ca-ratios between 0.69 and 0.88 µmol/mol (Table 2). For some locations, core-top samples from both 0–1 cm (fluffy layer) and 1–2 cm depth were measured separately. The different depths typically had deviating values. The data set was grouped based on seasons, and the equations and correlation coefficients are shown in Figure 5b. Highest correlation coefficients was found for summer (July/August) samples ($r^2 = 0.57$) and autumn (October/November) samples ($r^2 = 0.42$). A group consisting of both summer and autumn samples were also tested, resulting in a correlation coefficient of 0.62 based on 13 samples (Figure 5b).

5.3.3. *Nonionellina Labradorica*

The *N. labradorica* data set comprises CTD-temperatures between 0.01 and 3.9°C and Mg/Ca values between 1.43 and 2.40 µmol/mol (Table 2). As for *B. frigida* samples from the upper centimeter (0–1) and the deeper layer (1–2 cm) were measured separately for three stations. These gave deviating values. When grouping the data by season, a correlation to temperature was only seen for the group of autumn samples ($r^2 = 0.44$), based on 12 samples (Figure 5c).

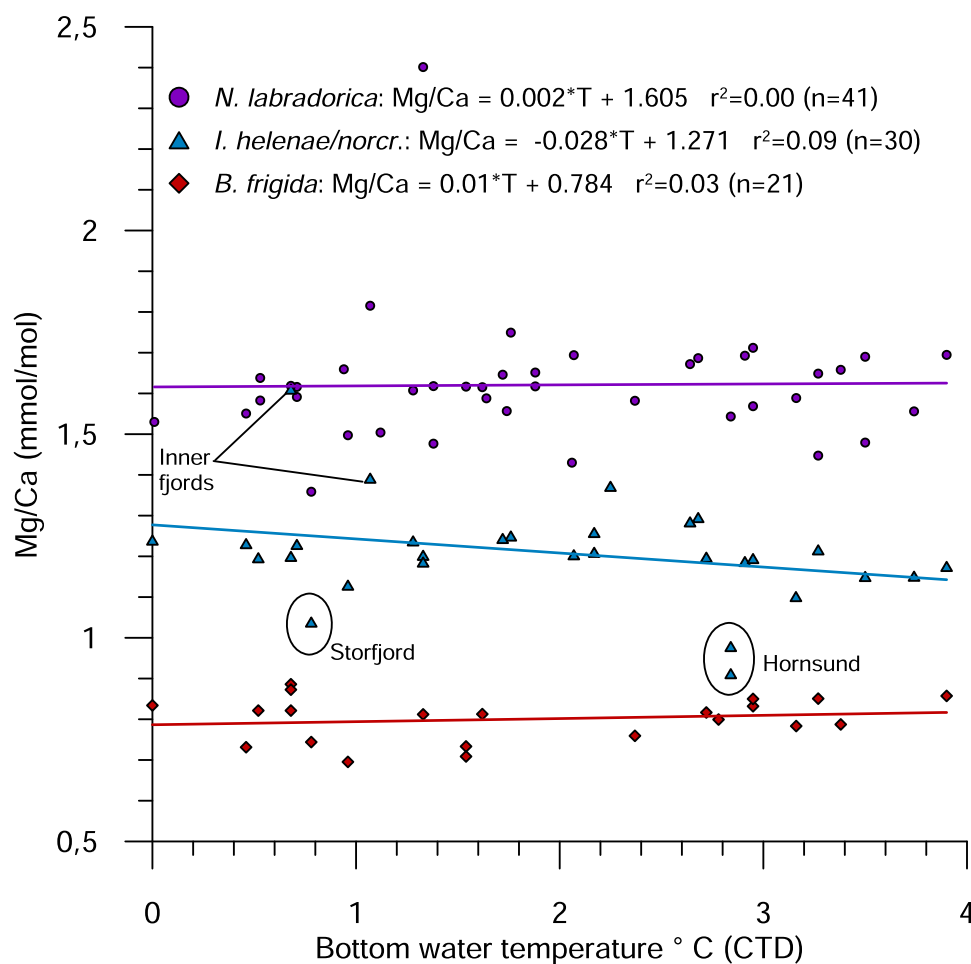


Figure 4. Mg/Ca-ratios and CTD-temperatures plotted for the complete data set (all seasons and locations) for *N. labradorica*, *B. frigida*, and *I. helenaenorcrossi*. All equations hold low correlation coefficients.

6. Discussion

6.1. Mg/Ca-Temperature Correlations

6.1.1. Temperature Control of Mg-Uptake

Several studies indicate that changes in carbonate ion concentration [CO_3^{2-}] can affect the uptake of Mg and Ca in benthic foraminifera [Martin et al., 2002; Elderfield et al., 2006; Rosenthal et al., 2006], and hence perturb the process where temperature alone controls the Mg/Ca ratio of benthic foraminifera. However, this effect seems to be of more importance in the deep sea, where [CO_3^{2-}] is low and temperatures are relatively stable [Elderfield et al., 2006; Rosenthal et al., 2006]. Presence of sea ice [Chierici and Fransson, 2009] and glacial ice [Evans et al., 2014] may also have an effect on [CO_3^{2-}], but considering the modern ice extent in the study area combined with core locations, such signals are not likely to reach the seafloor in the present study area. Postburial dissolution is also a potential source of error that could alter the chemical composition of foraminiferal tests, and hence disturb the temperature signal ideally stored within the calcite. Studies from the central Fram Strait west of Svalbard indicate significant dissolution of planktic foraminifera [Zamelczyk et al., 2012]. However, dissolution in that area is linked to the high productivity zone along the Arctic Front and the settlement of high amounts of organic matter [Walsh, 1991], as degradation of this leads to corrosive conditions at the seafloor [Henrich et al., 2002; Zamelczyk et al., 2012]. However, organic matter related to primary productivity (MOM) has an increasing gradient from fjord areas and going out toward the shelf in this area [Knies and Martinez, 2009]. Also, in Kongsfjorden the input of terrestrial organic matter is low (5–10% of total POM), and little of this material reach the benthic community [Kuliński et al., 2014]. Hence, dissolution of foraminiferal tests forced by organic matter oxidation is not considered to be of

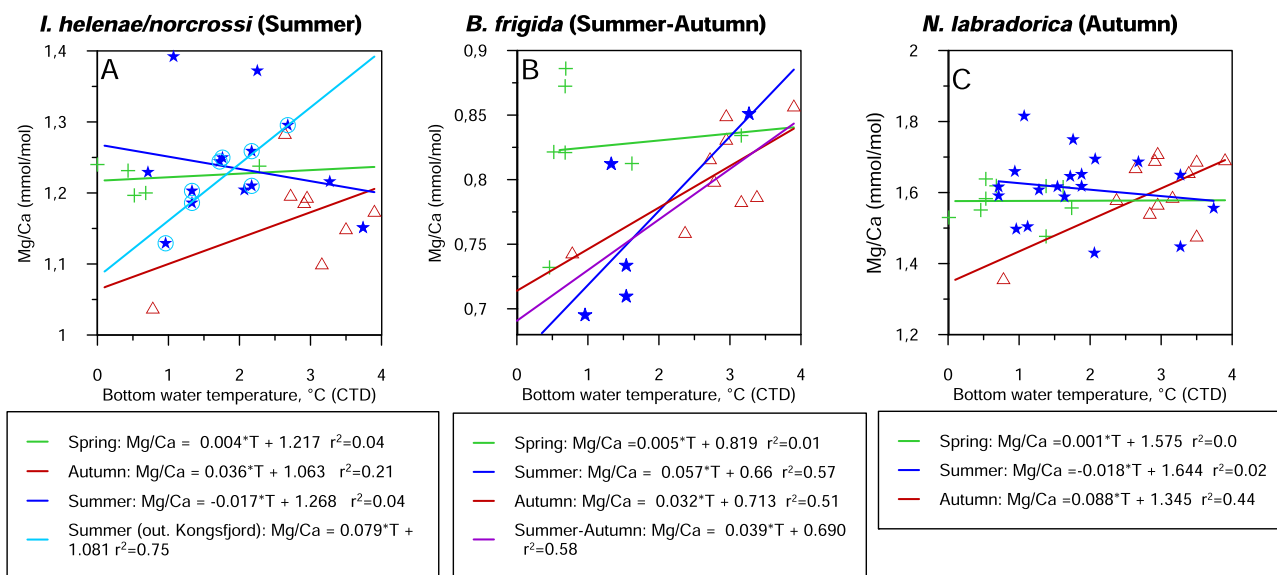


Figure 5. Mg/Ca-temperature correlations for (a) *I. helenaenorcrossi*; (b) *B. frigida*; (c) *N. labradorica*. The green crosses/lines indicate spring samples, the blue stars/lines indicate summer samples, and the red triangles/lines indicate autumn samples. Regression line equations and correlation coefficients are shown in the legend. The turquoise circles/line in Figure 5a show the Kongsfjorden stations for *I. helenaenorcrossi*. The purple line in Figure 5b show the regression line for mixed summer-autumn samples for *B. frigida*.

importance for the present study. In the following, we assume temperature to be the main control of Mg/Ca incorporation to foraminiferal tests in the present study area, but a potential influence of $[\text{CO}_3^{2-}]$ and postburial dissolution cannot be completely ruled out.

6.1.2. Mg/Ca-Temperature Calibrations

The results suggest that the three studied species of benthic foraminifera calcify during specific periods of the year, rather than with continuous reproduction cycles throughout the year. Conversely, *Jernas* [2012] did not observe any clear seasonal trends when studying faunal assemblages in the same data set as presented here. This may be explained by the staining method used. Even though Rose Bengal is used to identify living specimens of foraminifera, one main limitation with the technique is that it is not actively digested by the living organism, like for instance Cell Tracker Green (CTG) [Bernhard et al., 2006]. Hence, Rose Bengal stains the tests of recently dead specimens too. In cold-water environments, tests can contain their protoplasm for 1 month or more after the organism is deceased [Bernhard, 1988]. In addition, it is not known how long the studied foraminifera can stay alive after the main growth period. For instance, the study from Kongsfjorden indicated that they could stay alive or be preserved throughout the 116 days long polar night [Jernas, 2012]. In the following, three Mg/Ca-temperature equations representing the most significant correlations found in this data set will be presented. However, these equations are based on some assumptions (see discussion below) and relatively few data points, and cannot be viewed as robust, “ready-to-use” temperature equations. Rather, the data represent an indication of the importance of the seasonality aspect in such high latitude shelf environments when working with proxy data.

The data set from Kongsfjorden indicate that *I. helenaenorcrossi* calcify during the summer in the outer and central fjord. Following this, and the fact that they can remain stained for a long-period after calcification (see references above), Mg/Ca samples collected during the autumn (October/November) were correlated to CTD-stations from proximal sites (similar coordinates and depth) taken in July/August the same year. This was possible for two stations. The combined Mg/Ca samples from summer and CTD-measurements from spring were added to the data set (season corrected BWT; Table 2). It fitted along the regression line, altering the equation only slightly and increasing the coefficient of determination (r^2) to 0.82, now based on 10 data points (equation (1); Figure 6). The standard error of estimate for this fit is 0.02 mmol/mol, equivalent of 0.3°C (p value < 0.001).

$$\text{Mg/Ca} = 0.078^* T + 1.084 \pm 0.3 \quad (r^2 = 0.82; p < 0.001; n = 10) \quad (1)$$

Buccella frigida appear to reproduce and calcify in a period stretching from approximately July to October, covering two seasons in the present data set. Here Mg/Ca samples from spring (April/May) were correlated

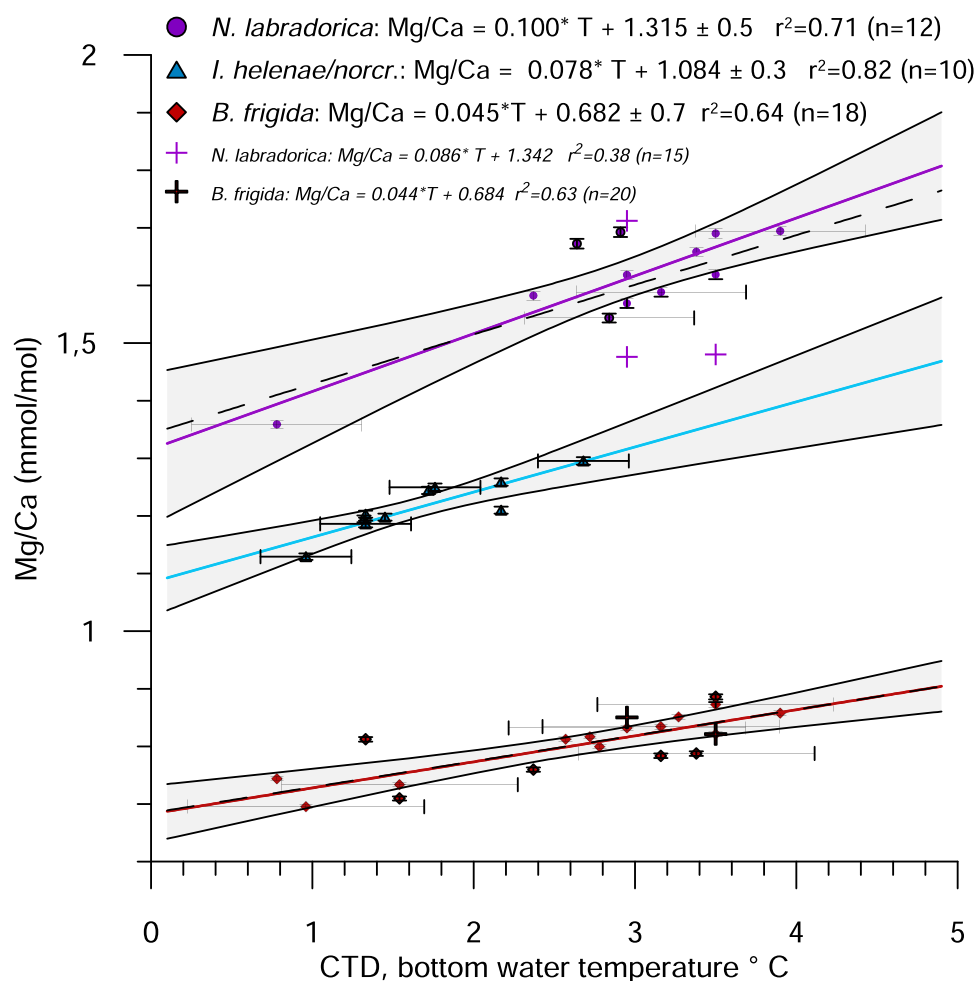


Figure 6. The most robust Mg/Ca-CTD-temperature correlations based on summer samples for *I. helenae/norcrossi* (equation (1)); combined summer and autumn samples for *B. frigida* (equation (2)); and autumn samples for *N. labradorica* (equation (3)). The crosses represent data points for samples taken beneath the fluffy layer (1–2 cm). The stippled line represents the regression line if these are included, while the equations written in italic includes those data points. Horizontal error bars indicate the uncertainties of the temperature measurements calculated from the standard error of estimate. Vertical error bars indicate uncertainties in Mg/Ca measurements based on Marchitto [2006].

to CTD-stations with similar latitude and depth taken in October/November the previous year. This altered the trend line slightly and increased the correlation coefficient to $r^2 = 0.63$, based on 20 data points (Figure 6). There are discrepancies in Mg/Ca-values between the fluffy layer and the deeper layer in stations where they had been measured separately (two stations). Little is known about life spans, decay rates of protoplasm and migration patterns of cold-water, benthic foraminifera, yet these are factors that may explain this discrepancy. Samples from the fluffy layer were considered more to likely represent the most recent fauna. In addition, using them would be in consistency with the remaining data set. Hence, an equation based only on samples from the fluffy layer is presented (equation (2) and Figure 6). The standard error of estimate for this fit is 0.03 mmol/mol, equivalent of 0.7°C (p value < 0.0001).

$$\text{Mg/Ca} = 0.045 * T + 0.682 \pm 0.73 \quad (r^2 = 0.64; p < 0.0001; n=18) \quad (2)$$

For *N. labradorica*, the data indicate a growing season during Autumn. Following the same procedure as for the other species, core-top stations from April/May were correlated to previous years autumn CTD-stations, having similar latitude and depth. The correlation was possible for two CTD-stations, and these fitted along the regression line without altering the temperature-equation much, resulting in a correlation coefficient of 0.38 (Figure 6). As for *B. frigida*, an equation based only on fluffy layer samples is also presented (equation (3)). For this species, this increased the correlation coefficient to 0.71, a significantly larger change than for

B. frigida. One possible explanation to the discrepancy in values between the fluffy layer and the deeper layer could be related to vertical migration of foraminifera in the sediment, as *N. labradorica* has been observed to migrate down to 10 cm in Svalbard fjords [Kucharska et al., 2015]. However, little is known about the dynamics of this behavior. An unanswered question is whether they are able to reproduce and calcify in this depth or if it is associated with a dormant life phase. Regression lines and equations for the full autumn data set as well as autumn fluffy layer samples are both presented in Figure 6. The standard error of estimate for equation three is 0.05 mmol/mol, equivalent of 0.5°C (p value < 0.001).

$$\text{Mg/Ca} = 0.100 * T + 1.315 \quad (r^2=0.71; p < 0.001; n=12) \quad (3)$$

The seasonal grouping of the data caused a reduction of the data set and resulted in equations based on relatively few data points. This is evident in both the temperature range represented and the amount of data points in the equations. Equation (1)–(3) presented in Figure 6 represents the most significant fits for the three species and holds correlation coefficients between 0.64 and 0.77 and p values < 0.001, which indicate that there is a correlation between temperature and Mg/Ca-ratios in all three species. Still, as evident by the 95% confidence intervals, they are not as robust as anticipated (Figure 6). Hence, this data set shows the importance of the seasonality perspective in a dynamic setting like Svalbard shelf and fjords when working with proxies, rather than “ready-to-use” temperature calibrations. In order to make more reliable temperature equations, more material is needed. However, if comparing the equations to other Mg/Ca temperature calibrations including temperatures on the lower end of the temperature range, they fall into a similar range as most of these calibrations (Figure 7). The slopes of the regression lines in the present data set are low compared to many studies, yet they are comparable to the cold-water temperature calibrations published by Kristjánsdóttir et al. [2008] and Lear et al. [2015]. Although many of them are exponential fits, they typically appear linear on the lower end of the temperature scale (Figure 7).

The 95% confidence intervals indicate the strength of the temperature intervals in the equations and where more data are needed. The *B. frigida* equation appears to be most robust. Conversely, *N. labradorica* has only a small interval where the equation reproduces reliable temperatures (2.5–~4°C), while the equation for *I. helenae/norcrossi* appears to be reliable up to 4°C. Outside these ranges, the equations must be used with caution, as they are less robust.

6.2. Test Growth of Arctic Benthic Foraminifera

Knowledge of life-spans including calcifying rates and seasonal growth of benthic foraminifera in their natural habitat is rather sparse. The available information is largely based on population counts from seasonal population-studies [Gustafsson and Nordberg, 1999, 2001; Korsun and Hald, 2000; Murray and Alve, 2000; Murray, 2006; Jernas, 2012]. However, the sampling frequency is often too low to record the complete life cycle. Studies from highly stratified fjords in southern Sweden point at calcification periods of less than 1 month for opportunistic species of foraminifera, such as *Stainforthia fusiformis*, *Elphidium incertum*, and *Elphidium excavatum* [Gustafsson and Nordberg, 1999, 2001]. Further, it has been reported that some particular deep-sea foraminifera build their test within 3 months [Corliss and Silva, 1993]. Cultivation studies indicate a rapid initial test-growth. Barras et al. [2009] showed that the open-marine species *Bulimina marginata* had built three chambers only 4 days after leaving the reproduction cyst. Growth rate for the remaining chambers seemed to depend and correlate positively to temperature and food supply. For the lowest temperature tested on *B. marginata* (<8°C) chamber growth took 3 months [Barras et al., 2009]. The coastal species *Ammonia tepida* had a third chamber built within 24 h after leaving the cyst [Stouff et al., 1999], and testing in a wide range of temperatures and salinities showed that they reached their maximum amount of chambers within 30–45 days [Bradshaw, 1957]. It was also observed that both species could stay alive for a long-time even though they did not add chambers or reproduce [Bradshaw, 1957; Barras et al., 2009]. No similar studies have been carried out on Arctic species of benthic foraminifera. Seasonal studies on benthic foraminifera from Svalbard fjords show no clear evidence on life spans [Korsun and Hald, 2000; Jernas, 2012]. Although, there are indications that various species might have specialized life strategies that confine their growth of carbonate tests to certain periods of the year [Korsun and Hald, 2000; Rasmussen et al., 2012]. However, higher temporal sampling resolution is required to understand the seasonality aspects of Arctic benthic communities.

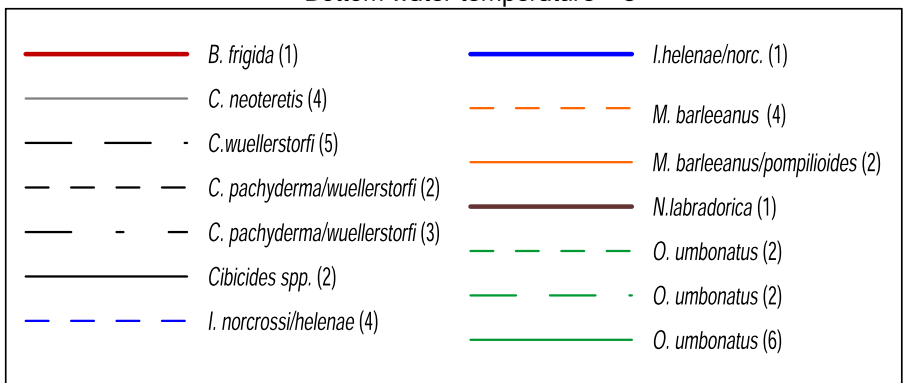
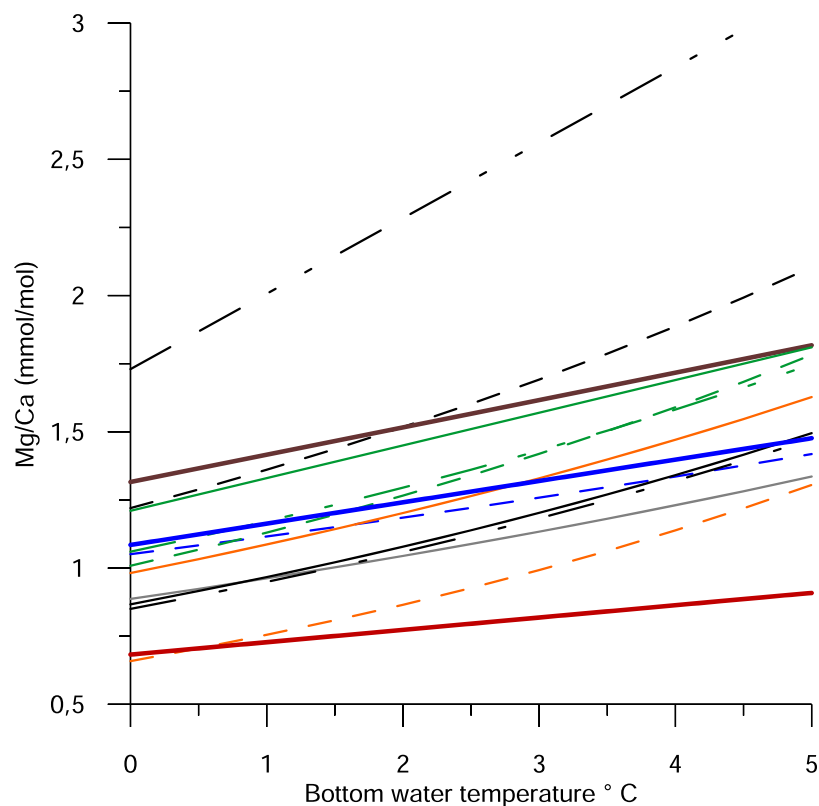


Figure 7. Mg/Ca-temperature calibrations from the three species in this study (1) compared to other published studies: (2) Lear et al. [2002], (3) Martin et al. [2002], (4) Kristjánsdóttir et al. [2008], (5) Rathburn and De Deckker [1997], and (6) Lear et al. [2015].

Benthic foraminifera living in unstable conditions, e.g., high seasonality environments, are often R-strategists, meaning that they reach maturity quickly and tend to be relatively small. Taking into account the highly variable conditions regarding water masses, temperatures and food supply in Kongsfjorden [Hall-dal and Halldal, 1973; Eilertsen et al., 1989; Hasle and Heimdal, 1998; Wiktor, 1999; Hop et al., 2002, 2006; Svendsen et al., 2002; Cottier et al., 2005; Gerland and Renner, 2007; Rokkan Iversen and Seuthe, 2011; Hodal et al., 2012], and the knowledge on lifespans and growing rates of other benthic foraminifera (see references above), it is reasonable to assume that the species investigated in the present study have a relatively rapid test formation, e.g., possibly weeks to months. This assumption will be discussed further below. If correct, it implies that benthic foraminifera from such environments can be used to reconstruct temperatures with a seasonal signature, rather than e.g., annual mean temperatures.

6.3. Seasonality

The current study areas are influenced by high annual variability in the water masses regarding light, turbidity, temperature, nutrients, and benthic-pelagic coupling. In addition, there is a large spatial difference

within Kongsfjorden characterized by a marked climatic and oceanographic gradient from the cold and glaciated inner fjord to increasing out-fjord influence of warmer and more saline Atlantic Water from the shelf.

Although the seasonal study of foraminiferal assemblages in Kongsfjorden did not show any clear seasonal signals for the species under discussion [Jernas, 2012], a study from the adjacent Tempelfjorden found some indications of seasonality, which will be discussed further below [Korsun and Hald, 2000]. Season-specific calcification of benthic foraminifera has previously been suggested by several authors [Toyofuku et al., 2000; Filipsson et al., 2004; Kristjánsdóttir et al., 2007; Cage and Austin, 2008; Zajaczkowski et al., 2010; Rasmussen et al., 2012].

The results for Mg/Ca-temperature calibrations for *I. helenae/norcrossi*, *B. frigida*, and *N. labradorica* indicate specific preferences for the season they calcify in. However, the term seasonality should be used with precaution in this context, as it may be misleading. First, the seasons described in this paper are strongly linked to oceanographic changes; hence, “seasonal” preferences of these species in this area may differ from another oceanographic setting, even if the same species are present. Second, what defines a season in a certain area may not be consistent through time. Looking at Kongsfjorden today, the timing of AW inflow to the fjord is changing [Hegseth and Tverberg, 2013]. This change also affects the timing of the spring bloom [Hegseth and Tverberg, 2013], which could possibly have a cascading effect to other trophic levels, including benthic foraminifera. If the spring bloom triggers a specific species, and a shift in oceanography simultaneously leads to AW dominance (instead of Arctic water dominance), this could potentially be interpreted as a rapid temperature change, when it in fact represents an oceanographic shift. This is important to keep in mind if applying this idea when working with paleoreconstructions.

The results indicate a calcifying season lasting from approximately July–November for *B. frigida*, while *I. helenae/norcrossi* and *N. labradorica* appear to calcify in summer and autumn, respectively. Below we discuss how these findings can relate to current knowledge on foraminiferal affinity and seasonal variations in western Spitsbergen.

6.3.1. *Islandiella helenae/norcrossi*

Our results indicate that *I. helenae/norcrossi* reproduce and calcify during summer (July/August) (Figure 6). In the seasonal study of living benthic foraminifera from Kongsfjorden, no clear pattern of seasonal abundance is recorded for this species, as they appear relatively stable throughout the year [Jernas, 2012]. *Islandiella helenae/norcrossi* is an Arctic species typically related to areas with seasonal sea ice coverage, in particular to enhanced productivity along sea ice edges [Korsun and Polyak, 1989; Steinsund, 1994; Jennings et al., 2004]. The spring bloom in Kongsfjorden is initiated close to and underneath sea ice in April–May, and is represented mainly by diatoms [Hasle and Heimdal, 1998; Wiktor, 1999; Hop et al., 2002; Hegseth and Tverberg, 2013]. However, the diatom fauna of the spring bloom differs from that found inside the ice, indicating that this bloom is not seeded by ice-associated diatoms [Keck et al., 1999; Wiktor, 1999]. Normally, the spring bloom lasts for approximately 2 weeks and favorable conditions for benthic-pelagic coupling suggest that it affects the sea bottom up to 1 month after initiation [Zajaczkowski et al., 2010a, 2010b]. Hence, the summer growing season of *I. helenae/norcrossi* is probably not triggered by this event. However, several studies show presence of diatoms in the water column also in July, occasionally in amounts sufficiently high to be defined as blooms [Halldal and Halldal, 1973; Hasle and Heimdal, 1998; Keck et al., 1999; Hop et al., 2002]. According to Hasle and Heimdal [1998], the predominant phytoplankton in July is sea ice associated diatoms, living deep enough (down to 70 m) to avoid being caught by the spring pycnocline (Figure 2). Concurrently with the sea ice diatom bloom, the phytoplankton community is dominated by coccolithophorids [Keck et al., 1999]. Following this, the reproduction and growth of *I. helenae/norcrossi* occurring in summer could be connected to several potential food sources, but the exact trigger mechanism is unknown. The fact that the reproduction and growth of *I. helenae/norcrossi* seems to coincide with blooming of sea ice diatoms is supported by several studies relating this species to areas of seasonal sea ice [Korsun and Polyak, 1989; Steinsund, 1994; Jennings et al., 2004].

A correlation between Mg/Ca and bottom water temperature was only seen in the data from outer parts of Kongsfjorden and Kongsfjorden Trough (Table 2; and Figure 5). During hydrological spring, heavy melting and cooled waters characterize the inner part of the fjord, while initial AW-inflow occurs in the outer part, causing an internally detached fjord-system, with large local variations. If assumed that *I. helenae/norcrossi* is controlled by a specific food source as discussed above, it is likely that the timing of reproduction and

growth will differ along the large climatic and environmental gradient in the fjord at this time. This can possibly explain the spatial limitation of the correlation data set.

In a Late-Holocene paleorecord published in *Kristjánsdóttir et al.* [2007], the reconstructed Mg/Ca-temperatures of *I. helenae/norcrossi* showed cooler temperatures than the Mg/Ca-temperature record of the benthic foraminifer *Cassidulina neoteretis*, possibly indicating different growing seasons for the two species. This suggests a calcification season under influence of cooler waters for *I. helenae/norcrossi* than for *C. neoteretis*. This assumption is supported by a study from Malangen fjord, northern Norway, comparing reconstructed proxy temperatures ($\delta^{18}\text{O}$) derived from *C. neoteretis* to historical seasonal temperature data [*Hald et al.*, 2011]. They found strongest correlation to the November temperatures, the warmest season in this fjord, indicating that *C. neoteretis* calcify during the temperature optimum of AW inflow [*Hald et al.*, 2011]. This can explain the difference in temperatures reconstructed by *I. helenae/norcrossi* versus *C. neoteretis* in *Kristjánsdóttir et al.* [2007]. It also supports summer as a growing season for *I. helenae/norcrossi* in Kongsfjorden as the bottom water temperatures at this time are not significantly influenced by the warmer AW.

It should be mentioned that the temperature equation for *I. helenae/norcrossi* published in *Kristjánsdóttir et al.* [2007] differs slightly from the equation presented here, and would generally produce warmer temperatures. This could relate to mixing of the two *Islandiella* species in the samples. The data presented here mainly consist of *I. helenae*, while this information is not given in *Kristjánsdóttir et al.* [2007]. It should also be noted that in the data set of *Kristjánsdóttir et al.* [2007], the temperatures are calculated from oxygen isotopes of samples consisting of both living and dead fauna. Altogether, these differences and uncertainties make it difficult to compare the two data sets.

6.3.2. *Buccella frigida*

The present study shows a temperature correlation for *B. frigida* for both summer (July/August) and autumn (October/November) samples (Figure 6). This can indicate two separate growing seasons, or that the species reproduce continuously in the period between July and November. *Buccella frigida* is present in many shelf and fjord faunas in the Arctic as a subdominant or minor species [*Østby and Nagy*, 1982; *Jennings and Helgadóttir*, 1994; *Hald and Korsun*, 1997; *Korsun and Hald*, 2000; *Polyak et al.*, 2002; *Jennings et al.*, 2004; *Zajaczkowski et al.*, 2010], with no obvious environmental preferences. In paleorecords from Svalbard fjords, it is introduced to the assemblages at the transition to the Holocene [*Ślubowska et al.*, 2005; *Ślubowska-Woldengen et al.*, 2007; *Skirbekk et al.*, 2010], possibly linking it to interglacial climates at high latitudes [*Skirbekk et al.*, 2010]. Also, in the Northeast Water Polynya, Greenland, *B. frigida* were present in significant numbers only in samples from late July [*Newton and Rowe*, 1995], and in Novaya Zemlya abundances are generally low, but still higher on the climatically favorable western side [*Korsun and Hald*, 1998]. Altogether, this might link the distribution of *B. frigida* to the warmer end of Arctic conditions.

There are several food sources available summer and autumn, which could support reproduction and growth of benthic foraminifera at this time. *Rokkan Iversen and Seuthe* [2011] found high biomass combined with low growth of microbial organisms in July, concurrently with high growth of phytoplankton. They pointed out that presence of bacteria could facilitate growth of phytoplankton in July due to its ability to remineralize limited nutrients [*Legendre and Rassoulzadegan*, 1995; *Rokkan Iversen and Seuthe*, 2011]. It should be noted that heterotrophic bacteria, picoplankton, and nanoflagellates are present in Kongsfjorden during all seasons [*Rokkan Iversen and Seuthe*, 2011]. These organisms are known to be important components of the lower part of the food web [*Fenchel*, 1982; *Sanders et al.*, 1992; *Vaqué et al.*, 1994]. Also, a large part of the settled phytoplankton cells in August is generally advected from the shelf [*Zajaczkowski et al.*, 2010a, 2010b]. A study from Kvitøyrenna, northeastern Svalbard, shows a high content of oceanic phytoplankton (coccolithophorids) in late August, originating from the WSC [*Hegseth and Sundfjord*, 2008]. Atlantic Water associated species of coccolithophorids are also found in Kongsfjorden during July [*Halldal and Halldal*, 1973]. In addition, fecal pellets produced by grazing zooplankton are likely to reach the bottom as a potential food source [*Wassmann et al.*, 1999]. In Kongsfjorden, the large copepod *Calanus glacialis* have been observed to peak from July to October [*Daase et al.*, 2013], while a distinct peak of smaller copepods have been reported for November [*Lischka and Hagen*, 2005].

In the present study, all Mg/Ca measurements from summer used in the temperature correlation are from outer fjord stations on Svalbard (Table 2). This coincides with the typical onset of Atlantic Water inflow to the fjord, initially influencing the outer fjord. The inflow lasts throughout the hydrological summer, terminating in November/December. Hence, our data may indicate that *B. frigida* reproduce and grow during the

entire period of AW-inflow, lasting from July to November, possibly linking their distribution to the presence of Atlantic Water masses in this area. It should be noted that bottom water temperatures are still relatively low during summer despite the AW-inflow; hence, the correlation is not directly linked to enhanced temperatures. In the calibration plots, Mg/Ca-samples taken during spring (April/May) were correlated to CTD-temperatures from autumn the previous year. The correlated data points fitted along the produced Mg/Ca-temperature plot, indicating that specimens of *B. frigida* survived in the sediments for approximately 5 months without reproducing or growing.

6.3.3. *Nonionellina Labradorica*

Mg/Ca-ratios for *N. labradorica* plotted against temperature indicate an autumn (October/November) blooming season for this species (Figure 5c). *Nonionellina labradorica* is a wide spread Arctic/Subarctic species associated with environments with high flux of organic matter [Schafer and Cole, 1986; Cedhagen, 1991; Hald and Steinsund, 1992; Steinsund, 1994; Hald and Korsun, 1997; Korsun and Hald, 1998; Polyak et al., 2002; Rytter et al., 2002; Husum and Hald, 2004; Jennings et al., 2004; Lloyd, 2006; Zajaczkowski et al., 2010]. It has been linked to episodic or seasonal high productivity events [Cedhagen, 1991; Hald and Steinsund, 1992; Polyak et al., 2002; Rytter et al., 2002; Jennings et al., 2004; Zajaczkowski et al., 2010] in many areas. In other areas, it has been linked specifically to organic matter associated with Atlantic Water influence [Schafer and Cole, 1986; Hunt and Corliss, 1993; Steinsund, 1994; Hald and Korsun, 1997; Jennings et al., 2004; Lloyd, 2006]. Seasonal studies from Kongsfjorden show a relatively stable annual distribution of *N. labradorica*, with minor peaks in abundance in May and August and lowest in October and April [Jernas, 2012]. As discussed above, low sampling resolution and issues related to the use of Rose Bengal in abundance studies make it difficult to record timing of reproduction and growth. In addition, the foraminiferal ability to stay alive for longer periods without reproducing or growing makes it difficult to correlate the seasonal abundance data of *Jernas* [2012] to reproduction and calcifying seasons. However, the low abundances in October differ largely to what is seen in the present study. This could be attributed to a recent reproduction event, as this often leaves tests without cytoplasm behind [Altenbach, 1992], demonstrating the difficulty of recording a complete life cycle with low sampling intervals. Studies of seasonal dynamics in Tempelfjorden, Svalbard [Korsun and Hald, 2000] indicated both a spring and an autumn reproduction event for *N. labradorica* [Korsun and Hald, 2000]. A dual bloom for *N. labradorica* is also supported by studies of Gustafsson and Nordberg [2001]. In the Swedish Gullmar fjord, they found a small increase of *N. labradorica* during the April-spring bloom, but the main peak was not recorded until 3 months later (July). A dual blooming season was not observed in this study area, but as for the Gullmar fjord, the growth season for *N. labradorica* occurs several months after the spring phytoplankton bloom. Cedhagen [1991] observed that *N. labradorica* could retain chlorophyll by ingesting it, subsequently isolate and store it within their protoplasm, for periods with low food supply. The retained chlorophyll probably has the potential to stay intact for weeks or months [Cedhagen, 1991]. Whether this can be linked to the delayed blooming season compared to the phytoplankton bloom in Kongsfjorden would be highly speculative. As described above, there are several other food sources available at this time in Kongsfjorden. It should also be noted that none of the *N. labradorica* specimens from Kongsfjorden appeared to be filled with chlorophyll. The growing season in autumn, coincide with the highest influence of warm Atlantic Water. This is supported by studies associating the distribution of *N. labradorica* to areas of high nutrient supply and presence of Atlantic Water [Schafer and Cole, 1986; Cedhagen, 1991; Hald and Steinsund, 1992; Steinsund, 1994; Hald and Korsun, 1997; Korsun and Hald, 1998; Polyak et al., 2002; Rytter et al., 2002; Husum and Hald, 2004; Jennings et al., 2004; Lloyd, 2006; Zajaczkowski et al., 2010].

7. Conclusions

We investigated the relationship between Mg/Ca and the ambient bottom water temperature in Arctic benthic foraminifera including *I. helenae/norcrossi*, *B. frigida*, *N. labradorica*, *E. clavatum*, and *C. reniforme* from the following fjords at Svalbard, European Arctic: Kongsfjorden, Krossfjorden, Vidjefjorden, Storfjorden, Hornsund, and Hinlopen Strait (all Svalbard). Mg/Ca-temperature calibrations for *E. clavatum* and *C. reniforme* are not presented, as most material was lost during the cleaning procedures prior to Mg/Ca measurements. It appeared as if the specimens became highly pulverized in the crushing process, probably linked to the small size of the tests. For future work, great care should be taken when preparing such samples.

For the species *I. helenae/norcrossi*, *B. frigida*, and *N. labradorica*, a correlation between Mg/Ca-ratios and measured bottom water temperatures was found when grouping the data by seasons, indicating specific

growing seasons for the three species. Coefficients of determination (r^2) are in the order of 0.64–0.82. However, these cannot be considered as robust, “ready-to-use” temperature equations, but rather as indications on the importance of seasonality when dealing with proxies in high-latitude shelf environments. Further, it indicates that temperature reconstructions from these Arctic benthic foraminifera reproduce seasonal temperatures rather than annual average temperatures. To establish reliable temperature equations, more data are needed.

The Mg/Ca-temperature correlations indicate that *I. helenae/norcrossi* reproduce and grow in outer Kongsfjorden during July/August, representing the summer season in Kongsfjorden. This is concurrently with the sea-ice diatom bloom in Kongsfjorden, and fits with observations connecting the species to the sea-ice edge. *B. frigida* appears to reproduce and grow over a long-period lasting from July to November, representing summer and autumn seasons in Kongsfjorden. This period is associated with inflow of relatively warm Atlantic Water to the fjord. Finally, *N. labradorica* appear to reproduce and grow in October/November representing autumn season in Kongsfjorden. This correlate to the period when the Atlantic Water masses has its highest annual temperatures in the area. Detailed knowledge on growth rate and annual timing of benthic foraminiferal calcification may enable reconstruction of season specific paleotemperatures.

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