

UNIVERSITÉ DU QUÉBEC À MONTRÉAL

CHANGEMENT DU CLIMAT ET DE L'OCÉAN LE LONG DES MARGES SUD-
OUEST GROENLANDAISES : RECONSTITUTIONS DE LA VARIABILITÉ
HOLOCÈNE À PARTIR D'APPROCHES PALYNOLOGIQUES.

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PALYNOLOGICAL APPROACHES.

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Snow on Ice (<https://blog.ldeo.columbia.edu/snowonice/>)

DÉDICACE

À ma famille qui tout au long de cette
aventure a été un soutien inconditionnel et à
mon petit Tom qui aura grandi en même
temps que ce manuscrit.

AVANT-PROPOS

Cette thèse a été rédigée sous forme de trois chapitres en anglais, soumis dans des revues à comité de lecture, avec une introduction et une conclusion en français. Le premier chapitre intitulé « *Distribution of dinocyst assemblages in surface sediment samples from the West Greenland margin* », a été publié en décembre 2019 dans la revue *Marine Micropaleontology*, avec la collaboration de Anne de Vernal, Diana Krawczyk, Matthias Moros, Taoufik Radi, André Rochon, Marit-Solveig Seidenkrantz et Sébastien Zaragosi. Le deuxième chapitre nommé « *Late Holocene Sea Surface Instabilities in the Disko Bugt Area, West Greenland, in Phase With $\delta^{18}O$ Oscillations at Camp Century* » a été publié en février 2018, dans la revue *Paleoceanography and Paleoclimatology* de l'*American Geophysical Union* (AGU). Il est le fruit d'un échange de savoir-faire, de données et de connaissances avec Anne de Vernal, Mads Faurschou Knudsen, Claude Hillaire-Marcel, Matthias Moros, Sofia Ribeiro, Marie-Michèle Ouellet-Bernier et Marit-Solveig Seidenkrantz. Enfin, le troisième chapitre, intitulé « *Ocean and land ice variations in southwest Greenland during the Holocene* » est en préparation pour soumission dans la revue *Boreas*. Cet article est rédigé avec l'appui et la contribution des coauteurs Anne de Vernal, Marit-Solveig Seidenkrantz, Claude Hillaire-Marcel, Christof Pearce, Lorenz Meire, Anders Møller Mathiasen, Mikkel Thy Nielsen, Kerstin Perner, Jane Lund Plesner.

Mon travail a consisté à analyser les assemblages de dinokystes. Les résultats sont présentés et interprétés dans cette thèse. J'ai réalisé des analyses statistiques afin de comprendre les relations dinokystes/environnement. J'ai été responsable de l'interprétation des résultats et de la rédaction des articles scientifiques, le tout sous la supervision de ma directrice, Madame Anne de Vernal, et de ma codirectrice, Madame Marit-Solveig Seidenkrantz.

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RÉSUMÉ

Des observations récentes ont montré que la dynamique glace-océan aurait un rôle non négligeable sur la fonte actuelle de la calotte glaciaire groenlandaise, la circulation thermohaline mondiale et l'élévation du niveau de la mer. La marge ouest groenlandaise est une zone propice à l'étude des interactions glace-océan en milieu subarctique en raison, d'une part, de sa proximité avec la calotte glaciaire, d'autre part, des apports d'eaux atlantiques, arctiques et de fonte glaciaire qui y circulent. Par ailleurs, dans ce milieu, la productivité primaire marine dépend de l'hydrographie et de l'apport en nutriments à la surface via la dynamique aux marges glaciaires qui engendrent des blooms au printemps, en été et à l'automne.

Afin d'étudier les relations entre les conditions océaniques, la dynamique de la marge glaciaire et la productivité marine, au cours des derniers milliers d'années, les assemblages de kystes de dinoflagellés (dinokystes) ont été utilisés comme indicateur principal. Dans le but de décrire la répartition régionale des assemblages de dinokystes, le premier chapitre de cette thèse est basé sur une étude détaillée des sédiments de surface prélevés le long de la marge ouest groenlandaise. Cette étude a permis de définir les relations entre la distribution des assemblages de dinokystes et plusieurs paramètres environnementaux connus via des données instrumentales. Cela a ainsi contribué à l'amélioration de la compréhension de la distribution régionale des assemblages de dinokystes modernes et de leur utilisation subséquente dans les reconstitutions quantitatives des paramètres hydrographiques de surface, à partir de la technique des analogues modernes. Cette étude a également mis en lumière la relation étroite entre les assemblages de dinokystes et les propriétés physico-chimiques des eaux de surface telles que la température, la salinité, le couvert de glace de mer et la productivité primaire. Elle remet aussi en cause l'interprétation environnementale des espèces *Islandinium minutum* et *Islandinium? cezare*, qui ont souvent été décrites dans la littérature comme des indicateurs de glace de mer saisonnière. Cependant, ici, leurs abondances relatives ne montrent pas de lien direct avec la concentration de glace de mer, mais plutôt avec la présence d'eaux polaires froides et peu salées. Enfin, l'analyse du ^{210}Pb et du ^{137}Cs a permis de distinguer les échantillons « modernes » (< 1950 CE) et « pré-modernes » et, par conséquent, de vérifier que les assemblages de dinokystes dans les sédiments de surface représentent bien les conditions environnementales dites « modernes ».

L'étude de deux carottes sédimentaires prélevées le long de la marge ouest groenlandaise a permis de retracer la variabilité océanique et climatique au cours de l'Holocène. La carotte SA13-ST3-20G, proche de Nuuk, fournit une résolution temporelle séculaire des derniers 12 000 ans, alors que plus au nord, la carotte MSM343310 située à Disko Bugt, montre une variabilité océanique et climatique avec une résolution temporelle décennale au cours des 3600 dernières années. Les assemblages de dinokystes permettent de retracer des variations importantes de la glace de mer, des apports d'eau de fonte glaciaire, de la stratification des masses d'eau et de la productivité primaire. Vers 10 000 ans avant l'actuel, une augmentation de la diversité des espèces et la présence de taxons phototrophes permettent de reconstituer des températures estivales de surface allant jusqu'à 10°C, marquant ainsi l'arrivée des conditions interglaciaires. De 9000 à 5000 ans avant l'actuel, les assemblages permettent de reconstituer une forte productivité primaire en lien avec le recul de la calotte glaciaire groenlandaise lors du maximum thermique holocène. Après 5000 ans, le déclin des taxons phototrophes au profit des taxons hétérotrophes accompagne un refroidissement dans les eaux de surface au début de la période Néoglaaciaire. Finalement, les deux zones d'études montrent la même intensification de la variabilité des conditions de surface des derniers 2000 et 1500 ans. L'étude détaillée de la carotte MSM343310 (Disko Bugt) a mis en évidence une oscillation de large amplitude avec une périodicité de 60 à 70 ans permettant de poser l'hypothèse d'un lien avec l'oscillation Atlantique multi-décennale et avec la migration du front atmosphérique polaire vers le sud-ouest.

Cette thèse a permis de démontrer l'influence de l'évolution des masses d'eaux océaniques sur les retraits et avancées de la marge sud-ouest de la calotte glaciaire groenlandaise au cours de l'Holocène, laissant ainsi supposer une relation étroite entre les conditions hydrographiques et le climat régional du Groenland. Elle a aussi montré un lien étroit entre les migrations humaines et les changements climatiques. Par conséquent, ces travaux mettent en évidence l'importance d'une variabilité naturelle des eaux de surface de l'océan qu'il est nécessaire de prendre en compte dans une perspective de changement climatique actuel.

Mots clés : Marge ouest groenlandaise; Dinokystes; Holocène; Dynamique glace-océan; Circulation océanique; Changement climatique; Technique des analogues modernes.

ABSTRACT

Recent observations indicate that ice-ocean dynamics play a significant role in the ongoing melting of the Greenland ice sheet, the global thermohaline circulation and sea-level rise. The west Greenland margin is a suitable area to document ice-ocean interaction in the subarctic area, because of its proximity to the Greenland ice sheet and because of the influence of Atlantic and Arctic water masses and glacier meltwater discharges. Moreover, in this environment, ocean primary productivity is related to hydrological conditions and ice dynamics, which contribute to nutrient inputs to the surface, thus triggering spring, summer and fall plankton blooms.

To address the issue of the interactions between ocean conditions, dynamics of the ice margin, and primary productivity during the last thousands of years, assemblages of dinoflagellate cysts (dinocyst) were used as the main proxy. In order to document the regional distribution of dinocyst assemblages, the first chapter of this thesis consists in a detailed study of surface sediments collected along the western Greenland margin. It highlights linkages between the distribution of dinocyst assemblages and the instrumental data. It contributes to improve the understanding of modern distribution of dinocyst assemblages, thus constraining their use for quantitative reconstructions of sea surface parameters with the modern analog technique. This study shows the close relationship of dinocyst assemblages with surface ocean water properties such as temperature, salinity, sea ice cover, and primary productivity. This study also sheds light on the environmental affinities of *Islandinium minutum* and *Islandinium? cezare*. Both species have often been associated to seasonal sea ice. This study suggests that these species do not necessarily depend upon sea ice concentration, but mostly reflect cold and low saline waters. Moreover, ^{210}Pb and ^{137}Cs measurements led to distinguish “modern” (< CE 1950) from “sub-modern” surface sediment, and to verify that dinocyst assemblages in surface sediments can be assumed to represent “modern” conditions.

The study of two sedimentary cores sampled along the west Greenland margin allowed to reconstruct the oceanic and climatic variability during the Holocene with a decadal temporal resolution. Core SA13-ST3-20G, off Nuuk, provides a 100-year time resolution over the past 12,000 years, while further north, core MSM343310 in Disko Bugt shows oceanic and climatic variability with a 10-year time resolution during the last 3600 years. Dinocyst assemblages are used to reconstruct important

variations in sea ice, meltwater discharge, water stratification, and primary productivity. About 10,000 years ago, an increase in species diversity and the high abundance of phototrophic taxa led to reconstruct high summer surface temperatures of up to 10°C, which marked the onset of interglacial conditions. From 9000 to 5000 years BP, the dinocyst assemblages led to reconstruct high primary productivity related to melting along the margin of the Greenland Ice Sheet during the Holocene Thermal Maximum. After 5000 years, the decrease of phototrophic taxa indicates a cooling corresponding to the onset of the Neoglacial. Finally, these two studies highlight the same increase of the variability in sea surface conditions since 2000 to 1500 years ago. Core MSM343310 in Disko Bugt shows a large amplitude oscillation with a periodicity of 60 to 70 years, which suggests linkages with the Atlantic Multidecadal Oscillation and southwestward migration of the atmospheric polar front.

This thesis illustrates the influence of changes in oceanic water masses on the retreats and advances of the Greenland Ice Sheet during the Holocene. It suggests a close relationship between hydrographic conditions and regional climate over Greenland. It also shows linkages between human migration and climate change. In conclusion, this work highlights the importance of the natural variability of sea surface conditions, and its consequences in the actual climate change.

Keywords: West Greenland Margin; Dinocysts; Holocene; Ice-Ocean dynamics; Oceanic circulation; Climate change; Modern Analog Technique.

INTRODUCTION

0.1 Mise en contexte

Au cours des dernières décennies, le réchauffement atmosphérique et océanique a entraîné des changements exceptionnels dans les régions arctiques et subarctiques, notamment une diminution drastique du couvert de glace de mer saisonnier et une accélération de la fonte des calottes glaciaires. Ces changements contribuerait de manière significative à l'élévation globale du niveau de la mer dans un futur proche (p.ex., GIEC, 2013). L'étude des climats passés, à partir d'archives sédimentaires, permet de caractériser la variabilité du climat à long terme. Dans le contexte actuel, il est donc pertinent de distinguer la part de la variabilité naturelle de celle liée au forçage anthropique afin de mieux définir les mécanismes de rétroactions qui dirigent le climat arctique et subarctique des derniers millénaires.

La baie de Baffin et la mer du Labrador font partie des principales voies d'écoulement des eaux froides et peu salées de l'Arctique ayant une influence majeure non seulement sur le climat régional, mais aussi sur la circulation océanique globale (Marshall et al., 1998; Tang et al., 2004; Myers et Donnelly 2008; Yashayaev 2007; Sévellec et al., 2017). La baie de Baffin est couverte de glace de mer en hiver et libre de glace en été (Tang et al., 2004). La glace de mer est un élément important du climat, car elle joue un rôle sur l'albédo, les bilans énergétiques et les échanges à l'interface océan-atmosphère. La diminution actuelle du couvert de glace provoque des changements majeurs dans les hautes latitudes de l'hémisphère nord, et elle est l'un des paramètres responsables de l'amplification des changements climatiques

(Overpeck et al., 1997; Moritz et al., 2002; Wohlfahrt et al., 2004; Renssen et al., 2005, 2006; Braconnot et al., 2007). La marge ouest groenlandaise est une zone idéale pour documenter la dynamique glace-océan en raison de sa proximité avec la calotte glaciaire groenlandaise (« *Greenland Ice Sheet* », GIS) et de la variabilité saisonnière du couvert de glace de mer. Au printemps et à l'été, les apports d'eaux douces dans le système sont déterminants pour la productivité primaire. Ils proviennent de la fonte de la glace de mer, de la fonte des glaciers et du ruissellement. Les masses d'eaux le long de la marge ouest groenlandaise sont sous l'influence du Courant Ouest Groenlandais (« *West Greenland Current* », WGC; Figure 1), qui résulte du mélange des eaux chaudes et salines du Courant d'Irminger (« *Irminger Current* », IC; Figure 1) avec les eaux froides et de faible salinité du Courant Est Groenlandais (« *East Greenland Current* », EGC; Figure 1) (Tang et al., 2004).

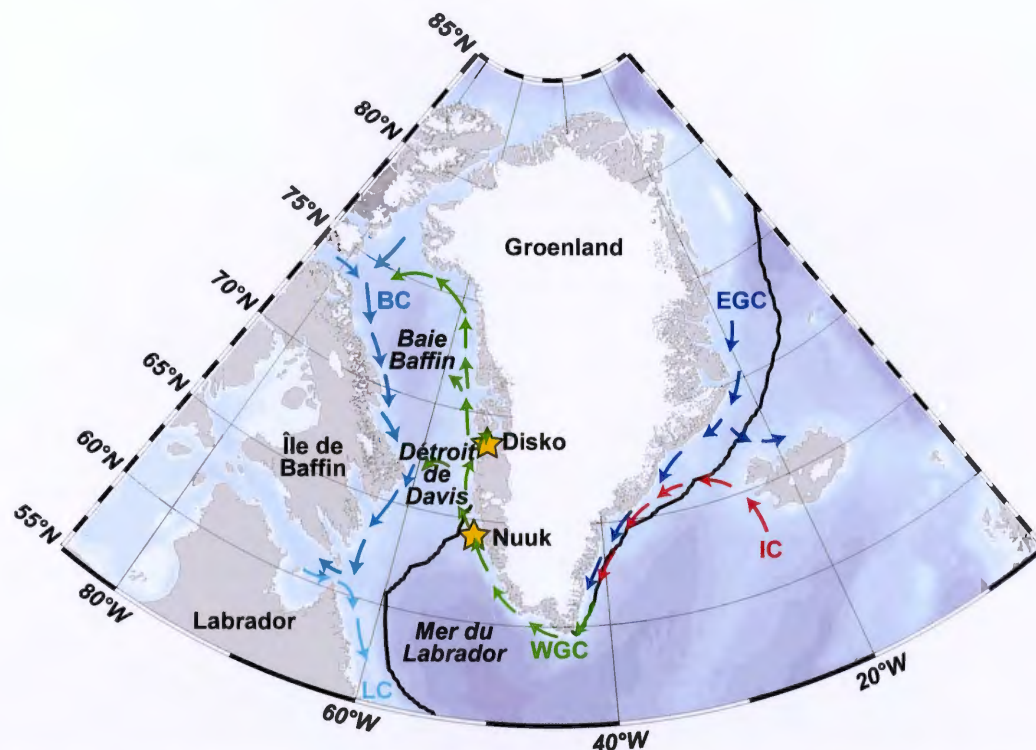


Figure 0-1 : Carte illustrant la circulation océanique de surface de la zone d'étude, avec les abréviations suivantes : EGC = East Greenland Current; IC = Irminger Current; WGC = West Greenland Current; LC = Labrador Current; BC = Baffin Current. Les glaciers sont représentés en blanc. La ligne noire représente la médiane de l'étendue de glace de mer en mars de 1981 à 2010, d'après National Snow and Ice Data Center (NSIDC; <http://nsidc.org/data/bist/>). Les étoiles jaunes localisent les sites de carottage utilisés dans cette étude.

Briner et al. (2016) ont publié une synthèse détaillée de diverses archives sédimentaires en provenance de carotte de glaces, de sédiments lacustres, de sédiments marins et de tourbe afin de synthétiser les changements climatiques au cours de l'Holocène (Figure 2). Les données retenues dans cette base de données devaient respecter les conditions suivantes : (1) latitude supérieure à 58°N, (2) relation avec au moins une variable climatique, (3) série temporelle continue sur une période couvrant au minimum de 6 à 2 ka, (4) résolution temporelle sub-millénaire ($< 400 \pm 200$ ans), (5) chronologie établie à partir d'au moins une datation tous les 3000 ans, (6) publication dans une revue à comité de lecture. Bien que ces conditions

soient peu sévères, les archives sédimentaires marines sont peu représentées (Figure 2). D'autres enregistrements que ceux retenus par Briner et al. (2016) permettent de retracer l'histoire de la marge ouest groenlandaise, mais d'une façon plus ponctuelle (Tableau 1), notamment dans la baie de Disko (Andresen et al., 2011; Jennings et al., 2014; Krawczyk et al., 2010, 2013; Moros et al., 2016; Ouellet-Bernier et al., 2014; Perner, et al., 2011, 2013; Ribeiro et al., 2012; Seidenkrantz et al., 2008; Sha et al., 2014). Toutefois, les données quantitatives de haute résolution temporelle des conditions des eaux de surface sont rares et aucune donnée ne permettait de retracer l'histoire holocène complète de la marge au sud du détroit de Davis (Figure 2 et Tableau 1).

Les enregistrements sédimentaires disponibles révèlent un établissement tardif des conditions interglaciaires, au cours de l'Holocène moyen, probablement relié aux eaux de fontes de la calotte glaciaire groenlandaise et à la stratification des masses d'eaux (Gibb et al., 2015 ; Hoogakker et al., 2015). En effet, pendant cette période une augmentation globale des températures atmosphériques ainsi qu'un réchauffement du WGC sont enregistrés, ce qui aurait contribué au retrait de la calotte glaciaire (Briner et al., 2016; Moros et al., 2016). Dans la région de Disko Bugt, les conditions interglaciaires s'instaurent vers ~7,5 ka BP avant un refroidissement général enregistré à environ 4 ka BP au cours du Néoglaciale (p.ex., Jennings et al., 2014; Moros et al., 2016; Ouellet-Bernier et al., 2014). Au cours de cette période, une alternance de conditions froides (3,5 à 2,7 ka BP) et plus douces (2,7 à 1,2 ka BP) serait liée à la variabilité de la calotte glaciaire groenlandaise, soit à des apports accrus d'eaux de fonte alternant avec les avancées glaciaires (Moros et al., 2016).

Afin de mieux définir les interactions glace-océan le long de la marge sud-ouest groenlandaise, ce projet de doctorat propose ici deux études détaillées de la distribution des kystes de dinoflagellés (ci-après dinokystes) présents dans des

carottes sédimentaires à Disko Bugt et à Nuuk (chapitre 2 et 3). Pour ce faire, il a été nécessaire d'améliorer les connaissances sur les relations entre les paramètres environnementaux et les assemblages palynologiques dans les sédiments de surface (chapitre 1 et 2). L'étude des assemblages de dinokystes dans le sédiment a permis de définir les relations avec les paramètres hydrographiques régionaux et, par la suite, de reconstituer les conditions de surface, notamment la température, la salinité, le couvert de glace de mer saisonnier et la productivité primaire.

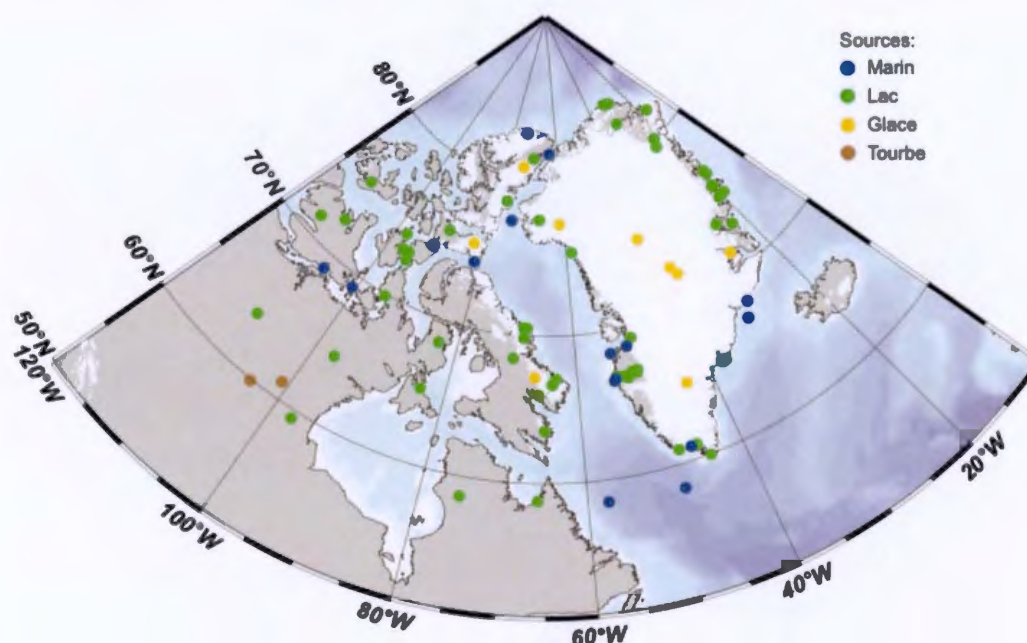


Figure 0-2 : Carte indiquant la localisation des enregistrements holocènes utilisés dans la synthèse de Briner et al. (2016) afin de reconstituer les changements climatiques des régions de l'Arctique canadien et du Groenland.

Tableau 0-1 : Liste des carottes sédimentaires marines couvrant l'Holocène le long de la marge ouest groenlandaise. Les sites en vert sont ceux intégrés dans la synthèse de Briner et al. (2016). Abréviations : dia = diatomées; dino = dinokystes; foram = foraminifères; sed = sédiments; QL = qualitatifs; QT = quantitatif.

Nom du site	Localisation	Latitude (°)	Longitude (°)	Période de temps (ka BP)	Proxy	QL & QT	Citation
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DA06-139G	Ouest Groenland	70,22	-53,05	5 to 0	dia, dino	QL & QT	Andresen et al., 2011; Sha et al., 2014
POR21	Ouest Groenland	69,26	-51,29	2 to 0	foram	QL	Lloyd et al., 2006
POR20	Disko Bugt	69,17	-51,35	2 to 0	foram	QL	Lloyd et al., 2006
DA00-03	Disko Bugt	69	-53,13	3 to 0,7	dino, dia, foram	QL	Moros et al., 2006; Lloyd et al., 2007; Seidenkrantz et al., 2008
DA00-04P	Ouest Groenland	69,16	-51,38	7,7 to 6	foram	QL	Seidenkrantz et al., 2013
DA00-02	Ouest Groenland	68,87	-53,34	3 to 0	dino, dia	QL	Seidenkrantz et al., 2008; Krawczyk et al., 2010
DA05	Ouest Groenland	68,72	-51,11	7 to 3,8	foram, dia	QL	Moros et al., 2006; Lloyd et al., 2007
DA00-06P	Ouest Groenland	68,74	-51,01	8,5 to 6	foram, sed	QL	Lloyd et al., 2005; Seidenkrantz et al., 2013
MSM 343300	Ouest Groenland	68,47	-54	10 to 0,8	foram, dia, dino	QL	Lloyd et al., 2011; Perner et al., 2013; Ouellet-Bernier et al., 2014; Moros et al., 2016
MSM 343310	Ouest Groenland	68,55	-54,03	3.6 to 0	foram, dia, dino	QL & QT	Lloyd et al., 2011; Perner et al., 2011; Ribeiro et al., 2012; Krawczyk et al., 2013; Moros et al., 2016
HU-2008-029-070	Ouest Groenland	68,23	-57,62	13 to 0,5	dino	QL & QT	Gibb et al., 2015
GA306-GC4	Ouest Groenland	66,75	-53,94	1 to 0	foram, dia	QL & QT	Erbs-Hansen et al., 2013; Sha et al., 2016
GA306-GC3	Ouest Groenland	66,63	-54,21	6,6 to 0	foram	QL	Erbs-Hansen et al., 2013
248260-2	Sud Groenland	64,1	-51,26	4,4 to 0	dia, foram	QL	Seidenkrantz et al., 2007
DA04-41P	Sud Groenland	64,09	-51,26	9 to 7 and 4,5 to 3,5	dia, foram	QL	Ren et al., 2009; Seidenkrantz et al., 2013

DA04-31P	Sud Groenland	62,56	-54,50	10,5 to 6	foram, sed	QL	Seidenkrantz et al., 2013
HU2002-029-04	Mer du Labrador	61,46	-58,04	15 to 0	dino	QL & QT	Gibb et al., 2015
Ga3-2	Sud Groenland	60,94	-46,16	8 to 0	foram, sed	QL	Nørgaard-Pedersen and Mikkelsen 2009
MD99-2227	Mer du Labrador	58,21	-48,37	12 to 1	dino	QL & QT	de Vernal and Hillaire-Marcel, 2006; de Vernal et al., 2013
HU-90-013-013	Mer du Labrador	58,22	-48,38	14 to 0	dino	QL & QT	de Vernal and Hillaire-Marcel, 2000; de Vernal and Hillaire-Marcel, 2006
HU84-030-021	Mer du Labrador	58,37	-5751	14 to 1	dino	QL & QT	de Vernal and Hillaire-Marcel, 2006; de Vernal et al., 2013

0.2 Océanographie régionale

La marge ouest groenlandaise est baignée du nord au sud par la baie de Baffin et la mer du Labrador, lesquelles sont séparées par le détroit de Davis. La baie de Baffin relie l'océan Arctique à la mer du Labrador, elle mesure 1400 km de long, 550 km de large et comprend au centre une vaste plaine abyssale. Les apports d'eaux douces arctiques proviennent du détroit de Nares, du détroit de John et du détroit de Lancaster. La quantité d'eau douce importée dans la baie est de 920 à 1460 km³.an⁻¹ (Tang et al., 2004). Le détroit de Davis est large de 300 km et profond de 640 m, il permet les échanges des masses d'eaux entre la baie de Baffin et la mer du Labrador (Azetsu-Scott et al., 2012). Les eaux de surface de la mer du Labrador et de la baie de Baffin présentent des différences significatives. Les eaux de surface de la mer du Labrador sont plus salées de 2 unités et plus chaudes de 7°C que les eaux de surface de la baie de Baffin (Tang et al., 2004), étant donné que la baie de Baffin est recouverte de glace de mer pendant une grande partie de l'année. La glace de mer se développe en septembre dans le nord-ouest de la baie et atteint son maximum en mars

lorsque toute la baie est recouverte de glace, sauf l'est du détroit de Davis (Tang et al., 2004). D'avril à août, la couverture de glace de mer diminue, initialement à partir de la côte du Groenland. La variation intra-annuelle d'étendue de la glace de mer est liée à la circulation océanique, au gradient saisonnier des températures atmosphériques et à la configuration des vents dominants (Tang et al., 2004).

La mer du Labrador est située entre le sud-ouest du Groenland, au sud du détroit de Davis et à l'est du Labrador (Figure 1). Après la baie de Baffin, la mer du Labrador est le bassin le plus froid de l'Atlantique Nord subpolaire (Yashayaev, 2007). Le WGC se forme à la pointe sud du Groenland et suit la marge ouest groenlandaise. Il traverse, par la suite, la baie de Baffin par l'est du détroit de Davis où il est ensuite dévié vers l'ouest au nord-ouest du Groenland, ce qui entraîne la convergence des eaux de l'Atlantique et de l'Arctique. Le courant alors formé (« *Baffin Current* », BC; Figure 1) suit la côte ouest de l'île de Baffin et rejoint la mer du Labrador par le côté ouest du détroit de Davis. Enfin, le BC incorpore les eaux douces sortant du détroit d'Hudson pour former le courant du Labrador (« *Labrador Current* », LC; Figure 1). Il a été montré que la variabilité de la convection des eaux profondes dans la mer du Labrador est liée aux changements dans les apports d'eaux douces et de glace de mer provenant de la baie de Baffin (Tang, Gui et DeTracey, 1999; Tang et al., 2004). Or, la convection dans la mer du Labrador est l'un des éléments de la circulation méridienne atlantique (« *Atlantic Meridional Overturning Circulation* », AMOC), jouant ainsi un rôle considérable sur la ventilation de l'océan profond et la circulation thermohaline mondiale (Marshall et al., 1998; Yashayaev, 2007; Myers et Donnelly, 2008; Sévellec et al., 2017).

0.3 L'histoire climatique holocène régionale

De la dernière glaciation à la période préindustrielle, la température moyenne globale à la surface de la Terre aurait augmenté de 3°C à 8°C (GIEC, 2013), avec des

variations importantes et parfois rapides, décennales à centennales (Mayewski et al., 2004; GIEC, 2013). Après le dernier maximum glaciaire (« *Last Glacial Maximum* », LGM), la calotte glaciaire groenlandaise a enregistré un important retrait de sa marge qui s'étendait jusqu'aux limites du plateau continental pendant le LGM et a atteint le littoral actuel entre ~11 et ~9,5 ka BP (Funder et al., 2011). La déglaciation rapide des marges de la calotte groenlandaise a été accompagnée d'une augmentation des températures estivales en raison de l'augmentation de l'insolation (Berger et Loutre, 1991). Le début du maximum thermique holocène (« *Holocene Thermal Maximum* », HTM; de ~9 à ~5 ka BP) est diachronique dans l'Hémisphère Nord (p.ex., Kaufman et al. 2009; Renssen et al., 2009). Ce n'est qu'après ~7,5 ka BP que les régions de la marge ouest groenlandaise au nord et au sud du détroit de Davis enregistrent des conditions interglaciaires optimales dans les eaux de surface (Jennings et al., 2014; Ouellet-Bernier et al., 2014). Par ailleurs, au cours du présent interglaciaire, le début de la formation des eaux intermédiaires, qui permet la mise en place de la convection dans la mer du Labrador, n'aurait débuté qu'après ~7 ka BP (Hillaire-Marcel et al., 2001; Gibb et al., 2015; Hoogakker et al., 2015). Durant le HTM, la calotte glaciaire groenlandaise se caractérisait par un bilan de masse négatif de l'ordre de plus de 100 Gt.an⁻¹ dans la région sud-ouest groenlandaise (Larsen et al., 2015). De manière générale, après le HTM, le Néoglaire correspond à un refroidissement global pendant lequel sont enregistrées des avancées glaciaires, dont la progression maximum est associée au Petit Âge glaciaire (« *Little Ice Age* », LIA ; Lamb, 1965). Durant cette période, la région ouest groenlandaise enregistre de nombreuses avancées glaciaires locales, notamment à ~3,7-3,6, ~2,9, ~1,8-1,7, ~1,7-1,6, ~1,4, ~1,2 et ~0,8-0,7 ka BP (Larsen et al., 2017; Schweinsberg et al., 2017; 2018). Le forçage anthropique du début de la période industrielle accompagné d'une augmentation des gaz à effet de serre a contribué à modifier la tendance climatique globale qui allait vers un refroidissement (p.ex., Ruddiman, 2003; Mann, 2007; GIEC, 2013; Ruddiman et al., 2016). L'augmentation des températures enregistrées depuis

1850 CE a des répercussions importantes sur les écosystèmes humains et naturels, incluant une augmentation des événements climatiques extrêmes (GIEC, 2014).

La variabilité climatique holocène résulte dans la réponse du climat aux forçages externes et aux mécanismes internes (p.ex., Ruddiman, 2003; Mann, 2007; Ruddiman et al., 2016). Les forçages externes incluent l'insolation (p.ex., Berger et Loutre, 1991), l'activité solaire (p.ex., Steinhilber et al., 2012) et le volcanisme (p.ex., Kobashi et al., 2017), alors que les mécanismes internes sont essentiellement liés aux boucles de rétroaction atmosphère-glace-océan (p.ex., Sévellec et al., 2017). Dans les milieux arctiques et subarctiques les interactions entre l'océan, la glace et l'atmosphère sont essentielles (p.ex., Briner et al., 2016). Les archives paléoclimatique nous permettent d'améliorer la compréhension de la variabilité naturelle du système pour une échelle temporelle décennale à millénaire, là où les données instrumentales sont inaccessibles (GIEC, 2013).

0.4 Les approches méthodologiques

Pour avoir des informations sur les environnements passés, l'étude de carottes sédimentaires permet de recueillir de nombreuses informations afin de reconstituer certains paramètres hydrographiques. Les traceurs utilisés peuvent être sédimentologiques, isotopiques, biochimiques ou micropaléontologiques. L'outil principal utilisé dans ce doctorat est l'analyse du contenu micropaléontologique et palynologique du sédiment. En effet, 1 cm^3 , soit environ 1 g, de sédiment peut contenir une multitude de microfossiles : de 10^2 à 10^5 foraminifères, 10^6 diatomées, de 10^2 à 10^5 dinokystes, de 10^1 à 10^5 grains de pollen, 10^9 coccolithes, etc. (de Vernal et al., 1996), et chaque assemblage microfossile est représentatif des conditions environnementales de leur milieu d'origine. En 1971, Imbrie et Kipp ont développé les premières fonctions de transfert à partir de l'analyse des assemblages de foraminifères; ils ont ainsi fait les premières estimations de température de surface

océanique, et cela a permis, dans le domaine de la paléocéanographie, la transition d'une science qualitative à une science quantitative.

Dans les milieux marins de haute latitude de l'Hémisphère Nord, les indicateurs utilisés pour reconstruire la variabilité océanique sont, entre autres, les foraminifères (p.ex., Kucera et al., 2005; Seidenkrantz, 2013), les diatomées (p.ex., Koç et al., 1993; Krawczyk et al., 2017), les biomarqueurs incluant les alkénones et l'IP25 (p.ex., Belt et al., 2007; Müller et al., 2011; Moros et al., 2016), les coccolithes (p.ex., Solignac et al., 2008), les ostracodes (p.ex., Cronin et al., 2010) et les dinokystes (p.ex., de Vernal et al., 2013 a-b). Ici, nous nous focaliserons sur l'étude des assemblages de dinokystes en raison de leur abondance, de leur préservation dans les sédiments de la marge ouest groenlandaise et de leur utilité pour reconstituer de façon quantitative les conditions hydrologiques de surface, incluant les températures estivales, la glace de mer, la salinité et la productivité (Matthiessen et al., 2005; de Vernal et Marret, 2007; Radi et de Vernal, 2008; de Vernal et al., 2013 a).

0.5 Les kystes de dinoflagellés : indicateurs des conditions de surface

Les dinoflagellés sont des organismes unicellulaires eucaryotes de taille comprise entre 15 et 150 μm de diamètre. Ils possèdent deux flagelles qui permettent leurs déplacements grâce à un mouvement hélicoïdal dans la colonne d'eau suivant leurs conditions de vie optimale (température, salinité, luminosité, nutriments). Les dinoflagellés occupent la plupart des environnements aquatiques : polaires à équatoriaux, saumâtres à salés. Ils jouent un rôle important dans le réseau trophique marin et évoluent dans les couches superficielles de l'hydrosphère (5 à 100 m de profondeur). Leurs stratégies de nutrition sont diverses. Certains sont phototrophes (photosynthèse), d'autres hétérotrophes ou mixotrophes.

La forme végétative des dinoflagellés ne se fossilise pas dans les sédiments. Durant leur cycle de vie, 10 à 20% des espèces de dinoflagellés actuels produisent des kystes (ou dinokystes) de nature organique, extrêmement résistants et pouvant se fossiliser dans le sédiment (Dale, 1976; Head, 1996; Matthiessen et al., 2005), lors de la reproduction sexuée (Figure 3). La cellule diploïde protégée par son kyste peut rester en dormance pendant un certain temps (jusqu'à plusieurs siècles) avant la phase d'exkystement qui consiste en émergence de la cellule via l'archéopyle (Figure 3). La membrane des dinokystes est composée d'un polymère organique complexe, la dinosporine (Fensome et al., 1993; Kokinos et al., 1998; Versteegh & Blokker, 2004), qui leur confère une grande résistance lors des digestions avec des solutions acides durant les traitements préalables à l'analyse palynologique. La résistance des dinokystes face à la dissolution constitue un avantage indéniable sur les microfossiles à tests calcaires ou siliceux dans le domaine océanique. En revanche, certains dinokystes sont sensibles à l'oxydation, en particulier dans les environnements pélagiques caractérisés par de faibles taux de sédimentation et dans les milieux bien oxygénés (Zonneveld et al., 1997). La préservation des dinokystes est généralement excellente dans les environnements de plateau ou de pente continentale (Matthiessen et al., 2005). Les formes végétatives (dinoflagellés) et les formes enkystées (dinokystes) ont une taxonomie différente. La nomenclature des dinoflagellés a été créée par les biologistes alors que celle des dinokystes est le fait de paléontologues et micropaléontologues. Des cultures *in vitro* ont permis de comprendre la relation thèque-kyste de plusieurs espèces (p.ex., Head, 1996).

De nombreuses études ont montré que les dinokystes dans le sédiment sont d'excellents traceurs des paramètres hydrologiques de surface, incluant la température, la salinité, la productivité et le couvert de glace de mer saisonnier (Matthiessen et al., 2005; de Vernal et Marret, 2007; Radi et de Vernal, 2008; de Vernal et al., 2013a, 2019). Dans la plupart des milieux marins de marge continentale, les dinokystes sont abondants et ont une diversité relativement élevée. De ce fait, ils

sont couramment utilisés pour des reconstitutions quantitatives des paramètres de surface grâce à la technique des analogues modernes (p.ex., de Vernal et al., 2001, 2013a-b; Allan et al., 2018). La technique des analogues modernes repose sur les trois principes suivants : 1) le climat et les conditions environnementales que l'on vise à retracer sont la cause principale des changements dans les assemblages; 2) les affinités écologiques des espèces n'ont pas changé entre le moment où les assemblages fossiles se sont déposés et le présent, et 3) les observations modernes contiennent toutes les informations nécessaires pour interpréter les données fossiles (Guiot et de Vernal., 2007).

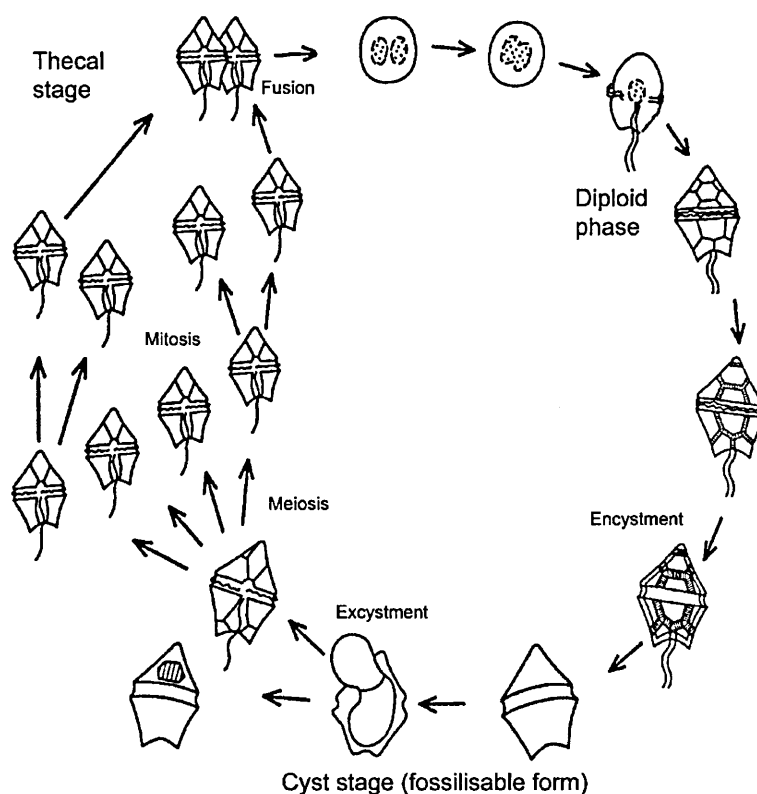


Figure 0-3 : Représentation schématique du cycle de vie des dinoflagellés montrant l'alternance des formes végétatives, mobiles (dinoflagellés) et des formes enkystées fossilisables (dinokystes) d'après de Vernal et Marret (2007).

Les travaux antérieurs de la mer du Labrador et de la baie de Baffin ont montré que l'étude des assemblages de dinokystes permettait d'améliorer nos connaissances sur l'évolution des masses d'eaux au cours du temps (Solignac et al., 2004; 2006; Andresen et al., 2011; Ribeiro et al., 2012; Ouellet-Bernier et al., 2014; Gibb et al., 2015). Ces études ont mis en lumière la relation étroite entre les assemblages de dinokystes et les conditions de surface, notamment la couverture de glace de mer, la température et la salinité. Elles ont aussi montré que les changements de la température et de la salinité surface pouvaient être indicateurs des apports d'eaux de fonte. Enfin, l'étude des assemblages de surface a permis de vérifier l'influence des courants de surface, d'origine atlantique ou arctique, sur les changements océanographiques et climatiques en général.

0.6 Objectifs et hypothèses

L'objectif principal de cette thèse est de caractériser la variabilité climatique et océanique naturelle le long de la marge ouest groenlandaise au cours de l'Holocène. Comme la variabilité climatique affecte les paramètres océaniques de surface et la couverture de glace de mer à l'échelle locale et régionale, cette étude met l'emphasis sur la reconstitution de la température, de la salinité, de la productivité et de la couverture de glace de mer à partir des assemblages de dinokystes. La région choisie se caractérise par un fort gradient de glace de mer en relation avec l'influence relative des apports d'eaux atlantiques, des apports de l'Arctique et des eaux de fontes glaciaires (voir supra). Les résultats obtenus dans cette thèse ont permis de tester les deux hypothèses suivantes : 1) les sédiments de surface possèdent l'information nécessaire pour interpréter le passé, et 2) les interactions entre l'océan, la glace et l'atmosphère ont joué un rôle essentiel sur la variabilité climatique holocène.

Cette thèse a été réalisée avec trois objectifs spécifiques, l'un méthodologique et les deux autres thématiques :

1. Enrichir la base de données de dinokystes de référence régionale pour augmenter la fiabilité des reconstitutions des conditions hydrologiques de surface.
2. Reconstituer les changements temporels des conditions océanographiques de surface de façon quantitative, tels que la température, la salinité, la productivité primaire et la couverture de glace de mer.
3. Établir des relations entre les changements climatiques, la dynamique glaciaire et la dynamique océanographique le long des marges sud-ouest groenlandaises.

Cette thèse se présente en trois chapitres rédigés en anglais, l'un publié, l'un soumis et le troisième en voie de soumission dans des revues avec comité de lecture.

Le chapitre 1, publié dans la revue *Marine Micropaleontology* en décembre 2019, fournit une étude détaillée des sédiments de surface, afin de caractériser et quantifier de façon aussi précise que possible le lien entre les assemblages de dinokystes de la région et les conditions de surface, incluant la température, la salinité, le couvert de glace de mer et la productivité primaire. Il permet de poser des bases solides pour des reconstitutions paléocéanographiques à l'échelle régionale.

Le chapitre 2, publié dans la revue *Paleoceanography and Paleoclimatology* en février 2018, est basé sur des reconstitutions des conditions de surface de la région de Disko Bugt au cours des 3600 dernières années. Cette étude a permis de mettre en évidence une grande instabilité des paramètres de surface océanique au cours des derniers 1500 ans et a démontré que les salinités et températures de surface reconstituées sont partiellement synchronisées avec les variations du $\delta^{18}\text{O}$ de la

carotte de glace de Camp Century au Groenland, indicatrices des anomalies de température atmosphérique, laissant supposer une relation étroite entre les conditions hydrographiques et le climat régional du Groenland.

Le chapitre 3 sera soumis à la revue *Boreas*. Il présente une reconstitution des conditions de surface des derniers 12 000 ans, au large de Nuuk, au sud-ouest du Groenland, afin de retracer l'histoire climatique holocène régionale, de la déglaciation au réchauffement actuel. Cette étude démontre l'influence des masses d'eaux océaniques sur les retraits et les avancées de la calotte glaciaire groenlandaise au cours de l'Holocène. Elle permet également de souligner les relations étroites entre les populations humaines et les changements climatiques à l'échelle des derniers milliers d'années.

CHAPITRE I

DISTRIBUTION OF DINOCYST ASSEMBLAGES IN SURFACE SEDIMENT SAMPLES FROM THE WEST GREENLAND MARGIN

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Abstract

Palynological analyses of 60 surface sediment samples from West Greenland margin revealed high concentrations of dinoflagellate cysts (dinocysts), particularly in the Disko Bugt area, where they reach $> 10^4$ cysts g^{-1} . Dinocyst assemblages are characterized by a relatively high species diversity and are dominated by *Operculodinium centrocarpum*, cysts of *Pentapharsodinium dalei*, *Islandinium minutum*, *Islandinium? cezare*, and *Brigantedinium* spp. On a regional scale, the overall assemblages show statistical relationships with sea-ice cover duration, primary productivity, salinity and summer-fall temperature. The cysts of *Pentapharsodinium dalei*, *Operculodinium centrocarpum*, and *Spiniferites elongatus* appear linked to high productivity and to characterize the late summer-fall bloom. Although *Islandinium minutum* and *Islandinium? cezare* are generally associated with a seasonally sea-ice covered environment, there is no linear relationship between their relative abundance and sea-ice concentration or duration on a regional scale, along the West Greenland margin. The abundance of these taxa primarily reflects cold and low-salinity water in the study area. Radionuclide measurements (^{210}Pb and ^{137}Cs) allow the distinction between two categories of samples, the “modern” ones likely encompassing the interval younger than 1950 CE, and the others that may be considered “sub-modern”. Statistical analyses indicate that dinocyst assemblages belonging to “modern” and “sub-modern” categories are not significantly different. Hence, the dinocyst assemblages of surface sediment samples, both “modern” and “sub-modern”, represent fluxes homogenized over a relatively long time interval, which illustrates a spatial distribution corresponding to the main gradient in oceanographic conditions. Consequently, dinocyst assemblages in surface sediments can be assumed to represent the average “modern” conditions with a sufficiently high degree of confidence for their use in environmental studies and paleoclimate reconstructions.

1.1 Introduction

The West Greenland margin, stretching from the eastern Labrador Sea across Davis Strait and into Baffin Bay, is an important area for documenting ocean-ice dynamics due to its proximity to the Greenland Ice Sheet (GIS) and the large gradient of seasonal sea-ice cover characterizing the area (Figure 1). The water masses along the West Greenland margin are under the influence of the West Greenland Current (WGC; Figure 1), which is formed at the southern tip of Greenland from the mixing of the warm and saline waters of the Irminger Current (IC) with the cold and low-salinity waters of the East Greenland Current (EGC) (e.g., Buch, 1981; Tang et al., 2004; Ribergaard et al., 2014). In Baffin Bay, north of Davis Strait, the northward flowing WGC is gradually modified by freshwater discharge from West Greenland. In northern Baffin Bay the WGC deviates westward, where it is fed by Arctic waters from Nares Strait, Jones Sound and Lancaster Sound contributing to a freshening and cooling of the surface waters. The current thereafter forms the southward flowing Baffin Current (BC). Towards the south, the BC feeds the Labrador Current, which is one of the main pathways for Arctic freshwater export to the North Atlantic, thus playing a major role in the global meridional overturning circulation (e.g., Marshall et al., 1998; Tang et al., 2004; Myers and Donnelly 2007; Yashayaev 2007, Sévellec et al., 2018). Hence, the sea-surface conditions along the West Greenland margin are characterized by very large north-south gradients of salinity and seasonal sea-ice cover extent.

In Arctic seas, water transparency and light, essential to photosynthesis and primary productivity, are influenced by the sea-ice thickness and snow cover (Tremblay et al., 2015; Juul-Pedersen et al., 2015; Limoges et al., 2018). Nutrient availability is a limiting factor. Whereas the spring phytoplankton bloom is often triggered by abundant nutrients when stratification is still weak, primary productivity in the Arctic generally decreases in summer due to nutrient depletion. Melting of sea

ice and meltwater inputs from the GIS, which cause reduced surface salinity and enhanced stratification during summer, can contribute to a decreasing primary productivity in many Arctic regions (Andersen, 1981; Tang et al., 2004; Andresen et al., 2011). However, in southwest Greenland, a second microplankton bloom occurs in late summer/fall (Krawczyk et al., 2015). This seems to be related to subglacial discharge from marine-terminating glaciers, which leads to mixing of the water column and thus the flux of nutrients from deeper waters into the photic zone (Boertmann et al., 2013; Juul-Pedersen et al., 2015). Hence, the inter-relationship between sea-ice cover, meltwater discharge and primary productivity along the Greenland margin is complex.

Here, we document the distribution of palynomorphs or organic-walled microfossils in surface sediments, with special attention paid to cysts of dinoflagellates (hereafter dinocysts). These include phototrophic and heterotrophic taxa and are commonly used for the reconstruction of the sea-surface parameters in subarctic environments (e.g., de Vernal et al., 2001, 2013a-b; Radi & de Vernal, 2008; Allan et al., 2018; de Vernal et al., this issue). We also present a regional update of the dinocyst database used by Allan et al. (2018), with 32 additional samples and oceanographic parameters for statistical analyses. The main objectives of our study are to evaluate the strength of the relationships between dinocyst assemblages and sea-surface parameters such as seasonal salinity, temperature, sea-ice cover and primary productivity on a regional scale, and to improve proxy-reconstructions of ocean parameters in ice-marginal marine settings such as the Greenland margins. The sediment samples analyzed here have been subjected to ^{210}Pb and ^{137}Cs measurements, which allow us to make a distinction between “modern” and “sub-modern” and to better evaluate the relationships that could be established with oceanographic data compiled from instrumental observations and remote sensing (cf. Krawczyk et al., 2017).

1.2 Hydrographic setting

The sea ice distribution along the West Greenland margin is typically characterized by the sea-ice cover in winter months north of Fyllas Banke and the almost sea-ice free conditions further south (National Snow and Ice Data Center; Figure 1).

Sea ice starts to spread in September in the northwestern Baffin Bay, reaching its maximum in March when the entire bay is covered by ice, except in the eastern Davis Strait (Tang et al., 2004; Figure 1). From April to August, sea-ice cover decreases, initially along the Greenland coast. These large intra-annual variations in sea-ice extent are related to the significant seasonal gradients in air temperatures and wind patterns (Tang et al., 2004). Most iceberg and freshwater inflow to Baffin Bay originate from the West Greenland coast, north of 68°N (Tang et al., 2004). The warm and saline WGC occupies the subsurface water column on the continental shelf with temperatures reaching up to 3.5-4°C, and salinities above 34.8 psu. By contrast, the surface mixed layer, which is less than 50 meters thick, is characterized by low temperatures and salinities ranging from 0-4°C and 32-33.7 psu, respectively, (Tang et al., 2004; Ribergaard, 2014; Figure 2). The low surface salinity is due to freshwater inputs from melting sea ice as well as glacier meltwater and summer runoff (Figure 2). However, the low surface salinity, which results in a thin mixed layer above a sharp pycnocline, also fosters low thermal inertia and summer warming at the surface (Boertmann et al., 2013; Ribergaard, 2014). From north to south surface air temperature gradient is very large in winter, ranging from -35°C to -15°C. It is much lower in summer, ranging from 0°C to 10°C. The coldest air temperatures are recorded north of Baffin Bay with an average of -35°C in January.

In Davis Strait, surface air temperatures range from -15°C in January to +10°C in July, on average (Tang et al., 2004; Boertmann et al., 2013). The spring (April, May, June) and summer (July, August, September) primary production in Disko Bay

is very high, with a maximum of $1790 \text{ mgC m}^{-2} \text{ d}^{-1}$, whereas it is about $646 \text{ mgC m}^{-2} \text{ d}^{-1}$ along most of the western Greenland margin (MODIS R2018; Figure 3). Because satellite retrieval of ocean color is unavailable in November, December and January for the entire margin, and as there are no data available north of Sisimuit in February (Figure 1), data on modern surface chlorophyll concentrations in fall (October, November, December) and winter (January, February, March) are limited. Hence, the calculated primary productivity is low, as is also expected from the lack of light at high latitudes due to both low solar incidence and extensive sea-ice cover (Balaguru et al., 2018).

1.3 Materials and methods

1.3.1 Hydrographic and productivity data

The average values for sea-surface temperature (SST), salinity (SSS), dissolved oxygen, nitrate, phosphate and silicate concentrations were extracted from the World Ocean Atlas 2013 (WOA13; <https://www.nodc.noaa.gov/OC5/woa13/woa13data.html>) for the period spanning 1955-2012 (Locarnini et al., 2013; Zweng et al., 2013). Data were provided with 1/4- to 1/10-degree spatial resolution for sea-surface temperatures and sea-surface salinity, and with 1-degree spatial resolution for nutrients. Sea-ice cover data were compiled for an interval spanning 1955 to 2012, provided by the National Snow and Ice Data Center (NSIDC) in Boulder (<http://nsidc.org/data/G10010>; Walsh et al., 2015). The sea-ice cover, from 0 to 12 months per year, was calculated based on monthly concentrations exceeding 50%. Hence, the mean annual concentrations and the occurrence of sea-ice cover expressed in terms of months yr^{-1} derive from the same data (cf. de Vernal et al., 2005, 2013a-b; Radi & de Vernal, 2008). Primary productivity data were calculated using the vertical generalized production model (VGPM) algorithm applied to the 2002-2017 chlorophyll data provided by the

NASA's moderate resolution imaging spectroradiometer (MODIS) program (<https://modis.gsfc.nasa.gov/data/dataproduct>). The VGPM is a "chlorophyll-based" model that estimates ocean primary productivity from chlorophyll, sea-surface temperatures, and photosynthetically active radiation (see Behrenfield & Falkowski, 1997 for more details). Both annual and monthly primary productivity data in the form of HDF files were obtained from the Oregon State University website (<http://orca.science.oregonstate.edu/2160.by.4320.monthly.xyz.vgpm.m.chl.m.sst.php>). The data are structured with a resolution of 1/6 degree in space and 8 days in time. When data are missing in given pixels (due to gaps in satellite observations, likely because of clouds), a statistical approach was used by taking the average value of zones within a radius of 150 km around the site. In the case of larger gaps, linear interpolations of values corresponding to the eight preceding and following days were used. The primary productivity values were extracted on a monthly basis (unit of $\text{mgC m}^{-2} \text{d}^{-1}$) and compiled to obtain annual values (unit of $\text{gC m}^{-2} \text{y}^{-1}$) using the ArcGIS software. The environmental data (mean and standard deviation) for each site are reported in Supplementary Information 2.

1.3.2 Palynological analysis

A total of 60 surface sediment samples (Table 1) were analyzed. They were collected from the uppermost 1-2 cm sediment of box cores and Day grab samples across an area from Qaqortoq (c. 59°N) to Uummannaq (c. 72°N) (Figure 1). The samples were collected during a three-leg cruise of the *R/V Paamiut* in June–July 2014 (Krawczyk et al., 2017).

Volumes of 3 to 5 cm^3 of wet sediment were prepared at Geotop, Université du Québec à Montréal, following the protocol described by de Vernal et al. (1996). The wet sediments were dried and weighed. *Lycopodium* tablets were added to calculate concentrations of palynomorphs versus dry weight. After wet sieving, the

10-106 μm fraction was chemically treated with HCl (10%) and HF (50%) at room temperature to dissolve carbonate and silicate particles, respectively. The final residue was mounted on microscope slides with glycerin jelly for further observation with transmitted light microscopy at 400X to 1000X magnification. Counting and identification were performed using three different microscopes: Leica DMR, Leica DM5000 and Orthoplan Leitz. All palynomorphs were counted including dinocysts, organic linings of benthic foraminifera, *Halodinium* sp., pollen grains and spores, resting cysts and loricae of some tintinnids without identification, and microalgae (Figure 4). It is of note that the loricae of the tintinnid *Parafavella denticulata* (Figure 4) were visible exclusively with an interferential contrast; these taxa were not included in the results. The total numbers and the concentrations of the palynomorphs are reported in Supplementary Information 1. At least 300 specimens of dinocysts were identified and counted in each sample (see Table 2), which is standard protocol for dinocyst counts and to assess diversity and relative abundances (e.g., Mertens et al., 2009). The taxonomic nomenclature of dinocysts was based on Rochon et al. (1999); Radi et al. (2013) and Zonneveld & Pospelova (2015).

1.3.3 Radionuclide data

Natural lead-210 (^{210}Pb) and artificial caesium-137 (^{137}Cs) radionuclide analyses were performed using gamma spectrometry at the Leibniz Institute for Baltic Sea Research, with the aim to identify “modern” and “sub-modern surface” samples. These categories of surface samples are also presented in Krawczyk et al. (2017). The ^{210}Pb activity $>150 \text{ Bq kg}^{-1}$ and traces of ^{137}Cs indicate that sedimentation occurred, at least in part, during the post-bomb period (1954 CE). While the measurement of a single sediment sample does not allow for an age calculation, we have considered all samples with $^{210}\text{Pb}_{\text{unSUPP.}}$ activity $>150 \text{ Bq kg}^{-1}$ and traces of ^{137}Cs to be relatively recent and we labelled them as “modern” (see Table 1; Supplementary Information 1; for method see Krawczyk et al., 2017). The other surface samples likely cover a

longer time interval (or very short time interval with a high lateral “old” sediment influx) and were labelled “sub-modern”. Some of these samples are composed of coarse-grained material (Figure 6), which suggest a depositional environment with bottom currents, possible winnowing and sedimentation processes.

1.3.4 Statistical data treatments

Multivariate analyses were performed using the CANOCO 5 software (ter Braak & Šmilauer, 2012; Lepš & Šmilauer, 2014) to describe the relationship between dinocyst assemblages and environmental parameters. To reduce the effect of dominant species and closed-sum percentage data, the Shapiro & Wilks (1965) statistical test for normality was performed (Legendre & Legendre, 2012). A logarithmic transformation was applied to dinocyst data reported in percentage as it yielded a close to normal distribution. The occasional occurrences were discarded and only the taxa recording more than 1 % in at least one sample and occurring in more than 3 samples were used for statistical analyses.

Hierarchical cluster analysis was used to highlight the dissimilarity between samples, using the unweighted pair group method with arithmetic mean (UPGMA) on Bray Curtis measurements (Legendre & Legendre, 2012; Oksanen et al., 2015), performed with the R software using the vegan package and the function “hclust” (Oksanen et al., 2015; <http://cc.oulu.fi/~jarioksa/opetus/metodi/vegantutor.pdf>). To compare the samples and to test whether there is a significant difference between the expected and observed frequencies in the data collected in close proximity (Figure 5), Pearson’s Chi-square (χ^2) measurements (Legendre & Legendre, 2012) were made using “chisq.test” function from the stats package in the R platform (<http://cran.r-project.org>).

Reconstructions of sea-surface parameters were obtained using the Modern Analog Technique (MAT), which relies on the similarities between fossil and modern

assemblages to assess corresponding sea-surface conditions (Guiot & de Vernal, 2007). Here, the dinocyst assemblages from sediments regarded as “modern” were used to reconstruct the sea-surface parameters in the “sub-modern” sediments and reciprocally, the dinocyst assemblages from “sub-modern” sediments were used to reconstruct the sea-surface conditions in the “modern” ones. The MAT was performed using the “bioindic” package developed by Guiot for the R platform and following the procedures described by de Vernal et al. (2013a). For reconstructions, searches of five analogs after logarithmic transformation of the relative taxa abundances were conducted. The best estimates were calculated from the mean of the corresponding sea-surface values weighted according to the similarity of the analogs. Moreover, we also performed a Weighted Averaging Partial Least Squares (WAPLS) analysis on both sub-datasets, the results of which are reported as Supplementary Information 3. The WAPLS was performed on the software package C2 (Juggins, 2007)

1.4 Results

1.4.1 Palynological content

The surface sediment samples mainly consist of fine-grained olive-green mud as well as fewer samples of coarse-grained detrital material (Figure 6; Krawczyk et al., 2017). They are characterized by very high concentrations of palynomorphs, with more than 10^4 dinocysts, 10^3 organic linings of benthic foraminifera and 10^3 *Halodinium* per gram (Figure 6). There is no apparent relationship between the overall concentrations of palynomorphs and the categories (“modern” and “sub-modern”) defined from radionuclide measurements.

The concentrations reach a maximum in the region of Disko Bay, which may correspond to particularly high dinocyst fluxes (Figure 6). The pollen concentration is

very low, around 200 grains per gram, and the dominant pollen taxa are from coniferous trees (*Picea* and *Pinus*) and shrubs (*Betula* and *Alnus*), which indicate long distance atmospheric transport (cf. Rochon & de Vernal, 1994).

1.4.2 Dinocyst assemblages

A total of 26 dinocyst taxa were identified (reported in Supplementary Information 1), 17 of which were common, including 14 taxa representing more than 99% of the total assemblages (Table 2). The dominant taxa are *Nematosphaeropsis labyrinthus*, *Operculodinium centrocarpum*, *Spiniferites elongatus*, *Spiniferites ramosus*, the cysts of *Pentapharsodinium dalei*, *Islandinium minutum*, *Islandinium? cezare*, *Brigantedinium* spp. and *Selenopemphix quanta* (Figures 4, 7, 8). *Nematosphaeropsis labyrinthus* occurs in relatively high percentages in the south, up to ~ 78.5°N at Aasiaat (Figures 1, 7). *Operculodinium centrocarpum* is dominant mostly in the northern region with its maximum abundances are recorded north of Disko Bay, where sea-ice cover persists during winter. *Spiniferites elongatus* is rare in the sea-ice free zone and is common (~ 5%) in the seasonal sea-ice domain. The cysts of *Pentapharsodinium dalei* are abundant in all samples. *Islandinium minutum* is also abundant in most samples with a tenuous maximum in Disko Bay. Other heterotrophic taxa such as *Islandinium? cezare*, *Brigantedinium* spp. and *Selenopemphix quanta*, are more common in the southern than in the northern region (Figure 7).

In order to assess the differences or similarities between the spectra, we have performed two tests. One is cluster analysis, which shows that the dinocyst distribution is primarily determined by geographical location, from south to north, regardless of the category of the sediment samples, “modern” or “sub-modern” (Figure 8). The only outlier among the sediment samples is DB6-10, which was not analyzed for its radionuclide content and was taken from a deeper water location (>900 m water depth) than most other samples. The second test is the χ^2 performed on

sets of samples located in close proximity to each other (Figures 5, 9; Table 3). The results indicate that the assemblages are statistically different from one area to another, with the exception of two dinocyst spectra from “modern” sediment samples in the Qaqortoq zone at the southern end of the study area. Hence, the results suggest that the dinocyst assemblages are regionally consistent regardless of their “modern” or “sub-modern” label.

1.4.3 Multivariate analyses and dinocyst vs. environment relationships

Multivariate analyses were performed on three separate sets of samples: 1) all sediment samples, 2) “modern” samples exclusively, and 3) “sub-modern” samples. Detrended correspondence analysis (DCA) indicates that the length of the first ordination axis is 1.3 to 1.4 standard deviations (SD) for all sets of samples. This suggests a linear distribution of dinocysts vs. environmental parameters, making redundancy analysis (RDA) the most appropriate technique for multivariate analysis (ter Braak & Šmilauer 1998). The first axis (RDA1) explains 42.9% of the variance for the analysis with all samples, 51.8% of the variance for “modern” samples and 43.1% for the other samples (Figure 9; Table 4). The first axis shows an inverse relationship between most phototrophic and heterotrophic taxa. It correlates with sea-ice cover and is characterized by negative correlations with sea-surface spring temperatures and salinity, fall temperatures as well as water properties including phosphate and nitrate concentrations. A shift from positive to negative RDA axis 1 characterizes the distribution of dinocyst taxa from south to north. The second axis (RDA2) explains 13.5% of the variance for the analysis with all samples, 13.1% of the variance for “modern” samples and 18.5% for the other samples. *Islandinium* spp., *Brigantedinium* spp., *Selenopemphix quanta*, the cysts of *Pentapaharsodinium dalei* and *Spiniferites elongatus* show negative correlations with dissolved oxygen, summer and fall sea-surface conditions (temperatures, salinity, primary productivity), whereas *Nematosphaeropsis labyrinthus*, *Impagidinium pallidum*, *Impagidinium paradoxum*

and *Impagidinium sphaericum* show positive correlations with winter sea-surface conditions (salinity, temperature, primary productivity), sea-ice cover, spring temperature and salinity, phosphate, distance to the coast, bathymetry, nitrate and silicate concentrations (Figure 9). The RDA2 scores seem to illustrate a distribution from coastal to offshore locations. In general, the composition of dinocyst assemblages appears closely related to sea-ice cover, winter and fall salinity, fall temperature, winter primary productivity, phosphate concentration, the distance to the coast and the bathymetry (Table 4).

1.5 Discussion

1.5.1 “Modern” vs. “sub-modern” sediment samples

It is difficult to systematically compare the assemblages from “modern” and “sub-modern” samples as they are all from different locations. A direct comparison is also hampered by the large environmental spatial heterogeneity in surface ocean conditions and sedimentary processes. Nevertheless, the number of the species present in the assemblages are the same in all samples and, moreover, the χ^2 values indicated that the data sets form distinct statistical populations regardless of the category of sample, “modern” or “sub-modern”, except for the group of samples in the Qaqortoq zone at the southern end of the study area (Table 3; Figure 8). In the Qaqortoq zone, however, the number of samples is very low (three in total) and the differences are more significant between the two “modern” samples than between these and the third, “sub-modern”, sample. Because the Qaqortoq zone is located in a boundary zone between the East Greenland Current and the Irminger Current, spatial disparities (e.g., in sea-surface temperatures and salinities) are important and probably explain the larger differences in assemblages within this zone. The cluster analysis also shows a latitudinal gradient in the distribution of assemblages and no significant difference between the samples from “modern” and “sub-modern”

sediments. Moreover, when comparing the results of multivariate analyses, despite some differences in absolute scores, the RDA yields quite similar vectors for samples from “modern” or “sub-modern” sediment samples (Figure 9). Consequently, we suggest that the dinocyst assemblages of surface sediment samples, both “modern” and “sub-modern”, represent fluxes over a long enough time interval to capture the mean environmental conditions over the last decades or even longer.

1.5.2 Relationships between dinocyst assemblages and sea ice

The analysis of dinocyst distributions and sea-surface parameters illustrates close linkages between dinocyst assemblages and sea-ice cover, sea-surface salinity and primary productivity. It has previously been shown in many studies that seasonal sea-ice environments with high primary productivity are often characterized by abundant heterotrophic dinoflagellates (e.g., Hamel et al., 2002; Radi & de Vernal, 2008; de Vernal et al., 2013a). At the sea-ice edge, notably in polynyas, heterotrophic taxa take advantage of high diatom biomass during the spring bloom, whereas phototrophic taxa cannot compete with diatoms (e.g., Gosselin et al., 1997; Poulin et al., 2011). While heterotrophic taxa are common in all the samples of our regional dataset, their relationship with sea ice is unusual, with higher percentages of heterotrophic taxa in the south, where sea-ice cover is low (Figure 7). The percentages of *Islandinium minutum* and *Islandinium? cezare*, which are typically common in environments characterized by seasonal sea ice (cf. Rochon et al., 1999; Head et al., 2001; de Vernal et al., 2001, 2005, 2013b), do not show a clear relationship with sea-ice cover extent in the study area as shown from the RDA results (Figures 7, 9). Based on DNA analyses in sea-ice samples, Potvin et al. (2018) demonstrated a direct link between *Islandinium minutum* and sea-ice cover. However, this does not imply a relationship between the proportion of *Islandinium minutum* in the assemblages and sea-ice concentration or seasonal extent. In a study from Svalbard, where *Islandinium minutum* and *Islandinium? cezare* are abundant, Grøsfjeld et al. (2009) recognized the

lack of direct relationships between their percentages and sea-ice cover but concluded that both taxa reflect cold and low salinity waters in this region. Furthermore, studies conducted by Heikkilä et al. (2014, 2016) in Hudson Bay also led to questioning the relationship between *Islandinium minutum* and *Islandinium? cezare* and sea-ice cover. In seasonally ice-covered regions, heterotrophic dinoflagellates (light-independent) may dominate over phototrophic dinoflagellates (light-dependent) because of limited light availability and not necessarily because of sea ice (Heikkilä et al., 2014; 2016). Although usually more common in sea-ice environments, no quantifiable relationships between the percentages of *Islandinium minutum* and *Islandinium? cezare* and sea-ice concentration could be demonstrated from the Northern Hemisphere dinocyst database (cf. de Vernal et al., 2013a; this issue). Along the West Greenland margin, these taxa clearly reflect cold and low saline waters and their proportions do not increase with sea ice concentration. However, as highlighted here by the RDA results (Figure 9; Table 4), close linkages between dinocyst assemblages and sea-ice cover make the overall dinocyst assemblages a reliable proxy to understand sea ice variations and meltwater runoff.

Relatively high percentages of phototrophic taxa characterize samples from Disko Bay, the Vaigat Strait and the Uummannaq area in the North. In these regions, the phototrophic taxa include mostly *Operculodinium centrocarpum*, cysts of *Pentapharsodinium dalei* and *Spiniferites elongatus*. From a regional perspective, the occurrence of these taxa is probably related to the late summer bloom due to meltwater input (e.g., Boertmann et al., 2013; Juul-Pedersen et al., 2015). The cysts of *Pentapharsodinium dalei* are commonly related to high stratification (Rochon et al., 1999; Allan et al., 2018), therefore here they may be linked to freshwater and meltwater input. In the southern part of the study area, the proportion of phototrophic taxa is lower than towards the north, but the assemblages are characterized by the common occurrence of *Nematosphaeropsis labyrinthus* (see Figures 7, 9). Hence, among phototrophic taxa, *Operculodinium centrocarpum*, the cysts of

Pentaparsodinium dalei and *Spiniferites elongatus* appear tolerant to environments with seasonal sea ice and may characterize the late summer-fall bloom, whereas *Nematosphaeropsis labyrinthus* seems rather intolerant to sea ice. If correct, the two samples from northern sites containing *Nematosphaeropsis labyrinthus* (U5-14 and U5-15; Figures 1, 7) are exceptions. As these two samples are “sub-modern” and located offshore, the occurrence of *Nematosphaeropsis labyrinthus* might be related to past fluxes under sea-ice free conditions and/or distal transport by currents.

1.5.3 Regional productivity

The spring bloom off West Greenland starts in April in the south and continues northwards with increased day-length leading to sea-ice break up (Pedersen et al., 2005). In summer, another bloom occurs, accompanied by increasing phototrophic biomass (Pedersen et al., 2005, Juul-Pedersen et al., 2015). Recent studies from Godthåbsfjord and Fyllas Bank have shown planktonic succession with haptophytes blooming in spring, followed by diatoms in summer and dinoflagellates and ciliates through late summer, fall and winter (Krawczyk et al., 2015; 2018). In seasonal sea-ice environments, primary productivity is generally high at the sea-ice edge as nutrients are brought to the surface (e.g., Gosselin et al., 1997; Matthiessen et al., 2005; Poulin et al., 2011). Wind-driven upwelling along the coast or the ice edge is also often involved (e.g., Ribergaard et al., 2006; Boertmann 2013). With respect to the Southwest Greenland margin, the diatom, dinoflagellate and ciliate blooms in summer-fall have been associated with freshwater inputs due to meltwater runoff from the GIS (Juul-Pedersen et al., 2015, Krawczyk et al., 2015, Meire et al., 2016, Krawczyk et al., 2018). This melting triggers upwelling of nutrient-rich waters and high productivity (Figure 7). Along most of the West Greenland margin, sea-ice melt and meltwater runoff from the GIS result in seasonal stratification of surface waters, which is amplified in summer by solar heat leading to relatively mild conditions (Juul-Pedersen et al., 2015; Tremblay et al., 2015). Hence, the exceptionally high

primary productivity in the Disko Bay area (Figure 3) is comparable to that of upwelling or polynya regions (Ribergaard et al., 2006; Myers & Ribergaard 2013; Tremblay et al., 2015). For example, from mid-April to mid-July 1998, the North Water polynya, recorded an average of production of $1.11 \cdot 10^3 \text{ mg C m}^{-2} \text{ d}^{-1}$ (Tremblay et al., 2002). In Disko Bay, upwelling of nutrient-rich bottom water is amplified by marine-terminating glaciers, the Jakobshavn Isbrae (Meire et al., 2017). Moreover, relatively mild conditions fostered by low thermal inertia in stratified surface waters and summer solar heat fluxes may benefit the phototrophic taxa. In our dataset, the upwelling in Disko Bay is detectable based on very high concentrations, up to 10^4 dinocyst per gram, which led to fluxes on the order of 10^3 to 10^5 cysts $\text{cm}^{-2} \text{ yr}^{-1}$ in late Holocene sediment cores (Allan et al., 2018).

1.5.4 Towards reconstructions of sea-surface conditions

In paleoceanography, microfossil assemblages are commonly used to reconstruct oceanographic parameters using modern analog techniques or transfer functions (e.g., Guiot & de Vernal, 2007). It is generally assumed that the surface sediment samples used for the establishment of a reference modern database represent modern conditions, which is problematic as the upper centimeters of sediment may encompass deposits from several decades to centuries, depending upon sedimentation rates and bioturbations. Here, we have distinguished “modern” from “sub-modern” samples based on the radiogenic isotope content (^{137}Cs and ^{210}Pb) of the sediment. This allowed us to explore the uncertainty that may be due to the time interval represented by surface sediment samples, which is inherent in the calibration of transfer functions or the application of analog techniques. In order to assess the uncertainty, we applied the modern analog technique (MAT) to reconstruct sea-surface conditions corresponding to the “modern” and “sub-modern” sub-sets of data (Figures 10, 11). Each subset of data is small, and for some samples no modern analog or poor analogs could be identified. Aside from these samples, the

reconstructed values are generally within the range of the instrumental data from the same sample location. To test our calculations, we also carried out MAT reconstructions using both the previously published Northern Hemisphere database ($n = 1492$; de Vernal et al., 2013a) and the most recently updated database ($n = 1968$; de Vernal et al., this issue) excluding the new set of the samples from “modern” or “sub-modern” surface sediments from the present study (Figure 12). This exercise demonstrated that the reconstructions at our study sites are better with increased number of data points in the modern database (Figure 12). The independent reconstructions using the two regional subsets of samples (“modern” and “sub-modern”) tend to indicate that the bias due to the age of the sediment is not significant in most cases (Figures 10, 11), whereas the reconstructions from the two versions of the Northern Hemisphere database show that increasing the number and diversity of analogs improves the results and reduces the uncertainty.

It has been argued that the performance of the MAT is overestimated due to spatial autocorrelation (cf. Telford & Birks 2005). Hence, we also applied WAPLS to reconstruct sea-surface conditions corresponding to the “modern” and “sub-modern” sub-sets of data (Figures in Supplementary Information 3). The root mean square error of prediction (RMSEP) we calculated from both WAPLS and MAT did not differ significantly (Supplementary Information 3). This does not resolve the spatial auto-correlation issue inherent to any dataset (cf. Telford & Birks 2005; Guiot & de Vernal, 2011) but indicates that our reference database established from surface sediment samples is suitable for the application of approaches such as MAT and WAPLS to quantitatively reconstruct sea-surface conditions.

1.6 Conclusions

The examination of dinoflagellate cyst assemblages from the West Greenland margin documents the distribution of various dinocyst taxa in relation to sea-surface

conditions. In this area, the surface ocean parameters are complex, with variable seasonal sea-ice cover, a large gradient of salinity and a narrow range of summer sea-surface temperatures. Even if the relationship between individual dinocyst species and sea ice is not straightforward, this study shows that dinocyst assemblages are closely related to sea-ice cover, salinity and temperature in addition to productivity parameters. Therefore, this study shows that dinocyst assemblages result from a combination of parameters, which makes them useful in describing general marine conditions.

The radiometric measurements in aliquots of the samples analyzed for their palynological content allowed us to distinguish between “modern” and “sub-modern” surface sediment samples. This made it possible to address potential biases due to the time interval represented in the surface sediment samples, which is critical when documenting the distribution of assemblages in relation to sea-surface conditions or when using the data to reconstruct past conditions. Apart from rare exceptions, our statistical analyses (χ^2 , cluster, RDA) did not show any significant differences in the assemblages from “sub-modern” and “modern” samples. Thus, the results suggest that surface sediments yield a picture of dinocyst fluxes, which result from a production representing surface ocean conditions within the range of the variations measured through instrumental observations. Therefore, the present study shows that the assemblages obtained in the top centimeter of the West Greenland margins represent averaged “modern” environmental conditions to a degree allowing their use in environmental studies and paleoclimate reconstructions.

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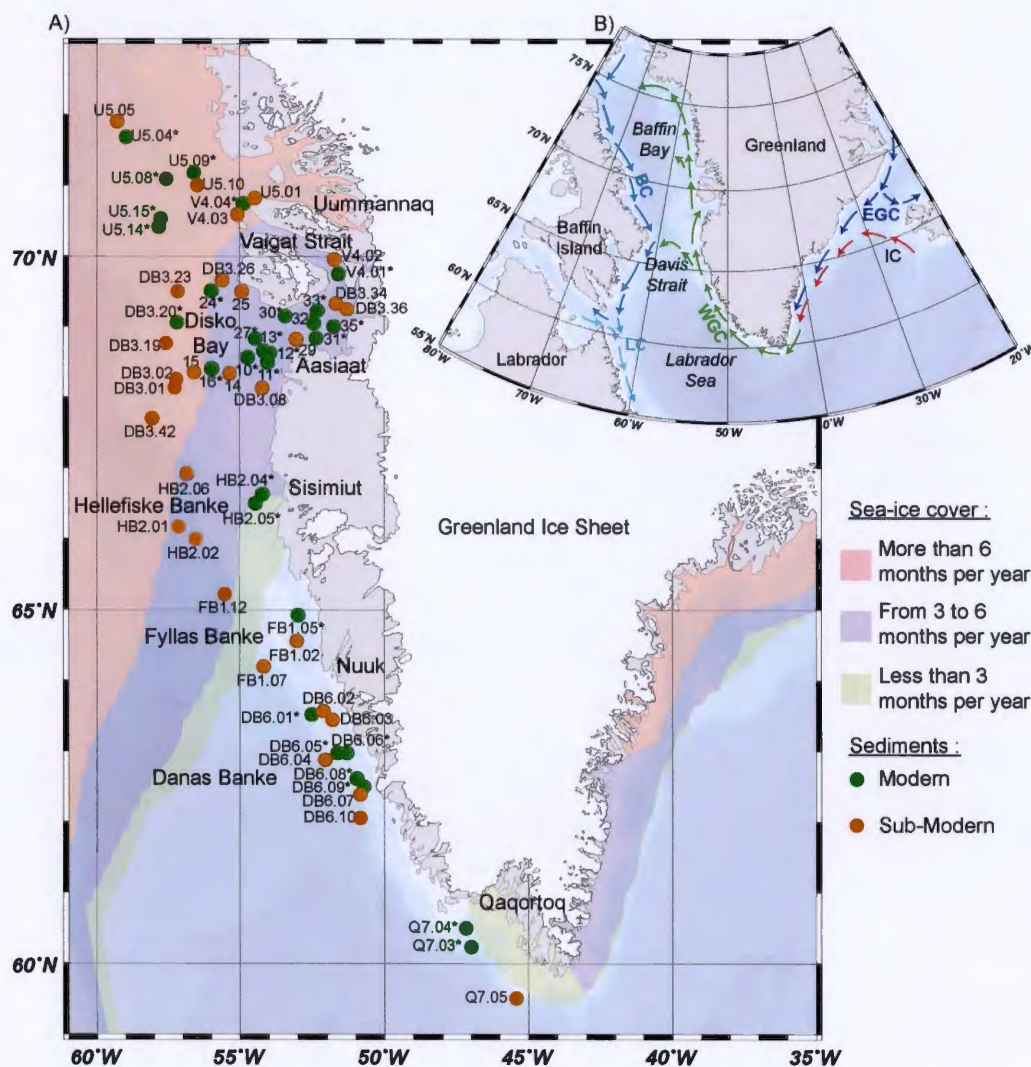


Figure 1-1 : A) The location of the studied surface samples along the West Greenland coast. Green dots and asterisks next to station names indicate sediment samples, which are considered “modern”, while red dots correspond to other samples, which were either not analyzed for their radiometric content or are regarded as “sub-modern” (cf. Krawczyk et al. 2017). The sea-ice cover, with data from the National Snow and Ice Data Center (NSIDC; <http://nsidc.org/data/bist/>), is represented as follows: less than 3 months per year, 3 to 6 months per year and more than 6 months per year. B) The dominant ocean circulation pattern around Greenland is shown by arrows as follows: EGC = East Greenland Current; IC = Irminger Current; WGC = West Greenland Current; LC = Labrador Current; BC = Baffin Current.

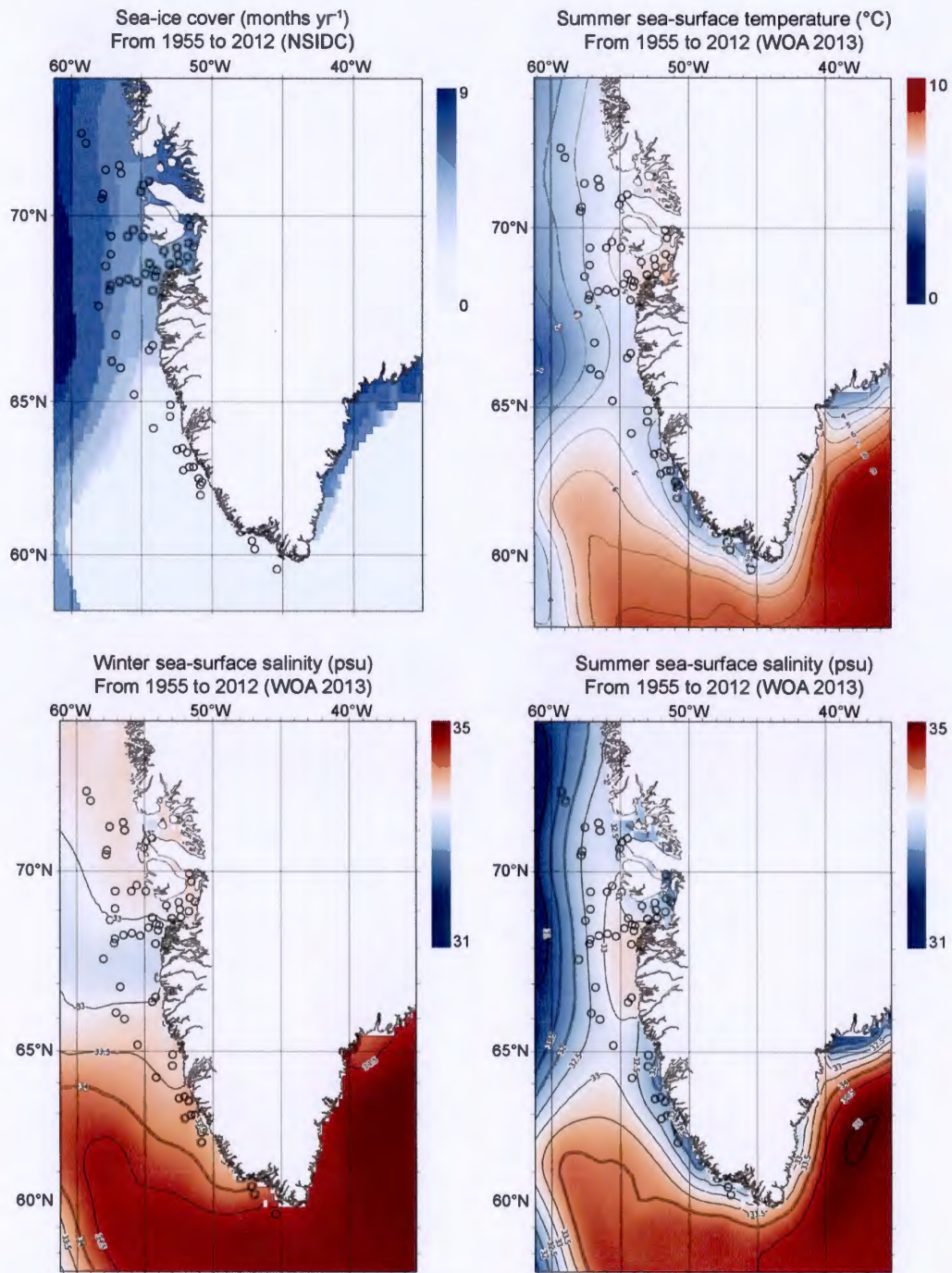


Figure 1-2 : Sea-surface conditions in the study area. Circles point to the location of the surface samples. The illustrated sea-ice cover is calculated as the average for the period spanning 1955-2012 according to the National Snow and Ice Data Center (NSIDC); the sea-surface salinity and temperature are derived from statistical mean from 1955 to 2012 of the World Ocean Atlas 2013 (Locarnini et al., 2013; Zweng et al., 2013).

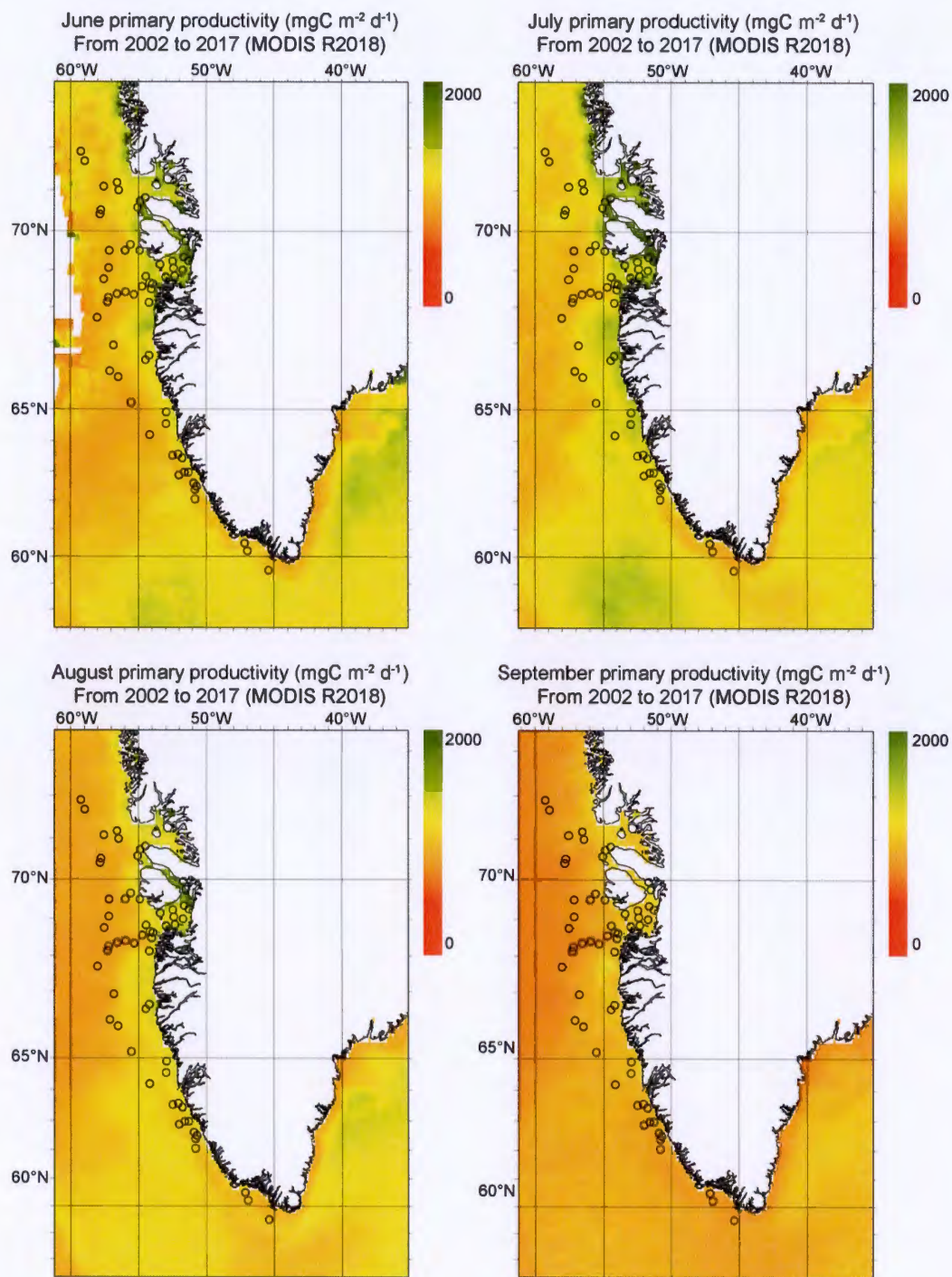


Figure 1-3 : Primary productivity of the study area. Circles show the surface sample locations. The data are from the NASA's moderate resolution imaging spectroradiometer website for the 2002-2017 interval (MODIS R2018).

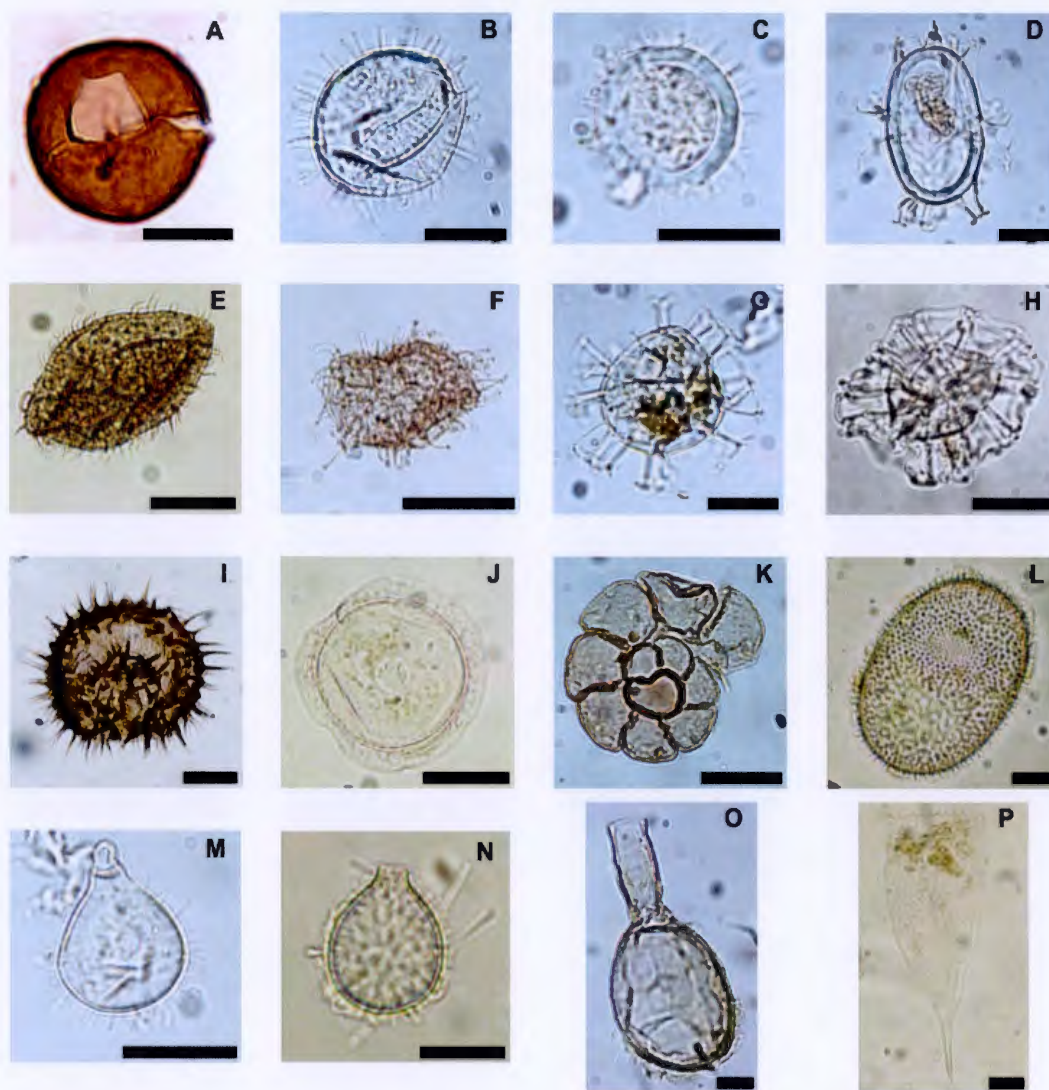


Figure 1-4 : Micrographs of organic-walled microfossils found in the surface samples of the west Greenland margin. A: *Brigantedinium* sp., B: *Operculodinium centrocarpum*, C: cyst of *Pentapharsodinium dalei*, D: *Spiniferites elongatus*, E: *Islandinium minutum*, F: *Islandinium? cezare*, G: *Spiniferites ramosus*, H: *Nemosphaeropsis labyrinthus*, I: *Selenopemphix quanta*, J: *Halodinium* sp., K: organic lining of benthic foraminifera, L: Copepod? egg, M-O: resting cysts of tintinnids, P: lorica of *Parafavella denticulata*. Scale bars = 20 μ m.

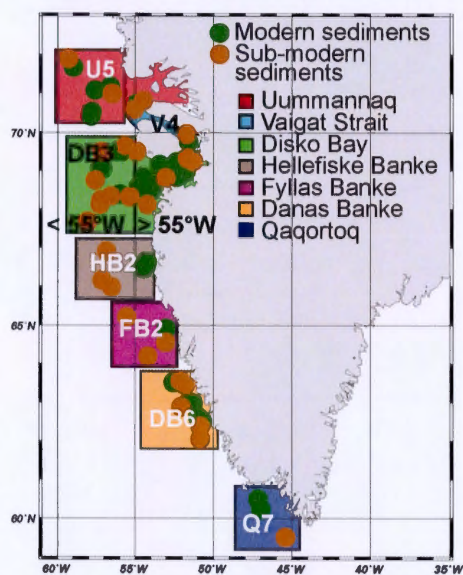


Figure 1-5 : Map showing the location of zones with samples from modern and sub-modern sediments used for Chi-square (χ^2) tests (see results in Table 3).

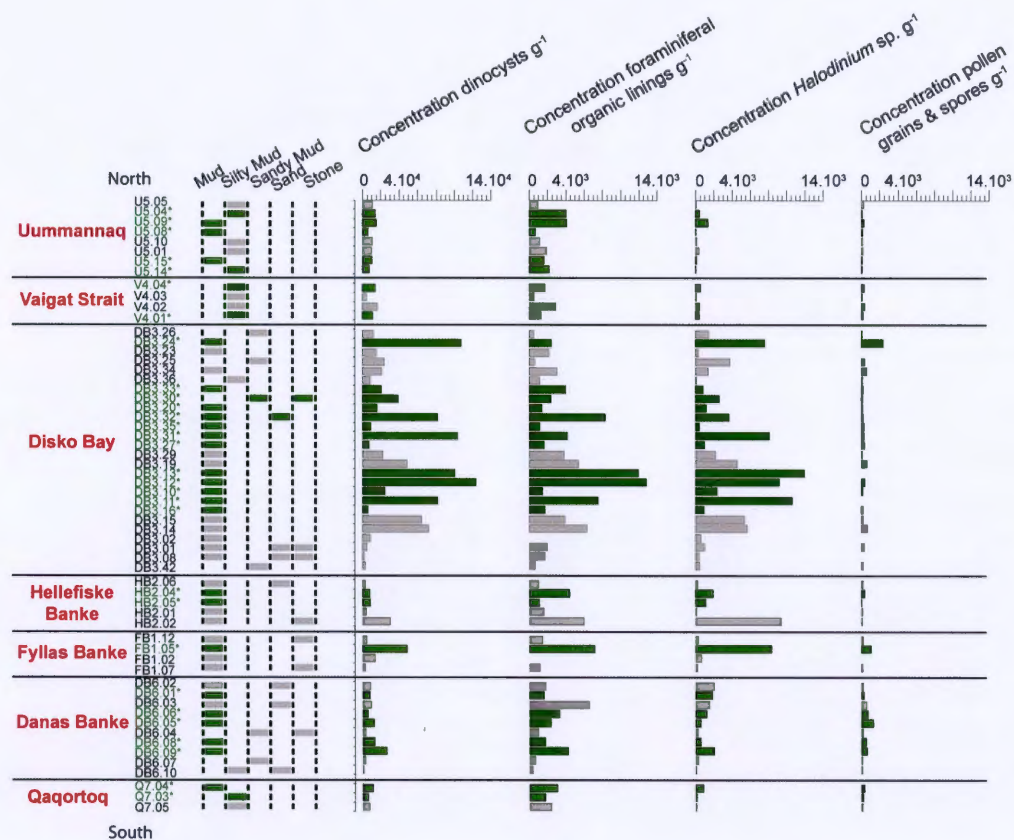


Figure 1-6 : Lithological description (cf. Krawczyk et al., 2017) and palynomorph concentrations in surface sediment samples from north to south along the West Greenland margin (cf. Figure 1). The green bars correspond to sediments assumed to be modern (cf. Table 1).

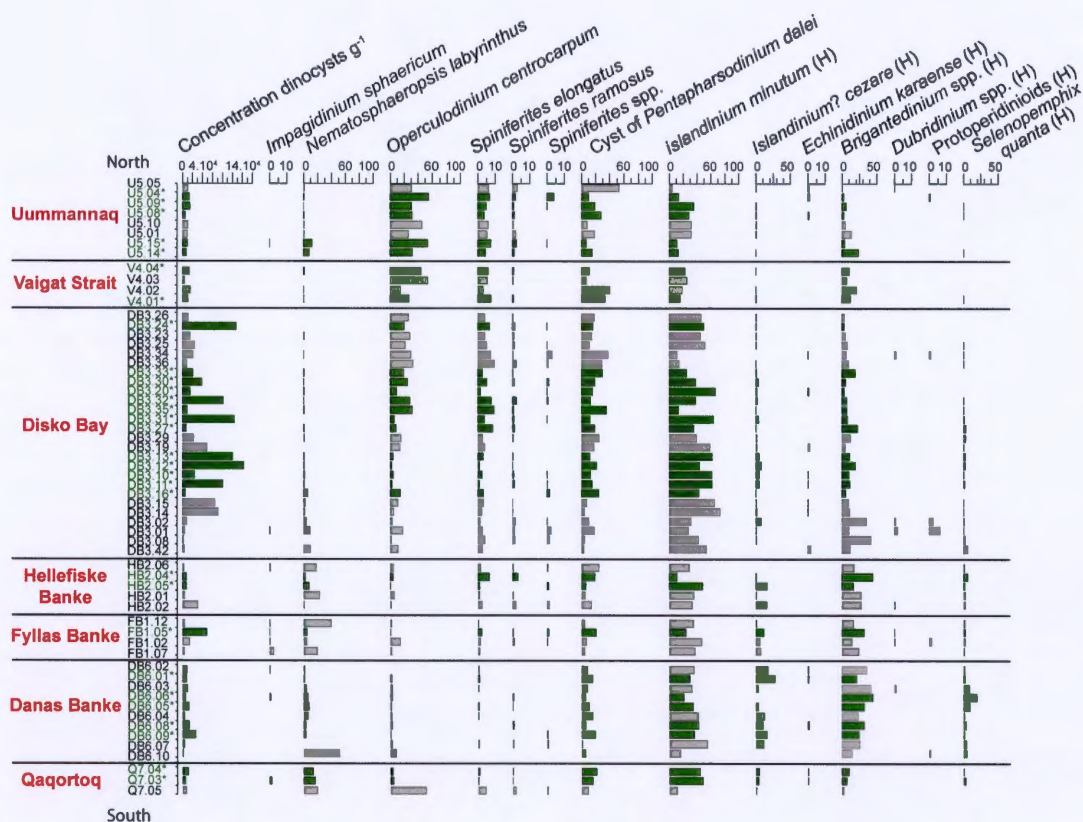


Figure 1-7 : Relative abundance (%) of the main dinocyst taxa in surface sediment samples from the Greenland margins, from north to south (cf. Figure 1). Heterotrophic taxa are distinguished by (H). “Modern” sediments are in green.

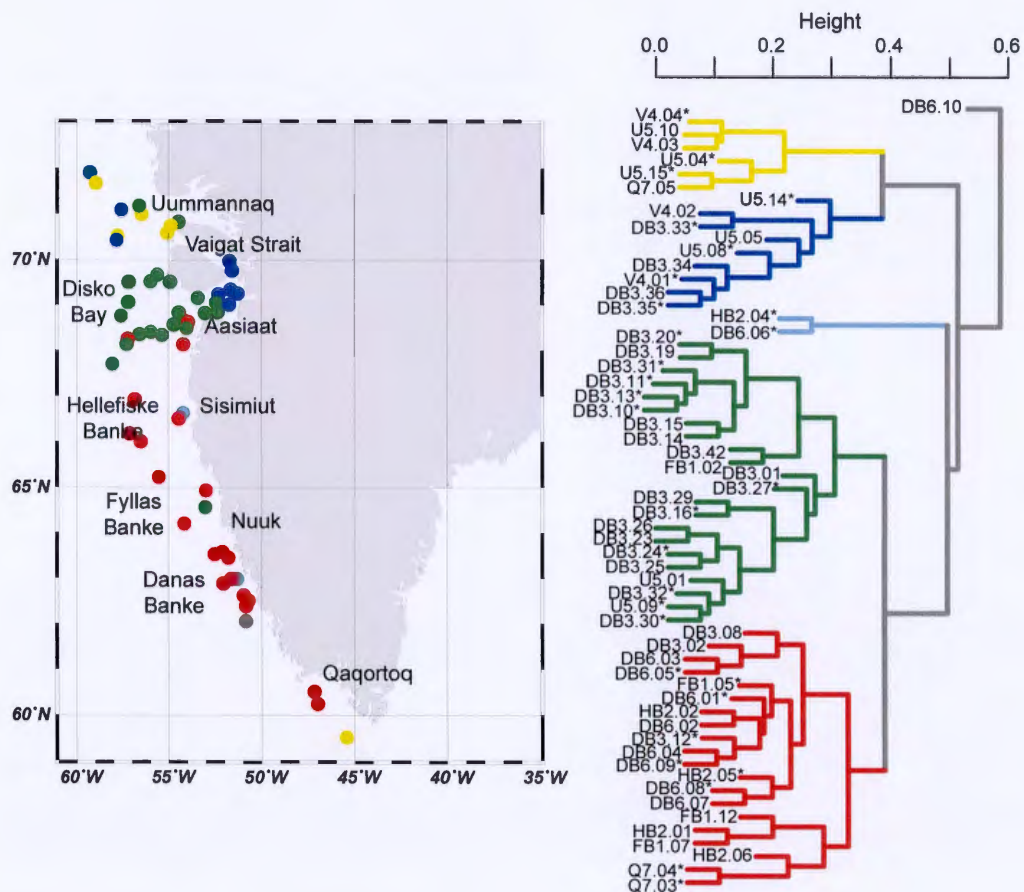


Figure 1-8 : Dendrogram showing the outcome of the hierarchical cluster analysis (UPGMA) on Bray Curtis dissimilarities of all samples, including “modern” and “sub-modern” sediments. The map shows the locations of the sample sites included in the cluster analysis.

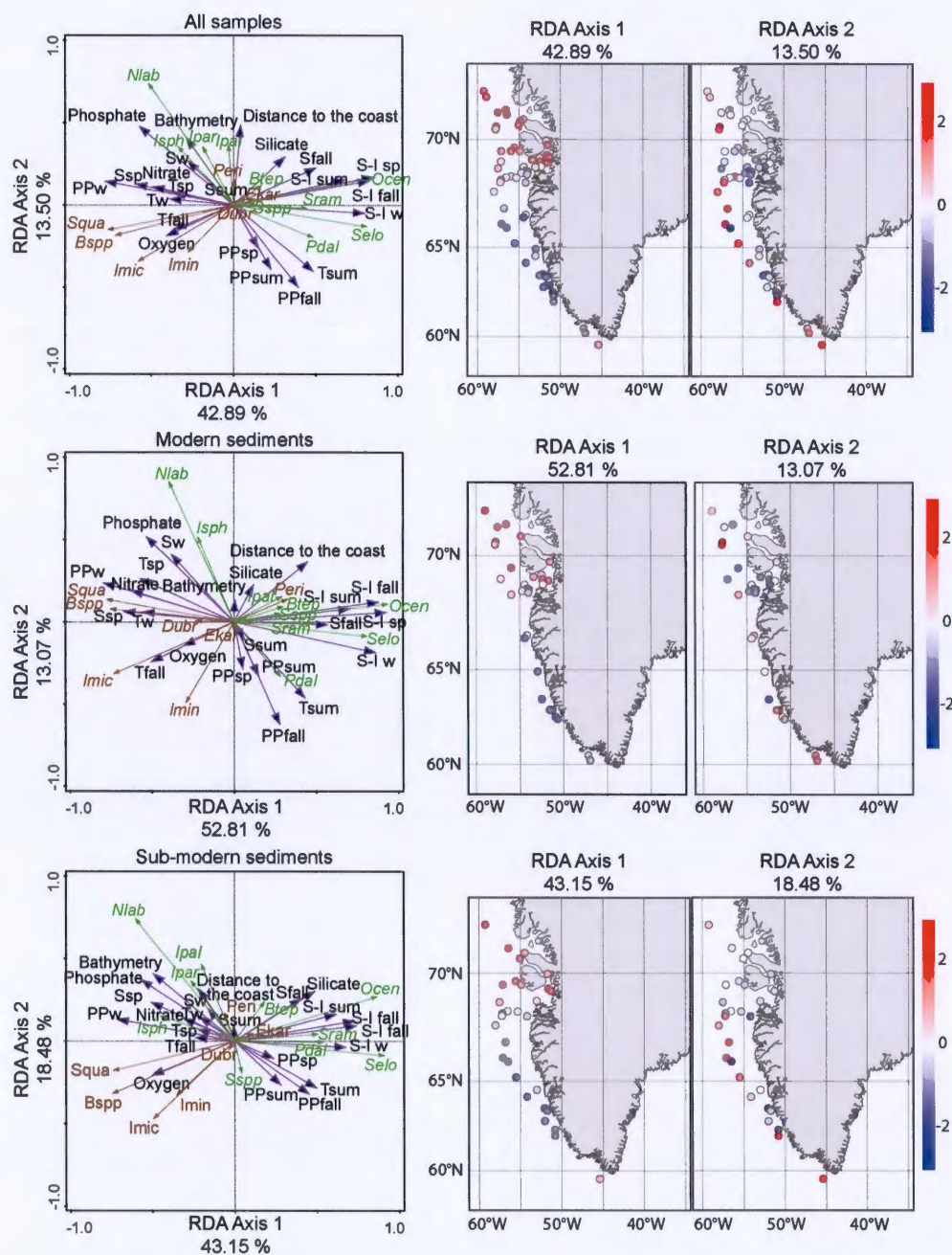


Figure 1-9 : Results of RDA. In the left panel, taxa are indicated by four-letter acronyms (see Table 2) and the environmental parameters are written in black (abbreviations see Table 4). The names of heterotrophic taxa are in brown and the names of phototrophic taxa in green. The upper graph shows the results of RDA applied to all samples, the middle graph presents the results with “modern” samples and the bottom graph refer to the results with the other samples (cf. Table 1). In the right panels, the maps illustrate the spatial distribution of the values (negative to positive) of the axis 1 and 2 from the RDA.

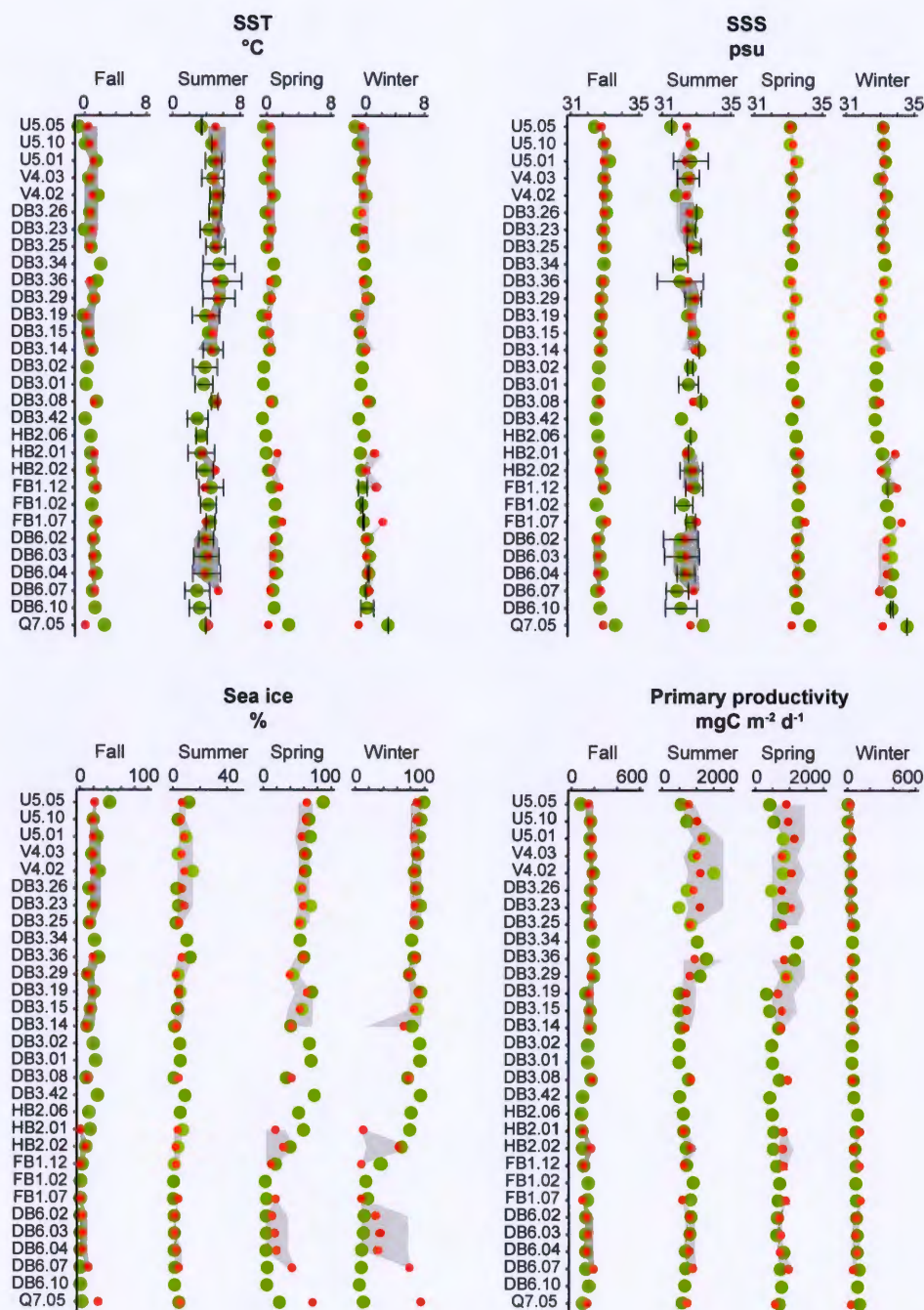


Figure 1-10 : MAT reconstruction of sea-surface temperature (SST), sea-surface salinity (SSS), sea-ice cover concentration and primary productivity from dinocyst assemblages in “sub-modern” sediment samples based on dinocyst assemblages of “modern” sediment samples. The green dots represent the instrumental data and the red dots the reconstructions. Maximum and minimum reconstructed values are represented in gray shading. No red dot indicates no analog. When available the standard deviations of the instrumental data were added on the graph.

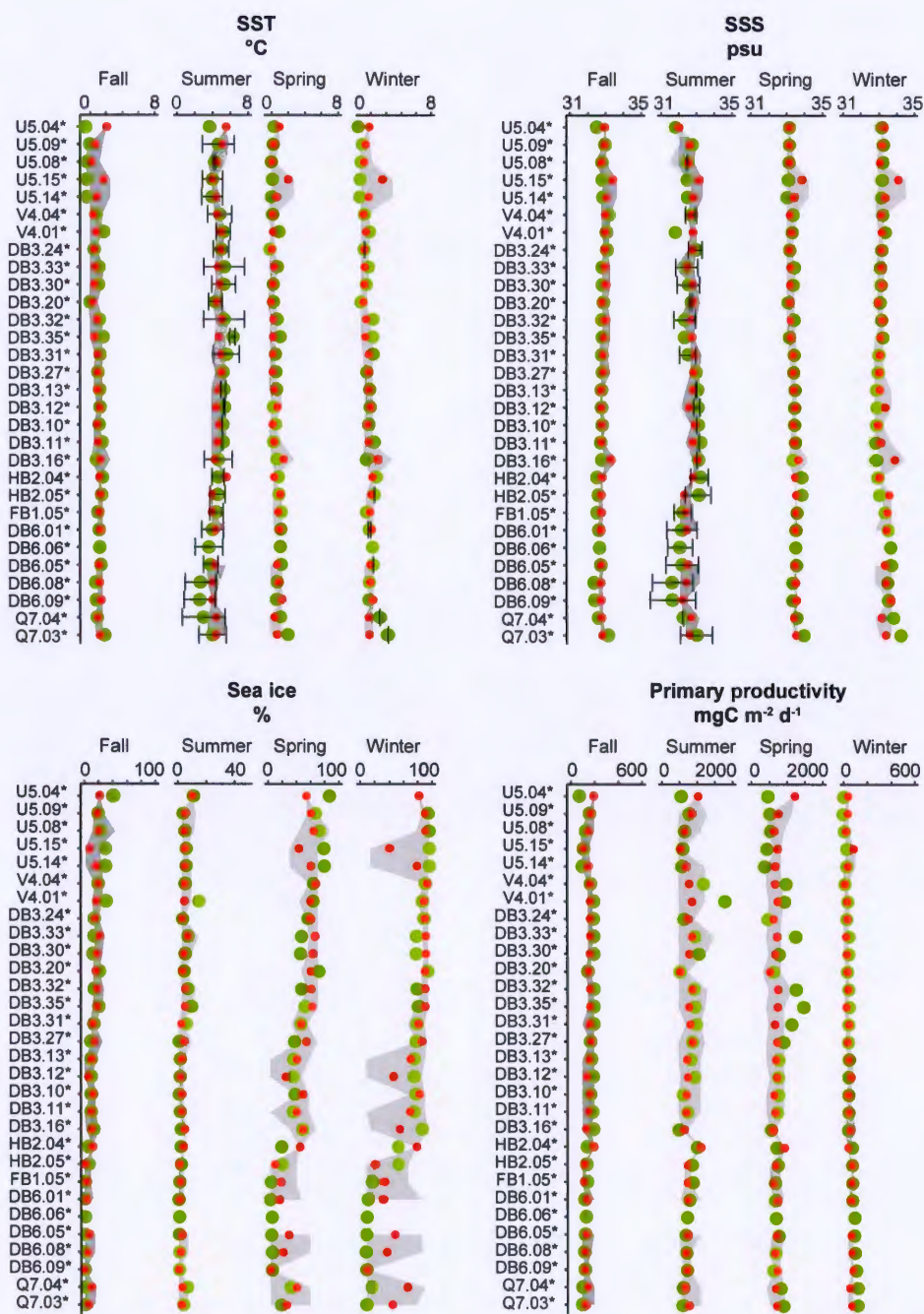


Figure 1-11 : MAT reconstruction of seasonal sea-surface temperature (SST), sea-surface salinity (SSS), sea-ice cover concentration and primary productivity from dinocyst assemblages in “modern” sediment samples, using the dinocyst assemblages from the “sub-modern” sediment samples. The green dots represent the instrumental data and the red dots the reconstructions. Maximum and minimum reconstructed values are represented in gray shading. No red dot indicates no analog. When available the standard deviations of the instrumental data were added on the graph.

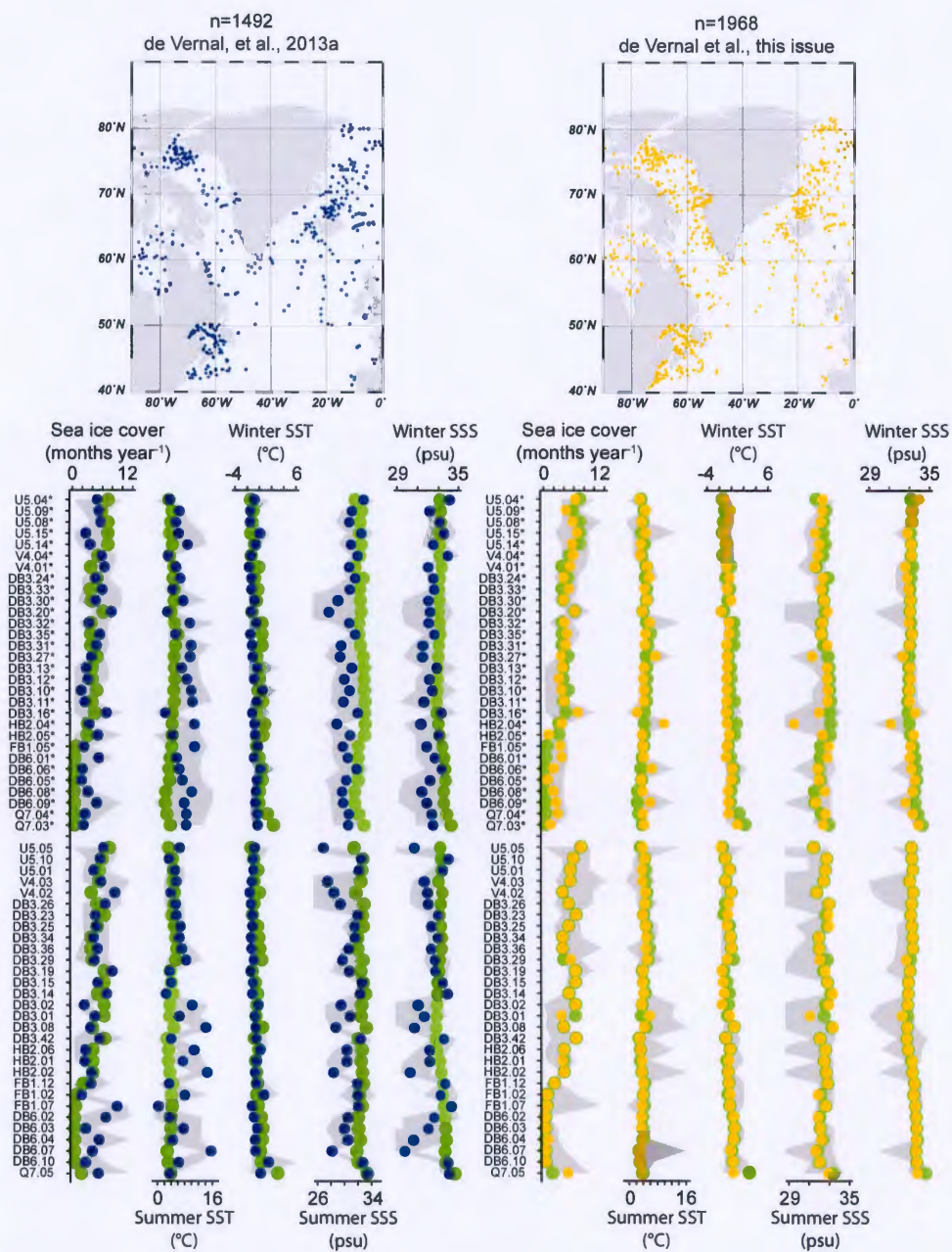


Figure 1-12: MAT reconstruction of seasonal sea-ice cover, summer and winter sea-surface temperature (SST) and sea-surface salinity (SSS), from the 60 dinocyst spectra, including those from “modern” and “sub-modern” sediments. The green dots represent instrumental data. The blue dots illustrate the reconstruction from the $n=1492$ database (de Vernal et al., 2013a) and the yellow dots the reconstructions from the $n=1968$ database (from de Vernal et al., this issue), by excluding either the 30 “modern” spectra or the “sub-modern” spectra from this study, which thus resulted in searching the analogs in a database including a total number of 1938 sites. Maximum and minimum reconstructed values are represented in gray shading. The maps at the top show the location of North Atlantic sites from the $n=1492$ and $n=1968$ databases.

Table 1-1 : List of stations (n = 60) with reference to geographical location and water depth. The asterisk indicates the sediment samples labelled as “modern” (n = 30) based on their radioisotope ^{210}Pb and ^{137}Cs content, which was measured in all samples except those in italic.

Station	Region	Latitude N	Longitude W	Water Depth (m)
U5.05	Uummannaq	71°54.5	59°16.9	413
U5.04*	Uummannaq	71°41.3	58°57.8	366
U5.09*	Uummannaq	71°11	56°35.7	293
U5.08*	Uummannaq	71°05.5	57°34.1	322
U5.10	Uummannaq	71°00	56°28.6	387
U5.01	Uummannaq	70°49.3	54°28.5	555
U5.15*	Uummannaq	70°31.6	57°46.4	455
U5.14*	Uummannaq	70°25	57°50.5	421
V4.04*	Vaigat Strait	70°44.8	54°52.6	522
V4.03	Vaigat Strait	70°35.1	55°03.9	322
V4.02	Vaigat Strait	69°57.5	51°42.8	381
V4.01*	Vaigat Strait	69°45.1	51°33.9	466
DB3.26	Disko Bay	69°39.4	55°35.8	160
DB3.24*	Disko Bay	69°30.4	55°59.4	231
DB3.23	Disko Bay	69°30	57°10	211
DB3.25	Disko Bay	69°30	54°54.7	161
DB3.34	Disko Bay	69°20	51°39.3	327
DB3.36	Disko Bay	69°14.9	51°17	367
DB3.33*	Disko Bay	69°13.9	52°30.2	505
DB3.30*	Disko Bay	69°08.9	53°25.2	347
DB3.20*	Disko Bay	69°03.6	57°11.5	219
DB3.32*	Disko Bay	69°02.9	52°25.7	300
DB3.35*	Disko Bay	68°59.8	51°44.1	327
DB3.31*	Disko Bay	68°50.1	52°20.2	281
DB3.27*	Disko Bay	68°49.7	54°26.4	188
<i>DB3.29</i>	Disko Bay	68°48.9	53°01.5	716
<i>DB3.19</i>	Disko Bay	68°45.6	57°33.7	308
DB3.13*	Disko Bay	68°39.3	54°09.9	486
DB3.12*	Disko Bay	68°37.5	53°56.9	678
DB3.10*	Disko Bay	68°33.8	54°43.2	293
DB3.11*	Disko Bay	68°29.5	54°01.3	575
DB3.16*	Disko Bay	68°24.2	55°57.9	539
DB3.15	Disko Bay	68°21.3	56°34.5	482
DB3.14	Disko Bay	68°20.1	55°20.7	532
DB3.02	Disko Bay	68°15	57°12.3	405
DB3.01	Disko Bay	68°08.4	57°16.1	342

DB3.08	Disko Bay	68°07.7	54°12.4	357
DB3.42	Disko Bay	67°42.1	58°02.7	282
HB2.06	Hellefiske Banke	66°55.2	56°49.6	647
HB2.04*	Hellefiske Banke	66°37.5	54°12.8	410
HB2.05*	Hellefiske Banke	66°29.7	54°27.2	430
HB2.01	Hellefiske Banke	66°10.4	57°07.3	672
HB2.02	Hellefiske Banke	65°59.6	56°30.9	589
FB1.12	Fyllas Banke	65°12.7	55°32	780
FB1.05*	Fyllas Banke	64°54.8	52°58.3	430
FB1.02	Fyllas Banke	64°33.3	53°00.3	420
FB1.07	Fyllas Banke	64°11.6	54°10.2	620
DB6.02	Danas Banke	63°34	52°05.6	456
DB6.01*	Danas Banke	63°31	52°30.4	364
DB6.03	Danas Banke	63°26.5	51°46.9	386
DB6.06*	Danas Banke	62°58.4	51°18.2	463
DB6.05*	Danas Banke	62°58.1	51°36.3	503
DB6.04	Danas Banke	62°52.4	52°02.9	350
DB6.08*	Danas Banke	62°36.5	50°56.6	394
DB6.09*	Danas Banke	62°29.6	50°42.1	384
DB6.07	Danas Banke	62°23	50°49.9	520
DB6.10	Danas Banke	62°03.7	50°49.8	954
Q7.04*	Qaqortoq	60°30.3	47°10	412
Q7.03*	Qaqortoq	60°13.7	46°58.2	455
Q7.05	Qaqortoq	59°30.7	45°24.7	338

Table 1-2 : Common dinocyst taxa found from the West Greenland margin. Trophic mode: A= Phototrophic (=Autotrophic), H=Heterotrophic. Family: G=Gonyaulacaceae; P= Protoperidiniaceae

Taxon name	Abbreviation	Trophic mode	Family	Percentage range	Mean	Standard deviation	Number of appearances
<i>Bitectatodinium tepikiense</i>	<i>Btep</i>	A	G	0 – 0.82	0.09	0.19	13
<i>Impagidinium pallidum</i>	<i>Ipal</i>	A	G	0 – 1.03	0.12	0.24	15
<i>Impagidinium paradoxum</i>	<i>Ipar</i>	A	G	0 – 0.52	0.02	0.10	3
<i>Impagidinium sphaericum</i>	<i>Isph</i>	A	G	0 - 2.27	0.11	0.34	10
<i>Nematosphaeropsis labyrinthus</i>	<i>Nlab</i>	A	G	0 – 54.04	5.31	9.31	51
<i>Operculodinium centrocarpum</i>	<i>Ocen</i>	A	G	0 – 55.67	15.92	15.91	59
<i>Spiniferites elongatus</i>	<i>Selo</i>	A	G	0 – 9.36	3.36	2.65	56
<i>Spiniferites ramosus</i>	<i>Sram</i>	A	G	0 - 3.27	0.86	0.82	46
<i>Spiniferites</i> spp.	<i>Sspp.</i>	A	G	0- 4.12	0.38	0.76	25
Cyst of <i>Pentapharsodinium dalei</i>	<i>Pdal</i>	A	P	0.65 - 53.08	15.71	10.29	60
<i>Islandinium minutum</i>	<i>Imin</i>	H	P	4.40 - 73.54	36.07	16.42	60
<i>Islandinium? cezare</i>	<i>Imic</i>	H	P	0 - 28.03	3.84	5.60	52
<i>Echinidinium karaense</i>	<i>Ekar</i>	H	P	0 – 1.59	0.16	0.31	19
<i>Brigantedinium</i> spp.	<i>Bspp.</i>	H	P	0.59 – 44.90	15.74	11.67	60
<i>Dubridinium</i> spp.	<i>Dubr</i>	H	P	0 – 1.99	0.10	0.31	8
Protoperidinioids	<i>Peri</i>	H	P	0 – 6.29	0.21	0.88	6
<i>Selenopemphix quanta</i>	<i>Squa</i>	H	P	0 -19.17	1.88	3.00	44

Table 1-3 : χ^2 results from the counts and the percentages of the dominant taxa from all sediments, “modern” and “sub-modern” (for zone locations see Figure 5), the degree of freedom (df) and the p-values. A p-value < 0.05 indicates that there is a statistically significant difference between the assemblages; the row highlighted in gray represents p-values > 0.05.

Samples			Counts			Percentages		
Zones	Sediments	Number	χ^2	df	p	χ^2	df	p
U5	All	8	920.01	49	< 2.2.10 ⁻¹⁶	256.55	49	< 2.2.10 ⁻¹⁶
	“Modern”	5	452.3	28	< 2.2.10 ⁻¹⁶	124.21	28	4.40.10 ⁻¹⁴
	“Sub-modern”	3	302.82	14	< 2.2.10 ⁻¹⁶	85.484	14	2.68.10 ⁻¹²
V4	All	4	332.1	21	< 2.2.10 ⁻¹⁶	78.653	21	1.354.10 ⁻⁸
	“Modern”	2	73.175	7	3.364.10 ⁻¹³	17.542	7	0.01421
	“Sub-modern”	2	223.53	7	< 2.2.10 ⁻¹⁶	57.094	7	5.727.10 ⁻¹⁰
DB3	All	26	2881.6	200	< 2.2.10 ⁻¹⁶	929.17	200	< 2.2.10 ⁻¹⁶
	“Modern”	13	1233.9	96	< 2.2.10 ⁻¹⁶	348.84	96	< 2.2.10 ⁻¹⁶
	“Sub-modern”	13	1554	96	< 2.2.10 ⁻¹⁶	540.6	96	< 2.2.10 ⁻¹⁶
DB3 < 55°W	All	15	1524.1	112	< 2.2.10 ⁻¹⁶	497.05	112	< 2.2.10 ⁻¹⁶
	“Modern”	10	997.08	72	< 2.2.10 ⁻¹⁶	270.52	72	< 2.2.10 ⁻¹⁶
	“Sub-modern”	5	375.99	32	< 2.2.10 ⁻¹⁶	180.12	32	< 2.2.10 ⁻¹⁶
DB3 > 55°W	All	11	965.34	70	< 2.2.10 ⁻¹⁶	292.93	70	< 2.2.10 ⁻¹⁶
	“Modern”	3	94.408	14	5.542.10 ⁻¹⁴	30.531	14	0.006445
	“Sub-modern”	8	732.43	49	< 2.2.10 ⁻¹⁶	224.41	49	< 2.2.10 ⁻¹⁶
HB2	All	5	381.37	32	< 2.2.10 ⁻¹⁶	169.28	32	< 2.2.10 ⁻¹⁶
	“Modern”	2	154.64	8	< 2.2.10 ⁻¹⁶	72.124	8	1.854.10 ⁻¹²
	“Sub-modern”	3	171.6	16	< 2.2.10 ⁻¹⁶	72.405	16	3.77.10 ⁻⁹
FB1	All	4	412.47	24	< 2.2.10 ⁻¹⁶	125.65	24	9.462.10 ⁻¹⁶
	“Modern”	1						
	“Sub-modern”	3	191.54	16	< 2.2.10 ⁻¹⁶	61.252	16	3.21.10 ⁻⁷
DB6	All	10	1157.7	72	< 2.2.10 ⁻¹⁶	501.76	72	< 2.2.10 ⁻¹⁶
	“Modern”	5	287.34	32	< 2.2.10 ⁻¹⁶	117.51	32	1.063.10 ⁻¹¹
	“Sub-modern”	3	629.1	32	< 2.2.10 ⁻¹⁶	259.91	32	< 2.2.10 ⁻¹⁶
Q7	All	3	346.68	14	< 2.2.10 ⁻¹⁶	120.8	14	< 2.2.10 ⁻¹⁶
	“Modern”	2	7.875	7	0.3437	2.5174	7	0.9258
	“Sub-modern”	1						

Table 1-4 : Correlation coefficients for each environmental parameter and percentage of the covariance explained by each axis. Significant relationships ($p < 0.05$) between environmental parameters and the dinocyst assemblages are shown in bold while the significant values are highlighted in gray.

Name	Abbreviations	All sites (n=60)			"Modern" sediments (n=30)			"Sub-modern" sediments (n=30)		
		Correlation coefficients		Conditional effects p	Correlation coefficients		Conditional effects p	Correlation coefficients		Conditional effects p
		Axis 1 (42.89 %)	Axis 2 (13.50 %)		Axis 1 (52.81 %)	Axis 2 (13.07 %)		Axis 1 (43.15 %)	Axis 2 (18.48 %)	
Sea-ice winter (%)	S-I w	0.7510	-0.0418	0.092	0.8396	-0.1744	0.968	0.6571	-0.0342	0.02
Sea-ice spring (%)	S-I sp	0.8006	0.1439	0.002	0.9041	0.0543	0.002	0.7082	0.1083	0.11
Sea-ice summer (%)	S-I sum	0.6354	0.1281	0.718	0.6859	0.0744	0.47	0.5986	0.1455	0.576
Sea-ice fall (%)	S-I fall	0.7797	0.1243	0.006	0.8569	0.1131	0.076	0.7209	0.0826	0.002
Primary productivity winter (mgC m⁻² d⁻¹)	PPw	-0.7364	0.1203	0.014	-0.7737	0.2199	0.222	-0.6963	0.1177	0.446
Primary productivity spring (mgC m ⁻² d ⁻¹)	PPsp	0.1408	-0.2201	0.536	0.0530	-0.2657	0.646	0.2301	-0.0943	0.778
Primary productivity summer (mgC m ⁻² d ⁻¹)	PPsum	0.2143	-0.3276	0.09	0.1449	-0.3075	0.382	0.2735	-0.2375	0.156
Primary productivity fall (mgC m ⁻² d ⁻¹)	PPfall	0.3679	-0.4191	0.11	0.2707	-0.5820	0.188	0.4392	-0.2873	0.398
SSS winter (psu)	Sw	-0.2602	0.2245	0.002	-0.3701	0.3809	0.182	-0.1571	0.1756	0.106
SSS spring (psu)	Ssp	-0.5599	0.1067	0.442	-0.6537	0.0586	0.416	-0.4920	0.2100	0.57
SSS summer (psu)	Ssum	0.0418	0.0292	0.894	0.0624	-0.1032	0.97	-0.0069	0.0826	0.804
SSS fall (psu)	Sfall	0.4704	0.1896	0.022	0.5536	-0.0159	0.654	0.3910	0.2304	0.008
SST winter (°C)	Tw	-0.3647	0.0310	0.294	-0.5363	0.0567	0.472	-0.2046	0.1311	0.162
SST spring (°C)	Tsp	-0.3399	0.0611	0.852	-0.5527	0.2441	0.12	-0.2134	0.0632	0.732
SST summer (°C)	Tsum	0.4561	-0.3391	0.988	0.4192	-0.4325	0.414	0.4834	-0.2535	0.408

SST fall (°C)	Tfall	-0.3384	-0.1243	0.224	-0.4883	-0.2267	0.396	-0.2287	0.0180	0.006
Phosphate ($\mu\text{mol l}^{-1}$)	Phosphate	-0.3831	-0.1569	0.528	-0.2960	-0.1361	0.002	-0.4870	-0.1860	0.142
Dissolved oxygen (ml l^{-1})	Oxygen	-0.4606	0.0929	0.172	-0.6074	0.1764	0.574	-0.3020	0.1220	0.24
Nitrates ($\mu\text{mol l}^{-1}$)	Nitrate	-0.5393	0.4016	0.984	-0.5172	0.4820	0.384	-0.5541	0.3322	0.868
Silicate ($\mu\text{mol l}^{-1}$)	Silicate	0.2932	0.2456	0.164	0.1166	0.2086	0.294	0.4711	0.2695	0.508
Distance to the coast	Distance to the coast	0.0412	0.4064	0.002	0.4359	0.3406	0.414	-0.2142	0.2839	0.006
Bathymetry	Bathymetry	-0.2691	0.3438	0.002	0.0060	0.1246	0.242	-0.4792	0.3637	0.068

CHAPITRE II

LATE HOLOCENE SEA SURFACE INSTABILITIES IN THE DISKO BUGT AREA, WEST GREENLAND, IN PHASE WITH $\delta^{18}\text{O}$ OSCILLATIONS AT CAMP CENTURY

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Abstract

Palynological analyses of sediment core MSM343310 from Disko Bugt (68°38'861 N, 53°49'493 W) document decadal- to centennial-scale variability of sea surface conditions during the last ~3,600 years. High dinocyst fluxes ($>10^4$ cysts/cm²year⁻¹) indicate a very high productivity. Dinocyst assemblages dominated by *Islandinium minutum*, *Brigantedinium* spp., *Islandinium? cezare* and the cyst of *Pentaparsodinium dalei* suggest low surface salinity and marked shifts of summer sea surface temperature. The application of the modern analogue technique to dinocyst assemblages, using an updated reference dataset with new sites from the West Greenland margin, led to reconstruct decadal-centennial scale variations in sea surface salinity and temperature, in phase with the $\delta^{18}\text{O}$ variations in the Camp Century ice core. At ~1.5 ka BP, the seasonal sea ice cover records an important regime change, from winter-only sea ice to more unstable conditions marked by successive cooling pulses with sea ice cover of up to 8 months/yr. The data suggest a close relationship between hydrographic conditions and regional climate over Greenland. Our record shows variations with a mean 200-years periodicity until ~2 ka BP, which supports the hypothesis of climate variations driven by solar variability. After 1.5 ka BP, our data show a variability characterized by a 60-70 year periodicity, which suggests linkages with the Atlantic Multidecadal Oscillation and southwestward migration of the atmospheric polar front. The most recent part of the record, from ~1900 CE to 2007 CE, is characterized by assemblages reflecting warmer surface conditions and reduced sea ice cover.

2.1 Introduction

Disko Bugt off West Greenland is an area of much interest for documenting ocean-ice dynamics because of its proximity with the Greenland Ice Sheet (GIS; Figure 1). The Jakobshavn Isbrae that flows towards Disko Bugt is presently the largest and fastest ice stream in the Northern Hemisphere. It drains about 6.5% of the GIS and produces about 10% of the total iceberg calving from the ice sheet (Weidick & Bennike, 2007; Young et al., 2011). Disko Bugt is thus a strategic area to monitor the GIS meltwater flow and its mixing with the West Greenland Current along the Greenland margin (WGC; Figure 1). The Disko Bugt area is strongly influenced by this current, which is formed from North Atlantic and Arctic Ocean waters entering the Labrador Sea and Baffin Bay (Figure 1a). These waters are the warm and saline Irminger Current (IC) and the polar and low salinity East Greenland Current (EGC), respectively (e.g., Buch, 1981; Cuny et al., 2002; Tang et al., 2004). In Disko Bugt, the water column structure is characterized by buoyant low salinity surface waters resulting from local and distal GIS meltwater supplies (Andersen, 1981), overlying subsurface water masses of WGC waters, which bear an Atlantic signature characterized by a temperature and salinity of about 3.5-4.5°C and 34-34.5 psu respectively (Holland et al., 2008; Figure 1d).

Over the last decades, climate warming has influenced the GIS mass balance through several processes, in particular surface melt, acceleration of glacier velocity, increased iceberg production and calving, as well as sub-surface melting of marine-terminating glaciers (e.g., Box & Colgan, 2013; Straeno & Heimbach, 2013). Such an acceleration of meltwater and iceberg discharge contributes to lower surface salinity and stronger stratification in the northwest North Atlantic. At the scale of the last century, hydrographic data indicate warming of subsurface waters of the WGC and a significant freshening of surface waters in Baffin Bay (Zweng & Münchow, 2006). These changes may ultimately interfere with deep-water formation and northward

heat transfer through the Atlantic Meridional Overturning Circulation (AMOC; e.g., Collins et al., 2013). Rahmstorf et al. (2015) and Jackson et al. (2016) proposed a direct linkage between the GIS mass balance and the recent slowdown of the AMOC. However, whereas the recent changes are relatively well documented, existing time series based on observations are still too short for assessing unequivocally robust and long-term linkages between ice and ocean dynamics along the Greenland margin and their impact on the AMOC (Haines, 2016). In this context, it is highly relevant to use proxies to explore past climate variations in Greenland, such as iceberg-meltwater discharge and near shore ocean conditions. Here, we present a reconstruction of sea-ice variability, sea surface salinity and temperature, and relate it to Greenland glacier melt discharge and ocean current variability based on detailed analyses of a sediment core collected during the R/V *Maria S. Merian* Expedition MSM05/03 in the Disko Bugt area (Harff et al., 2007; Figure 1).

Prior to our study, several expeditions in the Disko Bugt/ West Greenland shelf area have retrieved sediment cores records to document Holocene paleoceanographic changes at centennial to decadal resolutions, (Figure 1c; Table 1). Most of these previous studies thus provided information on centennial frequency climate variability. Several used benthic foraminifer assemblages to infer bottom water properties and their relationship with the dynamics of the WGC (Andresen et al., 2011; Lloyd, 2006; Lloyd et al., 2005, 2007; Moros et al., 2016; Perner, Moros, Jennings, et al., 2013). A few other studies referred to diatom assemblages and led to qualitative or quantitative interpretation of the paleo-sea-ice cover (Krawczyk et al., 2010, 2013, 2017; Moros et al., 2006; Sha et al., 2014). Alkenone biomarkers also provided information on surface waters and were interpreted in terms of sea surface temperature and/or meltwater input (Moros et al., 2016). Finally, palynological analyses with special attention paid to organic-walled dinoflagellate cysts, (hereafter dinocysts), as tracers of surface-water masses properties, were used to reconstruct sea surface parameters including the seasonal extent of sea ice cover, in addition to

summer salinity and temperature (Andresen et al., 2011; Ouellet-Bernier et al., 2014; Ribeiro et al., 2012; Seidenkrantz et al., 2008).

Previous studies demonstrated that the establishment of full interglacial conditions in the region was delayed to about 6 ka BP (Lloyd et al., 2007; Ouellet-Bernier et al., 2014; Perner, Moros, Snowball, et al., 2013). These also showed that millennial-scale oscillations with opposite changes in surface temperature and salinity occurred after 6 ka BP, pointing to variations in stratification of surface waters, probably due to freshwater and meltwater discharge from the GIS (Lloyd et al., 2007; Moros et al., 2016; Ouellet-Bernier et al., 2014; Perner, Moros, Snowball, et al., 2013). The Holocene thermal optimum in the Disko Bugt was recorded from 6 to 3.5 ka BP in both bottom and surface waters (Andresen et al., 2011; Lloyd et al., 2007; Moros et al., 2016; Ouellet-Bernier et al., 2014; Perner, Moros, Jennings, et al., 2013). Onshore, the warmest air temperatures as reconstructed from chironomids were recorded from 6 to 4 ka BP (Axford et al., 2013). This climate optimum was followed by the Neoglacial cooling, between 3.5 to 2 ka BP, marked by cold subsurface waters (Andresen et al., 2011; Lloyd et al., 2007; Moros et al., 2016; Perner, Moros, Jennings, et al., 2013; Perner et al., 2011) and a reduction in meltwater discharge (Andresen et al., 2011; Moros et al., 2016). Then, relatively warm conditions set in from 2 to 1.5 ka BP, followed by another regional cooling (Andresen et al., 2011; Krawczyk et al., 2010, 2013, 2017; Lloyd et al., 2007; Moros et al., 2006, 2016; Ouellet-Bernier et al., 2014; Perner, Moros, Jennings, et al., 2013; Perner et al., 2011; Ribeiro et al., 2012; Seidenkrantz et al., 2008; Sha et al., 2014).

Here, we add new information on late Holocene climatic changes, based on high-resolution palynological analyses of sediment core MSM343310 spanning the last ~3,600 years. This time interval is characterized by a particularly high sedimentation rate of about 3.5 mm/yr (Lloyd et al., 2011), enabling us to develop time series with a decadal to sub-decadal temporal resolution. The aim of this study is

to reconstruct changes in sea surface conditions, with special attention paid to salinity changes as indicators of freshwater-meltwater events and to sea ice cover variations as a diagnostic feature of regional climate changes. Moreover, comparison with benthic foraminiferal records (Perner et al., 2011) as tracers of bottom water properties, may help to evaluate the relationship between changes in surface waters vs those of the sub-surface water mass, which is more closely linked through the WGC, to paleoclimate conditions further south. Furthermore, comparison with isotopic data from Greenland ice cores (Vinther et al., 2009) is used to evaluate linkages between surface ocean and climate conditions over northwestern Greenland.

2.2 Regional hydrography

Disko Bugt is a large embayment located on the west coast of Greenland (Figure 1). The water depth mostly ranges from 200 to 400 m, with a maximum of 990 m in the Egedesminde Dyb Trough, which is associated with the Jakobshavn Isbrae ice-streaming route (Lloyd et al., 2007; Long & Roberts, 2003). The Disko Bugt area is covered by winter sea ice reaching up to 70 cm in thickness (Buch, 2000). Spring sea-ice melt results in low surface-water salinity and a sharp halocline and thermocline until September, when surface air-temperature cooling increases the surface-water density and high wind speeds break the upper water mass stratification (Andersen, 1981; Andresen et al., 2011; Ribeiro et al., 2012). Disko Bugt is under the influence of the WGC, which is formed from the mixing of the warm and saline IC, a side-branch of the North Atlantic Current (NAC), and the fresh and cold EGC (Andersen, 1981; Buch, 1981; Buch et al., 2004; Tang et al., 2004; Figure 1). Hydrographic profiles from Disko Bugt show that the WGC occupies the subsurface to the bottom with temperatures reaching up to 3.5–4.5°C and salinity ranging between 34.0–34.4 psu, respectively (Andersen, 1981; Buch, 1981; Buch et al., 2004; Holland et al., 2008; Lloyd, 2006; Moros et al., 2016; Perner et al., 2011; Figure 1d). SSTs of $4.4 \pm 1.24^\circ\text{C}$ and SSSs in the range 32.9–33.4 are recorded during the summer months

(July-August-September) at the coring site (National Oceanographic Data Center, 2001). In winter, freezing results in a sea ice cover averaging 3.8 ± 1.3 months/yr (cf. 1953-2003 data compiled from the National Snow and Ice Data Center; NSIDC). The mean annual primary productivity compiled from the MODIS satellite observation is estimated to $171 \text{ gC/m}^2\text{/yr}$ (<http://modis.gsfc.nasa.gov/index.php/>; cf. Radi & de Vernal, 2008).

2.3 Materials and methods

2.3.1 New regional sites for the dinocyst database

With the objective to improve the coverage of the standardized reference dinocyst database published by de Vernal, Rochon, et al. (2013) in the study region, we have used an updated version that includes twenty-eight new surface-sediment samples from the West Greenland margin (Figures 1 and 2). These samples were collected from the uppermost centimeter at the surface of box cores and of Van Veen grab samples (see supplementary material).

2.3.2 Sediment core material and chronostratigraphy

The multicore and gravity core from site MSM343310 ($68^{\circ}38'861 \text{ N}$, $53^{\circ}49'493 \text{ W}$; water depth = 855 m) were collected in the Egedesminde Dyb Trough during the *Maria S. Merian* expedition MSM05/03 in June 2007 (Harff et al., 2007; Figure 1). The sediments are mostly composed of olive-brown to olive-grey mottled clay (Harff et al., 2007). The fraction $> 63\mu\text{m}$ fraction averages 4% of the dry weight (Perner et al., 2011). X-ray analysis showed occasional detrital grains, related to ice rafting (Perner et al., 2011).

The chronological framework was published by Lloyd et al. (2011) and Perner et al. (2011). It is based on 30 AMS ^{14}C dates of mollusc shells and mixed benthic

foraminiferal samples. AMS radiocarbon dates were calibrated with the Marine09 calibration curve (Reimer et al., 2009), using the OxCal 4.1 software (Bronk Ramsey, 2009). The marine reservoir offset estimated from the database of Reimer and Reimer (2001) and McNeely et al. (2006) yields ΔR values of 140 ± 30 years. According to Lloyd et al. (2011) and Perner et al. (2011), age uncertainties averages ± 125 years with a 95 % probability (2σ). In the multicore, 10 AMS ^{14}C dates and ^{210}Pb and ^{137}Cs measurements indicate that the 32-cm-long core spans the period from about 1900 CE to 2007 CE, with an average sedimentation rate of 3.7 mm/yr, based on a constant sedimentation rate model (see Lloyd et al., 2011). In the gravity core, 20 AMS ^{14}C dates suggest uniform sedimentation rates of about 3.5 mm/yr (Lloyd et al., 2011). The gravity core, which is 939 cm long, encompasses the period from about 3685 to 135 years cal. BP, which corresponds to 1685 BCE to 1815 CE. There is a temporal gap of almost one hundred years between the top of the gravity core and the base of the multicore.

2.3.3 Palynological analyses

In the multicore, which encompasses the last century, analyses were performed at 2-cm intervals, providing a mean time resolution of 5 to 8 years. In the gravity core, the upper 300 cm spanning from ~ 0.1 to ~ 1 ka BP, were analyzed at 4 cm intervals, with a mean time resolution of 12 to 15 years. The lower part of the core was analyzed at 8 cm intervals, yielding a mean time resolution of 25 to 35 years in the period ~ 1 to ~ 3.7 ka BP. Volumes of 3 to 5 cm³ sediment were prepared at the Geotop following the protocol described by de Vernal et al. (1996). After wet sieving, the 106-10 μm fraction was chemically treated with HCl (10%) and HF (50%) to dissolve carbonate and silicate particles, respectively. The final residue was mounted on microscope slides with glycerine-jelly for palynomorph identification using transmitted light microscopy at 400x and 1000x magnification. At least 300 dinocyst specimens were counted in each sample, which provides statistically reliable counts (e.g., Mertens et

al., 2009). The taxonomic nomenclature of dinocysts was based on Rochon et al. (1999) and Radi et al. (2013).

2.3.4 Quantitative treatment and reconstruction of sea surface conditions from the dinocyst assemblages

Multivariate analyses were performed using the CANOCO 5 software (ter Braak & Šmilauer, 2012; Lepš & Šmilauer, 2014) to describe the relationship between dinocyst assemblages and environmental parameters. A square root transformation was applied to the species abundance to reduce the effect of very dominant species (Palmer, 1993) and closed-sum percentage data (Butler 1981). Multivariate analyses were performed on the Disko Bugt core data. In the downcore samples, very rare taxa (i.e., found in less than five samples) were discarded from the analysis.

Reconstructions of sea surface parameters were obtained from the modern analogue technique (MAT), which relies on the similarities between fossil and modern assemblages to assess corresponding sea surface conditions (Guiot & de Vernal, 2007). The MAT was performed using the software package developed by Guiot for the R platform (<http://cran.r-project.org/>) and following the procedures described by de Vernal et al. (2013). The updated database we have used includes 73 taxa and 1,776 reference sites from mid-high latitude of the Northern Hemisphere (see supplementary material). For reconstructions, we proceeded with searches of five analogues after logarithmic transformation of the relative taxa abundances. The reconstructed parameters include the summer SST and SSS as well as the sea ice cover and mean annual productivity. The best estimates are calculated from the mean of the corresponding sea surface values weighted according to the similarity of the analogues. Validation exercises after dividing the database in 6 parts (five of six for calibration and one of six for the verification) yielded root-mean square errors of prediction of $\pm 1.6^{\circ}\text{C}$ for the summer SST, ± 2.1 psu for the summer SSS, ± 1.3 months/yr for sea ice cover and ± 66.9 gC/m²/yr for the productivity (all $\pm 1\sigma$). It is

important to highlight that the error of prediction of SSS is large because the database includes low-salinity environments (down to 5 psu), where the variability of surface salinity is particularly high. When considering only the >30 salinity domain, the error of prediction is ± 0.63 psu. The distance of the modern analogues provides an additional indicator of the reliability of the environmental estimates.

2.3.5 Time series analyses

For the spectral analysis we used the Lomb-Scargle Fourier transform (Lomb, 1976; Scargle, 1982), as this method is directly applicable to unevenly spaced data. The spectral analyses were carried out on data grouped in 1,000-year time windows with a spacing of 50 years. The univariate spectra were bias-corrected using 1,000 Monte-Carlo simulations, based on the software package REDFIT (Schulz & Mudelsee, 2002), which automatically produces first-order autoregressive (AR1) time series with sampling times and characteristic timescales matching the measured data. This approach makes it possible to assess the statistical significance of the spectral peaks. For these time-dependent frequency plots, the dark red colour indicates 99% of significance, the light red colour indicates 95% and the yellow color 90%.

Wavelet analysis was done in MATLAB using the cross-wavelet analysis (XWT) software package of Grinsted et al. (2004). As the wavelet analysis requires evenly spaced data, the data were normalized and linearly interpolated onto an equidistant timescale with a resolution of 10 years. The time series were padded with zeros to dampen edge effects and reduce spectral leakage, which may result in underestimation of the lowest frequencies near the edges, as defined by the cone of influence in the figures.

2.4 Modern distribution of dinocysts along the west Greenland margin

We analysed 28 new surface sediment samples to be added to the existing dinocyst database. A total of 26 dinocyst taxa were identified, 16 of which were common (Figure 2) and 8 dominant. The dominant taxa were *Nematosphaeropsis labyrinthus*, *Operculodinium centrocarpum*, *Spiniferites elongatus*, the cyst of *Pentapharsodinium dalei*, *Islandinium minutum*, *Islandinium? cezare*, *Brigantedinium* spp. and *Selenopemphix quanta* (Figure 2). The diagram of Figure 2 shows a south to north distribution of taxa. *Nematosphaeropsis labyrinthus* occurred in relatively high percentages in the south, up to the latitude of the Disko Bugt. *Operculodinium centrocarpum* was dominant mostly north of 68°N and recorded maximum percentages north of 70°N, where the sea ice cover spans more than 5 months per year. *Spiniferites elongatus* was rare in the sea-ice free zone, south of 65°N, and common (~5%) in the seasonal sea-ice domain. *Pentapharsodinium dalei* was present in all samples but recorded its highest abundance in the Disko Bugt area where it accounted for more than 30% of the assemblage. *Islandinium minutum* was abundant in all samples. All other heterotrophic taxa such as *Islandinium? cezare*, *Brigantedinium* spp. and *Selenopemphix quanta*, were more common in the south than in the north (Figure 2).

In order to describe the environment versus dinocyst relationships in Arctic-subarctic regions where the modern analogues for the Disko Bugt core samples were found, we have built a sub-dataset from the hemispheric database. It includes 836 sites and the 16 taxa occurring in the assemblages from the Disko Bugt core (this study). It encompasses all sites of the Arctic Ocean and subarctic North Atlantic north of the Arctic Circle, in addition to lower latitude sites also characterized by winter sea ice cover (Figure 3). The detrended correspondence analysis (DCA) indicates that the length of the ordination axis is equal to 2.6 standard deviations, suggesting a linear relationship and making the principal components analysis (PCA) the most

appropriate technique (ter Braak & Šmilauer 1998). The first axis (PCA1) explains 46.87% of the variance and the second axis (PCA2) explains 22.09% (Figure 3). The first axis is characterized by positive scores of heterotrophic taxa, notably *Brigantedinium* spp. and *Islandinium*. It shows an opposition between the sea ice cover and the other parameters, which include summer SST, SSS and productivity (Figure 3). The new surface dataset show a decrease in abundance of these species with increasing sea ice cover, at least regionally (Figure 2) and higher occurrence of the cyst of *Pentaparsodinium dalei* in opposition to *Islandinium* (Figure 3), which suggests that temperature and sea ice plays a determinant role in the distribution of assemblages. Moreover, seasonal sea ice environments are often characterized by high diatom productivity (e.g., Gosselin et al., 1997; Poulin et al. 2011), which is usually favorable to heterotrophic dinoflagellates (e.g., de Vernal, Rochon, et al., 2013; Hamel et al., 2002; Radi & de Vernal, 2008). The second axis shows an opposition between productivity, summer SST and sea ice cover on the positive side, and salinity and winter SST on the negative side (Figure 3). Hence, the second component seems to reflect neritic versus open ocean gradients, with *O. centrocarpum*, *N. labyrinthus* and *I. pallidum* being associated with offshore conditions (cf. also, de Vernal et al., 2001; Matthiessen et al., 2005; Rochon et al., 1999).

2.5 Dinocyst ecostratigraphy and hydrographic variations of the last ~3,600 years in the Disko Bugt

2.5.1 Dinocyst assemblages

In this study, 170 samples were analyzed (17 from the multicore and 153 from the gravity core). We also included 41 sample results from the gravity core MSM343310 published by Ribeiro et al. (2012). We therefore report here on a total of 211 downcore samples spanning the last ~3,600 years. The palynological assemblages are largely dominated by dinocysts, which record concentrations ranging from 10^4 to 3.1

$\times 10^5$ cyst/cm³. Such concentrations are very high (cf. Rochon & de Vernal, 1994). Using a mean sedimentation rate of 3.5 mm/yr, we calculate fluxes in the order of 10^3 to 10^5 cysts/cm²/yr.

A total of 16 dinocyst taxa were identified. Nine of them represented more than 98% of the assemblages: *Islandinium minutum* sensu lato, the cyst of *Pentapaharsodinium dalei*, *Brigantedinium* spp., *Islandinium? cezare*, *Operculodinium centrocarpum*, *Selenopemphix quanta*, *Spiniferites elongatus* sensu lato, *Spiniferites ramosus* and *Nematosphaeropsis labyrinthus* (Figure 4).

2.5.2 Dinocyst zonation

Multivariate analyses were performed to characterize the dinocyst assemblages. The detrended correspondence analysis (DCA) resulted in an ordination axis of 0.9 standard deviations, suggesting a linear relationship and principal components analysis (PCA) as the appropriate technique (ter Braak & Šmilauer 1998). The first axis (PCA1), which opposes *I. minutum* and *I.? cezare* on the negative side and other dominant taxa on the positive side, explains 49.09% of the variance (Figure 5). *Islandinium* is characteristic of seasonal sea ice cover as mentioned above (Figure 3) and in the literature (cf. de Vernal, Rochon, et al., 2013; de Vernal et al., 2001, 2005; Head et al., 2001; Rochon et al., 1999). Both *I. minutum* and *I.? cezare* are common in subpolar to polar environments and their highest relative abundance is found in regions of low SSS and strong seasonal sea ice cover (de Vernal, Hillaire-Marcel, et al., 2013; de Vernal et al., 2001, 2008; Matthiessen et al., 2005). Hence, the first axis would mainly relate to sea ice cover and temperature. The large distance between the cyst of *P. dalei* and the other dominant taxa characterizes the second axis and explains 20.57% of the distribution. The cyst of *P. dalei* is common in Arctic and subarctic areas (Dale, 1996; Matthiessen et al., 2005; Rochon et al., 1999). It is characteristic of neritic environments. Its distribution suggests that it is dominant in areas experiencing large seasonal temperatures gradients linked to strongly stratified

surface waters, from freezing in winter to mild conditions in summer (Rochon et al., 1999).

The major change in assemblages at about 1.5 ka BP (from GC-B to GC-A; Figure 4) corresponds to a shift from positive to negative PCA1 marked by an increase of *I. minutum* and *I.? cezare* percentages. The dominance of *I. minutum*, the relatively high percentage of *I.? cezare*, and the very low occurrence of most phototrophic taxa in zone GC-A zone suggests colder surface water conditions (Figures 2 and 4).

Sub-zone GC-B2 is distinguished by positive PCA2 and spans from the base of the analyzed sequence to ~3.1 ka BP (Figure 4). It is characterized by abundant *P. dalei* and *I. minutum*, which on average represent 37 and 28% of the assemblage, respectively. This sub-zone also records the highest abundances of *O. centrocarpum* (~6%).

Sub-zone GC-B1 spanning ~3.1 to 1.5 ka BP shows negative PCA2. *I. minutum* is still common (~31%), but *P. dalei* is also abundant (~25%) together with *Brigantedinium* spp., (~24%). *S. elongatus*, *S. ramosus*, *O. centrocarpum* and *S. quanta* are present (Figure 4 and 5).

In the upper zone GCA, several sub-zones are distinguished. The lowest one, GC-A3 spanning ~1.5-1 ka BP, has negative PCA 1 and PCA 2. As mentioned above, it is characterized by abundant *I. minutum* (~47%) and *I.? cezare* (~8%). It is also marked by low *P. dalei* percentages (~21%), decreasing abundance of *Brigantedinium* spp. and very low occurrence of *S. quanta*. Sub-zone GC-A2, spanning ~1-0.6 ka BP, is defined by positive PCA2 scores. It is characterized by dominant *I. minutum*, *P. dalei*, *Brigantedinium* spp., and *I.? cezare*, and very rare *N. labyrinthus* and *S. ramosus*.

Sub-zone GC-A1, between ~600 and 150 years BP, is characterized by negative PCA1 and mostly negative PCA2. It records the highest percentages of *I. minutum* of the whole core (up to 68%), a decrease of *P. dalei* 20% and a very low abundance of phototrophic cysts.

Finally, the multicore spanning broadly the last century is characterized by positive PCA1 and PCA2. The dominant species are *P. dalei* (28-72%), *I. minutum* (~30%) and *Brigantedinium* spp. (~17%).

2.5.3 Reconstruction of sea surface conditions

The reconstructions from MAT using the $n = 1,776$ dinocyst database yield good results since close analogues are found for each sample, with distance well within the threshold value of 1.2 (Figure 6). Moreover, the fact that sea surface reconstructions from the recent MUC zone are within the range of modern instrumental data suggest that the estimates are reliable (Figures 6 and 7).

The reconstructions show a major change in sea surface conditions at about 1.5 ka BP corresponding to the transition from assemblage zone GC-B to GC-A. It is marked by an important shift from stable, winter-only sea ice cover (3-4 months/yr), to unstable conditions punctuated by pulses of sea ice spreading up to 8 months/yr and highly variable summer SSS and summer SST. The reconstructions also indicate a recent shift towards warmer and more stable reduced sea ice cover (2-4 months/yr) about one 100 years ago (Figure 6).

The SSS, SST, and productivity records oscillate throughout the entire sequence. The summer SSS generally varies from 30 to 32 with a centennial-scale pacing in addition to a long-term decreasing trend from averages of 31.5 psu in subzone GC-B2 to 30 psu subzone GC-A1. Reconstructed summer SSTs suggest large amplitude variations from about 4 to 10°C, with lower values and a general

increasing trend in sub-zone GCB, prior to ~ 1.5 ka BP. The mean annual productivity ranges 100 to 400 $\text{gC/m}^2/\text{yr}$ and records variations parallel to summer SST (Figures 3 and 6). In this seasonal sea ice environment, plankton blooms occur in the summer, when sea surface conditions are warmer (Matthiessen et al., 2005; Ribeiro et al., 2012) and primary productivity often co-varies with summer temperature (Radi & de Vernal, 2008). The most striking feature of the records is that the variation of summer SSS that is generally opposite to changes in summer SST. This strongly suggests variations in the stratification of the surface water layer, directly impacts the thermal inertia of surface water, a shallow pycnocline connected with lower salinity fosters summer warming within the shallow surface layer, whereas thermal diffusion is less efficient over a thick layer.

2.5.4 Time-series analyses of the dinocyst-based reconstruction and comparison with Greenland ice core data

The summer SST and SSS reconstructed from dinocyst assemblages show high frequency variations, which seem to follow a pattern not unlike that recorded in the Greenland ice cores through the $\delta^{18}\text{O}$ of ice, notably at the Camp Century site (e.g., Vinther et al., 2009; Figure 7). To test the consistency between the climate time series established from such independent proxy reconstructions, we carried out two types of analyses. The first one is the Lomb-Scargle analysis (Schulz & Mudelsee, 2002), which does not require evenly spaced data points, thus allowing us to analyze the time series without interpolation of the data. The results show a variability of summer SST and SSS with two distinct periodicities, one of 200-years before ~ 2 ka BP and the other of 60-70-years after ~ 1.5 ka BP (Figure 8).

The second analysis is a cross-wavelet analysis (Torrence & Compo, 1998) using both the dinocyst reconstructions from core MSM343310 and the Camp Century $\delta^{18}\text{O}$ data. The results indicate a significant degree of coherency between

summer SST and SSS with the $\delta^{18}\text{O}$ of the Camp Century ice core, notably after ~ 1.5 ka BP with a period of 60-80-years.

The results illustrate an important change in the mode of variability between ~ 2 and ~ 1.5 ka BP. Because the onset of the high frequency multidecadal variability occurred slightly before the change in the sampling interval (at ~ 1.1 ka BP), we wanted to make sure that the change of regime was not an artefact of the different temporal resolution of analyses. To avoid any misinterpretation due to sampling resolution, we resampled the dataset randomly to obtain constant time step record. The calculated resulting variability was the same for the reconstruction before and after resampling (Figure 7). Consequently, we are confident that the change of periodicity in sea surface variability at about 1.5 ka BP is real.

2.6 Discussion

2.6.1 The transition at about 1.5 ka BP

Our data show distinct types of variability in the regional hydrographic conditions of the Disko Bugt during the late Holocene. From ~ 3.6 ka BP to about ~ 1.5 ka BP, relatively stable sea ice cover conditions prevailed in the surface waters with variable sea surface salinity and temperatures during the summer. The variations during this time interval, in particular prior to ~ 2 ka BP, have a 200-year pacing. After ~ 1.5 ka BP, sea surface conditions record large-amplitude variations of summer SSS and SST and sea ice cover associated with cooling pulses during which sea ice cover reached up to 8 months/yr. The hydrographic variations during this interval follow a 60-70-years pacing, which appears consistent with the $\delta^{18}\text{O}$ -variability calculated for the Camp Century ice-core record (Figures 7 and 8). Hence, two different modes of climate variability prevailed in the area before and after a transition that occurred between ~ 2 and ~ 1.5 ka BP (Figure 8). The transition is marked by both a change in

the frequency of variations and an increase in their amplitude. The Lomb-Scargle analysis of the total solar irradiance (TSI), which is reconstructed from ^{10}Be in ice cores and ^{14}C in tree rings (Steinhilber et al., 2012), also suggests a global transition at ~ 1.5 ka BP (Figures 7 and 8).

The nature of the oceanic change in our dinocyst record can be illustrated from the location of analogues in the modern database. Before ~ 1.5 ka BP, the dominant analogues have modern locations along the southwestern Greenland margin and in the Gulf of St. Lawrence; after ~ 1.5 ka BP, the location of analogues is much more heterogeneous and includes samples from Hudson Bay and Chuckchi Sea, pointing to unstable and occasionally very cold conditions (Figure 7).

The major oceanic change at ~ 1.5 ka BP in the Disko Bugt has been reported in other studies (Andresen et al., 2011; Krawczyk et al., 2010, 2013, 2017; Lloyd et al., 2007; Moros et al., 2006, 2016; Ouellet-Bernier et al., 2014; Perner, Moros, Jennings, et al., 2013; Perner et al., 2011; Ribeiro et al., 2012; Seidenkrantz et al., 2008; Sha et al., 2014) and seems to correspond to a general cooling phase. However, the high-frequency variability in sea surface conditions we have reconstructed for the Disko Bugt area has not been previously reported. This could be due to insufficient time resolution or to the sensitivity of the proxies used. It is also possible that our reconstructions reflect hydrographical features that are more local and therefore not distinguishable in larger-scale regional records.

2.6.2 The mode of variability prior to ~ 1.5 ka BP

The interval prior to ~ 1.5 ka BP is characterized by a decreasing trend of summer SSS concomitant with an increase in summer SST. As mentioned above, the opposite trends in salinity and temperature most likely illustrate enhanced water column stratification. It might also reflect increased temperatures fostering higher glacier melt rates, and thus lower salinity. A relatively strong WGC at the subsurface seems to

have occurred during this time interval (Moros et al., 2016; Perner, Moros, Jennings, et al., 2013; Perner et al., 2011), which would be compatible with ocean warming contributing to enhanced glacier melt rates.

Superimposed on the main trends, there is a variability in summer SSS and SST with a dominant ~200 years periodicity (Figure 8). Whereas the amplitude of temperature variations is small, that is, lower than the associated uncertainty of the approach, the amplitude of the salinity oscillations is up to 2 psu and appears significant. Although SST and SSS show a phase opposition, the variations of both parameters are consistent. As above, these oscillations might be interpreted in terms of variations in stratification and/or as the result of enhanced glacier melting under warmer conditions. The isotopic composition of the ice is generally used as a climate proxy, as it relates to the isotopic composition of precipitation, which in turn depends upon air temperature and atmospheric circulation patterns (e.g., Johnsen et al., 2001; Jouzel et al., 1997; Masson-Delmotte et al., 2005; Steiger et al., 2017; Sturm et al., 2010; Vinther et al., 2009). In the present case, assuming that our reconstructions represent regional surface-water conditions, the relationship between sea surface temperature and the atmospheric-driven $\delta^{18}\text{O}$ of the ice is striking and may reflect causal relationship. The ocean-atmosphere exchanges in the Labrador Sea/Baffin Bay corridor necessarily play a role with respect to the isotopic composition of atmospheric vapour at the origin of precipitation over northwest Greenland. The isotopic composition and/or temperature of surface waters along western Greenland may have played a role on the $\delta^{18}\text{O}$ variability at Camp Century. Firstly, because the glacier ice is characterized by highly $\delta^{18}\text{O}$ -depleted isotopic compositions, any dilution of coastal waters by glacier meltwater would result not only in a lower salinity and more stratified surface waters, but also in lower water isotopic compositions in the surface layer. Secondly, a stronger stratification of surface waters would also result in stronger seasonal temperature shift, with enhanced summer warming, leading to enhanced melting along the ice margin. Therefore, the link

between the salinity at Disko Bugt and the $\delta^{18}\text{O}$ variability at Camp Century seems to be the production rate of glacier meltwater.

If this hypothesis is correct, then both our marine record and that of Camp Century are capturing episodes of enhanced glacier ice melting with a pacing of about 200 years. Such a periodicity seems to correspond to the Suess cycle, which is described as a ~210-year periodicity in solar activity, that is, a beating pulse that was particularly strong from 3.2 to 1.85 ka BP, as documented by ^{14}C in tree rings and ^{10}Be in ice cores (Damon & Sonnett, 1991; Knudsen et al., 2009, 2012). Speleothem $\delta^{18}\text{O}$ records also indicate that the Suess solar cycle exerted a higher influence on the climate system during intervals characterized by particularly large amplitude variations in solar activity (Knudsen et al., 2012). The ~200-year periodicity in SSS and SST observed in the Disko Bugt sequence has a frequency and timing that closely corresponds to the interval characterized by a high-amplitude of the ~210-year solar cycle, which is also recorded in the TSI (Figures 7 and 8), thus suggesting that solar variability drove changes in SSS and SST in the Disko Bugt prior to ~1.5 ka BP. The sea ice cover reconstruction is relatively stable during this time interval despite variability of other parameters. The apparent lack of variability in the sea ice cover, which occurred only in winter, led us to suppose that climate variability before ~1.5 ka BP mostly affected the summer conditions and not the winter sea ice cover.

After 1.5 ka BP, more unstable conditions are recorded with large amplitude changes of SSS, SST and sea ice cover, which reached up to 8 months/yr during cold pulses (Figure 7). Additionally, a more variable TSI also seems to be a characteristic feature of interval (Figure 7). Unlike the interval before 1.5 ka BP that was characterized by anti-phase behaviors of SSS and SST variations, pulses of cold summers coinciding with low levels of reconstructed salinity. Also, after 1.5 ka BP, increased sea ice cover corresponds to a decrease in summer SSS, with the melting sea ice adding low-salinity surface waters. Hence, not only the variability but also the

processes governing sea surface conditions differed before and after ~1.5 ka BP. Moreover, whereas phases of depletion in the $\delta^{18}\text{O}$ of the Camp Century ice-core are recorded, the low/high $\delta^{18}\text{O}$ -values no longer correspond to low/high salinity. The opposite seems more frequent (Figure 7). The low-salinity intervals rather than reflecting continental ice melts, likely relate to the melting of large volumes of sea ice due to pronounced cooling. Unlike continental ice melt, this process has limited impact on the isotopic composition of surface waters, when it does not lead to a slight enrichment in ^{18}O (cf. Hillaire-Marcel & de Vernal, 2008). Hence, after ~1.5 ka BP, both the marine and the Camp Century data seem to primarily record cooling pulses. Cross-wavelet analyses demonstrate a significant degree of coherency between summer SST and SSS and $\delta^{18}\text{O}$ values of the Camp Century ice core, with a periodicity of period of ~60-80-years (Figure 8). Such a mode of variability can be compared with the pacing of the Atlantic Multidecadal Oscillation (AMO; Knudsen et al., 2011, 2014). The AMO is an oscillation characterizing the average annual sea surface temperature of the North Atlantic (Kerr, 2000) with a periodicity of 55 to 70 years (Knudsen et al., 2011). During the late Holocene, the long-term cooling of western Greenland seems to have been associated with an increase in the sea ice cover, a southward migration of the sea ice front, a weakened WGC, and AMOC slowdown (Krawczyk et al., 2017; Moros et al., 2016; Ouellet-Bernier et al., 2014; Perner, Moros, Jennings, et al., 2013; Perner et al., 2011; Thomas et al., 2016). It would also correspond to a southwestward movement of the atmospheric polar front, which resulted in higher sensitivity of central Greenland to the AMO (Knudsen et al., 2011).

The high-frequency variability reconstructed here is not clearly recorded in earlier marine studies, but the trends towards cooler conditions after 1.5 ka BP is consistent with earlier records. Based on benthic foraminiferal assemblages, Perner et al. (2011) and Perner, Moros, Jennings, et al. (2013) suggested that the sub-surface WGC weakened after ~1.7 ka BP. Moreover, the gradual cooling has been associated

with regionally unstable climate conditions and intensification of storms, and enhanced water mass mixing (Moros et al., 2016). An intensification of the atmospheric circulation, which was notably documented over southern Greenland with a 50 to 55 years periodicity from 1.1 to 0.7 ka BP (Kuijpers & Mikkelsen, 2009), may have played a role in the climatic degradation along the west Greenland margin after 1.5 ka BP. The interval around 1.2 to 0.7 ka BP shows particularly harsh conditions, not only in the reconstructions of Kuijpers and Mikkelsen (2009), but also in our sea ice estimates reaching a maximum extent at 0.9-0.7 ka BP and an abrupt decline of alkenone-based temperature off west central Greenland around 0.85 ka BP (D'Andrea et al., 2011). Moreover, April sea-ice reconstructions by Krawczyk et al. (2017) from MAT applied to diatom assemblages suggest increase of April sea-ice concentrations to more than 70% from 1.2 to 0.7 ka BP.

A regional shift at ~1.5 ka BP in relation to a change in atmospheric circulation seems likely (see also Axford et al., 2013; Thomas et al., 2016), and is consistent with the hypothesis of a southwestward migration of the polar front.

2.7 Conclusion

This study demonstrates large variations of sea surface conditions during the late Holocene in the Disko Bugt area partly in phase with the Camp Century ice-core record.

One of the main features captured by this study is a strong shift in the dominant processes and mode of variability that occurred at ~1.5 ka BP. Relatively stable conditions with respect to winter sea ice characterized the Disko Bugt area prior to this transition, when oscillations in ocean salinity and temperature occurred with a pacing of about 200-years likely following the Suess solar-cycle burst (cf. Knudsen et al., 2009). These variations can be associated with glacier-ice meltwater

discharge changes that impacted both the salinity and isotopic composition of surface waters. In addition, increased discharge caused enhanced stratification and thermal inertia in the upper part of the water column causing anti-correlation of summer SSS and summer SST. Such variations appear to be triggered by warming pulses driven by solar forcing. After ~1.5 ka BP, the processes and mode of variability in surface waters changed. Much more unstable winter conditions with episodic spreading of sea ice up to 8 months/yr and high-frequency variations in ocean salinity and temperature were recorded with a dominant periodicity of 60-70 years. These variations are consistent with fluctuations in the isotope record of Camp Century and point to successive cooling phases that might correspond to a regional signature of the Atlantic Multidecadal Oscillation (AMO) mode of variability.

This study therefore highlights a major change marked by a cooling associated with a southwestward migration of the atmospheric polar front at about 1.5 ka BP and also suggests the onset of unstable hydrographic regime, at least regionally.

At last, the recent warming is reflected in the uppermost section of this record, over the last 100 years, by a shift in assemblage composition that corresponds to warmer sea surface and reduced sea ice cover.

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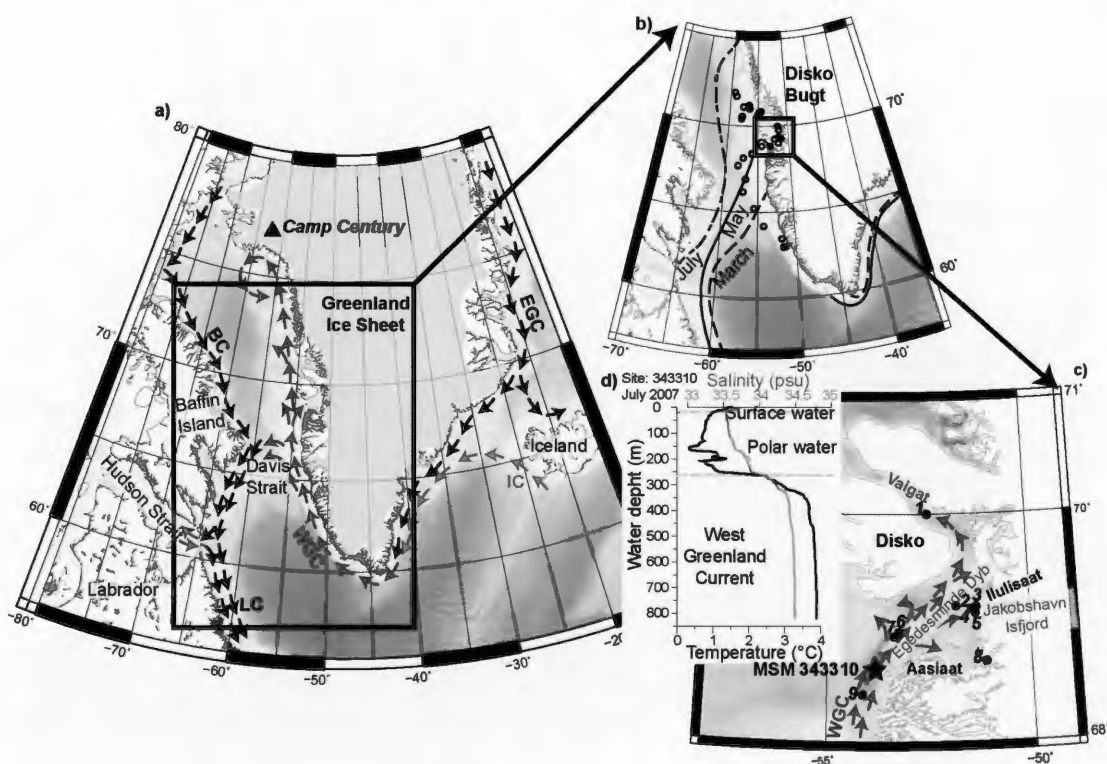


Figure 2-1: Location maps. (a) Predominant oceanic circulation pattern around Greenland. EGC = East Greenland Current; IC = Irminger Current; WGC = West Greenland Current; LC = Labrador Current; BC = Baffin Current; the gray arrows indicate warm and saline water and the black arrows indicate polar and low salinity water. (b) Location of new sites, near the West Greenland coast, included in the modern dinocyst database $n = 1,776$ (this study). The July, May and March sea-ice edge medians are drawn after the 1981-2010 data available from the National Snow and Ice Data Center (NSIDC; <http://nsidc.org/data/bist/>). (c) Detail view of the Disko Bugt area. The black star marks the study core location (MSM 343310) and the dots indicate the other cores collected on Disko Bugt and referred to in this study (cf. Table 1). (d) Temperature-salinity profile at site MSM 343310 in July 2007 (Harff et al., 2007).

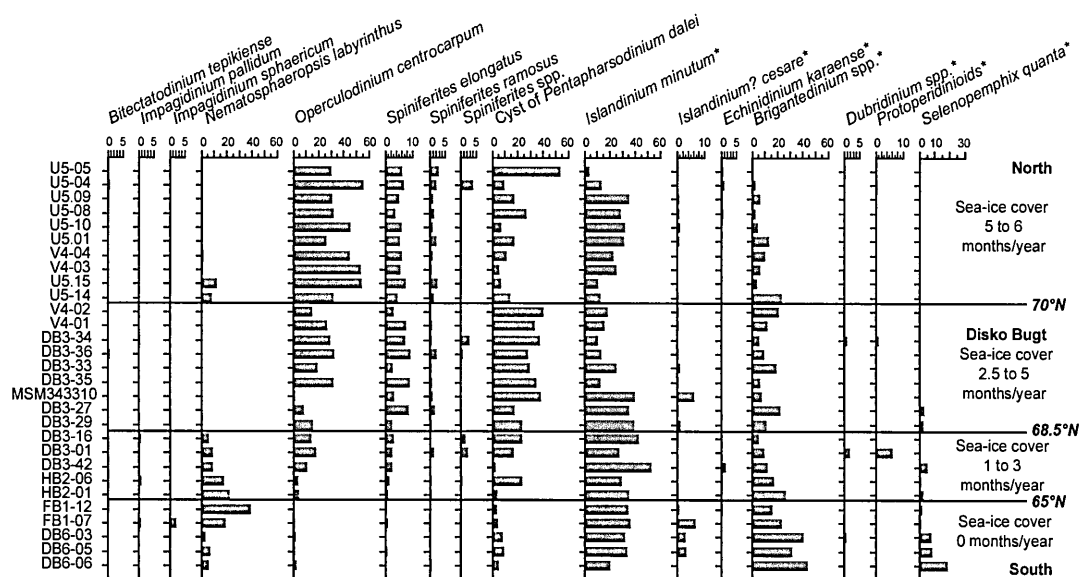


Figure 2-2 : Diagram of dinocyst percentages in the new surface sediment samples from north to south along the West Greenland margin (cf. Figure 1). For comparison, the data from the uppermost sample of core MSM343310 has been included in the diagram. An asterisk indicates the heterotrophic taxa. The zonation, from south to north, corresponds to seasonal extent of sea ice cover (cf. Figure 1).

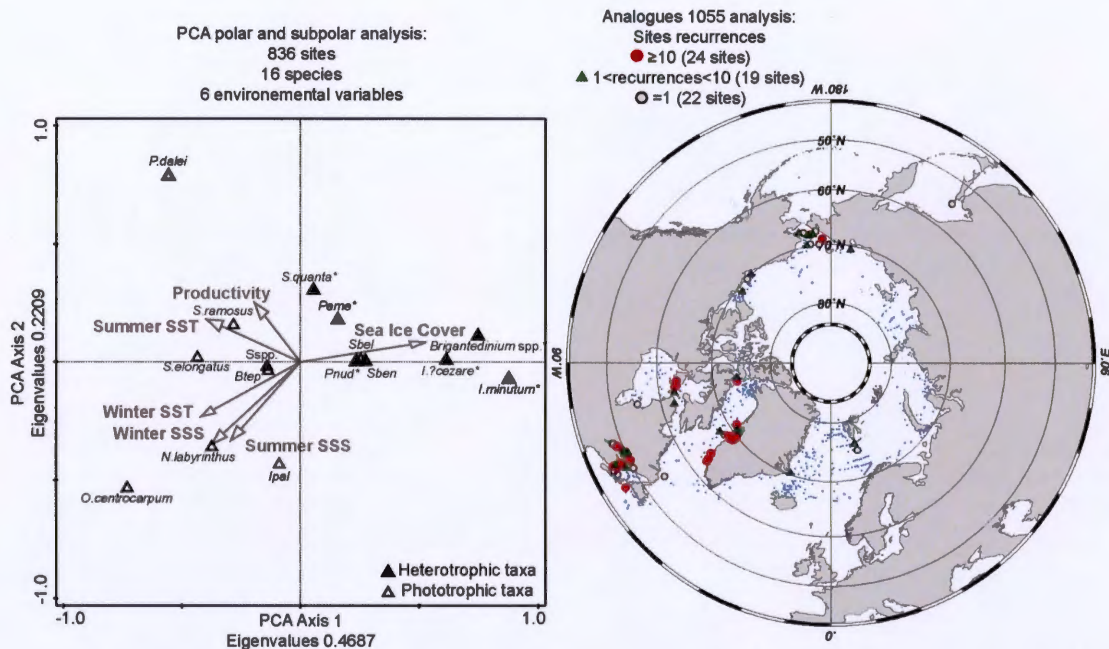


Figure 2-3 : Principal component analysis (PCA) analysis applied to the subset of sites ($n = 836$) from to polar and subpolar environments, including modern analogues sites selected during the downcore reconstruction (see map to the right). The taxa plot in the PCA are indicated either by their species name (dominant taxa) or by four-letter acronyms (*Btep*: *Bitectatodinium tepikiense*, *Pame*: cyst of *Protoperidinium americanum*, *Pnud*: cyst of *Protoperidinium nudum*, *Ipai*: *Impagidinium pallidum*, *Sbel*: *Spiniferites belerius*, *Sben*: *Spiniferites bentorii*, *Sspp*: *Spiniferites spp.*). The heterotrophic taxa are indicated by asterisks.

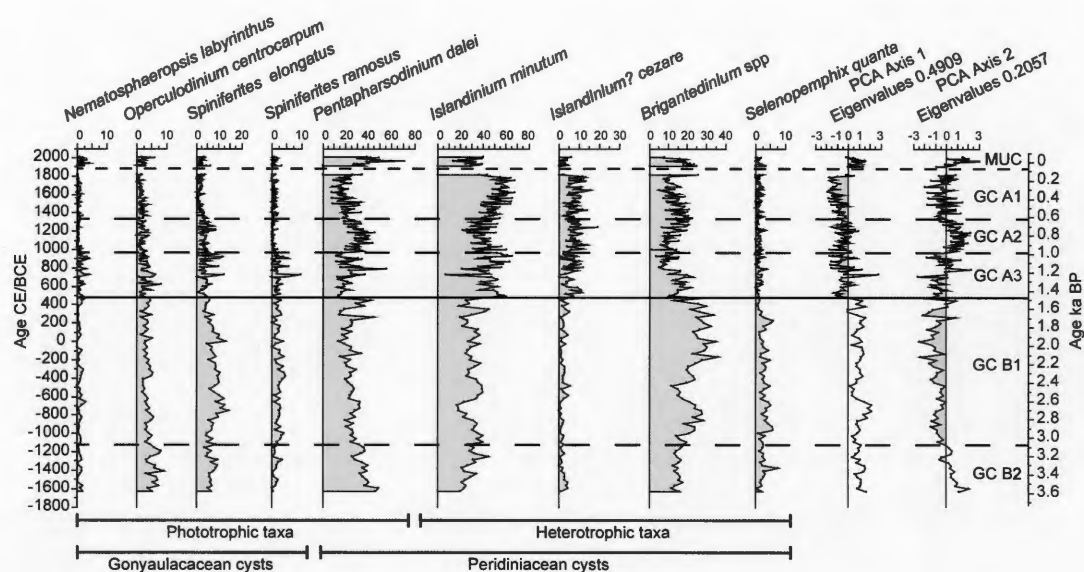


Figure 2-4 : Percentages of the main dinocyst taxa (>2%) and scores of principal component analysis (PCA) axes 1 and 2 in core MSM343310. The PCA1 led to distinguish three zones: MUC and GC B with positive values, and GC A with negative scores. MUC = multicore; GC = Gravity Core. The PCA2 allows us to distinguish subzones.

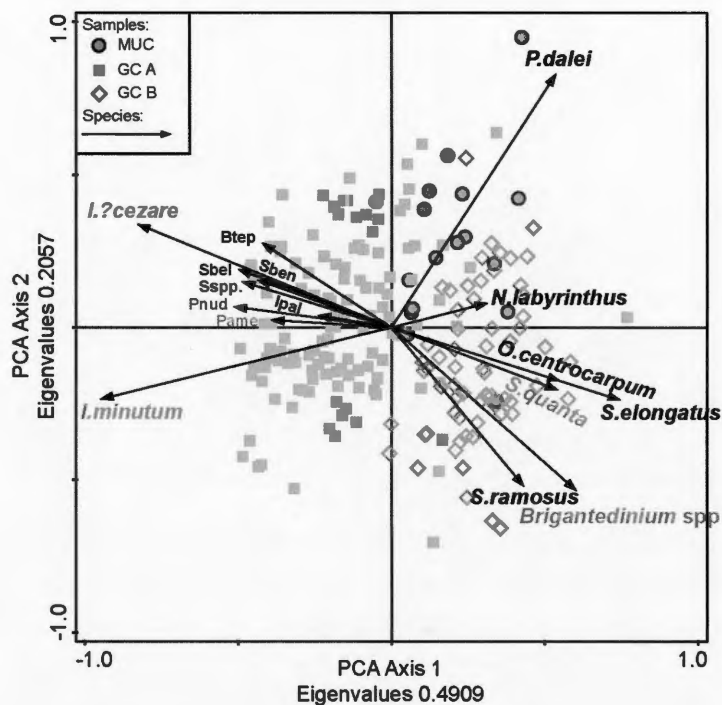


Figure 2-5 : Ordination diagram of the dinocyst taxa from the downcore assemblages of Disko Bugt, according to the two main axes, PCA1 and PCA2. The symbols correspond to the assemblage zones as shown in the diagram of Figure 4. The names of heterotrophic taxa are in grey and those of phototrophic taxa in black. The acronyms of taxa are the same as in Figure 2.

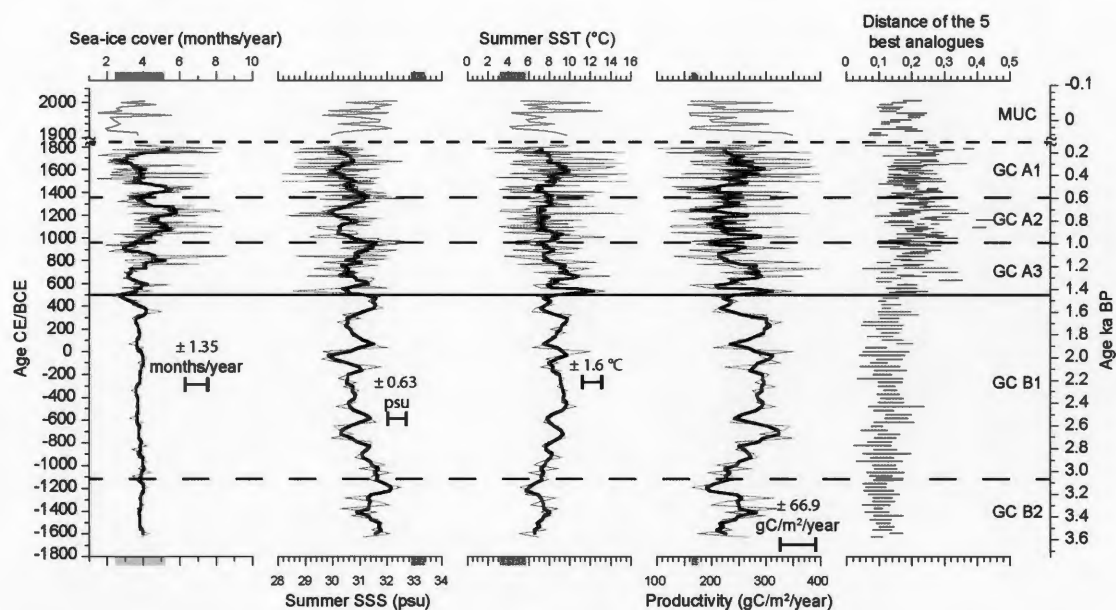


Figure 2-6 : MAT reconstruction of sea ice cover, primary productivity, sea surface temperature (SST) and salinity (SSS) in summer, and distance of the five closest analogues from dinocyst assemblages in core MSM343310. The modern values of sea surface parameters (mean $\pm$ one sigma) are indicated by horizontal rectangles on the upper axis and the bar indicates the error of prediction. The smoothing window of reconstructions from the gravity core is 90 ± 25 years.

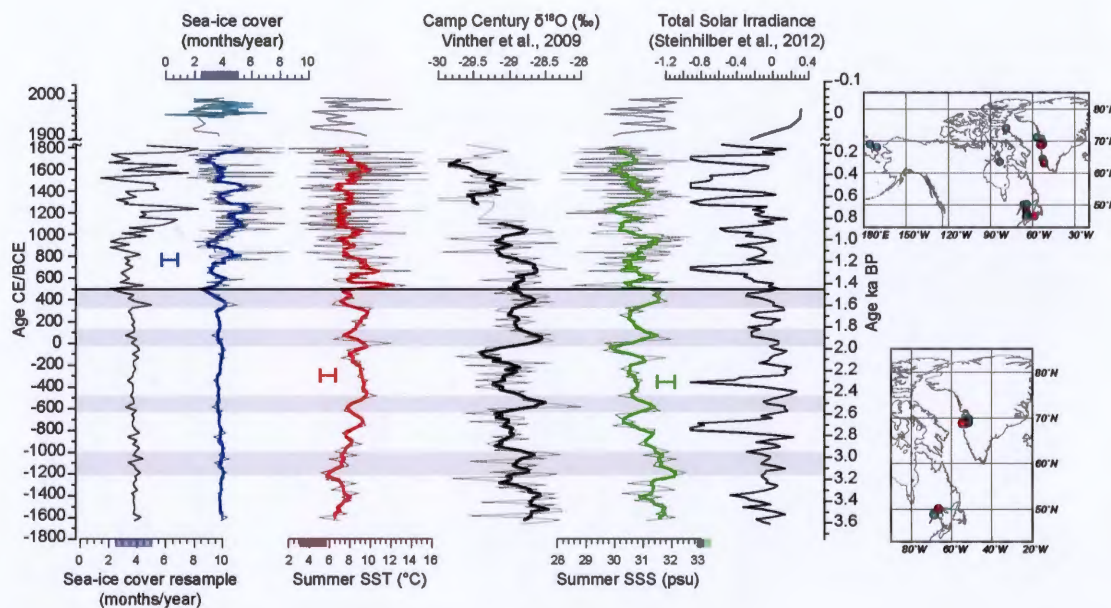


Figure 2-7 : Regional variations in oceanic and atmospheric conditions during the late Holocene. The sea ice cover (months/yr), summer temperature (SST, °C) and summer salinity (SSS, practical salinity unit (psu)) reconstructed from modern analog technique (MAT) applied to dinocyst assemblages, are compared with $\delta^{18}\text{O}$ values of Camp Century ice (‰) from Vinther et al. (2009) and the total solar irradiance from Steinhilber et al. (2012). Instrumental data for recent sea surface conditions are indicated by horizontal rectangles on scale bars. The sea ice cover graph on the left side shows results after random resampling for constant time step along the analyzed time series. The dots on the maps (right) indicate the location of the most common analogues (> 10 occurrences in blue and > 40 occurrences in red) used for reconstruction before (lower map) and after (upper map) ~1.5 ka BP. The grey bars highlighted the similar pacing in the variations reconstructed from dinocysts and the $\delta^{18}\text{O}$ values of Camp Century.

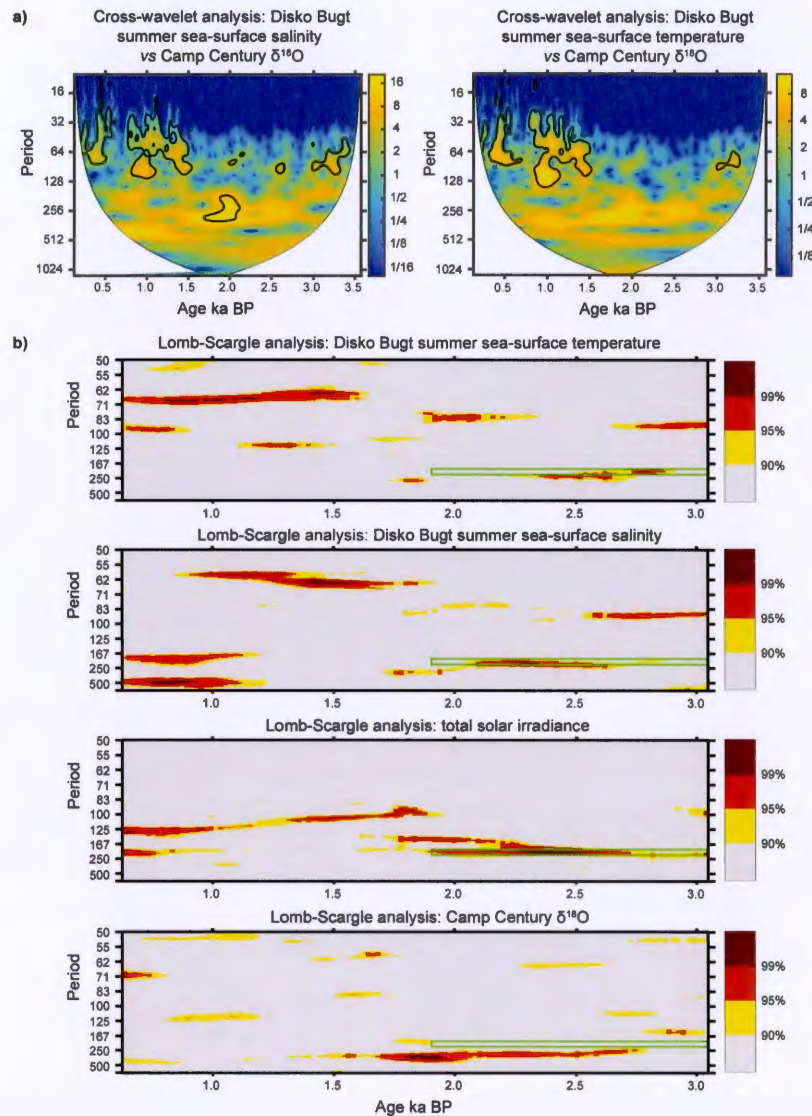


Figure 2-8 : Spectral analysis of the time series. (a) Cross-wavelet analysis between sea surface salinity and temperature marine reconstructions (this study) and the $\delta^{18}\text{O}$ values in the Camp Century ice-core (Vinther et al., 2009). (b) Lomb-Scargle analysis of sea surface temperature and salinity reconstructions (this study), total solar irradiance from Steinhilber et al. (2012) and the $\delta^{18}\text{O}$ values in the Camp Century ice-core (Vinther et al., 2009). In the power spectrum plots, the dark red, red and yellow colors correspond to 99%, 95% and 90% of significance. The green rectangle corresponds to the 1,850-3,200 years BP Suess solar-cycle burst (cf. Knudsen et al., 2009).

Table 2-1 : Overview of sediment cores studies and proxies referred to in the text and Figure 1c.

Site ID	Site name	Latitude	Longitude	Water depth (m)	Proxy	Citations
1	DA06-139G	70°05.48 N	52°53.58 W	384	Dinocysts, Foraminifera, Diatoms	Andresen et al., 2011; Sha et al., 2014
2	POR18	69°10.54 N	51°49.38 W	379	Foraminifera	Lloyd et al., 2005
3	POR21	69°10.3 N	51°17.6 W	279	Foraminifera	Lloyd et al., 2006
4	DA00-06	69°10.21 N	51°23.71 W	363	Foraminifera	Lloyd et al., 2005
5	POR20	69°10.0 N	51°21.5 W	313	Foraminifera	Lloyd et al., 2006
6	DA00-03	69°00.00 N	53°08.00 W	852	Diatoms, Foraminifera, Dinocysts	Moros et al., 2006, Lloyd et al., 2007, Seidenkrantz et al., 2008
7	DA00-02	68°51.88 N	53°19.72 W	840	Dinocysts, Diatoms	Seidenkrantz et al., 2008; Krawczyk et al., 2010
8	DA00-05	68°42.92 N	51°06.42 W	335	Diatoms, Foraminifera	Moros et al., 2006; Lloyd et al., 2007
9	MSM 343310	68°38.86 N	53°49.49 N	855	Foraminifera, Diatoms, Dinocysts, Alkenone, Diatoms	This study; Perner et al., 2011; Ribeiro et al., 2012; Krawczyk et al., 2013; 2017; Moros et al., 2016
10	MSM 343300	68°28.31 N	54°00.12 N	519	Foraminifera, Dinocysts, Alkenone, Diatoms	Perner et al., 2013a; Ouellet-Bernier et al., 2014; Moros et al., 2016; Krawczyk et al., 2017

CHAPITRE III

OCEAN AND LAND ICE VARIATIONS IN SOUTHWEST GREENLAND DURING THE HOLOCENE

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Abstract

Palynomorph analysis of marine cores collected off Nuuk (southwestern Greenland) provided records of sea-surface conditions and climate-ocean-ice dynamics at a centennial resolution over the last 12,000 years. Dinocyst assemblages provided information about the sea-ice cover, seasonal sea-surface temperature (SST) and salinity (SSS), as well as primary productivity. The quasi-exclusive dominance of heterotrophic taxa and low dinocyst concentration until 10 ka BP, characterized ice-marginal conditions. At about 10 ka BP, an increase in species diversity and the rapid increase of phototrophic taxa mark the onset of interglacial conditions at a regional scale, with summer SST reaching up to $\sim 10^{\circ}\text{C}$ from about 8 to 5 ka BP, corresponding to the mid-Holocene Thermal Maximum (HTM). During the HTM, low SSS and high productivity are recorded, likely in relation with increased meltwater discharge and nutrient input from the Greenland Ice Sheet. After ~ 5 ka BP, the decrease of phototrophic taxa marks a two-steps cooling associated with the Neoglacial. The first started at 5 ka BP and the second is recorded at about 3 ka BP with a change toward colder conditions and higher salinity resulting from reduced meltwater discharge. This second step coincides with the disappearance of the Saqqaq culture. The gap in human occupation in western Greenland, between the Dorset and the Norse settlements from about 2000 to 1000 years ago might be linked to the highly unstable conditions in surface waters.

3.1 Introduction

In Arctic and subarctic areas, ongoing climate change is accompanied by increased air and surface ocean temperatures, decreased sea-ice cover, and enhanced ice sheet melt (Golledge et al., 2019), especially along the marine-based ice margins (Rignot et al., 2010; Hanna et al., 2013; Young & Briner 2015; Briner et al., 2016; Schweinsberg et al., 2018). Direct linkages between recent changes in the Greenland Ice Sheet (GIS) mass balance and the strength of the Atlantic Meridional Overturning Circulation (AMOC) have been proposed by Rahmstorf et al. (2015) and Jackson et al. (2016). Sévellec et al. (2017) also hypothesized that a recent slowdown of the AMOC related to enhanced Arctic freshwater export into the North Atlantic would influence the global distribution of ocean temperature and thus GIS dynamics. Since the Last Glacial Maximum, southwest Greenland has recorded a large ice sheet reduction with the ice margin retreating by about 100-150 km from the continental shelf edge to inland positions (Funder et al., 2011; Briner et al., 2016, Schweinsberg et al., 2018, Cuzzone et al., 2019). The ice sheet retreat from the shelf occurred rapidly from 11.4 to 10.4 ka BP (Larsen et al., 2014, 2017). High summer insolation and high summer temperatures during the early and mid Holocene, until about 5 ka BP (Briner et al., 2016) resulted in a GIS ice mass loss of about 100 Gt yr^{-1} (Larsen et al., 2015). This was followed by a cooling trend in the South and central West Greenland area that was accompanied by the growth of the ice sheet, ice caps and local glaciers during the last 4000 years (Funder et al., 2011; Briner et al., 2016, Larsen et al., 2017; Schweinsberg et al., 2018).

The West Greenland coastal and shelf area is ideally located to document freshwater fluxes from melting marine-terminating glaciers, thus providing clues on the ocean-ice dynamics of the GIS margins. Currently, the West Greenland margins are bathed by the West Greenland Current (WGC; Figure 1), which results from the mixing of warm and saline waters of the Irminger Current (IC; Figure 1) with cold

and low salinity waters of the East Greenland Current (EGC; Figure 1) (e.g., Buch, 1981; Tang et al., 2004). Along the West Greenland margin, characterized by marine-terminating glaciers from the GIS, meltwater discharge accompanied by hyperpycnal flows contributes to vertical mixing in the water column and nutrient resuspension towards the surface, thus resulting in high primary productivity (Boertmann et al., 2013; Juul-Pedersen et al., 2015). Hence, the meltwater runoff from the GIS causes a second bloom in primary productivity to occur in summer-fall, after the spring blooms (Juul-Pedersen et al., 2015, Krawczyk et al., 2015, Meire et al., 2016, Krawczyk et al., 2018).

Ocean conditions during the Holocene have been well documented for selected regions off West Greenland, in particular the Disko Bugt area (Figure 1), where a number of sedimentological, micropaleontological and geochemical investigations have been conducted (Allan et al., 2018; Andresen et al., 2011; Jennings et al., 2014; Kolling et al., 2018; Krawczyk et al., 2010, 2013, 2017; Lloyd et al., 2007; Moros et al., 2006, 2016; Ouellet-Bernier et al., 2014; Perner et al., 2011, 2013; Ribeiro et al., 2012; Seidenkrantz et al., 2008; Sha et al., 2014). The records from the aforementioned studies have shown a very late establishment of full interglacial conditions in surface waters and a decoupling between surface and subsurface temperatures during the mid Holocene, which might be linked to meltwater discharge from the GIS and the relatively warm WGC. In the Disko Bugt area, full postglacial conditions in surface waters established at ~7.5 to ~7.3 ka BP until the general cooling of the Neoglacial that started at about ~4 ka BP (Jennings et al., 2014; Moros et al., 2016; Ouellet-Bernier et al., 2014). During the late Holocene, alternating cold (3.5 to 2.7 ka BP) and milder (2.7 to 1.2 ka BP) conditions were recorded regionally and were tentatively related to variations in meltwater discharge and advances of tidewater glaciers along the West Greenland margin (Moros et al., 2016). Studies from the Ameralik fjord in the Godthåbsfjord system (Møller et al., 2006; Seidenkrantz et al., 2007) and Narsaq Sound, South Greenland (Nørgaard-Pedersen & Mikkelsen, 2009),

indicated that variations of Atlantic water inflow into the fjords followed a long term North Atlantic Oscillation (NAO) pattern (Møller et al., 2006; Seidenkrantz et al., 2007; Nørgaard-Pedersen & Mikkelsen, 2009). However, these results have a local significance and their implication in the regional oceanography still needs to be fully documented. The study of cores HU2008-029-04 and HU2008-029-70 from the northern Labrador Sea (Gibb et al., 2015) permitted the reconstruction of low surface salinities during the late glacial to the mid-late Holocene in the central Labrador Sea, suggesting linkages between sea-surface salinity, ice sheet retreat and meltwater release.

In order to better describe the climate-ice-ocean interactions along the southwest Greenland margin area during the Holocene, we have investigated a series of marine sediment cores from station SA13-ST3, off Nuuk (Seidenkrantz et al., 2013 a). This site is located on the West Greenland shelf allowing us to identify variations in freshwater fluxes from the southern GIS margins. Detailed dating of the core indicates high sedimentation rates on the order of $0.08\text{--}0.1\text{ cm yr}^{-1}$ throughout the Holocene (Figure 1), which permit high temporal resolution analyses. Here, we present the results from palynological analyses, with special attention paid to the distribution of dinoflagellate cysts (hereafter dinocysts), which were used to reconstruct sea-surface conditions including sea-surface temperature (SST) and salinity (SSS). In addition, we present isotopic data from benthic foraminifers with the objective to decipher sea-surface conditions from bottom-water properties, which depend on the flow of the WGC.

We also compare our results to previously-published records of sea-ice cover and primary productivity from Disko Bugt (Ouellet-Bernier et al., 2014; Allan et al., 2018) and central Labrador Sea (Gibb et al., 2015) in order to assess the regional significance of the data.

3.2 Regional setting

Site SA13-ST3 (64°26.7425'N, 52°47.6486'W) is located off the Godthåbsfjord (Nuup Kangerlua) system in the Sukkertop Trough between Toqqusaq Banke and Fyllas Banke, where water depth ranges from 200 to 600 m (Figure 1). The Sukkertop Trough was marked by a rapid retreat of the ice margin after the last glacial maximum (Ryan, Dowdeswell & Hogan, 2016; Dowdeswell et al., 2016).

At present, the West Greenland Current (WGC) flowing northwards on the West Greenland shelf occupies the water column from the subsurface (~275 m) to the bottom of the Sukkertop Trough (Figure 1C). The WGC is formed from the warm and saline waters of the Irminger Current (IC), which is a side branch of the North Atlantic Current mixing with fresh and cold waters carried by the East Greenland Current (EGC) (Tang et al., 2004; Ribergaard, 2014; Figure 1). The upper water layer is characterized by relatively low salinity (31.9-32.9 psu) related to freshwater fluxes from melting sea-ice and glacier meltwater. The low-salinity surface waters form a thin mixed layer of about 20 m above a sharp pycnocline (Figure 1). It is marked by low thermal inertia and summer warming (Ribergaard, 2014) with SST ranging from 4.0-5.2°C (World Ocean Atlas 2013). At the sampling site, SSS ranged from 32.8 at the surface to 34.8 psu at the bottom (Figure 1). Primary productivity is high, averaging $894.6 \pm 50.7 \text{ mgC m}^{-2} \text{ d}^{-1}$ (<https://modis.gsfc.nasa.gov/data/dataproduct>). In winter, the West Greenland shelf at the vicinity of the study site is generally sea-ice free, whereas the fjords are covered by fast ice, forming in November and breaking up in May-June (Mortensen et al., 2011).

3.3 Materials and methods

3.3.1 Data and sample collection

All data and samples from station SA13-ST3 were collected from the shelf off the Godthåbsfjord complex in August 2013 during a cruise with the research vessel *Sanna* of Pinngortitaleriffik, the Greenland Institute of Natural Resources (Seidenkrantz et al., 2013 a).

During the cruise, a Conductivity-Temperature-Depth (CTD) profile of the water column was run continuously from the sea surface to close to the sea floor at the study site prior to coring using a Seabird SBE19+ instrument provided by Pinngortitaleriffik (see Figure 1). At the study site, several core were collected. They include gravity Core 20G (SA13-ST3-20GC; 64°26.7425'N, 52°47.6486'W, water depth 498 m, core length 587 cm), Rumohr Lot Core 16R (SA13-ST3-16R; 64°27.0694'N, 52°47.5783'W, water depth 475 m, core length 52 cm) and Rumohr Lot Core 15R (SA13-ST3-15R; 64°26.8855'N, 52°47.6544'W water depth 495.5 m; core length 53.5 cm). Geochemical data indicate that the cores overlap, with the upper 18 cm sediment in the Rumohr cores missing from the gravity core (Pelikan et al., 2019). Microbiological data have been presented by Glombitza et al. (2015), Braun et al. (2017) and Pelikan et al. (2019).

3.3.2 Age model

In the gravity core 20G, the chronological framework is based on 32 AMS ^{14}C dates of mixed benthic foraminifers and mollusc shells in addition to two samples of macro algae remains (Table 1). The samples were analysed at the accelerator mass spectrometry (AMS) facilities in Zurich, Ottawa and Aarhus (ETH, UOC, AAR). All the radiocarbon dates were calibrated using the Marine13 Calibration Curve and a marine reservoir correction with ΔR of 140 ± 35 years (Reimer & Reimer, 2001;

Lloyd et al. 2011; Moros et al., 2016). The age-depth model was constructed using Oxcal version 4.3.2 (Bronk Ramsey, 2008; 2009) and a Poisson-process deposition model for the core interval contained between 62.5 and 514 cm, from the oldest to the youngest radiocarbon date (Table 1). Above and below these levels, linear extrapolations were applied assuming a constant sedimentation rate (Figure 2). Apart from one radiocarbon date at 321 cm, which may be slightly too young relative to its position in the stratigraphy, possibly due to burrowing of the dated mollusc below the sediment surface, all dates are in good agreement. Dates indicate that the core covers the entire Holocene.

In the 52 cm long Rumohr Lot Core 15R, which contains no biogenic remains allowing direct ^{14}C dating, we analyzed ^{210}Pb . The measurements were made at Geotop-UQAM (Montreal, Canada), measuring the activity of the daughter isotope ^{210}Po by alpha spectrometry and assuming that secular radioactive equilibrium between ^{210}Pb and ^{210}Po was established.

3.3.3 XRF core scanning and magnetic susceptibility

The geochemical content in the sediment core was measured on split halves of cores 20G and 16R using an Itrax X-ray fluorescence (XRF) core scanner (Croudace et al., 2006) equipped with a Molybdenum tube at the Department of Geoscience, Aarhus University, Denmark. Measurements were carried out at 30 kv and 40 mA at 1 mm intervals for 10 seconds. We subsequently combined data at 2 mm intervals to reduce the noise level. Here, we have used the iron (Fe), titanium (Ti) and calcium (Ca). Data are reported in Supplementary Table S2.

The magnetic susceptibility (MS) was also measured on the split halves of the cores using a Bartington MS2E meter with a resolution of 5 mm on the ITRAX core scanner. Results are reported in Supplementary Table S2.

3.3.4 Calcium carbonate and organic carbon content

The calcium carbonate and organic carbon content of Core 20G were measured at the Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark. Analyses were carried out for every 5 to 10 cm on a Metrohm 855 Robotic Titrosampler by sodium hydroxyde titration until a neutral pH was reached using 1 M HCl and 1 M NaOH. Results are reported in Supplementary Table S2.

3.3.5 Particle size analysis

Grain size distribution was measured on 119 samples from Core 20G at the Department of Geoscience, Aarhus University using a Sympatec Helos laser diffractometer using the R4 lense for the fraction $<63 \mu\text{m}$ and an R7 lense for the $63 \mu\text{m} - 2 \text{ mm}$ fraction. The size distribution was grouped into three fractions: sand ($>60 \mu\text{m}$), silt ($2-60 \mu\text{m}$) and clay ($<2 \mu\text{m}$). Here, we have used the $>60 \mu\text{m}$ fraction as indicator of ice-rafted deposition. Data are reported in Supplementary Table S3.

3.3.6 Stable oxygen and carbon isotope analysis

We measured the oxygen and carbon isotope composition ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) of shells of the deep endobenthic foraminifer *Nonionellina labradorica*, which is common throughout most of the studied sequence. Approximately 100 μg (between 25 to 65 specimens) were heated at 90°C for 1 hour before analysis with an isotope ratio mass spectrometer (Micromass-Isoprime) coupled to a MultiCarb system in dual inlet mode at Geotop-UQAM. Because isotope values of the samples are expected to be close to our internal standard, only one internal reference material was used to

normalize the results on the VPDB scale ($\delta^{13}\text{C} = 2.21 \pm 0.03\text{‰}$; $\delta^{18}\text{O} = -1.48 \pm 0.03\text{‰}$), which was calibrated using NBS19 & LSVEC. The overall analytical uncertainty ($\pm 1\sigma$) is better than $\pm 0.05\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 0.08\text{‰}$ for $\delta^{18}\text{O}$. Results are reported in Supplementary Table S4.

3.3.7 Palynological analysis

In this study, 105 samples were analyzed for their palynological content. A total of 14 are from Rumohr Lot Core 16R and 91 from Gravity Core 20G. The Rumohr Core 16R was analyzed at 4 cm intervals and the gravity core at 3 to 7 cm in the upper 330 cm and every 10 cm to the bottom (Figure 2), which give a centennial temporal resolution.

Volumes of 3-5 cm³ of sediment were prepared at Geotop-UQAM following the protocol described by de Vernal et al. (1996). After wet sieving, the 10-106 μm fraction was chemically treated with HCl (10%) and HF (50%) to dissolve carbonate and silicate particles, respectively. *Lycopodium* tablets were added to calculate concentrations of palynomorphs. The final residue was mounted on microscope slides with glycerin jelly for further observation with transmitted light microscope at 400X to 1000X magnification. All palynomorphs were counted including dinocysts, organic linings of benthic foraminifers, *Halodinium* spp., pollen grains, spores of pteridophytes and bryophytes and the Cyst type P (cf. de Vernal et al., 1989). At least 300 specimens of dinocysts were identified and counted in each sample, which provides statistically reliable counts (e.g., Mertens et al., 2009). The taxonomic nomenclature of dinocysts is based on Rochon et al. (1999) and Radi et al. (2013) and conform that updated by Van Nieuwenhove et al. (2019). Here we report mostly on dinocyst assemblages and detailed results can be found in Supplementary Table S5.

3.3.8 Statistical data treatments

Multivariate analyses (detrended correspondence analysis and principal component analysis) were performed using the CANOCO 5 software (ter Braak & Šmilauer, 2012; Lepš & Šmilauer, 2014) in order to describe the combined distribution of dinocyst assemblages from the Cores 20G and 16R. To reduce the effect of dominant species and closed-sum percentage data, the Shapiro & Wilks (1965) statistical test for normality was done (Legendre & Legendre, 2012). A logarithmic transformation was applied to dinocyst data reported in percentage to emphasize the weight of accompanying taxa. The occasional occurrences were discarded and only the taxa recording more than 1 % in at least one sample and occurring in more than 3 samples were used for statistical analyses.

Reconstructions of sea-surface parameters were obtained from the modern analog technique (MAT), which relies on the similarities between fossil and modern assemblages to assess corresponding sea-surface conditions (Guiot & de Vernal, 2007). The MAT was performed using the “bioindic” package developed by Guiot for the R platform and following the procedures described by de Vernal et al. (2013). For reconstructions, we proceeded with searches of five analogs after logarithmic transformation of the relative taxa abundances. The best estimates were calculated from the mean of the corresponding sea-surface values weighted according to the similarity of the analogs. Here, we have used the Northern Hemisphere dinocyst database that includes 71 taxa and 1968 reference sites (de Vernal et al., 2019). The error of predictions were estimated as follows: 1.5 months yr^{-1} for sea ice cover, 719 $\text{mgC m}^{-2} \text{d}^{-1}$ for summer primary productivity, 1.75°C for summer temperature and 2.04 psu for summer salinity. Results are summarized here and detailed in Supplementary Table S5.

3.4 Results

3.4.1 Chronology

The calibrated ^{14}C ages indicate that the Gravity Core 20G encompasses at least the last 11,000 years (Figure 2). The mean sedimentation rates are approximately 0.06 cm yr^{-1} throughout the sequence, with an average of 0.1 cm yr^{-1} over the last 1500 years, 0.04 cm yr^{-1} from 1500 to 9000 years ago and 0.08 cm yr^{-1} from ca. 9000 to 10,700 years ago (Figure 2). Despite the loss of about 18 cm of sediment at the top of the core, the gravity core sufficiently overlaps with the Rumohr Lot Core (Pelican et al., 2019) to encompass a complete Holocene sequence. In this paper we report results against calibrated kilo-years (ka) BP.

^{210}Pb -excesses are observed down to ~15 cm in Core 15R (Figure 2; Supplementary Table S1), but the profile suggests some benthic mixing (Smith & Shafer, 1984), possibly due to bioturbation or to the heavy swells during sampling. Thus, the ^{210}Pb measurements confirm that modern sediment was recovered at the surface, but the evidence of mixing in the top layers of Core 15R makes the downward ^{210}Pb profile not fully reliable. The ^{210}Pb background values are reached at 15 cm, which indicate an age older than CE 1900 (five half-lives of ^{210}Pb) or > 50 years BP. Sediment accumulation rates based on the ^{14}C age model of Core SA13-ST3-20G, indicate an age of 120 years BP at 15 cm below sea floor. Due to potential issues with mixing, we could have chosen to use the sedimentation rate from Core SA13-ST3-20G for the age models of Core 15R and Core 16R. However, the precision of the age model is low as water content and pore volume increase towards the top cm of the core thus affecting apparent sedimentation rates. Therefore, we compared XRF and the magnetic susceptibility results from the Gravity and the Rumohr Lot Cores to confirm the age model.

3.4.2 Geochemical data

Concentration of iron (Fe) and titanium (Ti) based on XRF measurements show similar patterns. Both Fe and Ti concentrations record a rapid decrease from the bottom of the core to ~10 ka BP, prior to increasing towards the top of the core. A reverse trend is, however, observed in the uppermost 10 cm of Rumohr Lot Core 16R with a decrease of Fe and Ti concentrations (Figure 3). High concentrations of Fe and Ti may indicate higher terrestrial inputs as they both derive from the siliciclastic fraction of continental material (Rothwell & Croudace, 2015). In the study area, they can be related to runoff, meltwater discharge or ice rafting (e.g., St-Onge et al., 2007; Solignac et al., 2011; Pearce et al., 2014). The calcium carbonate (CaCO_3) content of the sediment ranges from 1.4 to 14.2% (Figure 3). They show variations opposite to those of the Fe and Ti concentrations and parallel to those of the calcium to iron ratio (Ca/Fe). This might suggest that the fluctuations of CaCO_3 are mostly driven by biogenic fluxes (foraminifers and coccoliths). Weight percentages of Total Organic Carbon (TOC) range from 0.02 to 2.4% (Figure 3). The TOC and the CaCO_3 show different trends. The TOC reach maximum values of 2.4% after ~5 ka BP and then lightly decrease until ~1 ka BP although remaining > 1.6% (Figure 3). The proportion of organic carbon versus inorganic carbon (cf. supplementary material Figure S1) that record maximum values (> 3 times higher) between about 3.8 and 1.8 ka BP and after 0.7 ka BP suggest major change in the nature of biogenic fluxes.

3.4.3 Palynological assemblages

The palynological assemblages of cores 20G and 16R are dominated by dinocysts with concentrations ranging from 10^3 to 3.2×10^5 cysts cm^{-3} , which lead to calculate fluxes in the order of 10^2 to 10^4 cysts $\text{cm}^{-2} \text{yr}^{-1}$ (Figure 4). The concentrations of organic linings of benthic foraminifer are 10^2 to 10^4 cm^{-3} (fluxes from 10^1 to 10^3 $\text{cm}^{-2} \text{yr}^{-1}$), those of *Halodinium* spp. 10^2 to 10^3 cm^{-3} (fluxes from 10^1 to 10^2 $\text{cm}^{-2} \text{yr}^{-1}$). Maximum concentrations of pollen grains and spores are 10^3 cm^{-3} (fluxes 10^2 $\text{cm}^{-2} \text{yr}^{-1}$).

¹) and the Cyst type P occur with concentration up to 10^4 cm^{-3} (fluxes $10^3 \text{ cm}^{-2} \text{ yr}^{-1}$) (Figure 4).

A total of 18 dinocyst taxa were identified: 16 taxa are common, occurring in more than five samples, and 14 represent more than 99% of the assemblages. The 10 dominant taxa are related to phototrophic dinoflagellate species. They include *Impagidinium pallidum*, *Nematosphaeropsis labyrinthus*, *Operculodinium centrocarpum*, *Spiniferites elongatus*, *Spiniferites ramosus*, and *Pentapharsodinium dalei*. Heterotrophic taxa include *Islandinium minutum*, *Islandinium? cezare*, *Brigantedinium* spp. and *Selenopemphix quanta* (Figure 4). Before ~10 ka BP, phototrophic taxa are rare but *Impagidinium pallidum*, *Nematosphaeropsis labyrinthus*, *Operculodinium centrocarpum*, *Spiniferites elongatus*, and *Spiniferites ramosus* occur in low percentages. *Nematosphaeropsis labyrinthus* starts to increase around ~7 ka BP, with maximum in the upper part of the core (< 4 ka BP). *Operculodinium centrocarpum* records maximum percentages between ~5 and ~2.5 ka BP and *Spiniferites elongatus* between ~9.5 and ~6 ka BP. The cyst of *Pentapharsodinium dalei* is dominant with up to 50% from ~10 to ~3 ka BP. The heterotrophic taxa dominate before 10 ka BP and after 3 ka BP. *Islandinium minutum* records a first maximum (~30%) before 10 ka BP and a second (~15%) after 3 ka BP. *Brigantedinium* spp. shows a similar distribution with up to 50% before 10 ka BP and about 40% during the last 3000 years. *Islandinium? cezare* progressively increases from an average of 1.5% before 10 ka BP to ~20% in the top of the sequence. *Selenopemphix quanta* is common all along the core with an average of 4-8% (Figure 4).

Heterotrophic dinoflagellates have the ability to survive in the dark arctic ecosystem (e.g., Heikkilä et al., 2014; 2016). The quasi-exclusive dominance of heterotrophic taxa in the bottom of the core can illustrate the dark conditions associated with a long seasonal sea-ice cover (Figure 6). Therefore, the rapid increase

in diversity and abundance of phototrophic taxa from *ca.* ~10 ka BP (Figure 4), may relate to an increase of light availability at the onset of interglacial conditions. The cysts of *Pentaparsodinium dalei* are often found in stratified water, they may be linked to freshwater, meltwater input and primary productivity (Rochon et al., 1999; Heikkilä et al., 2014; Allan et al., 2019). Its dominance from 10 to 3 ka BP (Figure 4) could be related to the late summer bloom due to meltwater input (e.g., Boertmann et al., 2013; Juul-Pedersen et al., 2015; Allan et al., 2019). Its decline relative to heterotrophic taxa, such as *Islandinium minutum* and *Islandinium? cezare* and *Brigantedinium* spp. (Figure 4), suggests the recurrence of cold waters (Allan et al., 2019) during the Neoglacial period.

Detrended correspondence analysis performed on the dinocyst assemblages showed the length of the first ordination axis to be 1.8 standard deviations, which suggests a linear relationship and that principal component analysis (PCA) is appropriate (ter Braak & Šmilauer, 1998). The first axis (PCA 1) explains 50.41% of the distribution. It is characterized by a positive correlation between *Islandinium minutum* and *Brigantedinium* spp. and by a negative correlation for the other dominant taxa (Figure 5). The second axis (PCA 2) explains 23.23% of the distribution and shows positive scores for *Selenopemphix quanta*, *Impagidinium pallidum* and *Spiniferites elongatus*, whereas all other dominant taxa have negative scores (Figure 5).

The PCA 1 scores are used to define 3 main zones, respectively labeled A, B and C (Figure 4). The PCA 2 shows a switch from positive to negative at ~5 ka BP, which separated the zone B in subzone B2 and B1, from ~10 to ~5 ka BP and from ~5 to ~2.7 ka BP, respectively (Figure 4). Zones A, which is defined based on negative scores of PCA 2 and mean PCA 1 close to zero, can be subdivided in 3 sub-zones: A3, from ~2.7 to ~1.3 ka BP with a PCA 1 close to zero, A2 from ~1.3 to

~0.65 ka BP is marked by a high variability of positive to negative PCA 1 scores and finally, A1 from ~0.65 to 0 ka BP with slightly positive PCA 1 scores (Figure 4).

3.4.4 Reconstruction of sea-surface parameters

Zone C (from ~12 to ~10 ka BP) is characterized by a low diversity and low fluxes (Figure 4), which is typical of Arctic environment (de Vernal et al., 2019). The quantitative estimates indicate dense sea-ice cover from 4 to 10 months per year, low summer SST ranging 0 to 6 °C, low summer primary productivity (PP) $\sim 800 \text{ mgC m}^{-2} \text{ d}^{-1}$ and summer SSS ~ 33 psu (Figure 6).

Sub-zone B2 (from ~10 to ~5 ka BP) is marked by high summer PP $\sim 2.9 \cdot 10^3 \text{ mgC m}^{-2} \text{ d}^{-1}$, high summer SST ranging 6 to 12 °C with an average of, ~ 9 °C and low summer SSS ~ 30 psu (Figure 6). After ~5 ka BP, sub-zone B1, spanning from ~5 to ~2.7 ka BP, records an increased variability of the sea-surface conditions, along with an increase of summer SSS ~ 31 psu and a decrease of summer SST ~ 8 °C and summer PP $\sim 2 \cdot 10^3 \text{ mgC m}^{-2} \text{ d}^{-1}$.

Sub-zone A3 (from ~2.7 to ~1.3 ka BP) is characterized by cold conditions with summer SST of ~ 5 °C, low summer PP $\sim 1.4 \cdot 10^3 \text{ mgC m}^{-2} \text{ d}^{-1}$ and summer SSS ~ 32 psu (Figure 6). Sub-zone A2 (from ~1.3 to ~0.65 ka BP) and sub-zone A1 (after ~0.65 ka BP) are marked by high instability, with summer pulses from ~ 3 to ~ 12 °C, ~ 29 to ~ 33 psu and $\sim 7.1 \cdot 10^2$ to $\sim 3.6 \cdot 10^3 \text{ mgC m}^{-2} \text{ d}^{-1}$. Moreover, a general cooling is recorded after 2.7 ka BP (Figure 6).

Sub-zones A1 and A2 described from the gravity core are also recovered in the Rumohr Lot Core. The reconstructions of the sea-surface parameters from both cores are similar. At the top of the core, the last century recorded a return to relatively stable conditions with low sea-surface temperature, high salinity, low productivity

and sea-ice cover close to nil. The reconstructions at the top of the core fit within the range of modern instrumental data (Figure 6).

3.4.5 Isotopic (^{18}O and ^{13}C) data from benthic foraminifers

Among benthic foraminifers, *N. labradorica* is often used as indicator of high productivity in subarctic settings (e.g., Bilodeau et al., 1994; Korsun & Hald, 2000; Perner et al., 2011; Seidenkrantz et al., 2013 b; Moros et al., 2016). It is one of the most common foraminiferal taxa in the core and permitted us to develop an almost continuous benthic isotopic record spanning about from 10,400 to 1000 years ago. No foraminifer was found in the core below 480 cm (> 10.4 ka BP). In the upper part of the sequence, up to 70 cm (< 0.8 ka BP), the number of foraminifers was too low for isotopic measurement.

N. labradorica recorded $\delta^{18}\text{O}$ ranging from 3.95 to 3.35‰, with a general decrease from 10.4 to 6.7 ka BP. This may suggest a warming of the bottom waters and/or a decrease in salinity. After 6.5 ka BP the $\delta^{18}\text{O}$ of *N. labradorica* averages 3.44‰ (Figure 7). These values are comparable to those of *N. labradorica* in the Disko Bugt sediment core (Figure 7; Ouellet-Bernier et al., 2014). The $\delta^{18}\text{O}$ of *N. labradorica* from Nuuk and Disko Bugt may consequently have the signature of the same water masse, the subsurface WGC. The $\delta^{13}\text{C}$ show very large amplitude variations with values from -3.92‰ to -0.83‰. From ~10 to ~4.6 ka BP, the $\delta^{13}\text{C}$ is characterized by high values averaging -2.06‰. Afterward, the $\delta^{13}\text{C}$ decreased to the reach minimum values of -3.92‰ at ~2.7 ka BP prior to increase again upward with a maximum of -0.83‰ at ~1.5 ka BP (Figure 7). Unlike the $\delta^{18}\text{O}$, the $\delta^{13}\text{C}$ from Nuuk and Disko Bugt showed different tendencies, which can be related to a local signals and different phytodetritus content in the sediment (Figure 7). In the core off Nuuk, the $\delta^{13}\text{C}$ in the deep infaunal *N. labradorica* shells record particularly low values (< -3‰) from 4 to 2 ka BP, which would indicate higher phytodetritus fluxes to the sediment (e.g., Murray, 2006; Rytter et al., 2002). These low values correspond to a

particularly high proportion of organic carbon in the sediment (Figure 3; cf. supplementary material Figure S1).

3.5 Discussion

3.5.1 The regional deglaciation and Fiskebanke moraines

The Fiskebanke moraines, located on the inner shelf of Southwest Greenland in front of the Sukkertoppen Iskappe area, have been suggested to date from the Younger Dryas (Funder et al., 2011; Ó Cofaigh, et al., 2013). In the Godthåbsfjord system, the retreat of the GIS from the coastline to inland occurred between ~11.4 and ~10.4 ka BP, with an ice retreat rate of about 125 m yr⁻¹, the mouth of the Godthåbsfjord being deglaciated at ~10.7 ka BP (cf. Larsen et al., 2014, Larsen et al., 2017). The oldest ¹⁴C date from the Core 20GC is at a depth of 514 cm and gives a modeled mean age of about ~10.7 ka BP (Figure 2; Table 1). Due to the lack of datable material, it was not possible to develop a precise chronology beyond that point. However, the sediments from the bottom of the core consist of relatively coarse-grained material with high magnetic susceptibility and an elemental composition indicating high terrestrial (high Fe and Ti) inputs (Figure 3). Together with the extensive sea-ice cover inferred from the dinocyst-based reconstructions and the low dinocyst abundance (Figures 4 and 6), the elemental composition suggests rapid sediment accumulation in an ice-marginal environment. This led us to further propose that the GIS margin was located close to our study site until ca. 10.7 ka BP. Consequently, the harsh conditions recorded at the bottom of the core could be related to the late Younger Dryas (YD; end ~11.5 cal. ka BP; Alley et al., 2010; Jennings et al., 2014), which is in agreement with proposed age of the Fiskebanke moraines (Funder et al., 2011; Ó Cofaigh, et al., 2013). Above, a peak of sand-sized particles and magnetic susceptibility indicates a rapid retreat of the ice margin accompanied with ice calving

and IRD, while our reconstruction indicate that sea-ice cover decreased (Figures 3 and 6).

3.5.2 Hydrographical conditions during the Holocene

The combined records of dinocyst assemblages, benthic foraminiferal isotopes and sedimentological data permit inferences about both surface and bottom water conditions at our study site (Figures 3, 4, 6 and 7). From the base of the sequence to about 7 ka BP, the decrease $\delta^{18}\text{O}$ in *N. labradorica* indicates enhanced flow of Atlantic-sourced water transported by the WGC in both surface and sub-surface waters (Figures 3, 4 and 7). Benthic foraminifer studies suggested that Atlantic waters were likely flowing on the shelf off Uummannaq, west of Greenland, and in the Nares Strait, in northern Baffin Bay as early as 14 ka BP, which led us to propose that warm subsurface water initiated the ice retreat (Knudsen et al., 2008; Sheldon et al., 2016; Jennings et al., 2017). The influence of warmer water from the WGC at the surface, however, is recorded later, at about 7.7 ka BP along the northwest Greenland margins in the Baffin Bay (Levac et al., 2001; Caron et al., 2019), and at about 7.3 ka BP in the inner Disko Bugt, North of the Davis Strait (core MSM343300; Ouellet-Bernier et al., 2014). At our study site south of the Davis Strait, the postglacial warming of surface waters, associated with the inflow of Atlantic waters through the WGC, started from the base of the core to reach optimal values at about 7 ka BP, thus in phase with the benthic $\delta^{18}\text{O}$ that reached minimum values of $\sim 3.5\text{‰}$ at about the same time (Figure 7). Such a timing closely followed the onset of intermediate-deep waters formation in the Labrador Sea (Hillaire-Marcel et al., 2001, Gibb et al., 2015), and would correspond to an important regional benchmark. Optimal thermal conditions in surface waters persisted until about 5 ka BP. On land, at the Qipisarqo Lake in southern Greenland, the July surface air temperature (SAT) estimated from pollen grains were ~ 10 to 12°C from ~ 7.5 to 5.5 ka BP (Fr  chette & de Vernal, 2009). Off Nuuk as well as onshore in southern Greenland, the Holocene thermal maximum

seems to have been regionally consistent, and furthermore appeared to have been in phase with the GIS retreat (Briner et al., 2016).

After 5 ka BP, a progressive cooling likely driven by the decrease in Northern Hemisphere summer solar insolation (Berger & Loutre, 1991) was recorded regionally and associated with the Neoglacial (Funder et al., 2011). At the Qipisarqo Lake, July SAT indicated a cooling of 1-2°C after 5.5 ka BP (Figure 6; Fréchette & de Vernal, 2009). Off Nuuk, our data show decreased SST, but also high-amplitude variations with pronounced cooling pulses between 5 and 4 ka BP as depicted from variable proportions of *Islandinium? cezare* and the cysts of *Pentaparsodinium dalei* (Figures 4 and 6). The variability of sea-surface conditions tends to suggest a non-monotonic cooling and an oscillatory mode linked with the respective strength of the North Atlantic currents contributing to the WGC and cold flow from the EGC or proximal meltwater supply. From ~4 to ~2.7 ka BP, the dinocyst data suggest relatively low SSS and high SST (Figures 4 and 6). After ~2.7 ka BP, we reconstructed generally low summer SST and high SSS, similar to present-day conditions (Figure 6). The reconstructions also suggest warming phases from ~1.6 to ~1.25 ka BP and from ~1.1 to ~0.6 ka BP (Figures 6 and 8). The warming around ~1.5 ka BP coincided with increased estimated PP and $\delta^{13}\text{C}$ in benthic foraminifers, suggesting a major oceanographic change (Figures 4 and 7). These episodes marked by relatively warm conditions seem to be a regional feature in both surface and subsurface water (see Figure 8). In Ameralik fjord, from ~1.6 to ~1.2 ka BP, the benthic foraminifers reflect increase advection of warm and saline Atlantic waters (Seidenkrantz et al., 2007); at Disko Bugt, a warming was also identified from ~1.8 to ~0.9 ka BP in bottom water (Perner et al., 2013). Hence, even if the precise timing of changes recorded in the different cores can be challenged, the overall data suggests variations in the strength of the North Atlantic water flow through the WGC that are consistent at the surface and subsurface over the southwest Greenland margins at least since 5000 years ago (see Figure 8).

Finally, our data indicate a cooling in surface and sub-surface waters after ~ 0.6 ka BP (Figure 6, Zone A1). It seems to correspond to the regional onset of the Little Ice Age (LIA) in western Greenland, where decreasing surface air temperature and local glacier regrowth were recorded at about the same time (Figure 8; Funder et al., 2011; Young & Briner 2015; Briner et al., 2016; Larsen et al., 2017; Schweinsberg et al., 2018). Off Nuuk, the LIA is characterized by a decrease in summer SST and PP and an increase of SSS, which probably relate to decrease meltwater discharge. It is also marked by increase magnetic susceptibility, Ti and Fe content, which reflect detrital input with values almost as high as those of the deglaciation, thus suggesting input from glacial erosion (Figures 3 and 6).

3.5.3 Ocean-ice sheet relationship

In the Godthåbsfjord system, the GIS recorded a quick retreat from the shelf to the land, between ~ 11.4 and ~ 10.4 ka BP (Larsen et al., 2014; 2017). However, in the fjord itself, the glacier continued to retreat until 7.7–7.5 ka BP (Seidenkrantz et al., 2013b). The synthesis of the Greenland Ice Sheet ice mass balance by Larsen et al. (2015), which focussed on southern Greenland, indicated that maximum ice retreat occurred from 8 and 5 ka BP with a centennial ice loss rate of as high as 100 Gt yr^{-1} for several millennia. Another synthesis from Arctic Canada and Greenland by Briner et al. (2016) led to suggest maximum warmth between ~ 9 and ~ 5 ka BP. In our study, the thermal maximum seems to be related to maximum summer SST, PP and minimum SSS from ~ 9.5 to ~ 5 ka BP (Figure 6). We interpret the contrast between SST and SSS as the consequence of glacier ice melt during warm phases resulting in dilution of surface water and thus low surface-water salinities (cf. also Gibb et al., 2015). Relatively fresh surface water in the Labrador Sea during the Early Holocene, with significantly lower salinity than during the mid and Late Holocene, has been documented from several studies (Hillaire-Marcel et al., 2001; Solignac et al., 2004; de Vernal & Hillaire-Marcel, 2006; Gibb et al., 2015; Hoogakker et al., 2015),

indicating that a basin-wide stratification delayed the formation of the modern deep water in Labrador Sea until about 7 ka BP (Hillaire-Marcel et al., 2001; Hoogakker et al., 2015).

In the Sukkertoppen region, north of Maniitsoq (Figure 1), the mountain glaciers were smaller than today by ~ 4.6 ka BP and experienced regrowth with the onset of the Neoglacial cooling (Schweinsberg et al., 2018). Major glacier expansions were recorded at ~ 3.6 - 3.5 ka BP in southwest Greenland (Larsen et al., 2017; Schweinsberg et al., 2017; 2018). They were associated with a decrease in summer air temperatures of about 1 to 2°C (Larsen et al., 2017). Many local glacier advances in West Greenland, notably at ~ 3.7 - 3.6 , ~ 2.9 , ~ 1.8 - 1.7 , ~ 1.7 - 1.6 , ~ 1.4 - 1.2 , ~ 0.8 - 0.7 and ~ 0.5 ka BP, were also recorded (Larsen et al., 2017; Levy et al., 2017; Schweinsberg et al., 2017; 2018; see Figure 8). The multiple phases of ice expansion point to a centennial-scale variability superimposed on longer-term changes forced by decreasing summer solar insolation. At our study site, we also reconstructed high frequency variations in SST and SSS, suggesting that instabilities also characterized the surface waters off southwest Greenland. Because SST and SSS estimates fluctuate in opposition, we may speculate that changes in surface water stratification and thermal inertia occurred, along with higher surface salinity and lower temperature corresponding to lesser stratification, possibly linked to episodic flow of the WGC at the surface. Conversely, lower surface salinity and higher temperature would reflect freshwater discharges, shoaling of the surface layer and lesser thermal inertia fostering summer warming. However, very high temporal resolution with precise timing would be necessary to infer linkages between the local glaciers dynamics and the surface ocean conditions.

3.5.4 Meltwater discharge and marine primary productivity

In Arctic and subarctic seas, primary productivity is controlled directly by light and nutrient availability, which indirectly depend upon meltwater discharge, vertical

mixing of the water column and sea-ice extent (Tremblay et al., 2015; Juul-Pedersen et al., 2015). The spring bloom is often triggered by abundant nutrient release at the melt of sea ice and by high solar irradiance, together with the stabilisation of the water column (Boertmann et al., 2013). In summer and fall, a second bloom occurs in southwest Greenland. It is driven by the basal meltwater discharge from terminating marine glaciers, which contribute to upwell nutrients from deeper waters into the photic zone (Boertmann et al., 2013; Juul-Pedersen et al., 2015). Recent studies from the Godthåbsfjord and Fyllas Banke have shown a planktonic productivity succession with blooming of haptophytes in spring, followed by diatoms in summer and by dinoflagellates and ciliates through summer, fall and winter (Krawczyk et al., 2015; 2018).

In the GISP2 ice core, the highest frequency of melt layer is recorded from 8.5 to 5.5 ka BP (Alley & Anandakrishnan, 1995; Briner et al., 2016). Hence, we may infer that the low salinity, reconstructed here from ~9 to ~5 ka BP (Figure 6), is related to the meltwaters from the GIS margins. Furthermore, from ~10 to ~5 ka BP, the estimated summer PP is very high, up to $\sim 3.10^3 \text{ mgC m}^{-2} \text{ d}^{-1}$. From ~10 to ~5 ka BP, the $\delta^{13}\text{C}$ of *N. labradorica* is also characterized by high values, $> -2.50\text{‰}$, which may suggest high marine PP (Figures 6 and 7), likely associated with biogenic calcium carbonate fluxes as indicated by the relatively high CaCO_3 concentrations and Ca/Fe ratio (Figure 3). Consequently, we may hypothesize that the enhanced melting of marine terminating glaciers was favorable for high nutrient inputs though upwelling with the hyperpycnal flow until about 5 ka BP. A major change in the style of productivity is recorded afterward as indicated by the sharp changes in the proportion of organic versus inorganic carbon and the decrease of $\delta^{13}\text{C}$ in *N. labradorica* shells (Figures 3 and 7). It seems to be a local feature, as it is not recorded to the North in the Disko Bugt (Figure 7). Therefore, we are tempted to associate the major change in productivity style and carbon fluxes at site SA13-ST3

off Nuuk with the retreat of the ice margin into terrestrial position in the southern Greenland.

3.5.5 Climate changes related to human history

Changes in past climate were important for human expansion. The history of human occupation in West Greenland is characterized by the arrival and disappearance of several cultures over the past 4500 years (Jensen, 2006; D'Andrea et al., 2011). It has been suggested that environmental change was the major cause for this pattern (McGovern, 1991; McGhee, 1996; Jensen, 2006; D'Andrea et al., 2011). The results from site SA13-ST3 permit us to propose a relationship between the surface ocean conditions and the human colonization phases (Figure 9). The arrival of the Saqqaq people corresponds to a warm period with a high summer SST and PP (Figure 9). Because the Saqqaq were open water hunters (Jensen, 2006; D'Andrea et al., 2011), such climatic conditions were probably suitable to their livelihood. At ~ 2.7 ka BP, the cooling over western Greenland that led to glacier expansion together with the decrease in marine PP (Figure 9) may have made subsistence more difficult for the Saqqaq culture, then replaced by the Dorset people, who were adapted to sea-ice hunting (Jensen, 2006; D'Andrea et al., 2011). At ~ 2 ka BP, the changes towards harsher and unstable conditions seem to coincide with the gap of about one thousand years of human occupation in western Greenland. By ~ 1 ka BP, relatively warm conditions and PP increase, correspond to the arrival of the Norse, who were a sedentary people (Figure 9). Finally, at the beginning of the LIA, about 650 years ago, a strong climate deterioration accompanied with glacial advance might have contributed to the abandonment of the western Norse settlements (D'Andrea et al., 2011), leaving the area to the Thule people, ancestors of the modern Greenlandic Inuit, who arrived in Greenland 850 years ago (McGovern, 1991). Our study suggests that not only climate conditions but also marine productivity played an important role on the human occupations along the southwest Greenland coasts (Figure 9).

3.6 Conclusion

The analyses of the sediment Cores 20G and 16R located off Nuuk allowed us to document variations in sea-surface and bottom water conditions, and to propose relationships with the dynamics of the southern Greenland ice sheet and mountain glaciers throughout the Holocene.

Our record illustrates that the central West Greenland shelf was characterised by extensive sea-ice cover and high terrestrial inputs, likely related to a nearby ice shelf margin until about ~10 ka BP. At that time, a rapid deglaciation occurred, accompanied by increasing summer surface water warming, with sea surface temperatures reaching up to ~10°C. During the Early Holocene, the retreating GIS caused strong meltwater discharges along the ice shelf, which led to establish an upwelling. In the area, the Neoglacial cooling started at ~5 ka BP, with an increase in the variability of surface waters and cold pulses marked by harsh conditions which possibly coincide with phases of glacier expansions.

This work highlights the close interaction between the changes in ocean water masses and the retreats and advances of the Greenland ice sheet and glaciers during the Holocene. It suggests that a combination of hydrographic conditions, regional climate and marine productivity influenced human cultural migration and development related to the Saqqaq, Dorset, Norse and Thule cultures.

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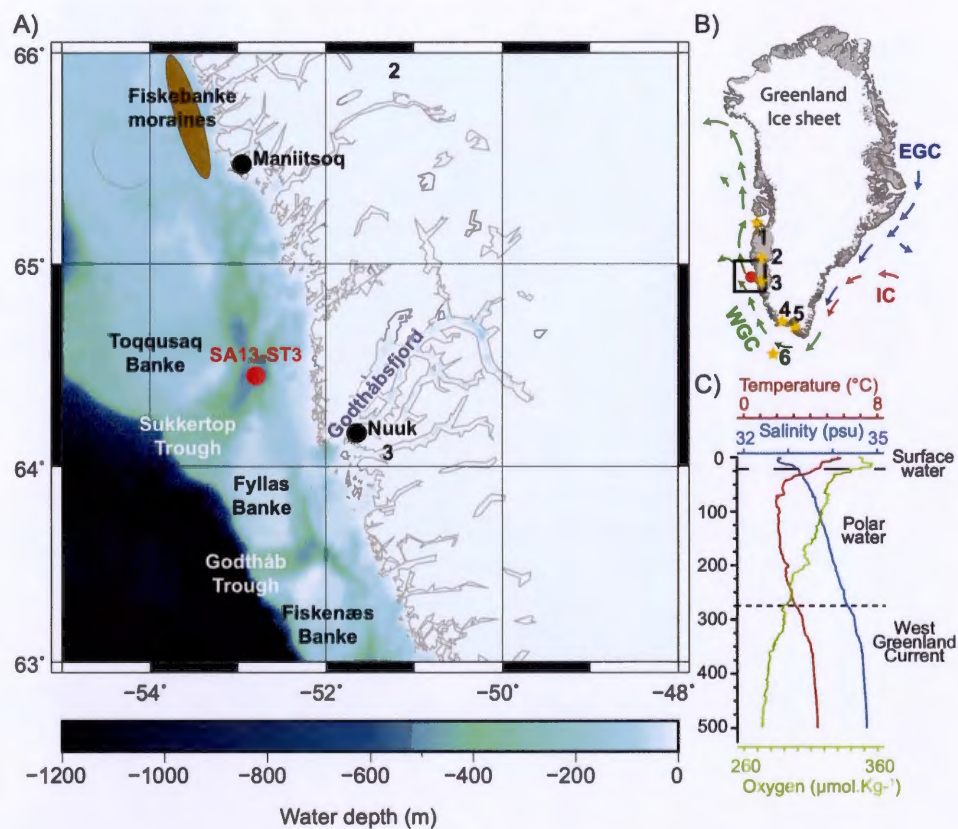


Figure 3-1 : A) Map of the study area. The red dots indicate the location of the coring site SA13-ST3. B) The map illustrates the dominant ocean circulation pattern around Greenland: EGC = East Greenland Current; IC = Irminger Current; WGC = West Greenland Current. The yellow stars indicate the location of cores referred in the text (1=Disko Bugt; 2= Sukkertoppen Iskappe area; 3=Ameralik fjord; 4=Qipisarqo Lake; 5=Narsaq Sound; 6=Greenland Rise). C) CTD profile at the site SA13-ST3 in August 2013 (Seidenkrantz et al., 2013 a).

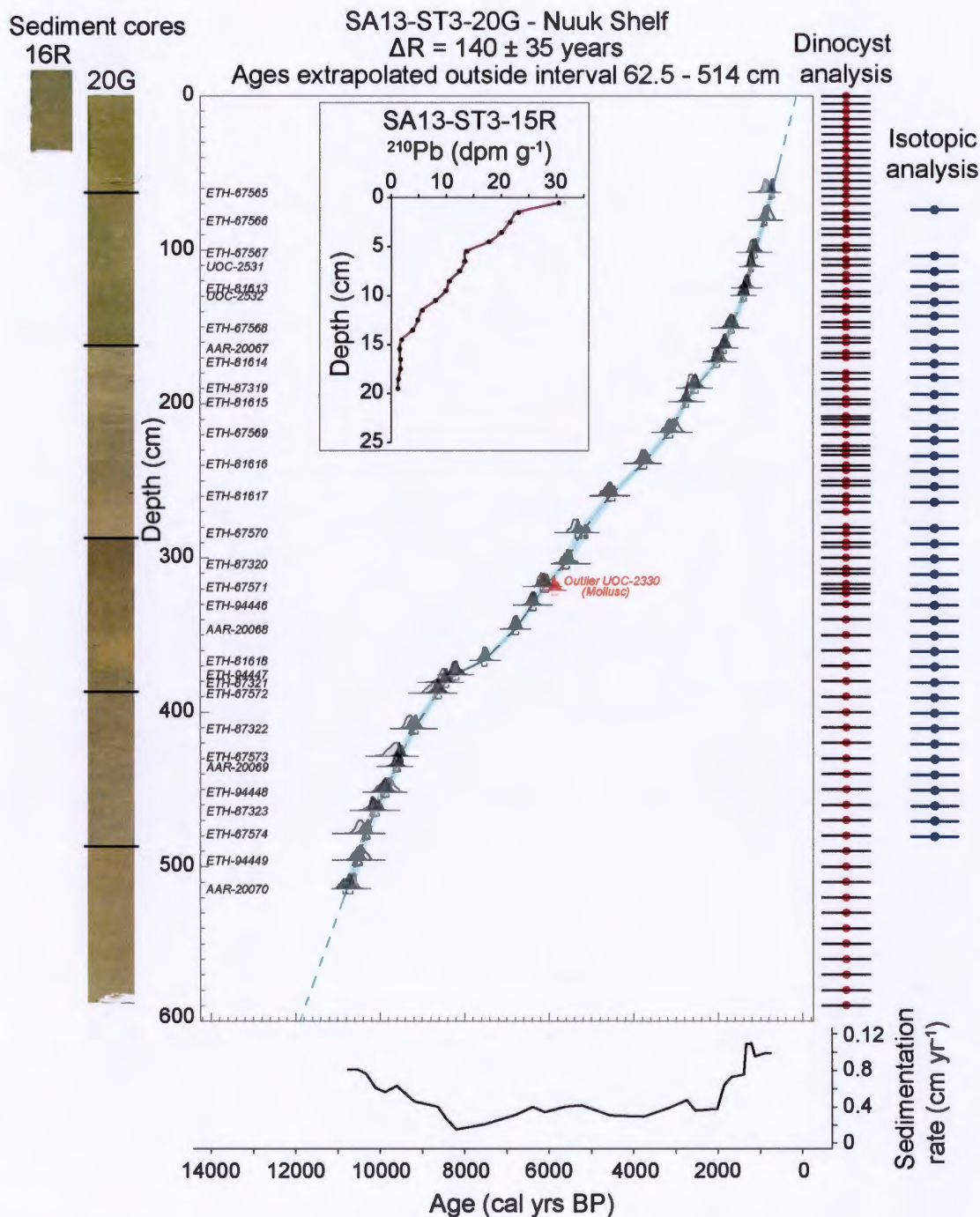


Figure 3-2 : Photograph of the sediments and age-depth relationship for cores SA13-ST3-20GC and SA13-ST3-16R; the slight color changes between sections are due to issues with full calibration of the camera. The blue shaded area displays the age-depth uncertainty. The bars on the right show the position of samples used for palynological analysis and the stable isotope analysis of benthic foraminifera in the core SA13-ST3-20GC.

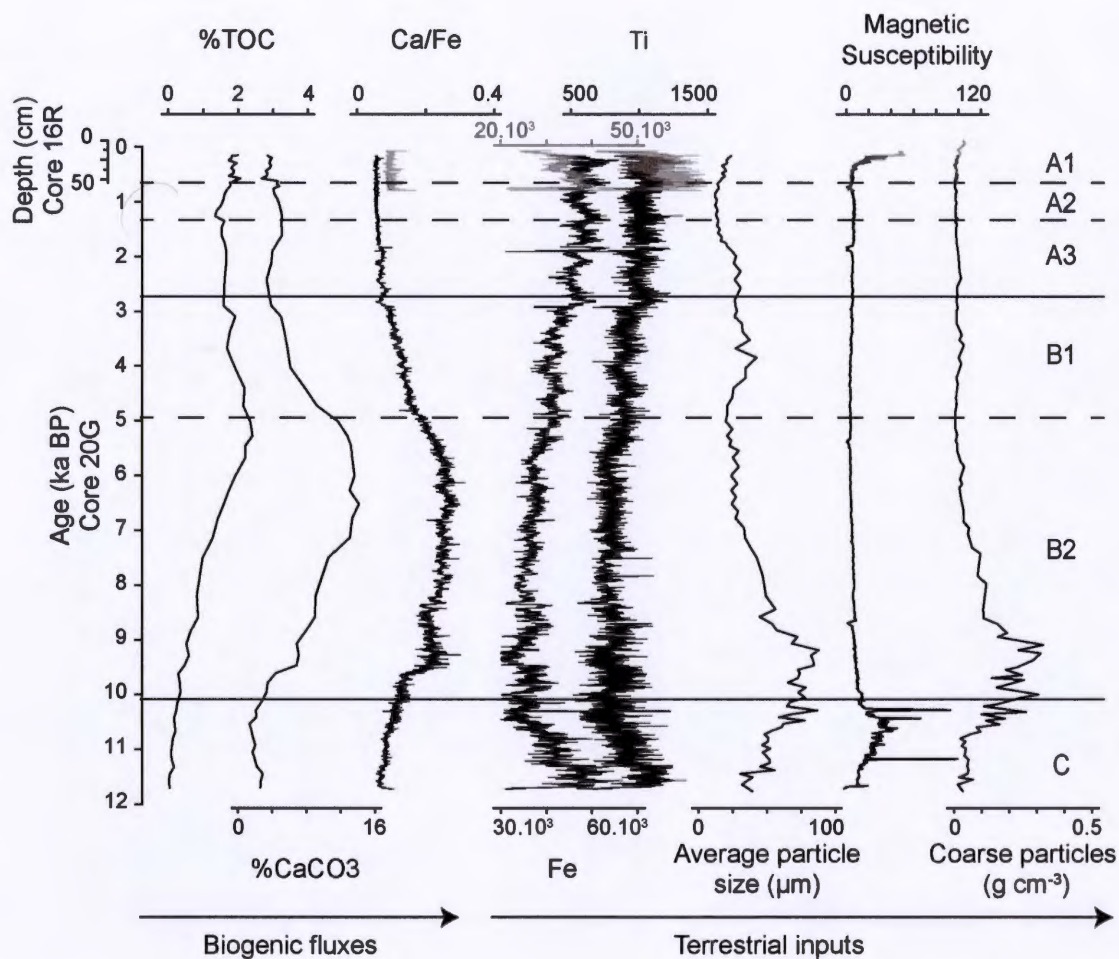


Figure 3-3 : Results of sedimentological and geochemical analyses of cores from station SA13-ST3 (20G in color and 16R in brown) and its physical properties: average particle size, magnetic susceptibility and weight of the coarse particles ($< 106\mu\text{m}$) from the palynological preparations. Zones defined from the PCA are indicated to the right (see Figure 4).

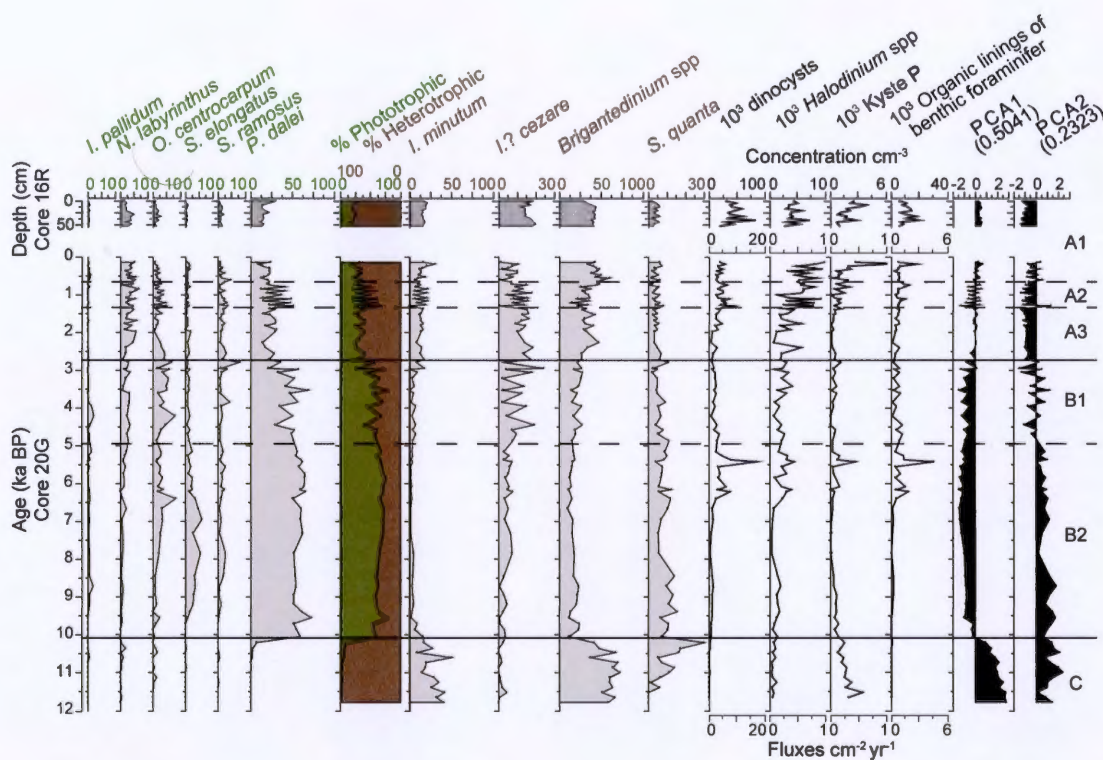


Figure 3-4: Percentage of the dominant dinocyst taxa, concentrations and fluxes of the main palynomorphs and scores of principal component analysis (PCA) axes 1 and 2 apply on dinocyst assemblages. The percentages of phototrophic and heterotrophic taxa are reported in green (phototrophic) and brown (heterotrophic). The PCA led to distinguish 3 zones (A, B, C), and 5 subzones A1, A2, A3 and B1, B2.

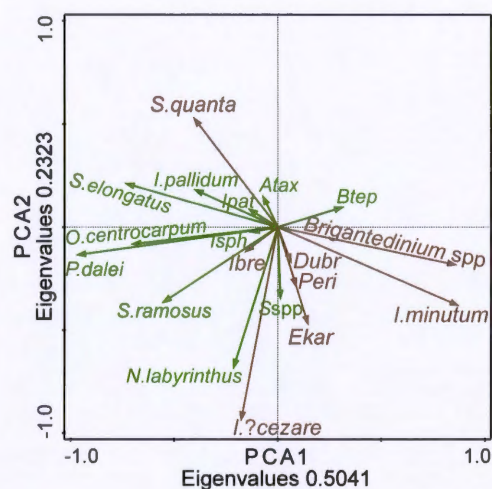


Figure 3-5 : Ordination diagram of the dinocyst taxa from the downcore assemblages, according to the two main axes, PCA1 and PCA2. The taxa plotted in the PCA are indicated either by their species name (dominant taxa) or by four-letter abbreviations (Atax: *Ataxodinium choane*, Btep: *Bitectatodinium tepikiense*, Ipat: *Impagidinium paradoxum*, Isph: *Impagidinium sphaericum* Sspp.: *Spiniferites* spp., Ibre: *Islandinium brevispinosum*, Ekar: *Echinidinium karaense*, Dubr: *Dubridinium* spp., Peri, *Protoperidinioids*). The phototrophic taxa are indicated in green and the heterotrophic taxa in brown.

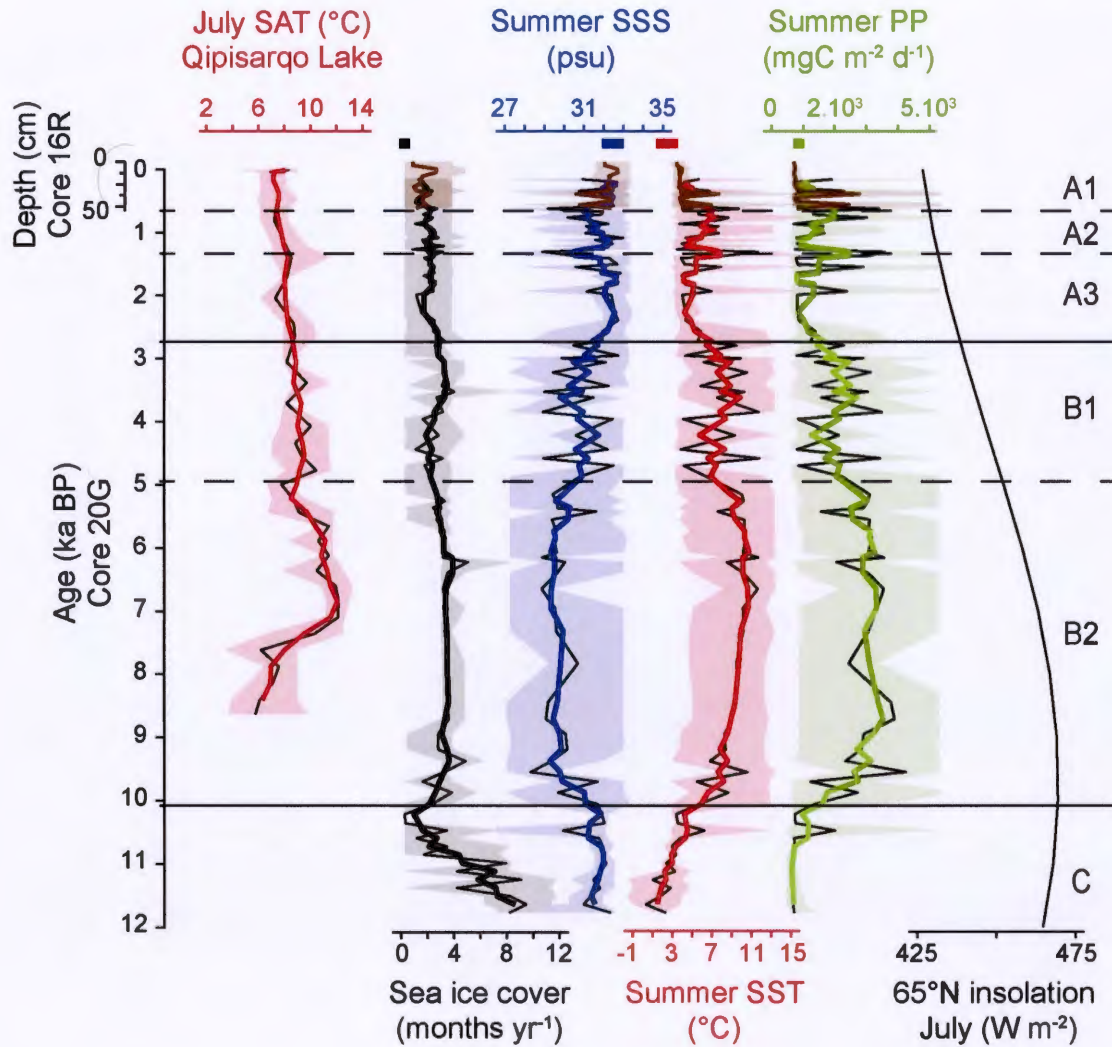


Figure 3-6 : Surface data: MAT reconstruction of July surface air temperature (SAT) from pollen grains assemblages at Qipisarqo Lake, southwest Greenland, from Fréchette & de Vernal (2009). MAT reconstruction of sea-ice cover concentration, summer sea-surface salinity (SSS), summer sea-surface temperature (SST), and summer primary productivity (PP) from dinocyst assemblages in cores SA13-ST3 (20G in color and 16R in brown) and insolation at 65°N in July (cf. Berger & Loutre, 1991). Instrumental values of present-day sea surface conditions are indicated by horizontal rectangles in the top of the sea-surface reconstructions and the shadow area around the reconstructions encompasses the minimum and maximum values according to the sets of 5 analogs. Zones defined from the PCA are indicated to the right.

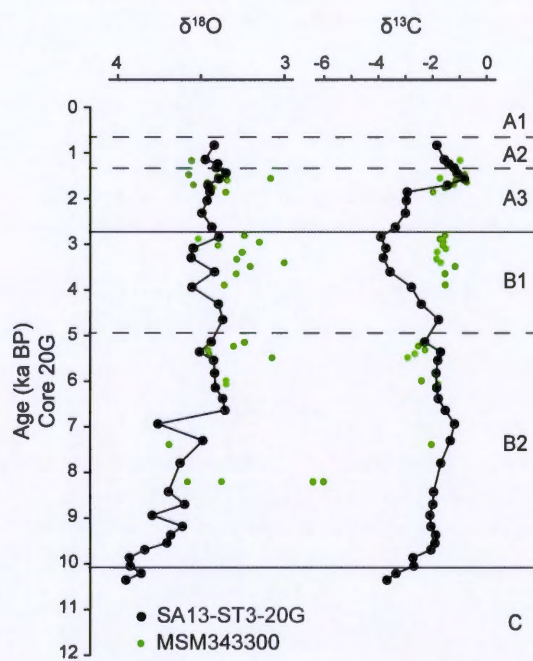


Figure 3-7 : Isotopic compositions, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ (‰ vs. VPDB) of *Nonionellina labradorica* tests from the core SA13-ST3-20G and MSM343300 (Ouellet-Bernier et al., 2014). For the core MSM343300, only the fractions < 250 μm are represented. Zones defined from the PCA are indicated to the right.

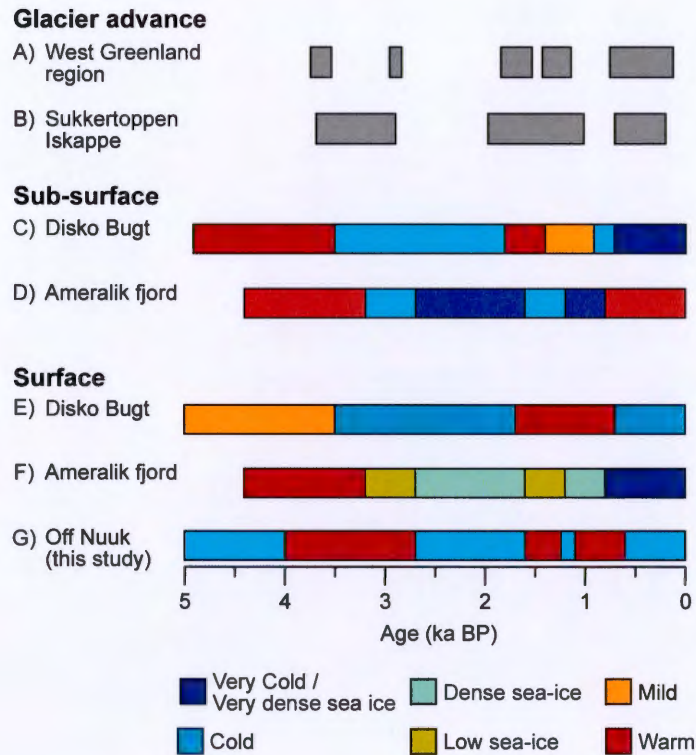


Figure 3-8 : Transition from warm to cold conditions along the West Greenland margin. A) Timing of local glacier advances in west Greenland region (Larsen et al., 2017; Levy et al., 2017; Schweinsberg et al., 2017). B) Timing of the local glaciers regrowth in Sukkertoppen Iskappe area (Schweinsberg et al., 2018). C) WGC properties at the sub-surface as deduced from benthic foraminifer assemblages in the Disko Bugt (Perner et al., 2013; Moros et al., 2016). D) Strength of WGC advection in the Ameralik fjord based on benthic foraminifer assemblages (Seidenkrantz et al., 2007). E) Sea-ice cover based on diatoms assemblages in the Ameralik fjord (Seidenkrantz et al., 2007). F) Summary of sea-surface conditions in Disko Bugt based on multiproxy data (Moros et al., 2016). G) Summary of sea-surface conditions at the study site based on dinocyst assemblages (this study; cf. Figure 5). Site localised in Figure 1.

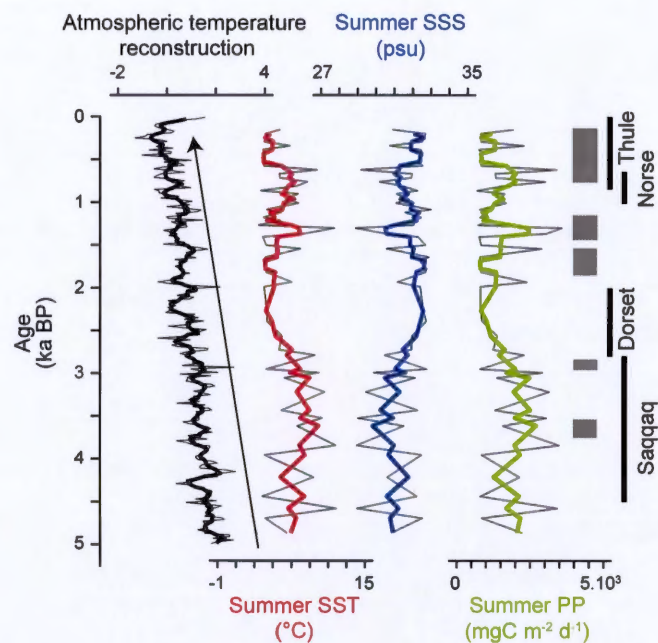


Figure 3-9 : Greenland temperature reconstruction from Vinther et al. (2009) using proxy data from six ice cores. Dinocyst-based reconstruction of summer sea-surface temperature (SST), salinity (SSS), and primary productivity (PP) in Core SA13-ST3 (this study). The gray rectangles indicate local glacier advances in west Greenland region (Larsen et al., 2017; Levy et al., 2017; Schweinsberg et al., 2017; 2018). On the right, the main phases of human occupation in western Greenland after d'Andrea et al. (2011).

Table 3-1 : Radiocarbon dates and calibrated ages from core SA13-ST3-20GC

<i>Depth (cm)</i>	<i>Lab Code</i>	<i>Material dated</i>	<i>Radiocarbon age (yrs BP)</i>	<i>Error (yrs)</i>	<i>Calibrated 2σ (95.4%) age range (cal yrs BP)</i>	<i>Modelled median age (cal yrs BP)</i>
62.5	ETH-67565	mix benthic forams	1460	55	712 - 1001	728
80.5	ETH-67566	mix benthic forams	1425	75	665 - 989	897
101.5	ETH-67567	mix benthic forams	1735	65	980 - 1286	1127
110.5	UOC-2531	organic	1791	25	1104 - 1295	1216
124.5	ETH-81613	mix benthic forams	1890	45	1175 - 1418	1333
129.5	UOC-2532	organic	1958	30	1274 - 1485	1384
150.5	ETH-67568	mix benthic forams	2240	60	1521 - 1852	1681
163.5	AAR-20067	mollusc shell	2362	25	1704 - 1932	1855
172.5	ETH-81614	mix benthic forams	2480	45	1821 - 2111	2025
189.5	ETH-87319	mix benthic forams	2975	50	2395 - 2732	2542
198.5	ETH-81615	mix benthic forams	3110	50	2601 - 2911	2745
218.5	ETH-67569	mix benthic forams	3370	65	2837 - 3249	3154
238.5	ETH-81616	mix benthic forams	3935	50	3570 - 3900	3771
259.5	ETH-81617	mix benthic forams	4550	50	4415 - 4776	4545
283.5	ETH-67570	mix benthic forams	5150	70	5134 - 5568	5259
303.5	ETH-87320	mix benthic forams	5300	60	5324 - 5648	5594
318.5	ETH-67571	mix benthic forams	5880	65	5961 - 6296	6102
321.0	UOC-2330	mollusc shell	5612	30	5719 - 5950	n.a. (outlier)
330.5	ETH-94446	mix benthic forams	6095	60	6231 - 6539	6386
346.0	AAR-20068	mollusc shell	6446	30	6646 - 6889	6789
366.5	ETH-81618	mix benthic forams	7145	60	7385 - 7625	7535
375.5	ETH-94447	mix benthic forams	7880	65	8030 - 8355	8200
380.5	ETH-87321	mix benthic forams	8180	70	8340 - 8710	8438
387.5	ETH-67572	mix benthic forams	8315	75	8465 - 8950	8627
410.5	ETH-87322	mix benthic forams	8755	70	9055 - 9450	9185
428.5	ETH-67573	mix benthic forams	9120	85	9456 - 9993	9524
435.0	AAR-20069	mollusc shell	9033	40	9444 - 9685	9601
451.5	ETH-94448	mix benthic forams	9235	70	9577 - 10110	9884
463.5	ETH-87323	mix benthic forams	9480	70	9919 - 10381	10118
478.5	ETH-67574	mix benthic forams	9725	75	10236 - 10651	10321
495.5	ETH-94449	mix benthic forams	9725	75	10236 - 10651	10523
514.0	AAR-20070	mollusc shell	9868	40	10490 - 10786	10757

CONCLUSION

La marge ouest groenlandaise a enregistré de fortes variations climatiques et océanographiques au cours de l'Holocène. L'objectif principal de cette thèse était de caractériser cette variabilité en reconstituant de façon quantitative des paramètres océanographiques de surface à partir d'enregistrements sédimentaires. Les résultats présentés dans cette étude témoignent de l'amplitude de ces changements et de l'importance du lien atmosphère-glace-océan dans les boucles de rétroaction du système climatique contrôlant la dynamique de la calotte glaciaire groenlandaise. Par ailleurs, nos travaux ont permis de mettre en évidence des liens étroits entre la glace de mer, la fonte glaciaire le long des marges immergées de l'inlandsis et la productivité primaire.

Dans les zones subarctiques, la productivité primaire est influencée en partie par la couverture de glace de mer et l'apport en nutriments (Tremblay et al., 2015; Juul-Pederson et al., 2015; Limoges et al., 2018). Au printemps, la fonte de la calotte glaciaire groenlandaise et de la banquise apporte des nutriments dans la colonne d'eau. Ces eaux plus froides et dessalées ont alors un impact sur la stratification de la colonne d'eau, ce qui joue un rôle non négligeable sur la mise en place du bloom planctonique printanier (Andersen, 1981; Tang et al., 2004; Andresen et al., 2011). À l'été et à l'automne, la fonte de la base des glaciers à terminaison marine permet le mélange de la colonne d'eau et la remontée à la surface d'éléments nutritifs par phénomène d'upwelling, ce qui déclenche un deuxième bloom planctonique tardif (Boertmann et al., 2013; Juul-Pedersen et al., 2015). Dans la région de Godthåbsfjord

et de Fyllas Bank, le bloom printanier débute en avril par le développement des espèces haptophytes, suivie par les diatomées, puis, lors du deuxième bloom planctonique, des dinoflagellés et des ciliés à l'été, à l'automne et en hiver (Krawczyk et al., 2015; 2018). L'analyse des kystes de dinoflagellés dans les sédiments de surface le long de la marge ouest groenlandaise a démontré une relation étroite entre les dinokystes, les conditions hydrographiques de surface et le bloom planctonique tardif (Allan et al., 2019).

Les sédiments de surface peuvent représenter quelques années, quelques décennies, voire quelques siècles, dépendamment des vitesses de sédimentation et des bioturbations. Comme les échantillons de surface sont utilisés pour calibration des assemblages microfossiles en référence aux conditions océanographiques modernes, la nature des sédiments de surface utilisés dans le développement de bases de données aux fins de fonctions de transfert ou l'application de la technique des analogues moderne est très importante. Le long de la marge ouest groenlandaise, la vitesse de sédimentation étant relativement élevée (Lloyd et al., 2007; Perner et al., 2011; Seidenkrantz et al., 2007, 2013; Krawczyk et al., 2017), les sédiments de surfaces devraient donc être de bons indicateurs des conditions environnementales modernes. Le premier chapitre de cette thèse a permis d'établir que malgré l'âge des sédiments, « moderne » ou antérieur, estimé à partir l'analyse des radionucléides naturels ^{210}Pb et artificiels ^{137}Cs , les assemblages de dinokystes représentent bien les conditions environnementales de surface des quelques dernières décennies. Ce chapitre a donc permis de vérifier que la fiabilité des reconstitutions quantitatives des paramètres hydrographiques de surface augmentait avec une forte couverture du nombre d'analogues modernes de la zone étudiée (Allan et al., 2019).

L'analyse des assemblages de dinokyste de Nuuk à Disko Bugt (Figure 1) a permis de reconstituer de manière quantitative la variabilité des conditions océanographiques de surface au cours de l'Holocène. Ici, nous avons utilisé des

reconstitutions réalisées avec la nouvelle base de données de dinokystes qui comprend 1968 sites de référence dans l'hémisphère nord (de Vernal et al., 2019). L'étude comparative est réalisée sur les carottes sédimentaires SA13-ST3-20GC prélevée au large de Nuuk (Allan et al., en préparation), et les carottes MSM343300 et MSM343310 prises dans la baie de Disko (Ouellet-Bernier et al., 2014; Allan et al., 2018). Il s'agit de sites situés de part et d'autre du détroit de Davis entre la baie de Baffin et la mer du Labrador où se font les échanges entre les eaux atlantiques et arctiques via le WGC à l'est et le courant de Baffin à l'ouest. Or, la circulation et les échanges dans ce secteur influencent la densité des masses d'eau et la convection d'eau profonde dans la mer du Labrador, contribuant à l'AMOC et par conséquent à la circulation océanique globale (Azetsu-Scott et al., 2012, Sévellec et al., 2017). L'emplacement des sites étudiés ici, au large de Nuuk et dans le chenal glaciaire de la baie de Disko, est donc idéal pour retracer l'évolution de la circulation océanique au cours du temps. Ce n'est qu'à partir du Néoglaciale, après ~5 ka BP, que les paramètres hydrographiques de surface enregistrent des conditions semblables au nord et au sud du détroit de Davis (Figure 1), suggérant ainsi que la mise en place de la dynamique hydrographique actuelle est relativement récente (Figure 1). Bien qu'il a été démontré que la formation des eaux intermédiaires dans la mer du Labrador n'a débuté qu'après ~7 ka BP (Hillaire-Marcel et al., 2001; Hoogakker et al., 2015), il est probable que les conditions hydrographiques similaires à celles de l'actuel ne se soit instaurées que plus tard le long de la côte ouest groenlandaise. En effet, comme les phases d'avancée et de retrait des glaciers de la région ouest groenlandaise diffèrent de celles du sud-ouest groenlandais au cours de l'Holocène (Briner et al., 2016; Cuzzzone et al., 2019), il est logique que les conditions océanographiques diffèrent au nord et au sud du détroit de Davis pendant le retrait des glaciers lors de l'HTM (Rignot et al., 2010; Hanna et al., 2013; Young et Briner 2015; Briner et al., 2016; Schweinsberg et al., 2018).

Au large de Nuuk, dans la mer du Labrador, des conditions interglaciaires s'établissent dès ~10 ka BP, alors qu'à Disko, dans la baie de Baffin, il faut attendre environ 7,3 ka BP (Ouellet-Bernier et al., 2014). Cela s'explique en partie par un retrait glaciaire rapide au début de l'Holocène le long des marges sud-ouest groenlandaises (Briner et al., 2016; Cuzzone et al., 2019), rendant compte d'une diminution de la masse glaciaire de plus de 100 Gt.an⁻¹ entre ~8 et ~5 ka BP (Larsen et al., 2015). Un tel retrait glaciaire s'accompagnant de grands volumes d'eaux de fonte aurait eu un effet sur la productivité primaire marine (Figure 1) via des apports en nutriments par upwelling engendrés le long des marges glaciaires immergées par des flux hyperpycnaux (Mulder et al., 2003 ; Allan et al., en préparation). Une telle hypothèse est valable pour la région de Nuuk au sud du détroit de Davis, mais ne peut s'appliquer à la baie de Disko où la productivité primaire n'a pas atteint des valeurs aussi élevées (Figure 1).

De ~4 à ~2,5 ka BP, la région de Nuuk enregistre un refroidissement avec une légère augmentation du couvert de glace de mer corrélée avec des avancées glaciaires (Larsen et al., 2017; Schweinsberg et al., 2018). Dans la région de Disko, ce sont des oscillations de large amplitude et une grande instabilité qui semblent caractériser les derniers milliers d'années. Grâce à de très fortes vitesses de sédimentation, on a pu analyser la carotte MSM343310 de Disko Bugt avec une très haute résolution temporelle. L'analyse des carottes voisines MSM343300 et MSM343310 livre des reconstitutions des paramètres hydrographiques de surface des derniers 4000 ans très semblables, notamment pour ce qui concerne le couvert de glace de mer. Cependant, à partir de 1000 ans avant l'actuel, les reconstitutions aux deux sites diffèrent, celui au large enregistrant une augmentation des températures et une diminution des salinités estivales plus prononcées (Figure 1).

Les analyses en ondelettes de la carotte MSM343310 permettent de suggérer que le forçage solaire du cycle de Suess, d'une périodicité de ~200 ans, contrôlerait

en partie la variabilité de la température et de la salinité de surface avant 2000 ans BP. De plus, la comparaison de nos reconstitutions de température et salinité de surface avec les courbes du $\delta^{18}\text{O}$ de la carotte de glace de Camp Century au nord du Groenland illustre une relation étroite entre les conditions de surface océaniques et le climat régional au Groenland (Allan et al., 2018). À partir de 1500 ans BP, les reconstitutions de la carotte MSM343310 montrent une variabilité caractérisée par une périodicité de 60 à 70 ans, suggérant un lien avec l'Oscillation Multidécadale Atlantique (« Atlantic Multidecadal Oscillation », AMO) et la migration sud-ouest du front polaire atmosphérique (Allan et al., 2018).

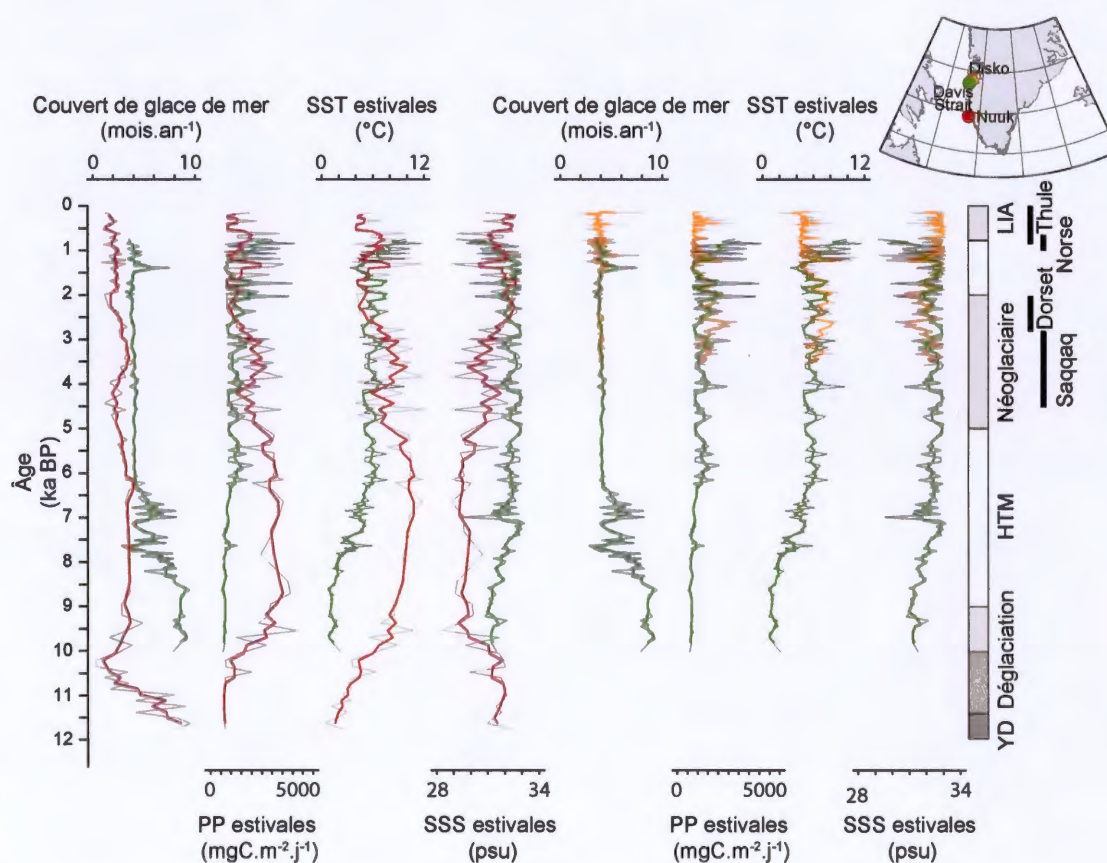


Figure 4-1 : Couvert de glace de mer, productivité primaire (PP), température (SST) et salinité (SSS) estivales dans les eaux de surface reconstituées à partir des assemblages de dinokystes dans les carottes sédimentaires MSM343310 et MSM343300 (courbes vertes et jaunes) ainsi que SA13-ST3 (courbes rouges) (voir la carte en haut à droite). Les reconstitutions ont été réalisées à partir de la base de

données moderne des kystes de dinoflagellé de 1968 sites présents dans l'hémisphère nord (de Vernal et al., 2019). Le diagramme à droite indique les zones paléoclimatiques (cf. Jennings et al., 2014 ; YD= *Younger Dryas* ; HTM= *Holocene Thermal Maximum* ; LIA= *Little Ice Age*) et les épisodes de colonisation humaine de la région ouest groenlandaise.

Les changements climatiques et océanographiques que nous avons retracés le long des côtes ouest groenlandaises semblent montrer une relation avec les mouvements de populations humaines. En effet, l'arrivée et l'installation de la culture Saqqaq il y a 4500 ans pourrait se corrélérer, notamment dans la région de Nuuk, avec une période plus chaude et une forte productivité primaire (Figure 1). Les Saqqaquiens qui étaient des chasseurs-cueilleurs, vivaient notamment de la chasse aux caribous et aux mammifères marins (Jensen, 2006; D'Andrea et al., 2011). Aujourd'hui, dans la région, une forte productivité primaire marine et des températures de surface douces ont un rôle important dans la mise en place du réseau trophique arctique (Boertmann et al., 2013). De ce fait, les conditions climatiques plus douces lors cette période auraient été propices à l'arrivée des mammifères marins et donc profitables à l'établissement de la culture Saqqaq. Il y a ~2800 ans, un refroidissement dans les reconstitutions des températures de surface au large de Nuuk (Figure 1) ainsi que des avancées glaciaires dans la région ouest groenlandaise (Larsen et al., 2017; Schweinsberg et al., 2017; 2018) sont observés. Ce refroidissement, corrélé à une diminution de la productivité primaire (Figure 1), aurait probablement conduit à une diminution de la migration des mammifères marins dans la région, et donc à un appauvrissement de la ressource alimentaire pour les Saqqaquiens (D'Andrea et al., 2011; Allan et al., en préparation). Ils sont alors remplacés par les Dorsétiens qui étaient mieux adaptés à des conditions froides et difficiles, et qui possédaient les outils adéquats à la pêche sur glace (Jensen, 2006; D'Andrea et al., 2011). Il y a ~2000 ans, l'instabilité des conditions hydrographiques de surface (Figure 1 ; Allan et al., 2018) serait corrélée avec un changement climatique régional vers des conditions plus rigoureuses et semblerait coïncider avec

les mille ans d'inoccupation humaine de la région ouest groenlandaise. Il y a ~1000 ans, le retour à des conditions plus douces et l'augmentation de la productivité primaire (Figure 1) concordent avec l'arrivée des Norrois qui étaient sédentaires et agriculteurs (Dugmore et al., 2007; D'Andrea et al., 2011). Enfin, au début du Petit Âge glaciaire, il y a environ 650 ans, une forte détérioration du climat accompagnée d'avancées glaciaires aurait pu contribuer à l'abandon des colonies par les Norrois (D'Andrea et al., 2011), laissant le territoire à la culture Thulé, les ancêtres des Inuits actuels, arrivés au Groenland il y a 850 ans (McGovern, 1991).

Ce doctorat a permis de mettre en lumière un lien étroit entre les conditions océanographiques et le climat régional du Groenland, sans pour autant identifier le forçage ou les mécanismes à l'origine de la variabilité enregistrée régionalement. Un mécanisme qui expliquerait le changement de régime hydrographique après ~1500 ans BP implique des modifications importantes de la circulation atmosphérique avec une migration vers le sud-ouest du front polaire, entraînant ainsi des conditions climatiques plus rigoureuses et des tempêtes plus fréquentes le long des marges du sud-ouest groenlandaise. Il s'agirait d'un changement de régime à l'échelle régionale qui pourrait faire suite à un effet de seuil.

ANNEXE A

ASSEMBLAGES DINOKYSTES DES DONNÉES DE SURFACE

Stations	<i>Nematosphaeropsis labyrinthus</i>	<i>Operculodinium centrocarpum</i>	<i>Pyxidinospis reticulata</i>	<i>Spiniferites delicatus</i>	<i>Spiniferites elongatus</i>	<i>Spiniferites ramosus</i>	<i>Spiniferites</i> spp.	<i>Cyst of Pentapharsodinium dalei</i>	<i>Islandinium minutum</i>	<i>Islandinium? cezare</i>	<i>Islandinium brevispinosum</i>	<i>Echinidinium karaense</i>	<i>Brigantedinium</i> spp.	<i>Dubridinium</i> spp.	Protoperidinioids	<i>Selenopemphix nephroides</i>	<i>Selenopemphix quanta</i>	<i>Trinovantedinium applanatum</i>	<i>Votadinium calvum</i>	<i>Cyst of Protoperidinium americanum</i>	<i>Cyst of Polykrikos schwartzii</i>
U5.05	3	104	0	0	21	10	0	181	15	2	0	2	2	1	0	0	0	0	0	0	0
U5.04*	3	162	0	0	20	6	12	31	40	0	0	3	9	0	2	0	0	0	0	0	0
U5.09*	1	123	0	0	20	4	1	76	142	3	0	0	26	0	0	0	2	0	0	0	0
U5.08*	4	113	0	0	13	5	0	99	102	3	0	2	10	0	0	0	1	0	0	0	0
U5.10	3	169	0	0	22	3	0	30	118	4	0	0	17	0	0	0	0	0	0	0	0
U5.01	3	97	0	0	20	8	0	69	118	3	0	0	50	0	0	0	0	0	1	0	0
U5.15*	48	213	0	0	30	10	1	28	44	0	0	0	16	0	0	0	0	0	0	0	0
U5.14*	34	128	0	0	18	5	0	60	52	2	0	0	94	0	0	1	1	0	0	0	0
V4.04*	8	257	0	0	35	5	0	67	134	2	0	0	62	0	0	0	0	0	0	0	0
V4.03	0	184	0	0	19	2	0	23	88	0	0	0	23	0	0	0	0	0	0	0	0
V4.02	1	72	1	0	15	0	0	195	89	3	0	0	101	0	0	0	0	0	0	0	0
V4.01*	1	78	0	0	22	2	0	97	46	2	0	0	36	0	0	0	1	0	0	0	1
DB3.26	0	79	0	0	12	1	0	55	139	3	0	0	10	0	0	0	0	0	0	0	0
DB3.24*	0	64	0	0	21	5	1	51	155	2	0	0	11	0	0	0	0	0	0	0	0
DB3.23	2	65	0	0	9	2	0	33	103	2	0	0	12	0	0	0	0	0	0	0	0
DB3.25	0	73	0	0	17	4	1	37	173	3	0	0	26	0	0	0	1	0	0	0	0
DB3.34	1	101	0	0	25	2	10	130	38	0	0	1	21	4	4	0	2	0	0	0	0
DB3.36	0	133	0	0	38	9	3	118	57	2	0	0	39	0	0	0	4	0	0	0	0

DB3.33*	4	84	0	0	12	2	0	131	111	5	0	0	83	0	0	0	0	0	0	0
DB3.30*	1	83	0	0	17	5	4	63	127	13	0	0	18	0	0	0	0	0	0	0
DB3.20*	3	32	0	0	5	0	1	55	231	6	0	2	12	0	0	0	0	0	0	0
DB3.32*	1	125	0	0	34	11	3	56	169	9	0	0	31	0	0	0	1	0	0	0
DB3.35*	4	121	0	0	35	3	0	134	50	2	0	0	26	0	0	0	2	0	0	0
DB3.31*	0	22	0	0	15	4	1	47	255	16	0	0	32	0	0	0	5	0	0	0
DB3.27*	2	23	0	0	23	4	0	50	94	1	0	0	60	0	0	0	9	0	0	0
DB3.29	3	48	0	0	8	2	0	76	121	4	0	1	37	0	0	0	9	0	0	0
DB3.19	0	43	0	0	12	0	0	55	186	4	0	3	13	0	0	0	1	0	0	0
DB3.13*	3	11	0	0	9	1	0	34	184	14	0	0	31	0	0	0	8	0	0	0
DB3.12*	3	6	0	0	3	1	0	73	147	28	0	0	65	0	0	0	9	0	0	0
DB3.10*	5	18	0	0	9	3	1	52	250	21	0	1	42	0	0	0	4	0	0	0
DB3.11*	4	9	0	0	3	4	1	59	245	18	0	1	46	0	0	0	6	0	0	0
DB3.16*	15	36	0	0	8	0	4	61	107	1	0	0	14	0	0	0	0	0	0	0
DB3.15	7	37	0	0	11	1	0	26	228	3	0	1	33	0	0	0	1	0	0	0
DB3.14	5	16	0	0	7	1	0	13	239	6	0	1	36	0	0	0	1	0	0	0
DB3.02	16	11	0	0	5	7	1	41	128	32	0	0	143	4	9	0	5	0	0	4
DB3.01	27	54	0	0	8	4	7	55	83	1	4	0	30	6	19	0	1	0	0	0
DB3.08	0	1	0	0	3	1	1	3	31	1	0	0	31	0	0	0	2	0	0	0
DB3.42	18	21	0	0	5	0	0	6	101	0	0	3	23	0	0	0	11	0	0	0
HB2.06	35	8	0	1	3	1	1	48	57	0	0	0	34	0	0	0	3	0	0	0
HB2.04*	6	11	0	0	16	8	0	47	27	2	0	0	110	0	0	0	16	0	0	0
HB2.05*	14	1	0	0	2	0	2	11	86	30	0	0	30	0	0	0	4	0	0	0
HB2.01	49	11	0	0	2	1	0	10	77	1	0	1	60	0	0	0	6	0	0	0
HB2.02	1	3	0	0	7	6	4	41	99	47	0	0	82	1	0	0	8	0	0	0
FB1.12	134	4	0	0	1	0	0	14	118	3	0	0	55	0	0	0	7	1	0	0
FB1.05*	16	2	0	0	7	2	3	69	82	39	0	0	109	1	0	0	9	0	0	0
FB1.02	14	47	0	0	4	3	1	22	155	19	1	0	47	1	5	0	9	0	0	1
FB1.07	43	4	0	0	2	0	0	10	81	15	0	0	53	0	0	2	3	0	0	0
DB6.02	4	0	0	0	2	0	0	25	111	55	0	1	111	0	0	0	5	0	0	0
DB6.01*	2	4	0	0	2	0	0	37	71	67	0	1	50	0	0	0	5	0	0	0
DB6.03	11	7	0	0	1	0	0	27	105	10	0	0	134	3	0	0	27	0	0	0
DB6.06*	12	5	0	0	0	1	0	11	40	0	0	0	86	0	0	0	37	0	0	0
DB6.05*	25	5	0	0	2	1	0	36	116	12	0	1	109	0	0	0	30	0	0	0
DB6.04	19	4	0	0	1	0	0	49	133	38	0	0	73	0	0	0	3	0	0	0
DB6.08*	8	6	0	0	0	2	0	16	123	30	0	2	94	0	0	0	11	0	0	0
DB6.09*	8	1	0	0	0	0	1	58	108	48	0	0	74	0	0	0	4	0	0	0
DB6.07	0	3	0	0	1	1	1	1	84	17	0	0	39	0	0	0	6	0	0	0
DB6.10	98	15	0	0	0	0	0	10	30	0	0	0	26	0	1	0	8	2	0	0

Q7.04*	40	11	0	0	3	1	0	65	135	14	0	1	32	0	0	0	3	0	0	0	0
Q7.03*	51	14	0	0	1	1	0	50	154	12	0	1	22	0	0	0	9	0	0	0	0
Q7.05	48	128	0	0	11	5	1	22	28	1	0	0	5	0	0	0	0	0	0	0	0

ANNEXE B

ASSEMBLAGES DINOKYSTES DU SITE MSM343310 (DISKO BUGT)

Multi core	<i>Achomospaera</i> spp.	<i>Bitectatodinium tepikiense</i>	<i>Impagidinium aculeatum</i>	<i>Impagidinium pallidum</i>	<i>Nematosphaeropsis labyrinthus</i>	<i>Operculodinium centrocarpum</i>	<i>Spiniferites elongatus</i>	<i>Spiniferites ramosus</i>	<i>Spiniferites belerius</i>	<i>Spiniferites bentorii</i>	<i>Spiniferites</i> spp.	<i>Cyst of Pentapharsodinium dalei</i>	<i>Islandinium minutum</i>	<i>Islandinium? cesare</i>	<i>Islandinium brevispinosum</i>	<i>Brigantedinium</i> spp.	<i>Dubridinium</i> spp.	<i>Lejeuneocysta</i> spp.	<i>Selenopemphix quanta</i>	<i>Cyst of Protoperidinium nudum</i>	<i>Votadinium calvum</i>	<i>Cyst of Protoperidinium americanum</i>	<i>Echinidinium</i> spp.
Age BP	ACHO	BTEP	IACU	IPAL	NLAB	OCEN	SELO	SRAM	SBEL	SBEN	SSPP	PDAL	IMIN	IMIC	IBRE	BSPP	DUBR	LSPP	SQUA	PNUD	VCAL	PAME	ESPP
-55,93	0	0	0	0	3	6	11	3	0	0	0	128	132	21	0	26	0	0	1	0	0	0	0
-50,94	0	0	0	0	7	21	8	6	0	0	5	145	105	12	0	25	0	0	7	0	0	0	0
-45,11	0	0	0	0	1	12	10	2	0	0	0	123	70	10	0	20	0	0	2	0	0	0	0
-37,8	0	0	0	0	6	11	8	6	0	0	0	102	132	11	0	53	0	0	5	0	0	0	0
-33,13	0	0	0	0	4	5	6	2	0	0	0	106	68	8	0	50	0	0	4	0	0	0	0
-26,95	0	0	0	0	10	9	10	6	0	0	1	151	57	5	0	53	0	0	3	0	0	0	0
-20,6	0	0	0	0	7	4	6	1	0	0	0	163	123	17	0	65	0	0	4	0	0	0	0
-14,62	0	0	0	0	7	8	8	4	0	0	0	488	94	8	0	62	0	0	1	0	0	0	2
-8,52	0	0	0	0	3	2	4	4	0	0	0	162	87	8	0	58	0	0	3	0	0	0	0
-1,94	0	0	0	0	10	6	9	3	0	0	0	189	165	12	0	92	0	0	5	0	0	0	0
4,44	0	0	0	0	11	12	11	5	0	0	0	196	138	15	0	88	0	0	6	0	0	0	0
10,71	0	0	0	0	15	11	10	2	0	0	0	148	94	4	0	79	0	0	5	0	0	0	0
18,77	0	0	0	0	3	6	5	0	0	0	0	95	122	7	0	67	0	0	7	0	0	0	0
23,58	0	0	0	0	7	11	5	2	0	0	0	122	170	15	0	104	0	0	7	0	0	0	1
29,87	0	0	0	0	3	1	6	4	0	0	0	103	110	14	0	55	0	0	8	0	0	0	0
36,05	0	0	0	0	8	10	15	5	0	0	0	117	81	4	0	75	0	0	11	0	0	0	0
42,21	0	0	0	0	4	8	19	10	0	0	0	83	92	2	0	76	0	0	11	0	0	0	0

Gravity core	Achomphaera spp.	Bitectatodinium tepikiense	Impagidinium aculeatum	Impagidinium pallidum	Nematosphaeropsis labyrinthus	Operculodinium centrocarpum	Spiniferites elongatus	Spiniferites ramosus	Spiniferites belerius	Spiniferites bentorii	Spiniferites spp.	Cyst of Pentapharsodinium dalei	Islandinium minutum	Islandinium? cesare	Islandinium brevispinosum	Brigantedinium spp.	Dubridinium spp.	Lejeunecysta spp.	Selenopemphix quanta	Cyst of Protoperidinium nudum	Votadinium calvum	Cyst of Protoperidinium americanum	Echinidinium spp.
Age BP	ACHO	BTEP	IACU	IPAL	NLAB	OCEN	SELO	SRAM	SBEL	SBEN	SSPP	PDAL	IMIN	IMIC	IBRE	BSPP	DUBR	LSPP	SQUA	PNUD	VCAL	PAME	ESPP
134,957	1	1	0	0	4	11	17	4	0	0	7	269	334	21	0	85	0	0	11	0	0	3	0
138,13	0	0	0	0	1	5	11	4	0	0	0	79	111	6	0	78	0	0	8	0	0	0	0
150,83	0	1	0	0	0	3	8	1	0	0	2	74	139	35	0	35	0	0	2	0	0	0	0
163,53	0	0	0	2	1	3	2	0	0	0	0	64	177	43	0	32	0	0	0	0	0	0	0
166,709	0	0	0	0	1	3	6	0	0	0	2	45	197	17	0	29	0	0	5	1	0	3	0
176,24	0	0	0	0	2	1	2	0	0	0	0	74	167	38	0	24	0	0	5	0	0	0	0
188,94	0	0	0	0	0	1	8	0	0	0	0	74	151	38	0	32	0	0	3	0	0	0	0
198,464	0	0	0	0	1	8	3	6	0	0	7	33	233	18	0	34	0	0	2	0	0	1	0
201,64	0	0	0	0	1	3	8	0	0	0	0	62	183	45	0	29	0	0	2	0	0	0	0
214,34	0	0	0	0	4	1	3	7	0	0	0	67	235	37	0	36	0	0	6	0	0	0	0
227,05	0	0	0	0	5	5	3	2	0	0	0	79	165	16	0	39	0	0	6	0	0	0	0
230,222	0	0	0	0	2	3	7	2	0	0	0	62	181	20	0	40	0	0	3	1	0	0	0
261,977	0	0	0	0	0	6	9	3	0	0	4	29	208	14	0	55	0	0	9	0	0	1	0
265,15	0	0	0	0	4	5	7	2	0	0	0	53	193	38	0	33	0	0	6	0	0	0	0
277,85	0	0	0	3	5	4	7	2	0	0	0	56	233	38	0	33	0	0	6	0	0	0	0
290,549	0	0	0	0	3	5	4	5	0	0	0	69	146	24	0	38	0	0	8	0	0	0	0
293,723	0	0	0	0	2	4	7	5	0	0	2	49	153	33	0	41	0	1	2	3	0	1	0
303,24	0	0	0	0	4	4	6	0	0	0	0	60	180	51	0	17	0	0	4	0	0	0	0
315,94	0	0	0	0	0	5	1	5	0	0	0	55	225	43	0	32	0	0	1	0	0	0	0
322,281	0	0	0	0	2	8	5	3	0	0	0	62	195	40	0	37	0	0	3	0	0	0	0
325,453	0	0	0	0	0	7	4	3	0	0	2	29	234	18	0	42	0	0	6	0	0	0	0
334,97	0	0	0	0	0	5	3	5	0	0	0	57	195	32	0	37	0	0	4	0	0	0	0
347,65	0	0	0	0	7	5	13	7	0	0	0	76	193	21	0	64	0	0	10	0	0	0	0
357,16	0	0	0	0	1	6	7	2	0	0	3	44	190	15	0	40	0	0	3	2	0	0	0
360,33	0	0	0	0	1	5	5	1	0	0	0	49	187	32	0	27	0	0	7	0	0	0	0
373	0	0	0	1	4	4	2	4	0	0	0	69	150	37	0	65	0	0	4	0	0	0	0
385,67	0	0	0	0	1	2	3	1	0	0	0	89	181	36	0	26	0	0	1	0	0	0	0
388,83	0	0	0	0	0	10	1	5	0	0	3	27	218	25	0	43	0	0	2	0	0	0	0

398,33	0	0	0	0	3	7	3	2	0	0	0	72	155	26	0	50	0	0	4	0	0	0	0
410,99	0	0	0	0	0	9	2	4	0	0	0	55	192	29	0	53	0	0	7	0	0	0	0
420,473	0	0	0	0	2	6	2	1	0	0	0	42	199	21	0	31	0	0	0	1	0	1	0
423,63	0	0	0	0	2	7	5	5	0	0	0	52	170	28	0	27	0	0	6	0	0	0	0
429,96	0	0	0	0	5	4	5	0	0	0	0	116	142	35	0	34	0	0	7	0	0	0	0
442,59	0	0	0	0	1	5	3	2	0	0	0	95	136	9	0	62	0	0	4	0	0	0	0
452,064	0	0	0	0	0	3	2	2	0	1	4	27	193	14	0	51	0	0	2	1	0	0	0
455,22	0	0	1	0	3	15	10	6	0	0	0	116	144	25	0	47	0	0	6	0	0	0	0
467,84	0	0	0	0	2	6	5	3	0	0	0	112	135	33	0	52	0	0	2	0	0	0	0
474,14	0	0	0	0	4	11	8	5	0	0	0	99	150	14	0	67	0	0	4	0	0	0	0
483,591	0	0	0	0	2	8	1	2	0	0	0	49	165	18	0	55	0	0	1	0	0	0	0
486,74	0	0	0	0	1	6	5	6	0	0	0	64	157	26	0	59	0	0	3	0	0	0	0
499,32	0	0	0	1	1	6	5	3	0	0	0	73	181	20	0	58	0	0	1	0	0	0	0
511,89	0	0	0	2	1	4	8	2	0	0	0	95	154	41	0	37	0	0	3	0	0	0	0
515,033	0	0	0	0	1	8	5	0	0	0	3	53	139	27	0	63	0	0	3	0	0	0	0
524,45	0	0	0	0	1	3	4	0	0	0	0	72	156	44	0	27	0	0	4	0	0	0	0
536,98	0	1	0	2	1	10	9	0	0	0	0	62	138	15	0	62	0	0	8	0	0	0	0
546,371	0	0	0	0	0	7	5	4	0	0	4	54	157	20	0	50	0	0	2	1	0	2	0
549,5	0	1	0	0	2	5	9	0	0	0	0	106	117	30	0	42	0	0	2	0	0	0	0
555,75	0	0	0	0	4	8	11	3	0	0	0	71	166	15	0	57	0	0	1	0	0	0	0
568,23	0	0	0	0	1	5	10	7	0	0	0	64	182	19	0	40	0	0	3	0	0	0	0
577,584	0	0	0	0	2	11	4	5	0	0	4	64	140	8	0	63	0	0	6	0	0	1	0
580,7	0	0	0	0	6	8	10	2	0	0	0	65	156	8	0	60	0	0	1	0	0	0	0
593,14	0	2	0	0	1	7	12	2	0	0	0	69	133	23	0	59	0	0	9	0	0	0	0
605,55	0	0	0	5	4	8	16	1	0	0	0	62	132	26	0	76	0	0	4	0	0	0	0
608,652	0	0	0	0	1	3	9	1	0	0	2	58	168	16	0	44	0	0	3	0	0	0	0
630,31	0	0	0	1	3	3	11	1	0	0	0	82	122	28	0	45	0	0	3	0	0	0	0
639,567	0	0	0	0	2	10	6	1	1	0	2	60	147	15	0	64	0	0	1	0	0	0	0
642,65	0	0	0	2	3	6	13	5	0	0	0	83	150	20	0	72	0	0	3	0	0	0	0
654,98	0	0	0	0	3	8	18	2	0	0	3	104	96	30	0	52	0	0	3	0	0	0	0
667,28	0	1	0	0	1	6	5	0	0	0	2	103	117	30	0	35	0	0	4	0	0	0	0
670,359	0	0	0	0	2	2	9	1	0	0	2	59	161	20	0	45	0	0	2	1	0	0	0
679,58	0	1	0	0	2	4	17	3	0	0	1	82	110	34	0	67	0	0	1	0	0	0	0
691,86	0	0	0	0	0	9	26	1	0	0	3	101	102	30	0	66	0	0	2	0	0	0	0
701,066	0	0	0	0	3	5	4	0	0	1	3	71	155	18	0	38	1	0	2	0	0	0	0
704,13	0	1	0	0	0	7	6	0	0	0	0	76	153	64	0	22	0	0	2	0	0	0	0
716,4	0	0	0	0	0	4	7	0	0	0	0	89	142	42	0	35	0	0	2	0	0	0	0
728,66	0	0	0	0	0	8	26	1	0	0	2	109	80	24	0	51	0	0	9	0	0	0	0
731,73	0	0	0	0	2	6	3	6	0	0	3	87	142	16	0	43	0	0	2	3	2	1	0

740,93	0	0	0	0	1	12	27	1	0	0	1	101	68	22	0	60	0	0	10	0	0	0	0
753,19	0	0	0	0	0	10	10	0	0	0	0	121	110	19	0	40	0	0	5	0	0	0	0
762,387	0	0	0	0	1	12	6	1	1	0	4	71	162	25	0	25	1	0	3	1	0	0	0
765,45	0	0	0	0	2	6	17	1	0	0	2	155	90	28	1	33	0	0	4	0	0	0	0
777,73	0	0	0	0	2	4	5	0	0	0	0	100	129	35	0	32	0	0	4	0	0	0	0
790,01	0	0	0	0	1	0	9	0	0	0	0	113	118	29	0	30	0	0	3	0	0	0	0
793,078	0	0	0	0	2	3	7	3	0	0	2	89	126	18	0	49	0	1	1	0	1	0	0
802,3	0	0	0	0	2	15	17	3	0	0	1	157	125	27	0	32	0	0	7	0	0	0	0
814,61	0	0	0	0	0	10	13	0	0	0	1	120	102	20	0	39	0	0	5	0	0	0	0
823,848	0	0	0	0	2	5	13	2	0	0	4	86	140	19	0	25	0	0	5	1	0	0	0
826,93	0	0	0	0	2	6	13	2	0	0	3	106	120	26	0	34	0	0	4	0	0	0	0
839,28	0	0	0	0	2	6	12	1	0	0	0	118	117	18	0	26	0	0	0	0	0	0	0
851,65	0	0	0	0	2	4	7	0	0	0	0	116	156	36	0	29	0	0	1	0	0	0	0
854,747	0	0	0	0	2	4	10	1	0	3	6	89	121	12	0	47	0	0	5	1	0	2	0
864,05	0	0	0	0	2	8	10	0	0	0	0	99	137	32	0	25	0	0	4	0	0	0	0
876,48	0	0	0	0	0	4	17	1	0	0	2	142	97	26	0	32	0	0	5	0	0	0	0
885,825	0	0	0	0	1	9	8	4	1	0	3	97	125	23	0	28	0	0	5	0	0	0	0
888,94	0	0	0	0	1	7	17	4	0	0	1	83	137	37	0	31	0	0	5	0	0	0	0
901,45	0	0	0	0	0	2	6	0	0	0	2	87	141	43	0	19	0	0	2	0	0	0	0
913,99	0	0	0	0	1	4	12	3	0	0	0	103	144	23	0	27	0	0	4	0	0	0	0
917,131	0	0	0	0	5	2	12	3	0	0	2	66	175	13	0	30	0	0	2	0	0	0	0
926,58	0	1	0	1	0	3	11	1	0	0	1	94	153	24	0	32	0	0	7	0	0	0	0
939,21	0	0	0	0	5	5	14	2	0	0	7	98	96	37	0	37	0	0	5	0	0	0	0
948,716	0	0	0	0	3	5	4	6	0	0	7	64	189	27	0	5	0	0	4	0	0	0	0
951,89	0	1	0	0	2	6	15	1	0	0	0	85	121	19	0	43	0	0	8	0	0	0	0
964,63	0	1	0	0	2	10	12	1	0	0	0	107	104	16	0	42	0	0	5	0	0	0	0
977,42	0	0	0	2	5	8	16	4	0	0	0	91	125	8	0	48	0	0	3	0	0	0	0
980,63	0	0	0	0	4	8	3	2	0	0	4	51	158	37	0	35	0	0	0	0	0	0	0
990,28	0	0	0	0	7	7	21	5	0	0	0	55	189	9	0	41	0	0	6	0	0	0	0
1003,19	0	0	0	0	4	5	29	4	0	0	0	58	195	9	0	40	0	0	0	0	0	0	0
1012,912	0	0	0	0	3	9	3	6	1	0	0	39	187	23	0	27	0	0	4	0	0	0	0
1016,16	0	0	0	0	5	5	11	4	0	0	0	39	206	28	0	11	0	0	5	0	0	0	0
1029,19	0	0	0	0	11	12	38	13	0	0	0	50	136	4	0	50	0	0	10	0	0	0	0
1042,29	0	0	0	0	13	5	32	17	0	0	1	97	112	3	0	29	0	0	4	0	0	0	0
1045,568	0	0	0	0	3	11	12	5	0	0	2	60	138	23	0	45	0	0	2	1	0	0	0
1055,44	0	0	0	0	11	5	7	0	0	0	1	110	149	11	0	24	0	0	2	0	0	0	0
1068,65	0	0	0	0	7	4	20	4	0	0	0	70	150	33	0	32	0	0	4	0	0	0	0
1078,596	0	0	0	0	1	11	8	2	0	0	3	38	192	22	0	19	0	0	3	0	0	0	0
1081,92	0	0	0	0	2	11	8	9	0	0	0	79	155	31	0	26	0	0	5	0	0	1	0

1108,64	0	0	0	0	6	14	15	7	0	0	0	61	208	22	0	27	0	0	1	0	0	0	0
1111,995	0	0	0	0	0	5	5	0	0	0	4	64	173	35	0	28	0	0	0	0	0	0	0
1135,59	0	0	0	0	4	14	32	19	0	0	0	103	116	9	0	21	0	0	4	0	0	0	0
1145,761	0	0	0	0	3	14	6	3	0	0	3	48	173	38	0	17	0	0	3	0	0	0	0
1162,78	0	0	0	0	11	7	12	6	0	0	1	197	76	6	0	26	0	0	14	0	0	0	0
1179,894	0	0	0	0	0	5	5	0	0	0	1	71	135	28	0	49	0	0	5	0	0	0	0
1190,21	0	0	0	1	4	12	14	7	0	0	0	84	129	23	0	54	0	0	4	0	0	0	0
1214,391	0	0	0	0	6	17	8	5	3	0	7	77	141	10	0	33	0	0	1	0	0	0	0
1217,86	0	0	0	0	12	19	36	29	0	0	0	110	23	2	0	58	0	0	7	0	0	0	0
1245,75	0	0	0	0	1	16	12	14	0	0	0	40	144	0	0	70	0	0	6	0	0	0	0
1249,248	0	0	0	0	3	3	3	0	0	1	2	74	142	12	0	56	0	0	3	1	0	0	0
1273,85	0	0	0	0	2	9	14	9	0	0	0	43	165	23	0	44	0	0	3	0	0	0	0
1284,446	0	0	0	0	1	6	15	8	0	0	6	50	156	16	0	38	0	0	6	0	0	0	0
1302,17	0	0	0	0	7	16	16	7	0	0	0	74	130	13	0	65	0	0	9	0	0	0	0
1319,965	0	0	0	0	3	3	13	5	0	4	2	76	139	13	0	41	0	0	2	0	0	0	0
1330,68	0	0	0	0	9	29	23	12	0	0	0	65	135	7	0	66	0	0	8	0	0	0	0
1355,782	0	0	0	0	1	6	9	3	0	0	2	57	159	13	0	49	0	0	2	0	0	0	0
1359,38	0	0	0	0	2	6	14	6	0	0	0	40	147	29	0	69	0	0	0	0	0	0	0
1388,25	0	0	0	0	4	16	10	4	0	0	0	80	128	37	0	55	0	0	4	0	0	0	0
1391,875	0	0	0	0	3	7	7	8	0	0	1	62	150	20	0	47	0	0	2	0	0	0	0
1417,29	0	0	0	0	1	4	2	5	0	0	0	54	173	37	0	49	0	0	2	0	0	0	0
1428,223	0	0	0	0	3	9	11	9	0	0	5	51	164	12	0	43	0	0	4	0	0	0	0
1446,49	0	0	0	0	6	5	13	2	0	0	0	47	191	23	0	35	0	0	4	0	0	0	0
1475,839	0	0	0	0	10	13	19	3	0	0	0	44	123	12	0	90	0	0	5	0	0	0	0
1505,37	0	0	0	0	6	15	19	10	0	0	0	136	81	5	0	43	0	0	5	0	0	0	0
1535,09	0	0	0	0	7	14	16	4	0	0	0	109	105	17	0	96	0	0	4	0	0	0	0
1565,01	0	0	0	0	2	13	12	7	0	0	0	110	59	6	0	91	0	0	3	0	0	0	0
1595,17	0	0	0	1	1	10	14	6	0	0	0	62	148	11	0	72	0	0	4	0	0	0	0
1625,57	0	0	0	0	1	5	12	10	0	0	0	53	140	18	0	90	0	0	8	0	0	0	0
1656,23	0	0	0	0	2	17	26	12	0	0	0	51	105	10	0	117	0	0	6	0	0	0	0
1687,16	0	0	0	0	1	5	13	2	0	0	0	140	63	3	0	78	0	0	9	0	0	0	0
1718,37	0	0	0	0	1	11	20	5	0	0	0	75	80	7	0	82	0	0	18	0	0	0	0
1749,87	0	0	0	1	4	15	20	1	0	0	0	96	98	10	0	106	0	0	20	0	0	0	0
1781,68	0	0	0	0	3	8	23	9	0	0	0	79	70	8	0	101	0	0	9	0	0	0	0
1813,78	0	0	0	0	4	12	23	7	0	0	0	54	108	4	0	80	0	0	11	0	0	0	0
1846,21	0	0	0	0	2	10	24	8	0	0	0	81	107	10	0	75	0	0	5	0	0	0	0
1878,96	0	0	0	0	5	5	32	4	0	0	0	53	115	14	0	77	0	0	5	0	0	0	0
1912,04	0	0	0	0	3	21	37	4	0	0	0	86	127	5	0	100	0	0	7	0	0	0	0
1945,44	0	0	0	0	0	13	56	17	0	0	0	61	118	6	0	152	0	0	12	0	0	0	0

1979,12	0	0	0	0	0	11	19	6	0	0	0	77	146	13	0	113	0	0	9	0	0	0	0
2013,05	0	0	0	0	1	14	26	1	0	0	0	97	112	2	0	117	0	0	11	0	0	1	0
2047,21	0	0	0	0	7	11	27	12	0	0	0	102	111	6	0	120	0	0	18	0	0	0	0
2081,56	0	0	0	1	3	11	24	8	0	0	0	103	78	4	0	72	0	0	6	0	0	0	0
2116,08	0	0	0	0	1	10	32	15	0	0	0	56	108	3	0	132	0	0	6	0	0	0	0
2150,73	0	0	0	0	3	13	17	4	0	0	0	72	86	7	0	84	0	0	15	0	0	0	0
2185,49	0	0	0	0	0	14	32	7	0	0	0	76	142	4	0	93	0	0	10	0	0	0	0
2220,31	0	0	0	0	3	17	31	14	0	0	0	77	119	11	0	74	0	0	13	0	0	0	0
2255,18	0	0	0	0	8	15	29	8	0	0	0	99	94	10	0	67	0	0	12	0	0	0	0
2290,08	0	0	0	0	6	18	34	14	0	0	0	78	90	10	0	68	0	0	6	0	0	0	0
2324,97	0	0	0	0	5	16	31	15	0	0	0	83	84	7	0	75	0	0	10	0	0	0	0
2359,86	0	0	0	0	5	9	39	15	0	0	0	81	139	9	0	97	0	0	10	0	0	0	0
2394,72	0	0	0	0	3	7	32	9	0	0	0	69	111	7	0	62	0	0	10	0	0	0	0
2429,54	0	0	0	0	0	7	27	7	0	0	0	83	125	18	0	37	0	0	16	0	0	0	0
2464,33	0	0	0	0	4	9	19	8	0	0	0	88	124	5	0	47	0	0	10	0	0	0	0
2499,08	0	0	0	0	3	7	29	11	0	0	0	96	147	10	0	60	0	0	6	0	0	0	0
2533,8	0	0	0	0	6	10	34	3	0	0	0	81	119	17	0	50	0	0	11	0	0	0	0
2568,48	0	0	0	1	3	14	43	10	0	0	0	81	120	9	0	62	0	0	7	0	0	1	0
2603,12	0	0	0	0	14	14	39	4	0	0	0	143	105	5	0	94	0	0	19	0	0	0	0
2637,73	0	0	0	1	9	17	61	13	0	0	0	152	82	3	0	118	0	0	25	0	0	0	0
2672,3	0	0	0	0	2	18	43	12	0	0	0	130	75	6	0	95	0	0	15	0	0	1	0
2706,8	0	0	0	0	3	11	45	8	0	0	0	89	58	1	0	86	0	0	12	0	0	1	0
2741,2	0	0	0	0	3	14	28	9	0	0	0	76	78	4	0	85	0	0	7	0	0	0	0
2775,49	0	0	0	1	7	22	38	10	0	0	0	109	89	2	0	89	0	0	16	0	0	0	0
2809,64	0	0	0	0	5	20	22	8	0	0	0	79	124	10	0	114	0	0	13	0	0	0	0
2843,62	0	0	0	1	2	10	25	5	0	0	0	86	112	7	0	60	0	0	14	0	0	0	0
2877,41	0	0	0	0	3	12	23	10	0	0	0	69	108	5	0	78	0	0	19	0	0	0	0
2910,99	0	0	0	2	2	11	24	4	0	0	0	90	108	3	0	84	0	0	21	0	0	0	0
2944,34	0	0	0	0	2	14	16	14	0	0	0	88	115	3	0	68	0	0	4	0	0	0	0
2977,45	0	0	0	0	5	22	18	14	0	0	0	102	164	11	0	59	0	0	14	0	0	0	0
3010,28	0	0	0	1	5	14	25	10	0	0	0	97	117	7	0	54	0	0	5	0	0	0	0
3042,84	0	0	0	0	5	11	17	6	0	0	0	88	138	4	0	68	0	0	9	0	0	0	0
3075,13	0	0	0	0	3	18	33	9	0	0	0	120	101	9	0	68	0	0	11	0	0	0	0
3107,2	0	0	0	0	2	21	13	3	0	0	0	125	110	3	0	58	0	0	9	0	0	0	0
3139,06	0	0	0	0	3	27	22	4	0	0	0	122	96	6	0	47	0	0	5	0	0	0	0
3170,76	0	0	0	0	3	28	18	4	0	0	0	119	117	11	0	48	0	0	10	0	0	0	0
3202,31	0	0	0	0	5	17	16	1	0	0	0	93	161	2	0	53	0	0	9	0	0	0	0
3233,76	0	0	0	0	6	11	31	12	0	0	0	91	103	4	0	55	0	0	11	0	0	0	0
3265,12	0	0	0	0	1	13	23	8	0	0	0	121	119	7	0	54	0	0	6	0	0	0	0

3296,44	0	0	0	0	3	24	36	7	0	0	0	153	101	1	0	48	0	0	10	0	0	0	0
3327,74	0	0	0	0	6	20	29	6	0	0	0	118	72	7	0	51	0	0	26	0	0	0	0
3359,04	0	0	0	0	9	46	37	3	0	0	0	192	117	7	0	66	0	0	14	0	0	0	0
3390,32	0	0	0	0	4	11	19	1	0	0	0	107	111	10	0	49	0	0	11	0	0	0	0
3421,61	0	0	0	0	1	22	19	3	0	0	0	117	97	10	0	54	0	0	9	0	0	0	0
3452,89	0	0	0	0	2	33	31	11	0	0	0	180	113	14	0	73	0	0	9	0	0	0	0
3484,17	0	0	0	0	2	24	26	7	0	0	0	172	92	20	0	74	0	0	7	0	0	0	0
3515,44	0	0	0	0	8	31	29	6	0	0	0	156	106	16	0	57	0	0	10	0	0	0	0
3546,72	0	0	0	0	5	15	20	1	0	0	0	190	94	18	0	46	0	0	2	0	0	0	0
3578	0	0	0	0	8	22	28	3	0	0	0	190	83	4	0	66	0	0	9	0	0	0	0

ANNEXE C

ASSEMBLAGES DINOKYSTES DU SITE SA13-ST3 (NUUK)

15R	<i>Ataxiodinium choane</i>	<i>Bitectatodinium tepikiense</i>	<i>Impogidinium pallidum</i>	<i>Impogidinium patulum</i>	<i>Impogidinium sphaericum</i>	<i>Nematosphaeropsis labyrinthus</i>	<i>Operculodinium centrocarpum</i>	<i>Spiniferites elongatus</i>	<i>Spiniferites ramosus</i>	<i>Spiniferites spp.</i>	<i>Cyst of Pentapharsodinium dalei</i>	<i>Islandinium minutum</i>	<i>Islandinium? cesare</i>	<i>Islandinium brevispinosum</i>	<i>Echinidinium karaense</i>	<i>Brigantedinium spp.</i>	<i>Dubridinium spp.</i>	<i>Protoperidinioids</i>	<i>Selenopenphix quanta</i>
Depth (cm)	ATAX	BTPE	IPAL	IPAT	ISPH	NLAB	OCEN	SELO	SRAM	SSPP	PDAL	IMIN	IMIC	IBRE	EKAR	BSPP	DUBR	PERI	SQUA
0-0.5 cm	0	0	0	0	0	5	3	0	1	0	92	52	58	0	5	91	0	1	6
4-4.5 cm	0	0	0	1	0	7	0	0	2	1	65	61	44	0	4	100	0	1	12
8-8.5 cm	0	0	0	2	0	5	4	3	3	1	47	62	55	0	3	124	0	0	18
12-12.5 cm	0	0	0	0	0	6	3	2	5	1	40	60	37	0	3	137	1	0	20
16-16.5 cm	0	0	0	0	0	5	3	1	4	0	37	49	37	0	4	114	1	0	8
20-20.5 cm	0	0	0	2	0	6	6	0	4	0	50	45	44	0	3	132	0	1	15
24-24.5 cm	0	0	0	0	0	10	5	1	2	0	65	48	42	0	3	121	0	0	8
28-28.5 cm	0	0	0	1	0	17	3	1	7	0	48	45	49	1	2	142	0	2	14
32-32.5 cm	0	0	0	0	0	12	9	2	2	1	46	48	44	0	0	131	0	2	19
36-36.5 cm	0	0	0	1	0	10	2	0	3	1	46	45	49	2	1	126	0	1	5
40-40.5 cm	0	0	0	1	0	12	6	2	3	0	44	49	54	1	4	114	1	0	11
44-44.5 cm	0	0	0	1	0	5	3	1	2	0	34	53	56	0	1	124	2	0	17
48-48.5 cm	0	0	0	0	0	14	1	0	4	1	53	57	69	0	2	140	0	0	11
52-52.5 cm	0	0	0	1	1	9	4	1	5	1	45	50	58	1	3	133	0	3	8

20G		<i>Ataxodinium choane</i> <i>Bitectatodinium tepikiense</i> <i>Impagidinium pallidum</i> <i>Impagidinium patulum</i> <i>Impagidinium sphaericum</i> <i>Nematosphaeropsis labyrinthus</i> <i>Operculodinium centrocarpum</i> <i>Spiniferites elongatus</i> <i>Spiniferites ramosus</i> <i>Spiniferites spp.</i> <i>Cyst of Pentapharsodinium dalei</i> <i>Islandinium minutum</i> <i>Islandinium? cesare</i> <i>Islandinium brevispinosum</i> <i>Echinidinium karaense</i> <i>Brigantedinium spp.</i> <i>Dubridinium spp.</i> <i>Protoperidinioids</i> <i>Selenopenphix quanta</i>																		
Depth (cm)	Age (cal yrs BP)	ATAX	BTEP	IPAL	IPAT	ISPH	NLAB	OCEN	SELO	SRAM	SSPP	PDAL	IMIN	IMIC	IBRE	EKAR	BSPP	DUBR	PERI	SQUA
0-1 cm	153,1	0	0	1	0	0	18	3	2	3	0	83	56	5	0	0	147	1	0	21
5-6 cm	199,8	0	0	1	0	1	12	3	4	3	0	26	88	3	0	1	96	1	0	19
10-11 cm	246,5	0	0	0	0	2	11	5	5	3	0	43	6	22	0	0	119	0	0	21
15-16 cm	293,3	0	0	1	0	0	13	6	2	6	0	72	48	17	0	0	143	0	0	11
20-21 cm	340	0	0	2	0	0	13	8	6	4	0	81	41	7	0	0	163	0	0	14
25-26 cm	386,7	0	0	1	0	0	6	3	3	2	0	7	43	31	0	1	142	0	0	7
30-31 cm	433,4	0	1	2	0	0	11	7	3	7	0	66	38	29	0	0	18	0	0	11
35-36 cm	480,1	1	0	4	0	1	8	4	3	2	0	7	36	15	0	0	161	0	0	18
40-41 cm	526,8	0	0	2	0	0	19	6	3	4	0	52	63	25	0	0	142	0	0	9
45-46 cm	573,5	1	0	3	0	0	9	5	3	4	0	35	28	18	0	0	171	0	0	5
50-51 cm	620,2	0	0	1	0	1	18	9	2	15	1	66	21	4	0	0	162	0	0	2
55-56 cm	666,9	0	0	0	0	0	14	6	3	8	0	69	38	21	0	0	139	0	0	9
60-61 cm	713,6	0	0	0	0	1	15	10	4	6	0	65	34	23	0	0	156	0	0	7
65-66 cm	760,3	0	0	0	0	0	3	2	0	2	1	7	39	46	0	0	14	0	0	4
70-71 cm	807	0	0	2	0	0	13	7	5	2	1	125	22	28	2	0	79	0	0	18
76-77 cm	863	0	0	0	0	1	23	4	2	3	1	41	71	42	0	2	123	0	0	15
80-81 cm	900,4	0	0	0	0	1	17	12	2	8	0	127	19	25	1	0	84	0	0	1
86-87 cm	965,3	0	0	0	0	0	11	6	1	2	1	63	63	55	0	0	95	0	0	8
90-91 cm	1008,6	0	0	0	0	2	12	12	3	4	0	114	18	15	0	0	18	0	0	19
97-98 cm	1084,3	0	0	0	0	1	7	3	4	5	1	46	63	46	0	0	19	0	0	13
100-101 cm	1116,7	0	0	0	0	0	17	9	1	8	0	153	2	25	0	0	69	0	0	8
106-107 cm	1176,3	0	0	0	0	0	9	5	1	7	0	45	62	45	0	0	3	1	0	11
110-111 cm	1215,2	0	0	1	0	0	8	17	4	12	0	176	35	3	0	2	55	0	0	22
116-117 cm	1267,6	0	0	0	0	0	11	1	0	3	0	7	6	44	0	4	18	0	1	13
120-121 cm	1302,5	1	0	0	0	0	15	16	5	12	0	167	3	2	0	0	74	0	0	27
127-128 cm	1369,2	0	0	0	0	0	14	5	0	8	2	72	49	41	0	2	1	0	0	14
130-131 cm	1404,3	0	0	0	0	0	16	5	2	7	0	93	5	5	0	1	9	0	0	1
137-138 cm	1501,5	0	0	0	0	0	9	10	2	7	0	47	42	49	0	0	119	0	0	15

140-141 cm	1543,2	0	0	0	0	0	8	4	0	5	0	77	39	43	3	0	141	0	0	8
147-148 cm	1640,3	0	0	0	0	0	7	3	3	3	1	9	42	52	0	0	94	0	0	15
150-151 cm	1682	0	0	1	0	0	22	7	3	5	0	19	49	45	3	1	15	0	0	12
157-158 cm	1776,3	0	0	0	0	0	5	6	3	7	0	84	46	26	0	0	89	0	0	16
160-161 cm	1816,7	0	0	0	0	0	16	6	4	7	0	68	54	56	0	0	157	0	0	14
167-168 cm	1931,8	0	0	0	0	0	5	3	0	5	0	94	5	38	0	1	9	0	0	15
170-171 cm	1987,8	0	0	0	0	1	15	2	5	3	0	76	35	27	0	0	87	0	0	9
180-181 cm	2269,1	0	0	1	0	0	18	2	4	4	0	56	32	53	5	0	178	0	0	12
184-185 cm	2391,1	0	0	0	0	0	5	9	3	6	0	48	38	48	0	0	88	0	1	13
190-191 cm	2566,1	0	0	1	0	0	7	15	5	1	0	98	42	45	0	0	9	0	0	23
197-198 cm	2724	0	0	0	0	0	3	13	1	5	3	69	53	54	0	3	84	1	0	19
200-201 cm	2787,5	0	0	1	0	2	1	22	3	26	0	116	26	11	0	0	7	0	0	36
208-209 cm	2951,2	0	0	0	0	0	8	5	2	4	0	65	55	75	0	0	81	0	0	8
210-211 cm	2992,1	0	1	0	0	0	4	18	5	1	0	172	5	12	0	0	54	0	0	15
213-214 cm	3053,5	0	0	0	0	0	1	1	2	4	1	94	26	51	0	0	8	0	0	6
220-221 cm	3217,1	0	0	2	0	0	8	4	6	4	0	199	1	8	0	0	98	0	0	19
227-228 cm	3431,8	0	0	1	0	0	4	15	4	3	2	13	19	42	0	0	72	0	0	16
230-231 cm	3523,8	0	0	1	0	0	3	18	5	4	0	24	1	9	0	0	5	0	0	16
233-234 cm	3615,9	0	0	0	0	0	1	6	3	3	3	138	15	37	0	0	64	0	0	15
240-241 cm	3843,6	0	0	1	0	0	12	15	3	16	0	2	8	7	0	0	55	0	0	33
243-244 cm	3955,2	0	0	5	0	0	1	9	3	4	0	19	23	46	0	0	83	0	0	17
250-251 cm	4215,5	0	0	1	0	1	11	35	8	8	0	219	14	19	0	0	75	0	0	31
253-254 cm	4438,6	0	0	3	0	0	11	14	2	3	0	87	22	57	0	0	8	0	0	12
260-261 cm	4578,7	0	0	1	0	0	12	12	7	4	1	25	14	29	0	1	74	0	0	32
264-265 cm	4693,2	0	0	2	0	0	8	8	3	3	0	151	23	3	0	0	62	0	0	16
270-271 cm	4864,8	0	0	2	0	1	9	4	4	3	0	15	12	23	2	0	46	0	0	33
280-281 cm	5150,8	0	0	7	0	0	11	15	12	9	0	264	13	14	1	1	79	0	0	42
284-285 cm	5255	0	0	1	0	0	6	1	3	5	0	173	12	19	0	0	58	0	0	33
290-291 cm	5365	0	0	3	0	1	4	6	5	3	0	216	7	11	2	0	68	0	1	31
293-294 cm	5420,1	0	0	0	0	0	4	5	5	4	0	212	14	25	0	0	56	1	0	14
300-301 cm	5548,5	0	0	3	0	1	1	14	1	14	0	29	6	31	2	0	79	0	0	39
307-308 cm	5736,6	0	0	0	0	0	4	9	4	5	0	219	8	18	0	0	45	0	0	25
310-311 cm	5836,5	0	0	2	1	0	6	14	1	7	0	259	5	15	0	0	5	0	0	27
317-318 cm	6069,4	0	0	1	0	0	5	7	8	4	0	227	1	21	0	0	52	0	0	2
320-321 cm	6150,4	0	0	2	0	0	2	12	8	8	0	18	4	15	1	0	33	0	0	38
323-324 cm	6222	0	0	2	0	0	0	6	4	5	0	195	7	23	0	0	37	0	0	17
330-331 cm	6389,1	0	0	3	0	0	3	28	12	4	0	169	1	11	0	0	5	0	0	4
340-341 cm	6647,9	0	0	1	0	1	7	11	15	2	0	191	5	17	1	0	32	0	0	33
350-351 cm	6953,5	0	0	2	0	0	2	12	2	4	0	194	4	11	1	0	53	1	0	23

360-361 cm	7316,5	0	0	1	0	0	3	9	9	2	0	191	5	2	0	0	47	0	0	17
370-371 cm	7828,4	0	0	2	0	0	3	7	18	9	0	166	16	24	0	0	58	0	0	18
380-381 cm	8442,6	0	0	2	0	0	1	3	1	6	0	164	13	9	0	0	54	0	0	44
390-391 cm	8704,5	1	0	6	0	0	3	3	11	2	0	166	9	2	0	0	73	0	0	3
400-401 cm	8946,7	0	0	2	0	0	3	3	1	1	0	167	12	9	0	1	7	0	0	43
410-411 cm	9189	0	0	3	0	0	3	6	11	5	0	195	17	17	0	0	77	0	0	41
420-421 cm	9374,2	0	0	1	0	1	1	0	6	2	0	2	1	9	1	0	44	0	0	52
430-431 cm	9546,6	0	0	0	0	0	2	8	3	1	0	229	8	2	0	0	38	0	0	21
440-441 cm	9696,5	0	0	0	0	0	2	4	0	0	0	168	3	3	0	0	79	0	0	36
450-451 cm	9869,7	0	0	0	0	1	0	1	1	1	0	216	26	13	0	0	9	0	0	41
460-461 cm	10053,4	0	0	0	0	0	0	2	0	0	1	182	49	11	0	0	35	0	0	23
470-471 cm	10212,6	0	0	0	0	0	1	0	0	0	0	19	42	6	0	0	13	0	0	76
480-481 cm	10354,4	0	0	0	0	0	5	3	1	0	0	7	73	1	0	0	125	0	0	45
490-491 cm	10470,4	0	1	1	0	0	1	5	0	1	0	7	29	1	0	0	22	0	0	5
500-501 cm	10593,6	0	0	1	0	0	2	0	0	1	0	4	82	2	0	0	61	0	0	9
510-511 cm	10724,2	0	0	0	0	0	1	0	0	0	0	1	4	4	0	0	143	0	0	15
520-521 cm	10854,8	0	0	0	0	0	2	2	1	0	0	3	59	1	0	0	199	0	0	44
530-531 cm	10985,3	0	0	0	0	0	0	0	0	0	0	2	46	0	0	0	232	0	0	36
540-541 cm	11115,9	0	0	0	0	0	0	5	0	0	0	2	93	3	0	0	191	0	0	21
550-551 cm	11246,4	0	1	0	0	0	0	1	0	1	0	0	77	3	0	0	134	0	0	3
560-561 cm	11377	0	0	0	0	0	1	1	0	0	0	1	55	5	0	0	135	0	0	13
570-571 cm	11507,6	0	1	0	0	0	0	0	0	0	0	0	27	3	0	0	33	0	0	0
580-581 cm	11638,1	0	0	0	0	0	1	0	0	0	0	0	46	1	0	0	95	0	0	0
590-591 cm	11768,7	0	0	0	0	0	0	0	0	0	0	0	42	0	0	0	59	0	0	0

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