ACDC

- Advanced Climate Dynamic Courses

Advanced Climate Dynamics Course – ACDC2016

August 8th –19th, 2016

Marine Station, Norris Point, Newfoundland

Role of High Latitudes in Centennial to Millennial Scale Climate Variability

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Final Report

The Advanced Climate Dynamics Courses (ACDC) is a series of annual summer schools aimed at advanced PhD students. The courses are coordinated by the University of Bergen (UoB) in collaboration with Massachusetts Institute of Technology (MIT) in Cambridge, and the University of Washington (UW) in Seattle. Core funding for the summer school is provided by a SiU (Norwegian Centre for International Cooperation in Education) Partnership Program in higher education and the Norwegian Research School in Climate Dynamics (ResClim), and this year also with additional funding from the National Science Foundation. Detailed information regarding the summer school can be found at http://www.uib.no/en/rs/acdc.

This year's summer school was the eight in the series. It was held at the Bonne Bay Marine Station in Norris Point, on the west coast of Newfoundland August 8^{th} to 19^{th}, 2016.

The main focus was on understanding the role of the high latitudes in centennial to millennial scale climate variability. And as in previous years the goal was to mix students and lecturers with both empirical and dynamical training within climate sciences.

26 students were admitted to the summer school, represented by 11 nationalities: 8 Americans (1 University of Pittsburgh, 1 University of Texas, 1 Dartmouth College, 2 University of Wisconsin-Madison, 1 University of Boulder, 1 University of Boulder / University of Iceland, 1 Lamont-Doherty earth Observatory / Columbia University), 3 Chinese (1 MIT/WHOI, 1 Brown University, 1 Climate and 1 Laboratoire des Sciences du Climat et de l'Environnement), 1 Italian (1 Georgia Institute of Technology), 2 British (1 University of Oxford, 1 Liverpool John Moores University), 2 Canadian (Memorial University of Newfoundland), 3 German (1 Max Planck Institute for Meteorology, 1 UNI Research Climate, 1 University of Bergen), 3 Danish (1 University of Bergen, 2 University of Copenhagen), 1 Austrian (University of Bergen), 1 French (Laboratoire des Sciences du Climat et de l'Environnement), 1 Swedish (University Centre of Svalbard), 1 Iranian (Memorial University of Newfoundland).

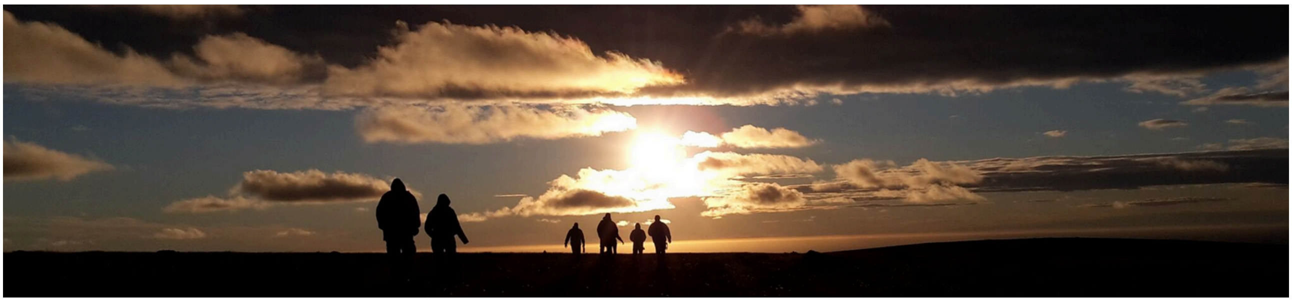
A complete list of participants is presented in the program.

<u>Scientific topics/ content of the summer school</u>

Each day the first week consisted of two fundamental lectures on core topics followed by student presentations. The second week each day consisted of 2-3 specialized lectures on advanced topics. Every morning started with student lead summaries of the previous days lectures followed by a discussion. The summary groups also wrote a written summary from each lecture. These texts can be found further down in this report.

Field trip week one to a local lake. Photo: Kerim Nisancioglu and Ragna Breines.

The first week we also arranged a field trip to a local lake. Lead by Øyvind Paasche and Matt Finkenbinder students cored lake sediments and surveyed the bathymetry and water sources. One of the cores was split and used in one of the student projects.



Sunset at the Tablelands. Photo: Nadine Steigner

During the weekend August 13th – 14th, the participants joined a field trip and overnight stay at Tablelands in Gross Morne National park. PhD students Lorelei, Søren and Benoit have summarized the field trip.

Over the weekend field trip, ACDC 2016 participants ventured to the Tablelands region of Gros Morne National Park. Our goals included learning to recognize and interpret glacial geomorphic features, learning the basics of cosmogenic exposure dating, and identifying potential dating targets that could improve our understanding of ice sheet history in western Newfoundland.

The Tablelands region had been previously characterized as a regolith terrain of unknown age, with deeply incised glacial valleys cutting down to the Trout River Gulch on the northern edge of the massif. Ice sheet models and other geomorphic studies indicate that this region would have been fully glaciated until ~16kya, however, whether the Tablelands, the small glacial valleys, and the Trout River Gulch contained warm-based glaciers, cold-based glaciers, or no glaciers at all during the LGM and other more recent glaciations, is still a contentious issue.

Preparations for the hike and hiking up Winter House Brook valley. Photo: Kerim Nisancioglu and Ragna Breines.

We set out from the Bonne Bay Marine station on the 9:00am ferry to Woody Point, drove west to the trailhead, and started hiking south up the Winter House Brook Canyon on the western flank of the valley. The flat area near the parking lot and on the bottom of Trout River Gulch appeared to be a mixture of fluvially re-worked peridotite boulders, with large talus slopes down the steep valley walls. Winter House also had steep talus slopes with benches of colluvium partway up the valley walls. We interpreted a large, lobate structure with large, angular peridotite blocks to be a relict rock glacier. Further up the valley, close to the valley floor, we found an outcrop of compacted diamict breccia. The head of the valley was a large amphitheatre with tall bedrock outcrops that showed no glacial smoothing or striations. The rim of the amphitheatre was deeply incised by the river.

The top of the Tablelands was covered with blocky rocks and was fairly flat, with some areas covered in thick peat and shallow ponds. Some areas had sorted stone circles, evidence for a previously active permafrost layer. We camped and hiked down through Dry Brook Canyon the next morning, which contained similar features to Winter House Brook Canyon (steep talus/colluvium slopes with a rock glacier, deeply incised creek bed near the head of the valley, no moraines). Before heading down the canyon, three separate groups learned about techniques for exposure dating and how to identify appropriate boulders, though we didn't actually find any.

Our camp on top of Tablelands. Photo: Benoit Lecavalier

Topics discussed included identifying erratics, shielding, using dual isotopes for overall exposure dates, inheritance, and weathering. It's unlikely that exposure dates from boulders on top of the Tablelands would reveal the age of formation for the regolith surface, as the active permafrost layer causes reworking and rotation of any blocks we might sample. We did find quartzite erratics, but we were not confident that they were in the same position in which they were deposited.

We interpreted the landforms we saw as evidence that no warm-based/erosive ice has been present in the areas that we saw in some time, though how long ago the original carving of the glacial valleys occurred is unknown. Published exposure dates give a range of 16kya-18.5kya for the deposition of rock glaciers and a terminal moraine in Devil's Punchbowl, implying that if there was a cold-based ice sheet covering the Tablelands during the LGM, it must have been gone by ~20kya.

During week two, we were invited to participate in a local radio show. PhD students Benoit and Jonathan were our representatives and talked about the summer school and about the climatic impacts for the region. Also during week two, PhD student Heather and post.doc. Matt gave presentation of our field trip to Tablelands to tour guides in Parks Canada at their office in Rocky harbour. They also presented some of the field works from the lake coring during our first week.

All students were assigned to a group project supervised by one of the lecturers. This year topics for the projects were:

- Julie Brigham-Grette: Layer analysis in Pliocene sediments from Lake El'gygytgyn
- Alan Condron: Icebergs in the North Atlantic
- Lev Tarasov: The importance of ice dynamics
- Jake Gebbie: Investigating the ocean circulation with a «simple» model

Photo: Kerim Nisancioglu, Ragna Breines and Anne Jennings

The social aspect is an important part of the summer school. Our "staff" chef Kristian Tinnen prepared great lunch and dinner for us each day. We had outdoors barbeque, ate blue clams prepared at a bonfire on the beach and had Italian night. We also arranged an "international supper" where all participants brought a food item special for their home country (that were legal to import to Canada). When people from 11 nationalities gather the food and the variety was great.

Summary of feedback

Evaluation of the Summer School ACDC

KEYS TO ANSWER

Ns	1	2	3	4	5
Don't know	Strongly disagree (Bad)	Disagree	Neutral	Agree	Strongly agree (Good)

	Ns	1	2	3	4	5
A – Before the beginning						
A1 Information received before registration			1	4	8	7
A2 The registration process was effective and efficient				1	5	14
B – Aim pursued in participating in the school						
B1 Interest in your general training.					6	14
B2 Complement to your university degree	1	2	1	2	5	9
B3 Updating knowledge				1	4	15
B4 Demand or requirement of your university	4	5	1	8	1	1
B5 Improving your CV	1		3	4	5	7
B6 Networking				2	4	15
C – Development of the courses						
C1 The level of the courses, in general, could be easily followed				2	13	5
C2 The lectures were well structured and clear			1	2	11	7
C3 The lectures were interesting and stimulating				1	7	12
C4 Lectures were approachable and responsive to students' needs					7	13
C5 The length of the lecturers has been adequate				2	6	12
C6 The programme you have received have been a good and useful guide				2	6	12
C7 The timetable has been properly publicised.					11	9
D – Global assessment of the school						
D1 On the whole you are satisfied with the level of training gained.					4	17
D2 I have clear understanding of how the school courses fit into my research					10	10
D3 The school was what I expected, based on the stated aims and objectives					13	7
D4 During the school I was able to develop professional relationships and networks				2	4	14
D5 Overall rating of the courses is good					4	16
D6 Information about the school and its general organization was good				2	6	12
D7 The quality of practical arrangements was good					7	13
D8 You will recommend the school for other students					1	19

Lecture Summaries

Fundamental Lectures

Ray Bradley – "Role of High Latitude in Centennial to Millennial Scale Climate Variability"

Summarized by Jonathan, Liz, Simon

When thinking about climate variability at high latitudes, abrupt climate events provide a valuable natural opportunity to assess the sensitivity and variability of a climate system. Four different abrupt climate events are prominent in the Arctic since Marine Isotope Stage 3 (MIS 380 ka). Dansgaard-Oeschger (DO) events are characterized by a rapid negative ∂18 O excursion (cooling) followed by a more gradual increase (warming) seen in Arctic ice cores. Twenty of these such events since MIS 3 are roughly anti – correlated with S. hemisphere warming suggesting global teleconnections. Teleconnections are also seen in terrestrial paleoclimate proxies, including: lacustrine records, hydrologic records (speleothems), and wind pattern shifts inferred via the provenance of dust particles. Heinrich events are increases in ice rafted debris (IRD) seen in marine sediments specifically sourced from the Laurentide Ice Sheet (LIS). The Younger Dryas (YD; ~12,900 - 11,700 cal BPyr) is a single, prominent cool event seen in Arctic ice cores as a negative ∂18 O excursion but also seen in terrestrial archives across N. Atlantic. The YD is generally associated with dryer and dustier conditions in the Northern Hemisphere. More recently, the '8.2 ka' event is smaller negative ∂18 O excursion is paired with the increase of polar forams, a decrease in sea surface temperature and salinity suggesting, a freshwater input trigger leading to abrupt cooling. Draining lakes on the LIS are suggested as a possible mechanism for the triggering of this event. 'Hosing' experiments assessing the original theory of large freshwater inputs from the LIS as the trigger of DO and Heinrich style events showed that reasonable fluxes of freshwater didn't produce the required reduction in the Atlantic Meridional Overturning Circulation (AMOC). However, the conditions of the Arctic Basin in MIS 2 set the stage of the 'Bradley Hypothesis'. Lower sea levels decreased the area of the Arctic Ocean, shut off in-flow from the Pacific through the Bering Strait and limited exchange from the North Atlantic. These conditions prompted the growth of 'paleocrystic' ice many tens of meters thick over the Arctic Ocean. Rising sea levels, the breakup of the Barents-Kara Ice Sheet, and the opening of the Bering Strait allowed inflow of warmer North Atlantic water, leading to the breakup of the paleocrystic ice cover and massive freshwater export south through Fram Strait. This flux suppressed the AMOC, leading to a southern hemisphere warming and southward migration of the Intertropical Convergence Zone (ITCZ). Eventual resumption of AMOC circulation prompted the export of ice from the LIS and the deposition of Heinrich Event 0.

Kerim Nisancioglu – "Role of DO-events versus H-events in high latitude climate variability"
Summarized by: Marie, Matt, Elizabeth

Paleorecords indicate the last glacial period was characterized by millennial variations in ocean-atmosphere interactions. These climate events include ice berg rafting discharges to the North Atlantic (Heinrich and Bond) and abrupt changes in atmospheric circulation (Dansgaard-Oeschger). Ice core and marine sediment records spanning the last 100,000 years show these events punctuate both stadial and interstadial periods, and provide evidence for the timing and relative magnitude of ocean-atmosphere climate variability. However, the exact mechanism(s) that drive millennial variations in high latitude climate are not yet well understood. Three possible mechanisms for these abrupt climate events were presented. First, the events could be driven by internal ice sheet oscillations, such as the binge-purge hypothesis. Second, internal interactions between components of the climate system could cause the Heinrich- and/or D-O events, such as variations in extent of sea ice, changes in the strength of the Atlantic Meridional Overturning Circulation, and changes in the deep ocean. Last, these abrupt climate events could be a response to forcing external of the ocean, atmosphere, and ice sheets. For example, variations in solar forcing and changes in the intensity of the geomagnetic field have been proposed as drivers of abrupt climate events. None of the previously stated explanations completely explain and elucidate the occurrence of all Heinrich- and D-O events, such as their timing, amplitude, and underlying dynamics. Other hypotheses were presented and discussed, to explain the discrepancy in the proposed mechanisms described above. For example, our group highlighted that differences in the initial mean state climate could alter the driving ocean and atmospheric circulation processes, resulting in threshold changes in ice sheets. In our discussion we suggested that a more inter- or cross-disciplinary approach should be used to investigate these questions, and that more paleodata is needed from strategic locations along with the application of new paleoproxy techniques to give different perspectives. Further, developing models and experiments targeting processes that control D-O and H-events as well as their interaction could help to fill some gaps in our understanding.

Jake Gebbie – "The dynamical ocean and millennial-scale climate variability: Basic processes"
Summarized by: Ylva, Dominic, Lise

The ocean contributes to climate variability through the transport and storage of heat and matter. The combination of ocean circulation and stratification leads to a wide distribution of water masses with distinct properties. Similar to the poleward heat transport by the atmosphere, the ocean also provides with a poleward heat transport except for the South Atlantic. The latter may seem surprising but reflects the deep water overturning.

The high latitudes have regions that funnel dense water, thereby largely filling the global ocean. This water is produced in polynyas where cooling of the surface water, sea ice production and subsequent brine rejection form dense water that sinks to the deep. This is especially important in the Antarctic e.g. in the Weddell Sea and the Ross Sea, but also occur in the Arctic shelf seas. Open ocean deep convection is another way for dense water formation, but only takes place in the North Atlantic e.g. in the Labrador Sea, the Irminger Sea and the Greenland sea. There are also focused zones for intermediate water mass production characterized by distinct salinity properties e.g. the Mediterranean Overflow Water.

The age of a water mass can be inferred from its radiocarbon signature if the surface disequilibrium is taken into account. This makes it possible to model the time it takes for a package of surface water to be transported to the deep Pacific Ocean, in this case roughly 1500 years.

$\delta^{18}O$ from benthic foraminifera in sediment cores drilled from the Atlantic and Pacific basins show a lag of 4,000 years in the timing of the last glaciation, substantially longer than the mean residence time of 1500 years. Jake Gebbie used a modeling experiment to fit both Atlantic and Pacific $\delta^{18}O$ records. Using globally uniform solutions he could either fit Pacific or Atlantic record but not both at the same time. Using a local injection solution, he could fit both records pretty well and that without invoking any big change in ocean circulation geometry that is suggested by paleo benthic $\delta^{13}C$.

Julie Brigham-Grette – "Land Records of High-Latitude Climate Variability over the last 4 million years"
Summarized by: Heather, Ning T, Fabian

The focus of Julie Brigham-Grette's talks was on climate variations in the region of Beringia extracted from a variety of land archives in this region. In particular, she presented data extracted from the longest continuous lake sediment core ever extracted, at Lake El'gygytgyn. This core extends from 3.6 Ma BP to the Holocene, and as such provides an unambiguous record of the sequence of climate events throughout these periods. Data from this core and other climate archives were employed to address three different scientific questions. Firstly, she discussed the characteristics of the gradual transition from the Pliocene to the Pleistocene, characterized by glacial cycling. Secondly, she drew comparisons between a number of so-called "super-interglacial" periods and proposed an orbital hypothesis to explain them. Thirdly, she illustrated the uniqueness of the LGM in its lack of glacial ice cover over Beringia as compared to previous glacial cycles.

The end of the Pliocene is characterized by decreasing atmospheric CO_2 concentrations, increasing lake ice cover, a shift in vegetation toward tundra conditions, decreasing summer temperatures and precipitation. This transition is not abrupt in most cases and the timing depends on the characteristic being examined. CO_2 concentrations gradually decline from 3Ma to 2Ma BP without abrupt transitions, although there are large-amplitude oscillations over the entire period. Vegetation types in this area gradually transition from cool mixed forest types to tundra over the same period, resulting in a shift from a more forested cover to a more open one. This transition was not uniform, and it involved many small transitions between these different vegetative types. Most interestingly, there was an abrupt decrease in precipitation at 2.73 Ma BP that was not reproduced in summer temperatures. This indicated a break in the coupling between these two variables in Beringia. Finally, glacial facies first emerge at 2.6 Ma BP in Lake El'gygytgyn, indicating a transition to perennial ice cover. Although there were other prior instances of proto-glacial conditions (i.e. M2), this appears to characterize the main transition to the Pleistocene.

From the late Pliocene, the typical glacial-interglacial cycles were periodically interrupted by extended interglacial conditions. These are observed in the Lake El'gygytgyn record through a shift toward laminar, anoxic facies containing biota in the sediment. These records closely follow (within uncertainties) collapses of the West Antarctic Ice Sheet (WAIS) as seen in the ANDRILL sediment core on the McMurdo Ice Shelf. The contemporaneous warm conditions in both the southern and northern hemispheres differentiates these periods from those of the bipolar seesaw. Brigham-Grette proposed an orbital mechanism of preconditioning that could explain the MIS31 super-interglacial. These WAIS collapses appear to occur in response to periods of low-eccentricity when insolation in the southern and northern hemispheres come into phase. The WAIS collapse leads to a decrease in sea ice concentration off the coast of Antarctica and loss of ice shelves, which reduces production of Antarctic Bottom Water (AABW). In consequence, upwelling in the North Pacific is also reduced, driving atmospheric circulation responses there that in concert with strong insolation anomalies in the Northern Hemisphere lead to warm conditions over Beringia. The timescale of these feedback mechanisms depends on the timing of the precessional signal and increase in eccentricity, but it is generally on the order of 10s of ka.

Finally, Brigham-Grette presented a separate set of terrestrial archives to discuss the singularity of glacial conditions over Beringia during the Last Glacial Maximum (LGM) as compared to its predecessors. Through a long list of different archives at a number of sites over the Eurasian and North American components of Beringia, she demonstrated that there was very little glacial ice cover in those regions during LGM. However, striations in basal sediments on the Eurasian shelf (“sole marks”), suggest that there was extensive ice cover at some time prior to MIS5. The dating of these marks is unconstrained. Due to physical limitations in the bed in this region and geopolitical conflicts any further data records are not feasible at this time. Thus, this question appears to be most readily addressed next by modelling.

Four themes emerged from Brigham-Grette's talks: the importance of multiple archives at multiple sites, the importance of geopolitical connections and will to facilitate these massive projects, and usefulness of evaluating far-field implications of given events - including both hemispheres.

Anne Jennings – "Records of past abrupt events from ocean sediments North Atlantic"
Summarized by: Iben, Yinsui, Ning Z

In order to better understanding the paleoclimate change, we need to study certain types of archives. The ocean sediments are great archive for understanding how the ice changes, including ice shelf and ice sheet. The first part of the lecture was about how we can recognize ice shelves and sub ice shelf environments in sediment records. The ice shelves are important for sea level rise threat from polar ice sheets. Antarctica has major ice shelves all around the ice sheet while Greenland ice sheet only has ice tongues in the far north. The ice tongues are more accurately termed than ice shelves because they are constrained within fjords, where the fjord walls provide stability for the ice tongues.

Examples (from Antarctica and Petermann Ice Shelf) on how to drill through ice shelves were given. By analyzing sediment cores from the sub ice shelves, we can gain the information about calving and the ice shelf retreat/advance. Calving events expose new sea floor that represents sub ice shelf environment. There are multiple proxies that can identify the change of ice shelf environments in paleo records. They are Ice Rafting Detrital (IRD), grain size distributions, detrital carbonate (freshwater flux), and bioturbation condition in the sediment cores.

One major question we have for this study case is how much we can say about the ice shelf environment based on the proxy records from the sub Ice shelf sediments? We can identify the features of bioturbation, grain size distribution and IRD from the sub ice shelf sediment. However, even we find these similar features from sediment cores, we can not infer that they were resulting from the ice shelf environment.

The second part of the lecture is about using detrital carbonate (DC) found in sediments to trace meltwater routing in the Labrador Sea in the early Holocene. DC events in North Atlantic sediment cores during the glacial period (often called Heinrich events) have been studied for more than two decades, but not many studies have been done to search for events in the Holocene. By studying the DC events in the Holocene, we can try to establish the correlation between those events and the massive deglacial events of Laurentide Ice Sheet (LIS) through Hudson Strait (e.g., 8.2ka event).

The proxies that are used to identify LIS deglacial events include planktic and benthic (for shallow cores, e.g., on continental shelf) $\delta^{18}O$ and fauna composition. The indicators of DC events consist of IRD abundance, sediment color, etc. Seven DC events are identified from a sediment core on the Labrador Sea shelf, and they are associated with low planktonic and benthic $\delta^{18}O$ values that are interpreted as freshwater discharge from LIS deglacial events. Compared to a sediment core record to the southwest of Iceland, some of the DC and freshwater discharge events are also found there, suggesting that the freshwater was entrained into the subpolar gyre.

Lev Tarasov – "What governs ice sheet evolution?"
Summarized by: Graeme, Erin, Nadine

In this lecture, Lev Tarasov addressed the modelling of ice sheet dynamics. The talk focussed around the various sources of uncertainty that are encountered when attempting to faithfully resolve the evolution of ice. This was largely concerned with complex, 3-dimensional numerical simulations, but the concepts discussed were applicable more generally. The main take home message was that the largest uncertainties of ice system modelling occur at the interfaces between the ice-sheet and neighbouring systems – the so-called boundary conditions of the problem. By contrast, the physics of ice flow are comparatively well known and easily reproduced, except at the grounding line where the ice sheet transitions to a floating ice shelf. Interfaces exist between the ice and the atmosphere, the ocean and the topography beneath. When numerically modelling large-scale ice sheet dynamics, the atmospheric and oceanic boundary conditions are taken from coupled ocean-atmosphere circulation models. There are significant uncertainties within these complex numerical models and large differences exist between different models, particularly in the magnitude, variability and location of atmospheric and oceanic temperatures as well as precipitation. These uncertainties are important constraints on the simulated ice sheet evolution. At the ocean interface, many small-scale processes operate that are not resolved on the numerical model grid, which is necessarily coarse for the timescale over which the ice sheet is evolved. Processes such as submarine melt, calving of icebergs and mixing of meltwater plumes must be approximated from the variables determined on the coarse grid. Topographic conditions under ice sheets are also poorly constrained. Whether the bedrock is hard or soft, the movement of water under the ice and the heating from geothermal sources can all strongly influence ice sheet dynamics, but are often poorly resolved both in the modern day and in past millennia. In the latter part of the talk, Lev showed some of the results from his own ice sheet modelling.

Alan Condron – "High Latitude Freshwater Forcing and Climate Change: A Modelling Perspective"
Summarized by: David, Giovanni, Ryan

Freshwater forcing has been, andremains poised as, a primary hypothesis for rapid climate change events such as the 8.2 ka Event and the initiation of the Younger Dryas. While many previous studies have been conducted around the ideas of so-called 'fresh water hosing' scenarios, few if any have investigated these scenarios using such detailed models as those shown in the works of Condron et. al. We've discussed the results and inferences garnered from the high-resolution general circulation model studies. Notably the role of coastal boundary currents was highlighted and focused up on as a key means of transporting fresh water during hosing experiments, a feature generally unresolved in current generation climate models. Given the difficulties in resolving these features we have found that future studies should attempt to address this problem. As well, a new branch of freshwater perturbation experiments was briefly discussed, namely that of a change in the routing causing large magnitude persistent shifts in Atlantic Meridional

Overturning Circulation strength. By a simple change of fresh water runoff from the former North American Ice Sheet Complex into the North Atlantic and Arctic oceans, changes of similar magnitudes and timescales of the freshwater hosing experiments may be obtained. It must be said that to obtain a significant slow-down of the AMOC, the amount of freshwater prescribed in the experiment must be larger than what climate proxies would suggest for 8.2ka Event and the initiation of the Younger Dryas. This problem, which affect most of the current state of the art climate models, arise fundamental questions about this type of climate simulations: Is the model unable to properly simulate these events or the proxy data are affected by large uncertainties? This feature remains somewhat unresolved and further modelling investigations are required.

Øyvind Paasche Fundamental – "Ice or cold ice or just no ice?"
Summarized by: Taimaz, Timothy, Andreas

Take home message: "There is nothing better to preserve a landscape than ice"

A lot of weathering is going on at the Earth's surface; turning rock to regolith. There are three main mechanisms for weathering: physical/mechanical (e.g. thermal stress, frost shattering), biological, and chemical weathering (dissolution). Some processes (e.g. root grows, acids produces by plants) can be seen as intermediate processes. Over time the weathering front migrates down and can reach 10s of meters below the surface. Weathering rates tend to be higher in the beginning and decrease later on. Estimates range from 0.2 to 10 mm/100 years.

A number of important questions remain regarding glacial cycles during the Quaternary. There seems to be a Mid-Pleistocene transition (MPT) around 1 Ma ago, the cause of which remains unexplained. The periodicity seems to change from 41ka to 100ka. An often cited explanation for the MPT is the Regolith Hypothesis (RH). The RH proposes a change from soft bed conditions to mixed hard-and-soft bed conditions caused by sub-glacial erosion of thick regolith which exposes unweathered crystalline bedrock.

The age of Scandinavian high altitude land surfaces has received much debate to due obliterative overlap which has removed much of the evidence for glaciation throughout the Quaternary. However, larges parts of the Fennoscandinanvian Ice Sheet are believed to have been cold based, potentially existing as stable land surfaces for more than 100ka. Landscape stability and an absence of glacial erosion has been shown by extensive regolith study across Scandinavia, with surfaces demonstrating evidence of thick weathering.

Offshore sediment records display pulses of "fresher" material being transported offshore at 5.5 to 4.5 Ma and a clear transition from weathered to "fresher" material at ca. 2.6Ma. This shift is in agreement with the first glaciations of Fennoscandinavia.

Topical lectures

Ray Bradley – "Norse Settlements in the North Atlantic: History, Archeology, and Climate"
Summarized by Lise, Fabian, Simon

There is strong evidence that Viking peoples from Norway and elsewhere had populated the Northern British Isles, up through Scotland and the Shetland Island between 8000 and 6000 BC. Popular theory places the settlement of the Faroe Island (some 600 km) NW of Scotland ~500 years ago. However, there is physical (e.g., pollen), historical, and archeological evidence to the contrary, suggesting that Norse people populated the Faroes many thousands of years prior. In order to better constrain the timing of Viking occupation on the Faroe Islands, the Bradley Research group is obtaining and analyzing new proxy records from lake sediments.

A previous study in northern Norway on lake Lilandsvatnet field tested a new biomarker method utilizing species specific fecal sterols that are preserved in the lake sediments. In this instance, since the catchment in question contains a Nordic settlement, the record of these fecal sterols should constrain the timing of Viking occupation in the local area. Additionally, polycyclic aromatic hydrocarbons (PAHs) constraining biomass burning, and leaf waxes showing the transition from a forested landscape to grasslands also constrain the timing of human habitation.

A project applying similar methods from the lake Lilandsvatnet study to lakes on the Faroe Islands will attempt to use the same proxies to determine the timing of Norse settle. However, the lack of settlements within the lake catchment may limit the utility of the sterol method, though preserved DNA in the sediments might be applicable in this case.

Another site in southern Greenland, where the timing of Norse occupation is well constrained, offers the opportunity to 'ground-truth' the fecal sterol method and further investigate the circumstances of the disappearance of settles from the area. The lack of cooling around the time of departure argues against a cold period forcing migration, but increased temperatures from GDGTs (and archeological evidence of irrigation) hints at drought as the driver of settlement abandonment. Investigation of a closed basin lake for a record of evaporation will hopefully test this hypothesis.

The global ^{18}O record appears to show that the Holocene is characterized by little to no change in overall climate, or at least free from dramatic change. However, further investigation shows that periods of rapid change during the last 10 ka is much more common than some records tend to show. From a hydrologic perspective, Northern Africa used to be far wetter, while the Middle East experienced extended drought, and even equatorial places such as Lake Titicaca experienced an exceptional lowstand. There are several more examples of dramatic climate, ecologic and/or hydrologic change from across the globe, many of which occur around ~4.2 ka. While there is a correlation to oscillations in solar irradiance, how a small perturbation forces such dramatic change is still unknown. Another possibility is volcanic forcings linked to feedback mechanisms that extend the initial cooling/drying.

Lev Tarasov – "Does ice dynamics matter?"
Summarized by: Dom, Nadine, Graeme

Science is a useful tool to understand the world, but descriptions alone are not enough. The scientist needs to deal with associated uncertainties in non-linear and complex systems. The earth system, with its intrinsic feedback mechanisms and with linkages acting on different scales, is a challenge. Model building always requires some kind of simplifications, but which processes can be excluded? The major tipping points in the earth system, for instance instability of Greenland ice sheet, permafrost thawing and methane release, commonly result from nonlinearities.

The model building steps, e.g. for investigating ice dynamics, include a clear definition of the system and a conceptualization step to create a simple model as a starting point. This involves excluding subgrid processes that may be of relevance like turbulences. The simple model, for example the ISMIP-HEINO for ice dynamics, is than used to investigate the parameter sensitivities and uncertainties in the system. The analysis of these uncertainties shows the shortcomings of the simple model. The simple model may already resolve internal oscillations as in the case of the ISMIP-HEINO experiments. This can give further insights into the model behaviour. For instance, the basal lubrication, surface temperature and accumulation seem to be key parameters when looking at ice sheets. In his talk, Lev discussed initial parameter sensitivity tests of basal properties, which showed little influence on the ice volume.

In the next step of model building a more complex system is developed. Refining the model is repeated until a more or less fully-coupled model is derived, but this model will still build on approximations with their associated limitations. If you want to know more about the importance of ice dynamics, make sure to ask Lev about his fully-coupled ice sheet model in 2018.

Kerim Nisancioglu – "Role of DO-events and H-events in high latitude climate variability"
Summarized by: Giovanni, Ning Z, Yinsui

The climate variability of the last glacial period is characterized by abrupt fluctuations some of which have been named Dansgaard–Oeschger(DO) events. The classic explanation for this DO events involve abrupt freshwater discharge in the high latitude which is hypothesized to drive a slowdown of the Atlantic Meridional Overturning Circulation (AMOC), the oceanic circulation responsible for the northward transport of oceanic heat. Although these fluctuations are reproduced in climate models, the mechanisms responsible for the onset of an event are still an open question. For instance, the warming at the start of a D-O event is extremely rapid and thus difficult to explain in term of the relatively slower AMOC variability and its associated pole ward heat transport (PHT). Moreover, AMOC changes have a minor impact on high latitudes PHT and temperature since atmospheric variability dominates the PHT budget.

A study case was provided to support the idea that growing sea ice was the trigger of the DO events. This study case compared the model simulation results and paleo-record results. The records are very consistent. Four different proxies were analyzed for this marine core which allows us to reconstruct the climate changes in the period between 31 ka and 41 ka BP. The authors argue that when the Greenland temperature was low (stadial stage), there was more sea ice growing which increased the brine release into bottom of the ocean. In the mean time, there was heat accumulated in the subsurface of the ocean and the subsurface ocean temperature increased. Increased brine release also led to the low salinity environment in the sub surface ocean. In contrast to the stadial stage, we see opposite trends of these climate proxies in interstadial stages and increases of Ice Rafted Detritus (IRD) abundance. The simulated sea ice response, surface and subsurface ocean responses from the MITemic model confirmed the reconstructed records in the sediment core.

Towards the end of the lecture, we touched upon the causes of Heinrich events. Heinrich events are detrital carbonate IRD events that mostly came from the Laurentide Ice Sheet through Hudson Strait, and focused towards the end of cold stadials. Some model studies suggest that subsurface warming during the stadials is the trigger of Heinrich events. However, the opposite occurrences of Laurentide vs. Scandinavian Ice Sheet IRD events (stadial vs. interstadial) is not consistent with the widely-distributed subsurface warming from the modeling results. Also, there seems to be no good answer for why Heinrich events are only associated a fraction of DO events.

Alan Condron – "Improving Ice-sheet-Ocean interactions: Simulating Icebergs in Climate Models"
Summarized by: Matt, Ning T, Ryan

Despite the ever increasing complexity of modern day climate models, few have attempted at the inclusion of iceberg physics for the transport of freshwater further south than the margins of ice sheets. Our discussions around this topic and the results of such an iceberg model revealed the key role icebergs play in the transport of freshwater in the climate system. Also key to this discussion was the ability of the general circulation model of the ocean being capable of resolving the boundary currents around Greenland and the East coast of North America. Preliminary results of the model simulations for a Last Glacial Maximum background climate show that it is possible for small numbers of icebergs to be transported to off the coast of Florida, when using a freshwater forcing scenario to amplify the lifetime of the icebergs below the 48th parallel. Of note is that recently discovered icebergs court racks off the coast of Florida and South Carolina, which is in agreement with the modelling results, albeit these modelling experiments showed a requirement for O(5Sv) of freshwater flooding into the Labrador Sea to transport the icebergs as far south as the scour marks. This magnitude of freshwater forcing rules out many of the large climate shift of the last deglaciation but sensitivity to the model configuration and dating of the scours remains to be done.

Anne Jennings – "Ocean Forcing of Ice Sheet Retreat in West Greenland from LGM through Deglaciation"
Summarized by: Graeme, Dominic, Nadine

The extent of the Greenland, Laurentide and the Innuitian Ice Sheets during the LGM is barely known. Sediment cores are used to constrain the position of the GIS western margin and the timing of the retreat.

Anne presented the results of three sediment cores that were taken at a depth of 1500 m at the continental slope on the west coast of Greenland. Marine proxies as Bethic/Planctic (proxy for surface productivity) and Brassicasterol (proxy for marine productivity) show that there was life in Buffin Bay during the LGM. This indicates that Buffin Bay could not have been fully covered by an ice shelf during LGM, as it was previously suggested (Hughes et al, 1977). It was also thought that the ice sheet in west Greenland retreated abruptly over the whole continental shelf during the deglaciation (Knutz et al., 2011). Moraines found on the middle shelf, however, show evidence of a stillstand during the Younger Dryas. (Sheldon et al., 2016).

The suggested theory for the ice sheet retreat in west Greenland from LGM is warming/ shoaling of the subsurface water along the west coast of Greenland, which initiated the retreat of the grounding line from the shelf break during HS1 (between 17 ka BP and 16.2 ka BP). The preceding warming of subsurface water is seen in an increase of benthic forams and led to the full establishment of the West Greenland Current in 14 ka BP. During the partial retreat, the sea ice cover becomes seasonal and icebergs form in the northern Buffin Bay, travelling southward. The GIS ice margin stabilized on the middle continental shelf during the Younger Dryas, which might have been caused by freshwater release from the Laurentide Ice Sheet. The following major retreat is driven by grounding line destabilization on a reversed bed slope.

Julie Brigham-Grette – "Sea Level History of Beringia: A check valve on global circulation via the Pacific-Arctic gateway"
Summarized by Taimaz, David, Marie

The Bering Strait is an important gateway for the flux of relatively fresh North Pacific into the Arctic and the North Atlantic, which influences the strength of the AMOC. The freshwater inflow has both local and global climate impacts: nutrient sourcing in the Chukchi and Arctic ecosystems, sea ice formation and ocean stratification and ventilation. When the Bering Strait is closed, the Arctic and North Atlantic receive no fresh water from the North Pacific, resulting in a stronger AMOC. The intensified AMOC transfers more heat to the North Atlantic, destabilizing northern hemisphere ice sheets. This leads to rapid ice discharges into the North Atlantic, which results in ocean surface freshening, sea level rise and therefore reopening of the Bering Strait. The renewed influx of North Pacific fresh water through the Bering Strait into the North Atlantic then weakens the AMOC, and thereby the heat transport to the North Atlantic. This leads to a growth of the northern hemisphere ice sheets. This simplified hysteresis cycle likely explains some of the Heinrich Events. However, there may be additional mechanisms involved such as sea ice formation and melt that influence this connection. The second focus of the lecture was the observational evidence for paleo sea levels in Beringia and the temporal evolution of the Bering Strait. Previous studies found submarine riverbeds, paleo-shorelines, Atlantic foraminifera and whalebones. Collectively these records are indicative of marine transgression and regression signifying the opening and closing of the Bering Strait. One case study analysed two marine sedimentary records in the North Pacific ocean to verify the connection of North Pacific Intermediate Water (NPIW) formation to the AMOC and if there is a see-saw mechanism between these two as shown by model simulations. The model results show that when the Bering Strait is open the NPIW is stronger and the AMOC is weaker. However according to the marine records from Pacific Ocean, there is no clear connection between the NPIW formation and strength of the AMOC. This may be because the NPIW formation is controlled by sea ice formation and subsequent brine rejection, which is not entirely dependent of the opening/closing of the Bering Strait. Hence, the opening/closing of the Bering Strait does influence the relative strength of the AMOC but not the NPIW. Future studies should consider whether or not the depth of the Bering Strait has remained constant over time and how GIA and/or dynamical topography may influence the Bering Strait's depth.

Tore Furevik – "Summary of topical lecture: The Role of the Arctic in Present Day Climate Variability"
Summarized by: Liz, Lorelei, Søeren

The effect that Arctic climate change may have on global climate change remains a pressing and unresolved problem. To date, there has been massive reduction in sea ice thickness –or the amount of sea ice present across multiple years –and extent. This is a well-documented observation and the question of its global impact is addressed (although not resolved). Global temperature change can be attributed on the yearly to multi-decadal time scale to 4 different processes: carbon dioxide in the atmosphere, ENSO, volcanoes, and solar variability. The 4 components largely capture the variability, and the remaining discrepancy between modeled and observed global temperature change can be attributed to the Pacific Decadal Observation (PDO), during which the positive phase correlates with increasing global temperatures, and the negative with cooling or stagnating global temperatures. The PDO links changes in the tropics or mid-latitudes to changes in high latitudes. So it is demonstrated that the Arctic is clearly affected by teleconnections to the tropics / subtropics, but unclear as yet whether the converse is true.

Warming North Atlantic waters lead to sea ice reduction / retreat, and sea ice extent can therefore be predicted with relative certainty. The remaining unresolved issue lies with how the loss of sea ice impacts shifts in Westerly Jets in the northern hemisphere. Studies have presented diverging results on the impact of sea ice loss on global climate change in the short term, although one hypothesis connecting the variability of sea ice to subtropical weather patterns suggests that a loss of sea ice, resulting in a decreased meridional heat gradient causes a weakening of the jet stream and associated southern shift. This could greatly impact future weather patterns, although other studies have suggested that this mechanism is metric-dependent, or an artefact of the original study.

Jake Gebbie – ”Arctic to North Atlantic Ocean connections over the last deglaciation”
Summarized by: Heather, Liz, Tim

Dr. Jake Gebbie's topical lecture focused on the hypothesisof Thornalley et al. (2015) that deep water in the Arctic Mediterranean (AM) during the Last Glacial Maximum (LGM) was poorly ventilated and may have affected sediment core isotopes in the North Atlantic. To this end, Jake introduced the oceanographic conditions of the modern and glacial Atlantic Ocean as well as introducing 13C carbon isotopes as water mass/nutrient tracers. He defined the AM as the combined water body of the Arctic Ocean and Nordic Seas and characterized their attributes during present-day and Last Glacial Maximum (LGM). Finally, he presented sediment core records that indicate that the AM deep water was highly depleted in 14C yet with a high δ13C ratio. Jake explained how this combination of features could possibly have arisen and warned of its implications for the interpretation of Δ14C measurements from sediment cores in the North Atlantic during this period. The AM is mostly cut off from other bodies of water by the Denmark and Bering Strait sills. These sills restrict flow to the top 1km of the ocean. During present-day, the deep part of the AM is filled by deep water formation from open-ocean deep water formation sites (in the GIN seas) or coastal polynyas (in the Bering Strait). It seems only the open-ocean deep-water formation route is currently active, but this is an open question. The residence time in the deep AM is about 500 years during present-day and is inferred to be between 7-10kyr during LGM. During LGM, the North Atlantic deep-water formation cell appears to have been much shallower, so the only source of deep water was from coastal polynyas. During deglaciation, the build-up of contributions from these coastal polynyas slowly filled the AM basin until the level of the deep water reached the sill. Then, some of this “old” water escaped the basin and contributed a depleted signature of 14C to the North Atlantic at intermediate depths. Jake also presented proxy evidence for deep AM ocean temperatures being 2-3° C warmer than present, which he attributed to geothermal heating over the long residence time. He further posited that such salty, warm water being overlain by cold, fresh water would eventually become unstable, which could lead to an overturning and a release of heat to the sea ice and ice shelves. However, he expected that the flow over the sill would occur before such an overturning would take place.

Jake's presentation raised an important question about the interpretation of Δ14C measurements from sediment cores in the North Atlantic during the last deglaciation. It is not clear to us whether Arctic overflows have led to mis-interpretations of these records. It appears they should be re-examined in light of the results of this study. This presentation also raised the question of how low Δ14C values in water from the AM basin could be distinguished from other sources of low 14C. Would there be signatures in other isotopes like δ18O? Although Jake Gebbie didn't tie the mechanism he presented to abrupt climate change events during the last deglaciation, the suggestion of there being a large reservoir of warm, salty water in the AM basin raises the question of what climate changes would be triggered if this water were mixed to the surface. Such a lot of warm water would have the potential to rapidly melt a lot of sea ice and possibly reinvigorate deep-water formation and the exchange of heat between the surface ocean and atmosphere. Can this provide a potential trigger for Heinrich events?

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