The REnland ice CAP project (Sapere Aude)

Summary

The Renland ice cap is situated in Eastern Greenland on a high elevation plateau on the Renland peninsula in the Scoresbysund fjord. Climatic conditions on the Renland ice cap are strongly influenced by the varying Arctic sea ice export along Greenland's east coast. An ice core from the Renland ice cap is thus perfectly suited for obtaining information on Eastern Greenland climatic conditions including the export of sea ice from the Arctic Ocean for the past 100,000 years. We therefore propose the *REnland ice CAP project* (RECAP). The RECAP ice core drilled to bedrock will be the backbone of a coordinated science program between Denmark, Germany and the U.S. The shallowness of the Renland ice cap furthermore assures that it does not have a brittle ice zone in the Holocene ice like the Greenland ice sheet. The RECAP ice core can therefore yield the first continuous Holocene profiles of gasses and chemical impurities extracted from Greenland.

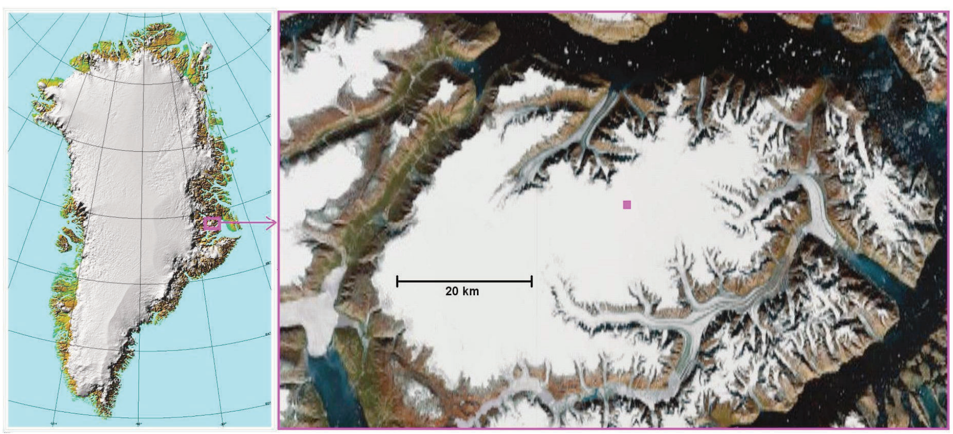

Figure 1: Left, map of Greenland, showing the location of the Renland Ice Cap (Danish Cadastre). Right, satellite image of the Renland peninsula, which is almost entirely covered by the Renland ice cap. The dome on the eastern plateau of the Renland ice cap is marked with a purple square.

Outline and Motivation

Entering an era of global warming, the decline in multi-year Arctic sea ice is a major concern[i]. Given that the rate of sea ice loss significantly exceeds model projections[ii], it is important to extend our knowledge on past sea ice variability under varying climatic conditions.

The multi-year sea ice from the Arctic Ocean is exported through the Fram Strait and flows southward along the East Coast of Greenland and around Cape Farewell into West Greenland waters. With a thickness greater than 3m, the multi-year sea ice has a major influence on navigation, hunting, fishery and other marine operations. The multi-year sea ice also exerts its influence on Greenland's climate as open water generate climatic conditions that are moist and mild.

Given its location in Eastern Greenland, the climatic conditions on the Renland ice cap are heavily influenced by the northernmost Atlantic, in particular the varying Arctic sea ice export along the Greenland east coast. The location of the Renland ice cap is thus perfect for obtaining ice core based information on the North Atlantic climate including the export of sea ice from the Arctic Ocean.

The Renland ice cap is situated in Eastern Greenland on a high elevation plateau on the Renland peninsula in the Scoresbysund fjord (figure 1). The ice cap is constrained by the surrounding topography and its eastern plateau reaches an elevation of 2340m at its summit, where the thickness of the ice cap is almost 400m and the accumulation rate approximately 0.5m of ice equivalent precipitation per year[iii]. Brittle ice, that is very detrimental to ice core quality, forms at depths below 600m, hence in contrast to the main Greenland ice sheet, the Renland ice cap contains no brittle ice zone. An ice core from Renland will therefore also yield the first continuous Holocene profiles of gasses and chemical impurities from Greenland.

Given the unique location and properties of the Renland ice cap, the RECAP core will provide data with direct bearing on the following high-priority science questions:

1) How did the East Greenland and thus Arctic sea-ice conditions evolve during the Holocene and the Glacial and how did conditions and variability compare to the present downturn in sea ice?
2) How did the atmospheric composition, including pole-to-pole gradients in trace gas contents, change during the entire Holocene?
3) What is the East Greenland signature of the abrupt climate shifts seen during the last Glacial?
4) Has the Renland ice cap always had the same shape and size, so the climate record from a Renland ice core can be assumed to stem from snow deposition on a site with unchanged elevation, yielding a Greenland climate record at fixed elevation?

These science questions are directly influencing how the scientific community will interpret the present decline in Arctic sea-ice; our future understanding of the dynamics of the climate system; our interpretation of Human and natural influences on the Earths atmospheric composition; and our future interpretation of the ice cores from the main Greenland ice sheet. To address these, as well as numerous other science questions, we propose to drill the RECAP core through the Renland ice cap down to bedrock. The core will be drilled with the modern well-proven Copenhagen intermediate drill system, capable of drilling high quality 4 inch diameter cores in liquid-filled boreholes.

Background and State of the Art

In 1988 a field campaign using the Copenhagen shallow ice core drill produced ice cores from the Renland ice cap[iii], however, the cores were not drilled at the optimum location on the Renland ice cap and bedrock was not reached. Furthermore the shallow drilling technology used in 1988 produce low quality ice core with a small diameter (3 inch). Therefore the cores permitted neither gas measurements nor continuous measurements of chemical impurities. The poor core quality of the 1988 ice cores was caused by the drilling setup being unable to support drilling in liquid. Without a liquid in the hole to equalize pressure, the core quality deteriorates at depth. Despite its shortcomings, the 1988 campaign did demonstrate that the ice cap has many unique properties which makes it highly desirable to retrieve a high quality core drilled to bedrock from a carefully selected location on the Renland ice cap:

- The Renland ice cap is very old. The deepest 1988 ice core contained an unbroken record for the past 110,000 years and ice dating back into the Eemian warm period ~125,000 years ago[iii].
- Given that both Glacial and Eemian ice was found in the Renland ice cap, it is assumed to have had a stable topographically constrained flow pattern, not permitting significant ice cap thickness changes during the past glacial cycle[iv].
- The Renland ice cap has always been isolated, so all ice in the ice cap stems from local precipitation[iii], significantly reducing the complexity of interpreting ice core data from the ice cap.
- The accumulation rate on the Renland ice cap is high, meaning that a Renland ice core yields a record with a high time resolution and rapidly decreasing annual layer thicknesses with depth.
- The Renland ice core provided proxy data closely related to Eastern Greenland climatic conditions including Arctic Sea Ice export through the Fram Strait (figure 2).
- The Renland ice cap does not have a brittle ice zone, hence a non-brittle ice core can be drilled.

Given the unique properties of the Renland ice cap, the new high quality RECAP ice core will permit progress in mapping out and constraining Greenland Holocene climatic conditions. For the Holocene, all ice cores drilled on the main Greenland Ice Sheet suffer from the problem that a 4000 year section of the mid-Holocene is situated in the brittle ice zone. This means that neither chemical impurities nor gasses have been measured continuously throughout the Holocene in the ice cores from Greenland. The RECAP core from Renland will remedy this gap in existing data. This is important, because such records are essential in determining past climatic greenhouse gas forcing, volcanism, sea ice conditions, biomass burning events etc.

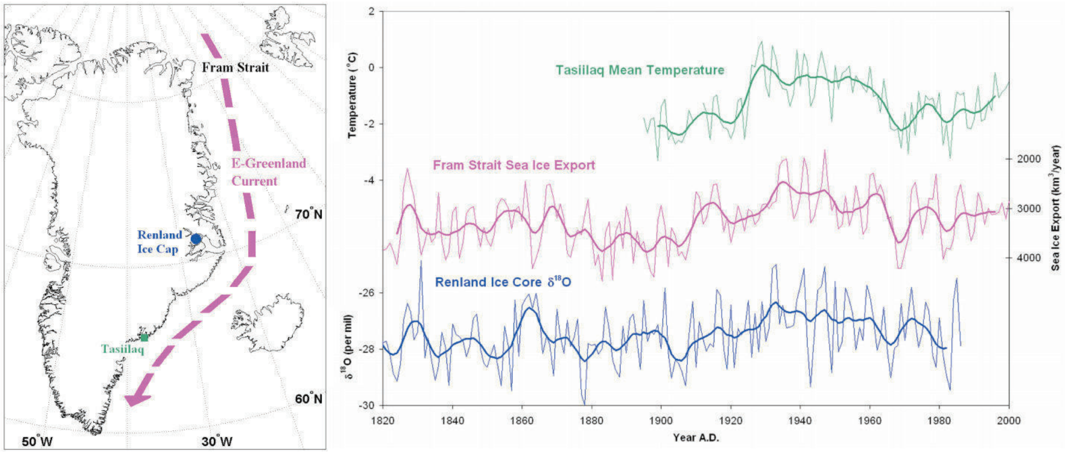

Figure 2: Left, locations of the Renland Ice Cap, Tasillaq weather station and the Fram Strait. Right, Tasillaq temperature[v]*, Fram Strait Arctic Sea Ice export*[vi] *(inverted) and Renland 1988 ice core $\delta^{18}O$.*

Relations to national and international research

The RECAP project will be complementary to the activities of the Centre for Ice and Climate (CIC), as ice core drilling projects are not part of the CIC funding. The science questions addressed by the CIC do, however, align with a significant part of the research planned for the RECAP project. Hence CIC research goals will be furthered by RECAP, making it very beneficial for CIC researchers to invest time in the RECAP effort. RECAP will also provide a great opportunity for the next generation of CIC masters and Ph.D-students to be trained in field work and the art of ice core measurements. Traditionally, most Greenland deep ice core research has been led by Denmark and to our knowledge no other nations are planning deep drilling operations in Greenland. The RECAP project will, however, be carried out in strong collaboration with our German and US partners:

- The Alfred Wegener Institute (AWI) for Polar Research in Bremerhaven, Germany.
- The Institute of Arctic and Alpine Research (INSTAAR), University of Colorado, US.
- Earth and Environment Systems Institute (EESI), Penn State University, US.
- The Center for Remote Sensing of Ice Sheets (CReSIS), University of Kansas, US

CReSIS is planning to carry out the airborne survey of the Renland ice cap needed for RECAP ice coring site selection. AWI will support RECAP with its ski-equipped Bassler planes, processing facilities and scientific expertise. INSTAAR and EESI plans to support RECAP with NSF sponsored C130 planes for west-to-east Greenland cargo transport as well as their scientific expertise. This logistics support from international partners exceeds 3.2 mill kr; essentially half of the total logistics budget for the ice coring. The RECAP budget is comparatively modest due to this support.

RECAP timeline and management

	2014 (1st year)	2015 (2nd year)	2016 (3rd year)
Logistics and drill preperation	Preperation for 2014 drillling; Preperation for 2015 main drilling effort. Readying field and drilling equipment for the RECAP camp.	Camp and drilling equipment packing and repairing .	
Ice Coring Activity	Firn-gas project 70m icoring.	RECAP deep ice coring effort	
Radar Survey	Renland Ice cap survey; RECAP site selection		
Laboratory activity	Shallow Ice Core Processing and measuring	Deep Ice Core Processing; CFA Measurements until end of 2015. Discrete measurements until summer 2016.	
Publications	Publications based on 2014 radar survey.		Data analysis and interpretation. Publications based on data from the RECAP cores.
SC Meetings and Conference	SC	SC	SC; RECAP Conf

The RECAP ice coring project will be in two stages.

During the first stage (May 2014) a 70m ice core will be drilled on Renland for firn-gas measurements and an airborne radar survey will be carried out of the ice cap for optimum deep drilling site selection. The most likely area for the new drill site is in the vicinity (or at) the dome of the Renland ice cap on the eastern plateau (figure 1). The ice thickness in this area varies between 300m and 600m. During the second stage (Apr-Jun 2015) the RECAP deep drilling will be carried out on the Renland ice cap. Electrical Conductivity Measurements (ECM) will be the only measurement carried out in the field.

The RECAP science campaign will be in three main stages.

Stage 1 is the processing: During August 2015, the RECAP deep core will be processed in the Alfred Wegner Institute cold laboratories where Di-Electric Profiling (DEP), and imaging (Line Scanning) will be carried out and the ice core will then be cut into samples for further measurements. Stage 2 is the main measuring phase: During Sep-Nov 2015, a 3.5cm by 3.5cm piece covering the entire RECAP core length will be melted for mm-resolution Continous Flow Analysis (CFA) in the Centre for Ice and Climate laboratory at the Niels Bohr Institute. This will yield continuous chemical impurity data, gas records and water stable isotope data from the entire length of the RECAP core. Measurements of discrete gas and chemistry samples will be carried out Sep 2015 to May 2016. Stage 3 is the interpretation phase: During 2016 analysis and interpretation of the new data sets will take place leading to RECAP publications. A preliminary RECAP ice core time scale based on volcanic reference horizon matching (detectable in DEP and ECM data) will be ready by Feb 2016.

The governing body for RECAP is the Steering Committee (SC). The SC consists of a representative from each nation. Assoc. Prof. Bo Vinther will be the Danish representative. The SC meets every autumn in Copenhagen, and the science consortia (given later in the *Detailed research plan)* will meet for planning and discussions during SC meetings. Travel costs are paid by the participating institutions.

The RECAP international conference will be held Nov. 2016. 170,000 kr is set aside for this event, to facilitate travel funding for invited speakers and students involved in RECAP.

Qualifications of the main applicant

Leadership, coordination and experience with ice coring: During the NEEM (North Greenland Eemian Ice Drilling) ice core project, I have coordinated the setup of the NEEM science trench, worked as the leader of the NEEM ice core processing line and have been the Field Operations Manager coordinating logistics from Kangerlussuaq (Greenland west coast). I have worked as an ice core driller, using both the Copenhagen intermediate and shallow drilling setups. Hence, I am well versed in the practical work of executing the many different parts of an international ice core operation. I participated in the Flade Isblink project, working in a camp that had a structure similar to what is envisioned for RECAP.

Extensive experience with leading and carrying out ice core measurements: As part of my Ph.D. project I successfully optimized a mass spectrometer for fast water sample measurements at the AMS 14C Dating Laboratory, University of Aarhus. Two years later I tested and optimized the dual isotope ratio mass spectrometer at the Centre for Ice and Climate. Since 2010, I have been the leader of the water isotope group at the Centre for Ice and Climate. Hence, I am experienced in ice core measurements, both from a practical level and from a leadership standpoint.

Ability to make novel interpretations and advanced analysis of ice core data: I wrote and published my first paper introducing the new concept of analysis of seasonal signals in multiple ice cores[vii] before I handed in my Masters thesis. I have also pioneered new techniques in ice core dating, using variability analysis in climatic signals to infer annual layer thicknesses[viii]. In a paper published in Nature in 2009, I presented a new approach to estimate past elevation change of the Greenland ice sheet, and at the same time derive a Greenland climatic history for the past 11,700 years. Hence, I have a proven track record of innovative and high-profile papers. RECAP science and publications will benefit from this.

Large international network: I have been a major contributor to international scientific projects, such as the Greenland Ice Core Dating Initiative, that produced a common chronology for many Greenland and Canadian ice cores[ix,x], and a new international guideline suggesting how to advance the use climatic proxies[xi]. I am a co-chair of the NEEM isotope consortium, a WP co-chair in the Past4future ERC project and I am a part of the International Partnership in Ice Core Sciences (IPICS). Furthermore I have participated in the West Antarctic Ice Sheet (WAIS) Divide Ice Core drilling, an ongoing U.S. ice coring effort. I have published papers together with researchers from more than ten different countries.

Detailed research plan and science consortia

While the qualifications of the main applicant are important, an excellent team of researchers is assuring that RECAP will be a successful ice core project. Senior scientists participating in RECAP have extensive experience in all aspects of ice core work. As RECAP will be supported by a centre of excellence (CIC) and international partners, the bulk of the RECAP funding will be spent on retrieving the RECAP ice cores. RECAP funding is, however, set aside for bringing to Denmark an outstanding young researcher (Dr. Vasileios Gkinis) currently working in the US. The RECAP funding will allow CIC to employ Dr. Vasileios Gkinis for 18 months during the RECAP measurement campaign. Unnamed Ph.D.-students involved in RECAP will start at CIC in 2013. Ph.Ds will participate in field work and measurements, and lead publications of results in their science area. Below the different RECAP science plans are divided into specific consortia and the corresponding teams are presented:

Gas Consortium science plan

High resolution gas records covering the anthropogenic increase all stem from Antarctic ice cores. RECAP offers the opportunity to obtain a similar record from Greenland. Important information about the development of the trace gas content (CH_4, N_2O) is in the pole-to-pole difference of the trace gases, including their isotopes which so far have not been exploited for pole-to-pole information. The record of the last 2000 years is contained in the top 200-250 m of the Renland ice cap, providing a high time resolution over the Anthropocene. Further, due to the relatively high temperature and high accumulation, the age difference between ice and gas records (Δage) is very small (~75 years) resulting in a small age uncertainty of the gas records to be obtained and reaching up to about 1950. The exact Δage of the present Renland ice will be separately investigated by drilling a shallow borehole (<70m depth) on Renland during the spring of 2014 and carrying out firn-gas pumping in the borehole. *Team: Prof. Todd Sowers (EESI), Prof. Thomas Blunier (CIC), Ph.D.-student #1 to be employed by CIC.*

Chemical Impurity Consortium science plan

High resolution dust, Na, NH_4 and conductivity measurements will be carried out using the Copenhagen CFA system. These measurements will allow seasonal cycles to be resolved for the past ~4000 years, greatly aiding the dating of the RECAP core. Na, being a well documented sea-ice proxy in Arctic ice caps heavily influenced by marine air masses[xii], will be a very important asset for ascertaining past sea ice conditions. AWI Ion Chromatography instrumentation will be used to generate an SO_4 record for the RECAP core, facilitating detection and quantification of volcanic deposition on the Renland ice cap. *Team: Dr. Paul Vallalonga (CIC), Dr. Anna Wegner (AWI), Assoc. Prof. Anders Svensson (CIC), Assoc. Prof. J.P. Steffensen (CIC), Ph.D.-student Helle A. Kjær (CIC).*

<u>Water Isotope Consortium science plan</u>

RECAP will for the first time, continuously measure δ^{17}O, δ^{18}O and δ D along the entire core using the latest laser technology. Having all three isotopic ratios it is possible to reconstruct both the local climatic variations known to be affected by the Arctic sea ice outflow, and changes in climatic conditions in the marine source regions for the Renland precipitation. δ^{17}O is a new parameter and we have great expectations to be able to see changes in source regions related to sea ice extent changes along the Greenland East Coast. Dr. Vasileios Gkinis, who we seek funding for within RECAP, is a pioneer in making these measurements with laser based instruments. *Team: Dr. Vasileios Gkinis (RECAP/CIC), Prof. Jim White (INSTAAR), Assoc. Prof. Bo Vinther (CIC), Dr. Trevor Popp (CIC), Senior Scientis Bruce Vaughn (INSTAAR), Ph.D.-student #2 to be employed by CIC.*

<u>Physical Properties Consortium science plan</u>

Measurements of the physical properties of the RECAP ice will mainly be undertaken by AWI.
AWI has unique x-ray instrumentation at its disposal, with the ability to make micrometer- resolution tomography of large ice core samples. This instrumentation will be used to study the densification processes and their dependence on the dust in the ice. Understanding the densification processes is of importance for the studies of gasses trapped in the ice, as Δage depends on the speed of densification. *Team: Prof. Sepp Kipfstuhl (AWI), Prof. Dorthe Dahl-Jensen (CIC), Dr. Johannes Freitag (AWI).*

<u>Dating Consortium science plan</u>

Measurements of water stable isotopes and chemical impurities will be used for annual layer counting for the past ~4000 years. For older ice the RECAP dating will be based on a volcanic reference horizon and abrupt event synchronization with ice cores from the main Greenland ice sheet, thus assuring that the climatic records from RECAP will be on the same time scale as the ice cores from the Greenland ice sheet. *Team: Assoc. Prof. Sune O. Rasmussen (CIC), Assoc. Prof. Emer. Henrik Clausen (CIC), Assoc. Prof. Anders Svensson (CIC), Assoc. Prof. J.P. Steffensen (CIC), Assoc. Prof. Bo Vinther (CIC).*

<u>Ice flow Consortium science plan</u>

The 2014 CReSIS radar survey of the internal layering of the Renland ice cap will allow a detailed study of the ice flow to be carried out by tracking internal reflectors in the ice cap. Comparison between ice deformation seen in the RECAP core and in the deepest 1988 ice core will allow sections of ice cap wide deformation anomalies to be found, facilitating an assessment of past Renland ice cap stability. *Team: Prof. Prasad Gogineni (CReSIS), Assoc. Prof. Christine Hvidberg (CIC), Dr. Nanna Karlsson (CIC), Ph.D.-student Christian Panton, Ph.D.-student #3 to be employed by CIC.*

RECAP Synthesis Group

To assure that all relevant RECAP data are brought to bear on the central science questions, a synthesis group is necessary. The synthesis group will both draft cross-cutting RECAP-community publications and task consortia with drafting papers using data from multiple research areas. To facilitate the synthesis effort funds are set aside for the main applicant to visit all international partners during 3-4 months in 2016. *Team: Assoc. Prof. Bo Vinther (CIC), Assoc. Prof Sune Rasmussen (CIC), Prof. Dorthe Dahl-Jensen (CIC), Prof. Sepp Kipfstuhl (AWI), Prof. Jim White (INSTAAR), Prof. Todd Sowers (EESI), Prof. Prasad Gogineni (CReSIS).*

Preliminary RECAP publication plan

Working titles for selected RECAP publications (involved consortia): *(1) Arctic sea ice export during the Holocene (Chemistry, Water Iso. Dating), (2) Pole-to-Pole gradients in trace gasses during the Holocene (Gas, Dating), (3) Abrupt climate change in East Greenland – the sea ice signal (Chemistry, Water Iso., Gas), (4) On the stability of the Renland ice cap (Ice Flow, Phys. prop.).*

Publication of results and outreach

The results of the project will be published in international peer-reviewed journals and presented at international science conferences including the 2016 RECAP conference.. When data are published, they will be made available through the CIC data-webpage and will be uploaded to the World Data Center for Paleoclimatology, the world's largest archive of paleoclimate data. The CIC and NBI web pages are excellent portals for presenting data to the public and will be used for news and press releases. The NBI communications office will be used for contacting relevant news media when high-profile publications are released. During the 2015 field season a web-diary will be updated daily, detailing field operations and the experience of personnel in camp working in polar conditions. Experience from the NEEM project shows that such a diary is followed closely by science journalists, fellow scientists, high school teachers and their students, increasing recruitment to science education.

Practical considerations and feasibility

Overall the RECAP project is deemed to be highly feasible and thus low risk. This is due to the long standing experience with logistics operations on the Greenland ice sheet of the participating nations and the reliability of the Danish intermediate drilling system. This system has already proven itself by retrieving two ice cores in excess of 400m length. Both of these cores were drilled within a period of

two months. The Renland ice cap is situated in a location were bad weather can interrupt flight operations for short periods, but not significantly alter the planned deployments. The planned measurements on the RECAP deep core have been tested during the NEEM project, with the exception of the laser based $\delta^{17}O$, which is a new approach. The logistics planning is managed by logistics coordinator Lars Berg Larsen, who is exceptionally experienced in Greenland ice core logistics having handled the logistics during a handful of drilling operations. Lars Berg Larsen will be funded 2014-2015 by RECAP. The logistics coordinator will be supported by a logistics group: *Engin. S.G. Sheldon, Drill Engin. S.B. Hansen, Assoc. Prof. J. P. Steffensen, Dr. T. Popp and Assoc. Prof. B.M. Vinther*.
The following is the preliminary schedule for the two field seasons envisioned in the RECAP project:

<u>RECAP firn-gas ice core logistics, May 2014:</u>

The logistical hub will be the civilian airfield at Konstabel Pynt (CNP). Supplies, equipment and personnel will be transported by AWI basler aircraft to CNP via Akureyri (Iceland) or via Kangerlussuaq (Greenland). Transportation between CNP and the Renland drilling site will be done with AWI Basler aircraft (mounted with skis). Field work on the glacier is planned to last approx. one week, involving four people. The operation is designed to be relatively light weight, approx. 2,500 kg and full deployment and pickup of the field camp can be accomplished using 2-4 Basler shuttles.
At present it is unknown if freezer capacity for 250 kg ice core samples will be available at CNP. If it is not available, the modular freezer intended for the 2015 field work will be brought to CNP in 2014.

<u>RECAP main ice core logistics, last week of April – last week of June 2015:</u>

Supplies and equipment will be collected, packed and configured in Kangerlussuaq over a period of one week. Transportation between Kangerlussuaq and Konstabel Pynt (CNP) will be done by U.S. C-130 (Hercules) aircraft. Personnel will be transported to CNP by C-130 from Kangerlussuaq, by AWI Basler from Akureyri or by scheduled Air Greenland passenger plane. During field work, the logistical hub will be CNP. Supplies, equipment and personnel will be shuttled between CNP and the Renland drill site by AWI Basler. Field work on the Renland glacier is expected to last ~8 weeks involving 8-10 people. A crew change is planned after four weeks (mid-season). Deployment of equipment (~20,000 kg) from Kangerlussuaq to CNP will be done with two C-130 shuttles. From CNP to the drill site the AWI Basler will use 14-20 shuttles to bring in and pull out camp equipment and personnel. A few shuttles between drill site and CNP with AWI Basler are planned during field work. As drilling fluid will be spent, and fuel will largely be consumed, most equipment, personnel and ice core samples will be flown from CNP to Kangerlussuaq on one U.S. C-130 flight. In Kangerlussuaq, ice cores, supplies and equipment will be re-packed, stored and shipped to final destinations over a period of one week.

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