Greenland Ice Sheet Stability Workshop

Monday September 11, 2017

I. **Jason Briner**—Introductory remarks
    a. Why are we here?
        i. Ice+heat=seal level rise; 7 m GriS sle
        ii. Uncertainty surrounding stability: Bierman and Schaefer papers in Nature Dec 2016
        iii. The big question: How stable is the GrIS?
    b. How to tackle the question?
        i. Framework of natural experiments: ice sheets growing/shrinking over the quaternary
        ii. Focus on current interglacial and last interglacial, major expansion and contraction
    c. Specific objectives: We are the community to answer this question…how? What are the research priorities?
        i. Break out groups for Tues afternoon:
            1. Below the ice & basal ice
            2. Beyond the ice
            3. On/in the ice
            4. Modeling
    d. Post meeting: white paper will be drafted, passed around for review
II. Mark: Arctic Section of NSF
    a. Bill Wisemen program manager retired; 3 program managers
    b. Arctic Section: natural sciences (process oriented), system sciences (processes, large-scale), observing network (long-term data), social sciences
    c. No deadlines: 3 panels a year, decrease in number of proposals
    d. How much money is there? $13 mil per program
        i. Split based on proposals: ocean/atmos 50%, land ice 25%, terr 25%
    e. Success rates: ~10%, up to 15-20% last rounds
    f. Misunderstanding about Arctic section: logistics and science are not separate; amount of funds for logistics on the order of $4 million
III. **Joerg Schaefer**—Direct constraints about the GrIS stability from cosmogenic nuclide analysis and Ar-dating
    a. Combination of direct archives for the GrIS: basal ice and bedrock
        i. Drilled, but largely untapped
        ii. New methods for dating
    b. Sea level rise: 7.4 m equivalents
    c. Reliance on proxy records, models—room for more direct data
        i. Most robust (only?) terrestrial record: Kap Kobenhavn Formation of climate at time of ice formation (Bennike)
        ii. Last Eemian ice (Dahl-Jensen): suggests that ice sheet did not respond dramatically

d. Basis for Ar isotope ratios to date trapped gases in ice cores:
    i. ^{40}K decay to ^{40}Ar, while ^{38}Ar constant
    ii. Constant increase of $^{40/38}Ar$ ratio to present
    iii. Limitations: need to correct for gravitational fractionation, contamination by radiogenic argon
    iv. Dating of GRIP basal ice: ~3000 m ice depth, dirty ice min age=980+/-190 ka; stratigraphically disturbed clean ice 400+/-180 ka
e. GISP2: 1993, 1.55 m drilled into bedrock
    i. Dated with cosmogenic nuclides—produced in near-surface rocks hit by cosmic rays from the atmosphere; combination of spallation and muonic reactions—spallation dominant at surface while muons dominate at depth
    ii. ^{26}Al decays 2x faster than ^{10}Be: both produced in upper meters of exposed Earth surface at ratio of $^{26}Al/^{10}Be$ 6.75
    iii. Ice sheet shielding: no production and radioactive decay, measured at 3.4
    iv. GISP2 bedrock profile (^{10}Be vs. depth) is not a straight line, approximates an exponential curve shape
    v. Presence of Be: exposure occurred at some point
    vi. $^{26}Al/^{10}Be$ production ~6.76 (always exposed) to $^{26}Al/^{10}Be$ 4.1 +/-0.3 to 4.2+/-0.6
    vii. Max shielding by GrIS=1.1 million years
f. Data analyses:
    i. Was the GISP2 bedrock at earth's surface? No, but very close
        1. Based on optimized curve fitting of ^{10}Be depth profile
        2. Max shielding ~3.8 m ice, 1.3 m rock, 1.7 m soil
        3. Based on extra shielding, total exposure ~280+/-30 kyr
    ii. Scenarios consistent with data
        1. Max stability end-member: 280 kyr exposure followed by 1.1 Myr shielding
        2. Other consistent scenarios: mixes of exposure, shielding
    iii. What does this mean for the GrIS?
        1. GISP2 bedrock-GrIS upscaling: if GISP2 ice free, ~95% of ice sheet ice free
g. Unpublished results: ^{36}Cl ($t_{1/2}$=300 kyr) in GISP2 feldspar bedrock
    i. Exponential spallation from neutrons, downside='nucleogenic' ^{36}Cl problem (^{36}Cl produced in mineral)
    ii. Measured ^{36}Cl normalized to K concentration with depth: in line with ^{10}Be depth profile
    iii. Lower ^{36}Cl than ^{10}Be: burial signal; ~78% of surface production
    iv. First order correction for about 6000 atoms/g nucleogenic ^{36}Cl; max period of GrIS at GISP2 ~400 +/- ? kyr
    v. Shorter stability than produced by 10Be dates
h. What's next?
    i. ^{3}He and ^{21}Ne: Gisela Winkler

        ii. ^{53}Mn
    i. How to reconcile with NEEM and antique ice ages?
        i. Regrowth of the GrIS from the Eastern Highlands
            1. Expose GISP2 and store ice in Eastern Highlands
        ii. GISP2 ice-free but GRIP covered by old ice?
            1. GRIP slightly upstream of GISP2, stratigraphically in order
    j. Conclusions:
        i. Need to understand how to deglaciate Greenland. What is the process?
        ii. Why is the GrIS still there in substantial warm period? Why has the GrIS not changed much during the Holocene?
        iii. Further pursuit of sub-ice sheet bedrock as a climate archive: 'agile sub-ice geology drill' to sample basal ice and bedrock
        iv. Sub-glacial basal ice and bedrock are basically untapped archives, and we now have tools to analyze them.
            1. Very old basal ice found elsewhere?
            2. Potential to do comprehensive GrIS bedrock survey with multi-cosmogenic nuclide approach
            3. 10 year plan: where to drill—margins for immediate drilling, major enterprise to drill in central Greenland
    k. Questions:
        i. If NSF had a rapid access ice drill for Antarctic could this help in Greenland?
            1. High end-member design drill, mobile drill would be cheaper

IV. **Paul Bierman**—Deciphering history and processes of GrIS using cosmogenic nuclides
    a. Attempt to accumulate everything we know about deep history of GrIS
        i. Back to 50 myr
        ii. Bulldozer problem—records of prior glaciations wiped out, eroded record from beneath ice cores
        iii. Only continuous records: ice cores, global isotopic ocean records
    b. Over the past decade, measurements of cosmogenic nuclides in bedrock outcrops, glacial, fluvial and marine sediment, basal ice, and ice-bound cobbles.
        i. Measurements reveal a dynamic and erosive ice sheet in some places, non-erosive in others, resulting in a complicated erosion history.
        ii. Need to think about process/glaciology in interpretation of ^{10}Be.
    c. Background: in situ ^{10}Be and ^{26}Al
        i. Concentration reflects near surface residence time
        ii. Measured in quartz, AMS
        iii. Require models to interpret results
    d. Cosmogenic dating in different areas of Greenland:
        i. Ilulissat: effective erosion, LGM ages=fiord bottoms
            1. Low inheritance
            2. Can develop ice model of margin retreat
            3. Simple case
        ii. Upernavik: little erosion, frozen bed

1. Boulder and bedrock pairs give different ages: complex erosion history
2. Weathered bedrock vs. fresh erratics
3. Paired isotopes indicate burial not erosion: can begin to constrain complicated history with multiple isotopes, can not simply pull out a date

iii. Thule: more inheritance, long uncertain burial ages, and shorter more certain exposure times; cold, weakly erosive

e. Sediment Tracing: Fluvial and glacial sediment
   i. Taking advantage of sed outwash from the ice
   ii. Sampling ^{10}Be down river networks outside of ice sheet (Nelson, 2013)
      1. River terraces: ~1000 years exposure, can measure but not well
      2. Rivers draining ice sheets: significantly more 10Be
   iii. Can measure ^{26}Al: most sample ratios consistent with surface production for samples out of the ice sheet today and river terraces
      1. Older sample for terrae representing last deglaciation
      2. Increased ^{26}Al/^{10}Be ratio with re-exposure
   iv. Ice-bound clasts reveal history of ice-sheet bed
      1. Sampled from margin dirty ice zone
      2. Most clasts have very little ^{10}Be, a few have 32 and 112 atoms ^{10}Be per gram (skewed distribution)
      3. Multi-isotope plots: many clasts consistent with only near surface exposure, some have long burial histories (up to hundreds of thousands of years)
      4. ^{10}Be vs. ^{14}C, ^{26}Al vs. ^{14}C: strong regressions
         a. Suggests clasts exposed before brought back to the margin
         b. Isotopic evidence for movement inboard of modern margin during Holocene
   v. Basal ice GISP2: a lot of ^{10}Be in dirty ice
      1. Presence of ^{10}Be argues for preservation—fairly stable GISP2, how to reconcile with instability?
      2. C/N consistent with peak, lake sediments
   vi. Marine cores: four cores show similar decreasing ^{10}Be over time; progressive glacial erosion of pre-glacial regolith
      1. Spikes in ^{10}Be: expansion of ice into parts of Greenland not previously eroded? Ice sheet shrinking and re-exposure?
      2. Resolution currently too low
      3. ^{26}Al data show ratios not indicative of complete coverage; most sediment sourced from areas with ratios consistent with long-burial; few periods of higher ratios

f. Pulling together evidence:
   i. Ancient soil in basal GISP2 ice—stable pre-glacial landscape at Summit?
   ii. Most ice-sourced clasts have little ^{10}Be—from deeply eroded areas

iii. Marginal rocks with high ^{10}Be and ^{26}Al—some ice cold-based, some warm-based
iv. Ice-marginal sand has little ^{10}Be and $^{26}Al/^{10}Be$ ~7—glacial sed from deeply eroded areas
v. Early Holocene terrace sed little in situ ^{10}Be

g. GrIS vs. other ice sheets
    i. Laurentide tills have most ^{10}Be (lots of exposure), Antarctica has very little (no exposure), GrIS intermediate

V. **Ole Bennike**—History from the dirt

a. Late Pliocene and Early Pleistocene deposits
b. Kap Kobenhavn Formation
    i. Boreal species, Arctic species, extinct species
    ii. Extremely well-preserved plant and insect remains (~200 species beetles, compared to 1 species today; 4 species ants compared to none today)
    iii. White cedar found in north Greenland, far beyond modern limit
    iv. Ice push: reverse faults and thrust faults, folds; covered by till
    v. Difficult to date: evidence from extinct rabbit and extant hare species
        1. Tooth of rabbit and fragment of hare jaw found
        2. Co-occurred in N. America ~2 myr ago (oldest bound)
c. Ile de France Formation (further south)
    i. Boreal species, arctic species, extinct species
    ii. Ocean quahog present at both formations, beyond modern day distribution
d. Store Koldewey Formation:
    i. Mixture of boreal, arctic and extinct species
    ii. Few meters thick, ~120 m asl
    iii. Shells
e. Lodin Elv Formation
    i. No boreal species, more like a glacial marine sequence with Arctic and extinct species
f. Patorfik Beds (West Greenland)
    i. Mixture of boreal, arctic, and extinct species
    ii. Extinct snail present in west Greenland formations
g. Amino acid dating: given same temperature history, older deposits have higher Alle/Ile ratio
    i. Difficult to definitively tell which is oldest/youngest
h. Magnetic reversal scale:
    i. Reverse polarity Kap Kobenhavn: early Pleistocene
    ii. L. Elv and Patorfik: earliest Pleistocene, latest Pliocene
i. How do these formations fit with super interglacials identified from Lake E?
    i. ~2.5 myr and younger
j. Last interglacial sites:
    i. Boreal species and arctic species
    ii. Comparison to modern-day geographic ranges

iii. Mean July temp ~5ºC higher than today

k. Pre-Holocene lake sediments, NE Greenland
    i. Oldest C-14 age: 65 kyr
    ii. Warm-demanding species: bivalves, charophye, pond-weed, ostracode, tadpole shrimp

l. LGM: ice margin at shelf edge?
    i. Increasing evidence that the margin of ice sheet reached edge in SE Greenland, off Disko Bay area, Melville (?) Bay area
    ii. NE Greenland—widest shelf, evidence ice sheet reached far out, possibly to edge of shelf

m. Conclusion: a dynamic Greenland ice sheet during past interglacials?

n. Questions:
    i. Sense of pathways of terrestrial species to Greenland?
        1. Data from Holocene of plant/animal immigration
        2. Some species from Canada, Baffin Island, Siberia
        3. Variable pathways, challenging to understand mechanism for travel
    ii. How well constrained are ages based on extinction dates (rabbit/hare ages)?
        1. More recent finds of extinct rabbit, survived into Pleistocene in Europe
        2. Suggests not mid-Pliocene

VI. **Dorthe Dahl-Jensen**—Studying the GrIS: Implications for climate past and present

a. Motivation:
    i. GRACE observations of GrIS mass changes: 2002-2016, summer losses>winter gains, avg loss 281 gigatons/year (0.8 mm sea level rise per year), present rate=10,000 years for ice sheet to melt; increasing uncertainty scaling sea level rise up with time

b. Ice cores of Greenland:
    i. Cores along the main north-south ice ridge
    ii. Dye3 on Southern Dome, GRIP NRIPG, NEEM, Camp Century on north dome
    iii. NEEM: Eemian climate information
        1. Temp up to 8º warmer than present at onset
        2. How to resolve presence of ice sheet with models?
        3. Ice thickness reduced 400 m, reaching a thickness 150 m less than present
    iv. Produce $d^{18}O$ record reaching back 128,500 years before present
    v. Deep drill sites: warmer isotopic signature than present at the bottom of cores=Eemian ice at all sites
        1. Located at different depths in different cores: basal melt, folding, older ice below
        2. No doubt the GrIS is older than Eemian
        3. Different $d^{18}O$ values: surface warming and elevation changes

                a. Avg Eemian warming of 5.7ºC
            4. Can compare profiles along the ridge: volume change less than 25%
        vi. Basal material:
            1. Larsen, 1994
            2. Camp Century: 1390 m ice thickness, 17 m basal material; boreal forest DNA present
            3. NEEM: Folded ice at bottom, mixture of ice and sediment
            4. NGRIP: strong basal melt, no basal material retrieved but silt with willow and spruce macrofossils
            5. GRIP
            6. DYE3: cold basal temp, remnants of boreal forest DNA
            7. Compare to ODP646 marine core: big peak of pollen ~400,000 years ago; further back in time—more pollen
            8. Kap Kobenhavn formation
            9. Together, provide evidence of boreal forest. No remains from tundra/shrub. No intermediate period observed (boreal forest to glaciated). Conclusions: Greenland was forested; north 10ºC warmer, south 5ºC warmer.
                a. When? Super-interglacial, stage 31 or further back in time, co-existent with Kap Kobenhavn?
                b. Relationship between warming and sea level? Not a direct relationship; differences between Antarctica and Greenland

c. IceFlow: NEGIS
    i. EGRIP drill site in the center of NEGIS with surface velocity 55 m/yr
    ii. Nice stratigraphy in center, strange structures outside of ice stream
    iii. Can see velocity vs. depth profile: flow depends on ice type
        1. Interglacial ice—faster, spread crystal structure
        2. Glacial ice—slower velocity
    iv. Study of microscopic and macroscopic models of ice crystals to understand flow dynamics in an ice stream
    v. Future studies: study of basal structure near ice stream
    vi. Key component in understanding sea level rise

d. Summary:
    i. Mass balance projections are key in projections/reconstructions
    ii. Did the mass loss change pace? As you reduce the volume of the GrIS, how do ice dynamics change?
    iii. Need to understand ice streams better, including topography under ice streams
    iv. Need to be able to work with unstratified ice: Cl, Be, Al and Kr methods developing

v. BGRIP (Beyond—GRIP?): looking for oldest ice; identifying depressions from IceBridge data which may contain old ice, though not stratigraphic (waiting for dating methods to improve)

e. Questions:
   i. What are the structures outside of the ice stream?
      1. Buckling Eemian ice in smaller scale
      2. Measurement of ice chips: d-excess, can determine if refrozen water or snow
      3. 2 cm hole through structures: how to monitor? Track movement over time
   ii. How do you get temperature estimates from $d^{18}O$ considering change in seasonality?
      1. Ice cap at high island: 2.5 km asl, 300 m thick ice—no elevation change, included in calibration
      2. Hans Tauppen and other cores disappeared in last IG
   iii. Ice sheet volume vs. temp—what ice sheet volumes might be unattainable given a stable configuration?
      1. No information in plot on rate of change for ice sheet volume
      2. What if Eemian configuration never reached stability? Likely the case. Ice sheets not truly in stable state because adjusting to temp.
   iv. Last interglacial temperature: how to determine proportion of summer/winter precipitation?
      1. We don't know—other proxies suggest surface melt additionally
      2. Could reduce magnitude of warming

VII. *Discussion Session:*

a. How do we get ages from formations?
   i. Burial isochron work
   ii. Uncertainty tied to initial Be/Al ratio and sediment history; what do we know about the facies?
   iii. Not easy measurements to make, but doable
   iv. OSL and magnetics?
      1. Too old for OSL
      2. Strontium isotope dating, didn't work well
      3. More work could be done in paleomagnetics
   v. Development of new methods—enormous potential to analyze archived samples (ice cores)
   vi. Some constraints from racemization dating

b. Offshore Be plots, what do slopes mean?
   i. May not be seeing first ice on Greenland; lowermost samples challenging to measure above blank
   ii. Improvement of accelerator technology
   iii. Cannot detect beyond ~8 my

iv. Stochastic effects: drop off ice bergs, integration over thousands, .5 million years
v. Basic agreement, interesting information in noise?
vi. Could push towards better Be measurements
vii. Thinking about source and transport of grains—what erosional environments do these grains comes from, and how does the source change over time?
viii. What if we had two marine cores separated by a meter, a kilometer, would it look the same?
1. Similarly, would sub-glacial bedrock look the same?
a. Expect same basic signal unless unlikely with erosive regime
b. If you can see spallation signal, likely safe
c. Schaefer optimistic about reproducibility
2. Work on understanding spatial variation

c. How to rectify Joerg and Paul's results from meteoric measurements?
i. Early long exposure—not contradictory
ii. What about the changing overburden?

d. GrIS sea level rise vs. temperature change synthesis plot
i. Schaefer—expect a more rapid/abrupt element; possible change in precipitation
1. Forcing smaller than temperature change due to temp feedback with loss of ice (magnitude and duration of forcing important)
2. Stage 11 not warmer but longer than the Eemian (based on far field records)
ii. Duration piece: stage 11 vs. stage 5; prior to Kap Kobenhavn large ice, but then significant shrinking of ice
1. What happens as you switch from 44,000 to 100,000 year periodicity?

e. Connecting Be in marine cores and exposure ages from margins: we have to be careful not to think of the ice sheet today as the same erosion regime in the past
i. Erosion of expanding vs. contracting ice sheet
ii. Impacts of fjord systems: ice sheet with deep fjords can come apart much faster
iii. Importance of understanding why/how ice sheet contracted in the past
iv. Different erosive behavior in phases of expansion/contraction

f. How much has been eroded? How much does sediment flux contribute to ice sheet elevation?

g. Is there a drilling site to prioritize to pin down ice sheet stability?
i. Rapid access to a bed in several places would be useful
ii. Seismic work to learn about the bedrock

VIII. **Robert Hatfield**—Reconstructing the response of the south Greenland ice sheet to climate using marine sediments

a. Why the marine geological record?

i. Eirik Ridge: sed drift south of Greenland
ii. Terrestrial record often most complete, but bulldozed by glacial re-advance
iii. Ocean sed offers record of multiple G/IG periods
iv. Sediment from Greenland and Iceland via longer distance transport
v. Can look at mag sus and mag grain size
    1. Peaks in mag sus and grain size in IG
    2. Often seen across Atlantic, but generally during glacials
    3. Coincide with peaks in iron, titanium
    4. May reflect GrIS

b. How can this signature be isolated in marine sed?
    i. Fingerprint sed source: if Greenlandic can track changes in GrIS
    ii. Characterization of sed around Greenland and Iceland in terrestrial samples
        1. Magnetics—silt fraction 2-5X conc of mag grains than clay fraction
        2. Iceland fractions possess similar magnetic grain sizes
        3. Greenland clay similar to Icelandic fraction
        4. Greenland silt magnetically coarser
        5. The silt fraction can be used to establish magnetic end-members
        6. This is also supported by radiogenics: can also distinguish between terrains of southern Greenland
    iii. MD99-2227: 42 m piston core, 3460 depth
        1. Bulk susceptibility: sensitive to the proportion of silt (r=0.66)
        2. Silt Mrs/Ms values fall between Greenland and Iceland end-members
            a. Unmixing of marine sed Mrs/Ms values yield average Precambrian Greenland contribution of 48%
        3. Radiogenic unmixing shows similar trend
        4. Quadrant plots: sed texture and source
            a. Silt increases, where does sed come from?
            b. Ex. Last termination: during LGM mid PG contribution, increase silt with Greenlandic signature, movement towards Icelandic end-member; rotation deglacial signature
            c. Can look at last 5 terminations and see same cyclical pattern, but variability between position in quadrants
        5. Stepping through interglacials:
            a. Stage 11: strong Greenland signature with sustained insolation and high CO_2, followed by loss of Greenland contribution=loss of southern Greenland Ice Sheet; consistent with boreal forest evidence
            b. Stage 7: Low CO_2 and insolation forcing; high sand throughout the interglacial, weak sGrIS retreat

            c. Stage 9 and 5: similar; long Greenland silt signature past peak insolation and CO_2, retreat signature decoupled from insolation
            d. MIS 2/1: Same early signature, loss of Greenland signature around peak insolation
        iv. Summary of sGrIS Behavior:
            1. End-members: loss of most of sGIS and maintenance of marine calving margin
            2. Two thresholds: decoupling from insolation forcing, land based ice sheet
            3. Different interglacials plot between these points
    c. IODP Site U1307: same cyclicity in magnetics to the Pliocene
        i. Loss of MS signal ~3.3 Ma?
            1. Loss of sGIS
            2. Diagensis
            3. Change in source material?
        ii. High sand intervals linked to glacial cycles
    d. Spatial Variability Across the Drift
        i. Influence of the DWBC: deepens during interglaciations, shoals during glacial periods
        ii. Is there a coherent story between sites related to SGIS behavior on I/G cycles
    e. Understanding the Eirik Ridge Record
        i. Capture deglacial behavior over multiple G/IG cycles
        ii. Current observations may capture only one mode of variability
        iii. Future drilling targets: longer records—seds to the Miocene; redrill ODP sites for longer records
    f. Questions:
        i. Interpret silt as meltwater transport?
            1. Carried in undercurrent
        ii. How to deal with east Greenland basalt?
            1. Radiogenics
            2. Would need volcanic samples

IX. **Anne Jennings**—Greenland Ice Sheet History from NW Greenland Margin Trough Mouth Fans
    a. Foraminifera—ocean forcing on the shelves to look at the influence of warm Atlantic water on ice sheet retreat
    b. IODP proposal: Melville Bugt
        i. Trough mouth fan, mapped by industry data
        ii. Contourites developed during mid Pleistocene to LGM
        iii. 11 progradational units from ice advance/retreat cycles (Late Pliocene-LGM)
        iv. 8-11 correlative to contourite drifts on lower slope
        v. Potential for developing full history of trough mouth fan

        vi. Hypothesis: units (8-11; mid-Pleis) may be related to readvances following super interglacials
        vii. Pair with Be measurements

X. **Nicolas Young**—Using cosmogenic isotopes to reconstruct Greenland's minimum Holocene ice extent
    a. Main question: how small did the GrIS get during the Holocene?
        i. W margin retracted an unknown distance
        ii. Model examples: produce variable estimates of time and distance of retreat
    b. Methods:
        i. Threshold lakes: lakes fed by meltwater=glacial flour signature; ice outside of catchment=organic sedimentation
            1. Only tell about late Holocene maximum if modern organic
            2. Need to look at current proglacial lakes to understand Holocene minimum
        ii. Cosmogenic isotopes in recently exposed bedrock: what is the total duration of time these sites were covered in ice prior to the last few hundred years
            1. In situ $^{14}C/^{10}Be$ vs. ^{10}Be: can distinguish continuous exposure from extended periods burial prior to the last few hundred years

XI. **Meredith Kelly**—A Case for Understanding GrIS Stability
    a. When was the GIS most recently "stable"?
        i. Stability—'geomorphic stability'
        ii. Most recent max position during last ~500-1000 years ('historical max')
        iii. At max, formed moraines, trimlines, and drift lines
        iv. Inflection point between advance/retreat
    b. Ex. Jakobshaven (Csatho)—10s of km
    c. Ex. Southwest Greenland: meters infront of modern position
    d. Fluctuations around max spatially and temporally, but suggest understanding recent time may be useful to investigate processes of stability
        i. What were the climate conditions?
        ii. What has changed since then?
        iii. Magnitude of ice sheet loss and climate forcings
    e. Potential approaches:
        i. Remote and field mapping
        ii. Paleoclimate proxy development
        iii. Modeling

XII. **Joseph Graly**—Discontinuous pre-glacial regolith preserved in at least three GrIS locations
    a. Meteoric ^{10}Be isotope chronometer, meteoric ^{10}Be incorporated into surface sed and transported to depth; ^{10}Be-bearing seds fluxed from ice sheet margin
    b. Measurements in Greenland: ice bound, subglacial, glaciofluvial
        i. Two major trends: higher conc at northern sites compared to southern sites; difference between fluvial and ice bound (significantly more)

        ii. Inference of source soil age from ^{10}Be age: Summit 128-321 ka=either preglacial regolith or bit of super-interglacial development; requires low erosion
    c. Conclusions:
        i. Northern Greenland—preglacial or progressively exposed sed (not found in s Greenland)
        ii. Requirement of low erosion for preservation

XIII. **Yarrow Axford**—Past climates at the Greenland Ice Sheet margin:
    a. Paleolimnology—Holocene and into Eemian
    b. Survey of Holocene air temp reconstructions:
        i. From Greenland margin, quantitative and continuous; surface melt
        ii. 7 record: 2 Agassiz and Renland, 5 from lakes
        iii. Annual integrated vs. summer temp records (drive surface melt)
        iv. HTM summers 3-5º warmer than present
        v. Is there spatiotemporal variability? Too soon to say
    c. Eemian temps on Greenland: ice cores and 2 extralimital taxa
        i. Lake in NW Greenland supports NEEM (v warm); cold-based ice protected Eemian sed from erosion; based on insect assemblages
        ii. Which archives support peak warmth? Is there geologic bias towards underestimating peak warmth?
        iii. Goelzer et al. COP 2016—Must scale back temperature forcing from proxy data reconstruction to prevent ice sheet from disappeared (4-8ºC)

XIV. **Jessica Badgely**—Holocene climate reconstruction from Greenland ice cores
    a. Goal: reconstruction to force ice sheet models
    b. Approaches:
        i. Single-Proxy Scaling: does not allow for spatial patterns, limits number of proxy records incorporated
        ii. Paleo data assimilation: incorporates the physics of climate models (spatial covariance) and temporal data of climate records
            1. Start with guess of climate state (climate model output—CCSM4 Last Millennium model output)
            2. Compare to proxy record, look at difference
            3. Run through data assimilation filter; accounts for error in proxy record and model
    c. Results: comparison of Kobashi et al. 2017 record and DMI reanalysis for GISP2, and initial partial ice core database
        i. Damped variance compared to other reconstructions
        ii. Can see some expected climate events (i.e. 8.2 event)
    d. Summary:
        i. Low computational cost
        ii. Can incorporate multiple proxy records

XV. **Robin Bell**—Sampling Basal Ice Units in Greenland
    a. Similar basal structures in Antarctica and GrIS
    b. Ice Bridge data

c. Two types: north and south
    i. Basal structures within 1000 m to top of ice; basal units
        1. Not along water networks from interior
        2. Unlikely to be from basal melt
        3. Beneath surface lakes, sourced from surface melt: may be refrozen water
    ii. Large structures in interior of ice sheet, less than 1 km from ice surface
        1. Tend to form beneath Eemian ice
        2. Large folded structures
        3. Deformed ice bodies, possibly triggered by basal melt
        4. Model water at base of ice sheet—deformation, self propagating feature
d. Will these structures influence the rheology of the ice sheet in the long term?

XVI. **Gifford Miller**—Does the Laurentide Ice Sheet ever disappear? CRN data constrain the stability of the Barnes Ice Cap

a. Differences between LIS and GIS in late Holocene: LIS retreat until ~2 k, stable (Barnes Ice Cap), disappearance expected within a few hundred years
b. In situ 14C for duration of postglacial exposure, 10Be/26Al for burial history
c. Barnes Ice Cap history: minimal erosion, minimal landscape exposure
    i. Range of glacial erosion rates possible
d. Colver: Low inventories, nearly continuous burial for past 2.5 Ma
    i. Inheritance signal
e. Conclusions: LIS deglaciation always follows the same pattern, ending in the Barnes Ice Cap
    i. If not, would require more inventory
    ii. In an early Quaternary 40 ka world, insufficient time for complete LIS deglaciation
    iii. In 100 ka world, complete deglaciation rare, possibly only MIS 53 and 11 (duration of IG important)
f. Goal: dedicated field campaign along NE margin sampling bedrock for CRN at the ice margin

XVII. Discussion Session:

a. 3-5ºC Holocene warming (to pre-industrial): where was the minimum Holocene ice margin configuration?
    i. Warmest time periods about when today reached todays margin; prolonged response even with differential temperature
        1. Min ice position not at same timing as max temp
        2. Lag time—how long does it have to be held warm; predicting instability but has not happened yet
        3. Influence of LIS melt on ocean temperatures
    ii. Seasonality of temperature change: summer vs. winter?
        1. Summit signal—dominantly winter temp; changes in precipitation
        2. Know less about the coast and ocean

                3. Present warming in Arctic—ocean in wintertime and atmospheric moisture
    b. Different sizes of LIS and GIS
    c. Linking observations ocean deposition and beryllium records?
        i. Highly variably erosion regime
    d. Meteoric Be: Evidence suggests Illulisat area from ice divide to edge of ice sheet is a zone of intense erosion, how do we get the equivalent of 40,000 years of erosion from a site like this?
        i. Site north of main Illulisat ice fjord
        ii. Sed from far inland?
    e. Spatial heterogeneity of basal ice: proxies for bottom of the ice prior to drilling?
        i. Ice penetrating radar across Greenland
    f. Assume GIS shrunk and readvance, how much time would you need to get a signal for how far the ice got back?
        i. How much time to get in situ radiocarbon sufficient for measurement but not decay
        ii. Blank ~800 years
        iii. Contribution of muogenic ^{14}C—higher ^{14}C ages than ^{10}Be, but should not be the case due to shorter half life
            1. Ice on surface (~10 m)—muons penetrate but neutrons do not
            2. Thin ice vs. no ice still relevant for understanding Holocene change
        iv. How much of ^{14}C is potentially inherited from before LGM? Where was ice 25,000 years ago?
        v. ^{14}C dating of shells on moraines: valuable for proving ice was smaller, but hard to constrain by how much
        vi. How much of the ice sheet can be studied with proglacial lakes?
            1. Cannot get very far inland with coring of relatively small lakes

XVIII. **Jeremy Fyke**—Translating climate forcing to ice sheet response
    a. Gossips, Normal Rockwell—analogy for ice sheet system
        i. External forcings (changes in energy from sun, emissions of radiatively active gases, comets, volcanoes)
        ii. Atmospheric processes/mechanisms: global scale and local meteorology
        iii. Ice sheet surface processes: snow, firn, melt processes, hydrology
        iv. Ocean system: atmosphere-ocean interactions, sea ice dynamics, fjord style oceanography
        v. Global carbon cycle, internal climate variability
        vi. Result: climate-derived ice sheet mass balance, feedback to climate
    b. Long-time scales: feedback loops may dominate evolution of ice sheet
        i. Ex. Height-SMB feedback, solid-earth/gravity/discharge feedback, melt-circulation feedback
    c. Carbon/climate modification: forcings in the future different from the past
        i. Ice sheets coupled components to climate system—coupling ice sheets into climate model promising way to understand the system

1. Can feed in different types of external forcings: can translate forcings into climate responses

d. Results of coupled climate-ice sheet models
   i. Many climate models at different CO_2 concentrations to force ice sheet models: uncertainty ranges from no to complete deglaciation
   ii. Fully coupled ice sheet-climate model: tweaks of model to equilibrium climate sensitivity and polar amplification; can get almost identical response of ice volume for different configurations of ice volume; huge range from no to ~50% ice loss over same time for same boundary condition forcing
   iii. These uncertainties make it difficult to answer questions such as how much ice remained in previous interglacials.
   iv. How do we constrain this?
      1. More realistic configurations identified through observations
         a. Ex. Eocene IRD, GISP2 bedrock
         b. Observations 'off the map' of model simulations; indicates that major things are missing from the model
      2. Probabilistic results
         a. Running large ensembles of models varying parameters and boundary conditions to produce range of model results
         b. Present most likely estimate and range of uncertainty that arises from uncertainty in model deisgn and boundary conditions
         c. GrIS volume vs. time under different cumulative carbon emissions scenarios
         d. Threshold remapping to cumulative emissions CDF allows for IPCC-style likelihood statements: risk assessment statements

e. Summary:
   i. Greenland is a coupled component of the Earth's system.
   ii. GIS response to external climate forcings is regulated by Earth system process, ice sheet dynamics, and feedbacks.
   iii. Coupled ice-sheet/earth system models capture while system dynamics with a wide range of results
   iv. Greenland/global paleo-observations are critical for identifying accurate models or missing model processes
   v. Ensemble-based approaches are powerful at providing probabilistic results and reflecting uncertainties

f. Questions:
   i. How do you account for unknown uncertainties vs. parametric uncertainties?
      1. Assessing uncertainties inherent to the models is difficult (i.e. lack of ocean-ice sheet couplings): structural model uncertainty

            2. Easy to tweak scalar values
      ii. Is it possible to do a higher resolution model to figure out shorter timescale processes (i.e. Holocene)?
            1. Yes—difficulties arise in including finer processes
            2. Changes may be small relative to grid cell resolution

XIX. **Andreas Born**—Data-Model Integration for Ice Sheet Models
   a. Ice sheet flow: ice cores contain depositional and dynamical history of ice sheets
      i. E.g. GISP2: two peaks in proxy with depth contains information about dynamics of ice
      ii. Numerical diffusion: simulated diffusion is not effective
   b. Isochronal ice sheet model: simulation of tracer, reconstructed $d^{18}O$ as a boundary condition at surface of ice sheet, model $d^{18}O$ looks very similar
   c. Multiple ice core records
   d. Other archives: ground penetrating radar (radiostratigraphy)
   e. Summary: bridge the gap between real world data and physical models to improve models and improve sea level estimates

XX. **Petra Langebroek**—Ice on Greenland during the Eocene-Oligocene transition
   a. Early Cenozoic: high CO_2, drop in CO_2 at E-O transition with cooling 5ºC at high latitudes and expansion of AIS
      i. Evidence for ice on Greenland: IRD in Norwegian/Greenland Sea or against: temp ~10ºC higher than present
   b. E-O geography and topography: high bedrock
      i. Icelandic mantle 'plume'
      ii. Opening of North Atlantic and collision of NW Greenland with Ellesmere Island
   c. E-O transition temp: ~15ºC higher than today to ~10ºC higher than today, with orbital variations ~40,000 of 3ºC
      i. Possible to create ice in highlands, but does not reach the coast
      ii. In early Oligocene, still a bit of ice
      iii. Scenario with coastal ice consistent with temp records
   d. Need to include solid Earth and geodynamical processes when assessing past GIS stability

XXI. Constraining and understanding the deglacial history of the GrIS
   a. Why this period?
      i. Large response of system—big signal
      ii. Rates of change on 100s to 1000s of years
      iii. Determine initial conditions for future simulations (temperature memory of the ice)
      iv. Relatively data rich period in terms of paleo-data
   b. Main issues in model development:
      i. Solution non-uniqueness
            1. Need data control on ice sheet forcing and response, regional Earth structure
            2. Improving model complexity enhances this problem

ii. Model accuracy vs. efficiency
    1. Number of runs vs. model sophistication/resolution
    2. Target specific time periods and regions
iii. Ex. Rapid thinning at Camp Century
    1. Ice core isotope record—rapid thinning in early Holocene
    2. Consistent with new reconstruction from Agassiz ice cap
    3. What about contribution from separation of Greenland and Innuitian ice sheets?
iv. Ex. Retreat from continental shelf
v. Fitting GPS constraints—can fit one dataset, but perhaps not another; need data to tell how well models are performing

XXII. **Bette Otto-Bliesner**—Coupled long-term evolution of climate and the GrIS during the Last Interglacial
  a. Last Interglacial (129-116 ka)
    i. Large boreal summer insolation anomalies (129-124 ka) from orbital forcing
    ii. Stable GHG concentrations similar to late Holocene
    iii. Continental and oceanic configuration almost identical to modern
    iv. 5-10 m sea level above present
  b. Model: CESM climate model coupled to CISM ice sheet dynamic model
  c. Simulation: GIS thickness
    i. LIG 127 ka orbital forcing; 2000 CISM yrs, 155 CESM yrs
    ii. Overall SMB >0: strong snowfall precipitation signal
    iii. Ice sheet area: ~96% modern
    iv. SLE=0.6 meters
  d. Simulation to include long-term feedbacks: include boreal forests to Arctic Ocean
    i. Greater retreat in south-central western portion of ice sheet
    ii. SMB<0
    iii. SLE: 1.8 m
    iv. Ice sheet area: ~85% modern
    v. Thickness changes of ~200 m elevation by NEEM; ~0 at NGRIP
  e. Summary:
    i. Models—must simulate preindustrial well
    ii. Simulations of late Pleistocene

XXIII. Discussion Session:
  a. When do Arctic island channels open as a connection to the Arctic ocean?
    i. Unknown
  b. How do temperature simulations compare to model?
    i. NEEM—similar reconstructions with vegetation feedbacks (~6ºC)
    ii. Beginning to predict isotope signals
  c. Mechanisms for ice sheet disappearance in Fyke models?
    i. Dynamical model including feedbacks, but lacking ocean warming control and detailed representation of subglacial hydrology
  d. Initial shape of ice sheet in Otto-Bleisner models?

        i. Present day, with present day temperature structure
e. Fyke models—thresholds driving spatial variability?
    i. Similar geometric evolution paths for runs that end up with the same result
    ii. Differences with CO2 vs. insolation
    iii. Consistency with paleo-records? Eemian scenarios
f. What about forest expansion is driving significant warming at NEEM in Otto-Bleisner model?
    i. Albedo, water vapor feedbacks, change with sea ice
g. Modelers—we know topography, we know that Jakobshavn is losing mass rapidly. How does adding deep fjords change models? What does it mean that models are doing a relatively good job when leaving out the current main mechanism for ice loss?
    i. Response related to the warming ocean
    ii. ~1/3 from ice dynamics currently
    iii. End-members for major ice sheet loss—ocean will not matter once not touching ice sheet
    iv. In absence of ocean forcing, general bias to create an ice sheet too big
    v. What is the role on long-time scales—are fast ice stream dynamics 'ice sheet weather'?
    vi. Distinction between land-based and marine-based ice sheet stability artificial; cannot disentangle processes from proxy data? Can suck ice out without margin retreating
    vii. Models do include ice sheet dynamics and ice streams
    viii. Distribution of frozen vs. thawed parts of ice sheets, bedrock vs. sed basins, not necessarily well known
    ix. Can look at present ice—rapidly changing regions do have marine-terminating glaciers; thermodynamic vs. rate question
    x. Ice dynamic stability—flotation
h. Models can be built at any resolution (nested grid, high res)—how to move towards typical model? What do we need to do to resolve known topography?
    i. Without topography, area around Jakobshavn always retreat; rate may be incorrect but history is consistent
    ii. Depends on additional physics (calving laws), need <1 km
    iii. Limited resolution of such long term models
    iv. Model vs. paleo-data uncertainty?
    v. Topography is important, but would it change an Eemian simulation? Forcing and mass balance more important; temp/precip of climate models more important uncertainty?
    vi. Models ignore topography in the same way
    vii. Depends on what you are trying to get at? Global relative sea level rise or local ice sheet changes? Can you run different resolution models in different places? What is the relevant timescale for policymakers?

1. i.e. sea level on a hundred year timescale: how to transfer understanding of Eemian, or Holocene, or last deglacial knowledge to be useful to policymakers
2. Different timescales as different natural experiments
3. Next hundred years: ice-ocean interaction
4. Eemian provides an end-member: determine max rates of change
5. Validate predictive models by testing them against the past scenario—but this is strongly dependent on accurate knowledge of forcing

i. Parameter space is nearly infinite but constraints are improving—there are many ways to look at what the system has done is the past. How to reconcile multiple constraints? Models to bring us to extent, timing

j. Most recent models have calculated temps at Summit ~2ºC warmer than present (lower than isotope results ~6ºC); invocation of regional warming to produce sea level rise of 2 m, if warmed by 6ºC 5 m sea level inc
   i. Otto-Bleisner models: small warming at NEEM and sea level rise
   ii. Periods warmer than Holocene only times to validate warmer times—critical for future projections
   iii. Is x m/ºC different at different temperatures? Is this a linear relationship?

k. Timescale question—do climate models suffer same issues as GIA models? If climate models work over the Eemian (long-timescale), will they work over the short time scale?
   i. More parameters than constraints
   ii. Models not tuned to Eemian; tuned to present—then, does it provide anything useful?
   iii. Uncertainty in data as well…concern with tuning to the data

l. With an optimal dataset at different timescales, what would that dataset be to verify models?
   i. Present models—2D, 3D models, more data than parameters; could use dataset given coverage
   ii. What is the relative importance of forcing and ice physics in models?

m. Consensus of community on most likely range of scenarios for the Eemian?
   i. Need targeted pieces of data to answer this question; what are the targets and how do we know these are the right pieces of data?
   ii. Sea level synthesis paper, 2015
   iii. Centers for sea level rise/cryosphere development

n. Holocene neoglacial ice—how much do we know about the large scale atmospheric circulation in the past?
   i. Nested atmospheric/cryospheric models
   ii. Networks of paleoclimate records

o. Coupled models—tell us how the ice sheet pushes back on the atmosphere; what constraints on models are useful? What questions do you want the model to answer?

p. Distribution of sea ice in the Arctic Ocean—beaches in N Greenland in the Holocene; totally open question in LIG; big question in Arctic energy balance

Tuesday September 12, 2017

I. **Sophie Nowicki**—Stability of the GrIS: Insights from model intercomparison projects
   a. PLISMIP: long term focus—ice sheet in equilibrium with climate
      i. mid-Pliocene warm period: 3.3-3.0 mya; similar to projected temp with higher CO_2 than preindustrial and sea level rise
      ii. Experimental framework: three experiments
         1. Ice-free: climatology from GCM Had_prism—model begins with no ice
         2. Plio_prism: GCM forcing calculated with initial ice sheet topography
         3. Climate model run with no ice at the beginning and without ice
         4. How much does simulation depend on climate and initial state of the ice sheet?
            a. With no ice sheets—temperature warmer in north central Greenland but colder in south; precipitation inc in south
         5. Model characteristics:
            a. Six models: four shallow ice, 2 combination shallow shelf/shallow ice
            b. SIA models: shear driven flow; ice sheet frozen to bed
            c. SSA: shallow shelf approximation; ice sheet flows over the ocean, buoyancy driven flow
            d. Transition zone: complex flow model
            e. None include calving, two do not include basal sliding
            f. Typical resolution 20 km grid cells
         6. What does ice sheet volume evolution look like?
            a. Begin with no ice
            b. Goal to get to equilibrium state
            c. All models behave similarly—ice sheet grows, in a few cases to equilibrium flat line, in some cases oscillating (movement between maximum and minimum based on ice sheet interactions with bedrock)
            d. Same climatology but different initial ice sheet: produce similar behavior
            e. Different climate for same initial ice sheet: produce different equilibrium ice sheets—forcing climatology is very important
         7. What does the ice sheet surface elevation look like?

    a. Pliocene GrIS is less sensitive to differences in ISM configurations and internal physical quantities, but is much more sensitive to changes in climate forcing
    b. Using regional proxies of terrestrial and ocean origin—can identify most likely configuration of Pliocene ice sheet
8. How much does climate model dependency affect the ice sheet?
    a. One model, forced by 15 GCM forcings
    b. 7 AGCM (atmospheric only—ocean fixed forcing), 8 AOGCM (ocean is free)
    c. Incorporation of ocean in model has a strong influence on climatological forcing
    d. What does the ice sheet look like given these various climate forcings?
        i. Produces range of ice sheets;
        ii. 2 with exact same volumes but different shapes
    e. Simulations are highly dependent on the forcing climatology used, and not so much on ISM
9. Projections for the end of the century?
    a. SeaRISE Sensitivity Experiments
    b. How to incorporate water to base of ice sheet?
    c. Two experiments:
        i. Sensitivity to atmosphere
        ii. Sensitivity to basal sliding
    d. Present day—initial states do matter; strong influence on volume
10. How should surface forcing be computed?
    a. How to explain response of ice sheet to atmosphere?
    b. Models (shallow ice and full stokes) give same trend based on use of same forcing
11. How should basal sliding be implemented?
    a. Least sensitive response is PSIM ice sheet model, nearly plastic sliding law
    b. Ice sheet physics does matter for SICOPOLIS
    c. Produces spread in models
    d. Despite spread, some consensus…consensus on regions of melt, regions of high basal sliding and mass loss
    e. Near linearity of combined forcings—fingerprint different responses from climate, ocean, and sliding; considered together, can add for first order approximation
12. Ice sheet models becoming more fancy, but many processes poorly known
    a. Resolution important
    b. Basal hydrology difficult
    c. Rheology

d. How to deal with feedbacks?

13. Equilibrium focus vs. transient focus:
    a. Length of run, spatial resolution, complexity, initial state, climatic drivers, bedrock feedbacks

b. Questions?
    i. After how many years do you get to stabilization?
        1. Stabilization ~200-500 years
        2. Depends on the process you are looking at: more instant response for basal sliding

II. **Matthew Morlighem**—Modeling the response of Northwest Greenland to enhanced ocean thermal forcing and subglacial discharge
    a. Aim: assess how vulnerable individual glaciers are in the northwest sector
    b. Location: Upernavik to Sverdrup
    c. Improved bed topography: Oceans Melting Greenland
    d. What controls ice movement? Ice front velocity
        i. Calving law: None reproduce observations
        ii. Melt rate: also tough to model, need to resolve ocean circulation within 1 m; develop parameterization—depends on depth, subglacial water flux, thermal forcing (thermal forcing at the fjord's mouth and effective depth)
        iii. Model run 50 years: most glaciers stable, some retreat
            1. Rate of retreat comparable to observations
            2. Multiply subglacial discharge by factor of 10 and increase forcing by 3 degrees: some glaciers are stable—ice front jumps from bump to bump, which may stabilize ice (important to capture topography)
            3. Can see ice volume in response to different forcings—response more sensitive to thermal forcing than subglacial discharge
    e. Conclusions:
        i. Bed topography controls extent of retreat
        ii. Most glaciers are currently sitting on a stabilizing sill
        iii. More sensitive to thermal forcing

III. **Ben Kiesling**—Climatic controls on the initiation and persistence of ice in Greenland during the Pleistocene
    a. Goal: come up with modeling framework to take points from
    b. Modern and preglacial model set ups to drive Pleistocene climate simulation; applied to REGCM3 with various climate forcings
    c. Use preglacial results to drive model: temp warmer and increase precipitation through northeast-central Greenland
    d. Simulation: 500,000-1 myr
    e. Idealized forcing to represent most salient feature of Pleistocene climate evolution over Greenland
    f. Produce schematic diagrams of burial and exposure, similar to produced by cosmogenic isotopes; hope to produce framework to examine sensitivity of ice sheet to different climate forcings, and infer past climate histories

g. Simulations with same climate forcings but different lapse rates
h. Overall questions:
    i. Relationship between GIS volume and benthic d18O: not 1:1?
    ii. What are possible volumes of grounded ice when GISP2 is ice-free?
    iii. Thinking about retreat and advance separately

IV. **Feng He**—Comparison of Transient Simulations of the Interglacial Climate Evolution over the GIS in a Coupled Global Climate Model
a. Climate forcing for TraCE-21K: orbital forcing, greenhouse gases, ice sheets, ocean heat transport; all boundary conditions prescribed
b. Transient simulation of the last 21,000 years: comparison of reconstructed and modeled temperatures, no scaling applied; produce Greenland and Antarctic stacks
c. Can look at seasonality, seasonality anomalies
d. Comparison of Eemian and Holocene—annual mean and summer
    i. Summer: Eemian 3º warmer

V. **Rachel Carr**—Dynamic response of Northern Greenland outlet glaciers to ice tongue loss and calving front retreat
a. Northern Greenland—currently not contributed much dynamic ice loss; 40% Greenland by area
    i. Many glaciers have floating ice tongues—what happens to inland ice as ice tongues are removed?
b. Humboldt Glacier: Trough with potential pinning point
    i. Modeling along transects with flow-line model
    ii. Changes in crevasse water depth and sea ice buttressing
    iii. Inclusion of remote sensed data
    iv. Doing good job at replicating Humboldt
    v. Need for detailed basal topography
c. Peterman Glacier:
    i. As terminus approaches grounding line, velocity increases after a certain point
d. What next?
    i. Hagen Brae—velocities responding to losses of ice tongue
    ii. ‘Steady-state’ glaciers of eastern Greenland at shorter timescales
e. Conclusions:
    i. Northern Greenland outlets relatively stable
    ii. Variable response to ice tongue loss
    iii. Order of magnitude difference in response to climate due to bedrock
    iv. Need detailed bed topography
    v. What does it mean for a glacier to be stable?

VI. **Alex Robel**—Beyond the Ice Sheet (In)stability Binary
a. Punch line: speed matters. Important role for understanding the physics of fundamental processes.
b. The problems:

i. The rate of unstable ice sheet collapse is sensitive to many factors: basal friction, sea level
ii. Crossing an instability threshold does not mean you will get immediate rapid collapse
iii. Assessing uncertainties and transient propagation is difficult because models have a million degrees of freedom

c. Results for simple models:
   i. Ice sheet volume as a function of ELA from the Weertman model: critical climate threshold; if run with linear rate of ELA, produce different rates of sea level rise
      1. Not a single instability—multiple instabilities associated with domes of GIS
      2. The rate and timing of deglaciation is strongly dependent on the rate of forcing and the geometry of surface melting in ice saddles
      3. The way in which the ice sheet goes unstable is important for sea level rise.
   ii. Takeaway points:
      1. Ice sheet stability is the beginning of challenge.
      2. Simulating unstable ice sheet evolution requires accurate processes, forcing speed and variability.
      3. Ensembles help. Parametric and stochastic forcing ensembles to understand uncertainties in processes and forcings.

VII. **Erich Osterberg**—GreenTrACS In Situ Surface Mass Balance Measurements from the Western Greenland Percolation Zone

a. Motivation: Regional mass balance reconstructions vary by 100% or more. Need snowfall and melt data from the field to calibrate models.
b. Can get data using accumulation radar data to calculate accumulation from top of ice sheet and compare to modeled accumulation
   i. See strong regional differences
   ii. MAR—regional underestimation by ~18%
   iii. RACMO does good job everywhere
   iv. Regional differences often opposite in sign in different locations
   v. Can't do on margins of ice sheet where there is melt; require traverses to collect radar data and short cores
      1. 2016 traverse DYE2 to Summit
      2. Reconstructions of melt layer thickness; significant increases in total ice layer thicknesses in cores 1-5 following the late 1990s
      3. What are the atmospheric drivers?
         a. High melt years associated with unusually strong blocking high and warm sea surface temperatures throughout the Atlantic (AMO)
         b. Enormous control of AMO and GBI on west/southwest Greenland summer temperatures

VIII. **Ian Joughin**—Greenland Ice Mapping Project: Measuring Rapid Ice Flow

a. 1985-2030 prediction in first IPCC: 0.8 mm/yr slr from Greenland
    i. Sheppard et al: 1992-2011 SLR 0.4 mm/yr Greenland
    ii. 2005-2010 slr 0.7 mm/yr Greenland
    iii. Pretty good estimate
b. Triggered vs. forced processes
    i. Transient triggering: retreat may continue after forcing
    ii. Sustained forcing: retreat stops with forcing
c. Jakobshavn Isbrae: floating ice tongue in 1990s, ~4000 m/yr; break-up of ice tongue in early 2000s, seasonal small floating tongue 2006-2008, rapid flow with small seasonal signal recently
    i. Position of calving front through time
    ii. Terminus position and bed topography—glacier out sitting in shallow water, with retreat into deeper water glacier goes faster; peak speeds in 2012 hitting deepest part of trough, slow summer speeds at second bed peak; slow down with basal friction as opposed to floating
d. Kangerdlugssuaq Glacier: terminus variations and variations in speed
e. Helheim Glacier
f. Link between climate and glacier retreat remains unclear.
    i. Likely causes:
        1. Warm ocean causing basal melting
        2. Atmosphere/ocean modulating mélange
        3. Warm atmosphere accelerating calving through hydrofracture
    ii. More observations are important
g. Greenland Ice Mapping Project to produce more observational data
    i. Velocity maps for outlet glaciers
    ii. Monthly Landsat, Sentinel Monthly, TerraSAR-X
    iii. Three month velocity with low error, higher temporal resolution products with more error (seasonal signals)
    iv. Sentinel data: 12 day; 1 a & b: 6 day products
    v. Winter and annual velocity mosaics, multi-year velocity mosaics, image mosaics, DEM, individual pair products

IX. **Mark Fahnestock**—Ice Flow and Ice Sheet Stability in Greenland
a. Ocean-ice interactions:
    i. Tidewater instability: thinning leads to faster flow and enhanced thinning
        1. Valley glacier: unstable retreat triggered by initial thinning
        2. Ice sheet: large reservoir behind; rapid acceleration-driven thinning propagates back into ice sheet, changes patterns of flow
    ii. Melt of ice front modulated by sub-glacial discharge: increased surface melt leads to higher discharge and increased melt at front
    iii. Atmosphere-ice feedback: surface melt leads to faster flow and surface lowering, leading to more melt
b. Tidewater retreat: glacier bay ice loss—100 km retreat and 2500 km3 of ice loss in ~100 years
    i. Mm/yr of uplift rate measured

ii. LeConte Glacier: southernmost tidewater glacier in northern hemisphere
    1. Melt rate dependence on subglacial discharge
    2. Large amount of heat from ocean moved towards glacier front—boundary layer problem: turbulent buoyancy driven convection
iii. Greenland as a model with all of the physics included—monitor
    1. Almost all glaciers accelerating
    2. Front position change (observational) against glacier velocity change (up to 200%)
        a. Both speed up and slowing are occurring
        b. By 2016, 58% glaciers sped up by at least 20%, 12% slowed by at least 20% (much due to ice piracy)
        c. If significant advance considered 1 km, no significant advance
        d. Stagnant glaciers if source ice is gone

c. Projected models: three IPCC scenarios produce similar results, but different rates of retreat without the ocean
d. Full ice thickness calving event—bring dirt to surface; high rates of basal melt would eliminate dirt and would not reach the surface
e. In Alaska, tidewater glaciers can't readvance without moving along a terminal moraine; in Greenland, sediment is not needed—different systems but do not understand why; tidewater glacier instability does not translate to ice sheets, but unclear why not.

X. Discussion Session:

a. Abrupt warming in Eemian?
    i. Model—only convection of Labrador Sea, Norwegian Sea convection not until later
    ii. End of Eemian
b. Is velocity change in outlet glaciers significant above noise?
    i. Look back at older data; Greenland fairly stable in older landsat data
    ii. As front retreats to a point, seasonality is better developed because increased sensitivity
    iii. Tidewater glaciers behave differently in different years based on climate year to year—highly responsive systems; also controlled by long-term response of ice sheet.
c. Given the topography and bathymetry, how detailed is this information?
    i. Historical photos: bathymetry where there used to be ice
    ii. Resolution ~300 m, seems to be appropriate for modeling retreat
    iii. Depends on resolution of ice sheet models additionally
    iv. Atmospheric and GCMs don't get AMO—anything with increased meltwater would shift further to AMO negative which should offset warming; climate models don't see cyclicity into 21st c., but expect to happen; potential hiatus is AMO shifts as projected (2030, 2040)
        1. Cannot apply geometric estimates to climate projections

2. Think about end of the 21st c.—shift back into positive AMO phase, combined with anthropogenic forcing

d. Latest high res observations for velocity changes in non-marine terminating glaciers?
    i. Area south of Jakobshavn—slowing down
    ii. Pulling signal out from longer timeseries
e. Large-scale: centurial timescales of circulation is a big step to reconcile, yet how do we take small scale varaibilities and make them work in larger models?
    i. Degrading model resolution and physics to determine difference from coarser models
    ii. How does the physics change the results, but must address specific question? Probe the models to ask what the relevant physics. What is going on, and what do we need to be aware of to figure out what is going on? Take is beyond how to degrade model.
    iii. Can a high resolution or low resolution model answer large-scale questions? Degrade a model to figure it out.
    iv. Importance of climate forcing and complicated physics
    v. Play with resolution—make results consistent
    vi. In the time period, do we capture the processes that really matter?
    vii. Useful—independent Pliocene precipitation record; models—largest factor for ice sheet where precipitation occurs
        1. Know more about Holocene than Pliocene (climate, margin positions); geologists have data from the Holocene, not the Pliocene. Is there progress to be made by modelers to understanding ice sheet physics using Holocene?
        2. Do not currently have fully coupled ice sheet-ocean-climate model
        3. Models back in time—where can we find good places to drill cores? Can we use data to inform us to find good sites? Amount of till?
        4. Pliocene records: Eirik drift, incomplete sequences but could probably find records to constrain things around the margin
        5. Holocene changes may be too small to resolve above model biases
        6. Coupled ice sheet-climate models: 7 currently doing first spin up simulations
        7. Use of paleo-data to improve ice sheet models: for what purpose are you doing the model?
            a. Holocene might be most relevant to timescale of the next hundred years
            b. Maybe should focus on reducing model biases to be less than Holocene change
            c. Make difference between Holocene more significant than difference between models

    d. Understand perturbation to initial condition
    e. Holocene changes small compared to Pliocene, but evidence from taxa—if we can't capture this is models, how can we use models to say anything about change soon?
    f. Precipitation records very important—especially in the accumulation zones at the margins
    g. Holocene—small, transient variations: must know the forcing: solar, volcanic, more than just orbital; getting at small changes—need to run large ensembles because of the transient nature
    h. If goal was to identify ice sheet extent position, would you prefer to work in the Holocene or Pliocene?
        i. Last interglacial—big enough response
        ii. Holocene—need to be cognizant of high resolution of outlet glaciers
        iii. Stage 11? Need to know factors such as sea ice, precipitation, vegetation
        iv. PMIP time periods—if you are going to choose a period to focus effort, pick one where there are a few well defined experiments
8. Is a 3-5º warming over a few thousand years a small forcing (Holocene)?
    a. Modelers need more data than one value; need temp and precip data from more locations
    b. Have more data from Holocene
    c. Response significantly smaller?
    d. Complicated by signal of coming out of glacial—far from steady-state
9. Can we take an ice margin position 8ka around Greenland—are atmospheric parameters compatible with shape?
    a. Can use ice sheet as part of information
    b. Is the right amount of ice from the Holocene present in todays ice sheet?
    c. Ask the ice sheet to tell us something about the climate system
    d. A piece of information as much as something to be reproduced
10. Not about picking the right time period, but of picking timescale to model relevant processes (next several hundred years)
    a. Change funding directive to 1000 yr timescale?
    b. If we know things about the Holocene and certain times, are we getting processes right in the models?

        c. Can paleo-data test models at various times to determine if models are capturing processes correctly.
        d. We know more about retreat phase than advance phase from geologic records: different timescales and different amounts of warming
        e. Choosing point of time: compounding uncertainty in model climate forcing and response

XI. **Bea Csatho**—Ice dynamics and geology in Greenland
  a. Ice dynamics, ice ocean interaction, solid earth processes (isostatic adjustment)
    i. Focus on bed dynamics—complicated: internal structure, faults, inclusions
    ii. Altimetry data: IceSat2
      1. Ex. 1993-2016
      2. RACMO—surface processes; can subtract surface processes to leave changes due to ice dynamics
      3. Interpretation of dynamic thinning patterns: spatial variation
        a. Thinning timescale, magnitude, onset different around Greenland: patterns relatively simple
        b. Jakobshavn Isbrae: series of diffusion patterns
          i. Elevation mirror of surface temperature
          ii. Decadal/hundred year timescale correlation between temp and behavior=typical behavior
        c. Helheim
          i. Superimposition of simple behavior and surge-like behavior
          ii. Complex behavior which stabilizes Helheim
  b. Solid earth processes
    i. Geophysical/geodetic data
      1. Seismic networks, GNET (GPS), gravity and magnetics
      2. Ice penetrating radar
      3. Identify location of sediments beneath the ice sheet
      4. Characterize tectonic evolution (structures) and volcanism (Central Greenland magmatic province, Icelandic Hotspot Track)
        a. Rebounded subglacial topography: field magnetic and free-air gravity anomalies—compare to hotspot reconstruction: 3D numerical model of hotspot tracks

XII. **Meredith Nettles**—Seismic constraints on the crust and upper-mantle structure of Greenland
  a. Motivation:
    i. Rock rheology temp dependent, composition
    ii. Heat flux depends on dT/dz and correlates well with seismic wavespeeds
    iii. Seismic wavespeeds depend on temperature and composition

iv. Interpretation of paleo record and prediction of future ice/sea level depends on knowledge of local sea level variation (solid earth subsidence)
   1. Bermuda/Bahamas on peripheral bulge of GrIS
   2. Sensitivity of surface deformation to viscosity variations
   3. Observations close to where load is changing
v. Heat flux models for Greenland: poorly constrained
   1. Improved map—limited in spatial coverage
   2. Global seismic-tomography models: resolving wavelength ~size of Greenland

b. GLISN: Seismic network
   i. Short-period data from noise cross correlation
   ii. Earthquake observations to get deeper into the mantle—Icelandic Hotspot track, structural variations in craton

XIII. **Aurelien Mordret**—3D image of the Greenland lithosphere

a. Technique: ambient seismic noise tomography
   i. Can convert noisy surface waves into more coherent signal; velocity measurements match measurements from earthquakes
b. The model: Iceland hotspot track
   i. Crustal features=high velocity anomalies—magmatic intrusion?
   ii. Low velocity anomaly in the upper mantle—temperature anomaly?
   iii. Fits with southernmost geodynamic models of track
   iv. Temperature and viscosity modeling: velocity profiles converted into temperature and viscosity—can resolve heat flow, heat production, potential temp, grain size
      1. Maps of heat flux

XIV. **Richard Alley**—Ice-sheet/lithosphere interactions and Greenland ice-sheet stability—ways forward

a. Problem: Holocene ice didn't shrink much. But some point in the past deglaciation occurred.
b. Easier to deglaciate in the past?
   i. Ice sheet started on regolith, not on bedrock
   ii. Hypothesis: geological events left melted rock deep beneath Greenland, ice-age cycling brought melt to near surface
   iii. Center of hotspot under Greenland a long time ago—perhaps edges of hotspot still reaching Greenland but may have been under recently
      1. Left partial melt—Archean lithosphere, may not have gotten through
      2. Lithospheric stresses associated with ice ages similar to dike driving stresses in magmatic systems
      3. High stresses migrate over time and bring up melted material
c. Anomalous heat fluxes in NE Greenland: huge heat fluxes in something that should be an Archean craton
d. Dave Pollard's model: make bed more slippery, makes deglaciation easier

e. Hypothesis: Deep heat---ice age cycle brings melt up—GISP2 deglacation—Holocene
    i. How to test?
    ii. Geophysics, especially over head of NEGIS
    iii. Ar dating on volcanics

XV. **Sridhar Anandakrishnan**—NEGIS: Tectonic Setting and Ice Dynamics

a. NE Greenland Ice Stream: mysterious location and processes maintaining flow; high velocities, little topographic control, possible significant contribution to mass balance
    i. Seismic velocities: GLISN
        1. Shear wave velocities reflect temperature (high T resulting in low Vs)
        2. Seismic and radar survey: margins marked by distinct troughs
    ii. Basal properties
        1. Surface troughs lead to basal hydrologic funneling; bed is till/sediments, not bedrock
    iii. Surface properties
b. NEGIS future work: Need to understand mid-upper crustal velocities and structures, basal boundary conditions, bedrock and sediment

XVI. **Joe MacGregor**—Radiostratigraphy of the Greenland Ice Sheet and its potential constraints on millennial-scale ice-sheet stability

a. 1993-2017 survey of Greenland
b. Trace radargrams and date with ice cores; variety of spatial structures
c. Three perspectives:
    i. Layers will resolve everything: data available, contains information regarding the Eemian, spatial variability suggesting regionally varying ice-sheet response could be unraveled
    ii. Layers won't resolve anything: layers integrate ice sheet strain history (non-unique depths despite specific ages); deeper/older layers rarely straightforward to map; almost no layers traced to edge of the ice sheet; physical assumption to date layers (uniform vertical strain rate)
    iii. Layers will resolve some things: coherent glaciological signals exist; evidence for Eemian ice, but not in southern Greenland despite presence in ice cores; completed v1 of the layers—can improve

XVII. **Mary Albert**—Ice Drilling Program Office and Ice Drill Design and Operations

a. Vision: Enable discoveries about changes in climate and environment to inform policy
b. Mission: integrated planning for community
c. Science advisory board: three working groups
    i. Ice Core
    ii. Borehole Logging
    iii. Subglacial Access
d. Long range science plan: updated every year looking ten years out
    i. When/where will we drill?

ii. Planning matrix

e. Money balanced between field programs and technology development

i. IDPO-IDDO: goal to retrieve a 10 m rock core from under <700 m ice

XVIII. Drills

a. Winkie Drill System: small, depth of 120 m, 33.4 mm core; ~5000 lb system

b. ASIG: Man portable drilling rig; able to handle firn/ice to bedrock, requires cold bed; max depth 1500 m, 39 mm core; ~30,000 lbs; transportable via Twin Otter, helicopter

i. WAIS: 2 holes attempted, 5 m ice, 8 m bedrock

c. RAID: 3000 m max depth, ~300,000 lbs

XIX. **Joel Harper**—Acceleration of GrIS Sliding Motion in Response to Surface Meltwater Input

a. 2002: Zwally—correlation between ice speed and melt; process occurring in large scale

b. Debate as to importance: more melt promotes sliding? Are the physics of mountain glaciers transferable to ice sheets?

c. Controversy of if linkage likely to speed up?

d. Constraints:

i. Focus on land terminating parts of ice sheet; may not be trigger for massive calving

ii. Spatial patter of surface runoff different than Greenland melt anomaly

iii. How much meltwater is generated from heating processes? mms-a cm per year of basal melt, meters/yr at surface

e. Learned:

i. Water can penetrate to the bed; lakes can drive fracture processes; more to learn as to how crevasses might do this

ii. Moulin spacing: mapped in great detail, ~1 per 5 km2

iii. Water spreads out: old conceptual model—basal melt and steady state solution suggesting channelization; updated model results: channels melt back ~20 km, beyond that water spreads

iv. Drainage system is dynamic: bed water pressure undergoes seasonal changes, with big diurnal swings

v. Speed follows melt: summer seasons, diurnal cycles, rain events

vi. Motion by basal sliding: 700x700x700 m block on ridge with hard bed; all strain limited to bottom of ice; high winter sliding speeds

vii. Sliding impacts geometry: moving down the surface, slope drops across the ELA and driving stress drops, speed increases

f. More water=more sliding? How important is this for stability?

g. Goal of parameterization: meltwater to sliding speed to mass

i. Bed conditions unconstrained

ii. No prognostic sliding law

iii. How long does it take for the system to adjust? Long-timescale mechanism

iv. Challenging to project this linkage forward in time

XX. **Rick Forster**—Greenland firn aquifers: remote sensing, field measurements, and modeling

a. Firn aquifer: liquid aquifer saturating pore space in firn, situated at ice-firn transition; liquid water existing throughout the winter
b. Field area: Helheim drainage basin
    i. GPR to measure top of aquifer
    ii. Airborne radar from IceBridge to map top of firn aquifer system
    iii. Agreement between GPR and airborne radar
    iv. Undulations at top of aquifer: reflecting surface slopes
    v. Aquifer extent: 21,900 km^2
    vi. Data from 2010: how to look back further?
        1. Radar with longer wavelength to penetrate to bed
        2. Loss of bed returns implies presence of aquifer
        3. May use older radar data
    vii. Seismic data to measure aquifer thickness
    viii. Measurement of meltwater flow: direct observation through borehole
        1. Measurement of conductivity—salt tracer to monitor flow of fresh water
c. Modeling: 2D groundwater flow model, developed for permafrost by USGS
    i. 3 different recharge rates: increase recharge rate=inland propagation of aquifer

XXI. **Winnie Chu**—Using radar sounding to constrain temporal changes in subglacial hydrology across southern Greenland

a. Outlet glaciers behave different: some glaciers speed up earlier while some speed of later
    i. Is variability related to subglacial hydrology? How much water get to the bed? How much water reaches the ice sheet margin?
b. Approach: Two radar parameters as proxy for basal water
    i. Bed reflectivity—presence of basal water
    ii. Angular distribution—type of drainage system: diffusive vs. channelized
c. Next stage: tease out temporal information—repeated survey in NW Greenland, West Greenland, and North Greenland 1993-2017
    i. Temporal shift in water system linked to bed topography and material properties of bed
    ii. Estimate storage using a water routing model
    iii. Goal: extend through time, link spatial variability to paleo-proxies

XXII. **Christine Dow**—Greenland's slippery slope: examining subglacial hydrology development driven by high-elevation melt input variability

a. Synthetic system based on Helheim glacier
b. Model domain: BC flux, firn input, Moulin input; 2D
c. Two scenarios:
    i. High input rate diminishes over time='long ramp' scenario
        1. Longer input time causes channels and lower pressures downstream

        ii. Relatively rapid firn water change over time (7 mo intervals—not always summer melt seasons)
            1. Multiple periods of short-term high pressure; complex signal where pressure wave may move all the way to terminus; dependence on timing on water to surface
    d. Conclusion: are firn aquifers game changers?
        i. Depends on when/where aquifers are reaching the bed
        ii. All high elevation inputs cause higher pressure upstream
        iii. Spatial variability is important
        iv. Timing and location of input is important

XXIII. *Discussion Session:*
    a. Channel maps under Greenland: unrealistic vs. physically based for last two speakers
        i. Spatial variability likely based on surface slope
        ii. Would not expect penetration inward of the ELA
        iii. Motivation for radar maps: map boundary from distributed to channelized flow to determine upstream extent of channels
        iv. Compare drainage of eskers from LIS
            1. Lack good dating chronology for esker, not sure about how far channels go up
            2. Eskers cross ice margins—dateable
            3. Sediment presumably subglacial collected from surface, deposited in a pressurized system sub-glacially
            4. Transient signal at the end of deglaciation
            5. Eskers in Greenland? LIA only
    b. How do modelers see the future of including sub-glacial hydrology? How are we getting there?
        i. Model attempts to follow sub-glacial hydrology; disconnected but recognized as important; not often coupled
        ii. We now know things about sub-glacial hydrology and processes; jump between adding a little and a lot of water; where does access to the bed migrate in? especially when sweeping over frozen bed? Upstream limit of bed access may be most important thing to track, not necessarily just ELA
    c. What does the shape of the ice sheet surface tell us? Break in slope, but the slope also gets too low to support tunnels? Why huge ablation region, not present on the east coast (aquifers)? What can we learn about sliding from the ice sheet shape and the way surface melt gets to the bed?
        i. Ablation zone—ice sheet went away in Holocene; Sukkertoppen right downstream, dry with little accumulation; lack of marine outlets; wide because of sliding or accumulation shadow? All related
    d. Sitting on top of Iceland Hotspot, modulate but repeat hotspot melting; if source of deep melted rock, not replenished. Pulse would fade away over time because hotspot is no longer there

e. Geothermal flux important to include in modeling melt. Surprising borehole temp are not used—low in south and high in north. Most maps are opposite. Do know heat flux from boreholes.
    i. Understanding lithosphere useful for interpreting seismics
    ii. Sweden—map of heat flow from beta particles; max/min within distances of 10-20 km; unrealistic to assume one value all over Greenland
    iii. Higher heat flux=greater spatial variation
f. What is the horizontal resolution of seismics?
    i. 300 km minimum
    ii. Need more stations
    iii. Meredith Nettles—unpublished models. Where does resolution need to go? Headed in the right direction. Heat flux models incorrect because disagree with borehole temperatures.
g. Converting velocity to temp in crust is difficult. How can this be done accurately?
    i. In ocean basins, a simpler case: mostly thermal cooling signature, can use as a calibration.
    ii. West Antarctic simpler case because lack of craton.
    iii. Need additional data from multiple empirical methods—gravity, lab experiments, multiple empirical results; works well if seismic model well enough resolved. Need constraints from boreholes and ice loss at bed. Need to come at it for multiple directions because of uncertainties.

XXIV. *Synthesis: Break Out Sessions*

a. Group 1:
    i. Questions:
        1. Origin of the Greenland ice sheet?
            a. Sedimentary deposits
            b. Drilling in east Greenland—oldest ice on Greenland?
        2. Mid-Pleistocene transition: unclear how to study
            a. Nature of Greenland ice sheet evolution
        3. Eemian:
            a. Connections between Eemian and broader world: sea leve rise contribution from Greenland compared to Anaractica; two maxima may have been associated with response of two ice sheets
        4. Modern
    ii. How to study:
        1. Combination of modeling and data
        2. Ice cores/basal ice/stratigraphy
        3. Process-based studies
        4. Sediment cores—climate information
b. Group 2:
    i. When did the minimum extent of the Greenland ice sheet occur?
        1. All warm periods of past: interglacials, Pliocene, MIS11

        2. Extent and timing
        3. Spatial variation of measurements
        4. Rate of change
    ii. What are the scales of useful inputs to models?
        1. i.e. Basal slipping, surface mass balance
        2. Scaling depends on time period
    iii. What are the basal conditions and how have they changed through time?
        1. Where do sed/bedrock occur
        2. How has erosion changed
    iv. Looking beyond the ice sheet, what role do changing oceans, vegetation, and sea ice play? Compare to Antarctica
    v. Demands:
        1. Basal data
        2. More modelers, more computers
        3. Increased interdisciplinary research: sea ice, atmospheric scientists
c. Group 3:
    i. Extent of Eemian Greenland Ice?
        1. Generate pan-Greenland paleoclimate archive to drive ice sheet models to estimate extent
        2. Are there Eemian beach ridges?
        3. Given that knowledge, identify drilling targets for sub-ice bedrock.
    ii. Stability going forward in modern times?
        1. Need realism in terms of physical properties (e.g. calving)
        2. Are we at the point to start to do hind-casting? Compare models directly to datasets (GRACE)
d. Group 4:
    i. Hypothesis:
    ii. Experiments:
        1. More cores—basal ice, bedrock, back to GRIP, east
    iii. Modeling:
        1. Issues of coupling: coupling atmosphere, ocean, sea ice and ice sheet
        2. Role of resolution
        3. Sea ice history
        4. Better job on heat flux and possible time evolution
        5. History of regolith removal and affect on bed
e. Group 5:
    i. What happened in the Eemian?
        1. Where do models agree/disagree?
        2. Where would more constraints be useful?
        3. Use of IODP, sed cores to generate temperature and precipitation histories

            4. Identify places to drill to pin down history of retreat: drill traverse guided by modeling
        ii. Present times:
            1. Modern data for modern modeling and hindcasting

f. Group 6:
    i. GrIS is a system known to act abruptly. Potential for abrupt changes in ice volume. Most important parameters to understand past small ice volumes and how they got there: models to inform drilling to inform models.
        1. Recover basal ice, sediment, and rock
    ii. 'Kill mechanisms': how can you abruptly remove ice?
        1. Need to use geophysics to look at ice structures and deformation
        2. Understand past exposure from the bed, and what record is in the ice above

g. Group 7:
    i. Time scales of importance:
        1. Short-term (10^2)—human and natural forcings
            a. Max possible rates and integrated rates of mass loss?
            b. What's the state of the ice now? Surface elevation, uplift, surface melt, accumulation, ocean data, meteorologic
            c. Modeling—high resolution; identify data gaps; integrated model frameworks important (ocean, ice, atmosphere, GIA)
        2. Long-term (10^5-10^6)—long term response to natural forcings
            a. What's the size and volume history of the GrIS over deep time?
            b. Find and analyze old ice wherever it may be
            c. Deep records of climate: radiocarbon dead lakes
            d. Collaboration with ocean communities
            e. Better dating methods and access to them
            f. Modeling: ice in the right place at the right time? Where are areas of erosion and areas of stability; model temperature through glacial cycles and with ice streams

h. Discussion:
    i. Maintain breadth of research.
    ii. GISP2 bedrock: n=1; identify key experiments from models (i.e. BGRIP)
    iii. Strategies for drilling to bedrock:
        1. Drilling to the oldest ice—the divide, least erosion. Moving downstream introduces the problem of erosion. What is the best estimate of exposure time?
        2. Where can you predict that the ice has been frozen to the bed for the longest?
        3. Disentanglement of exposure, erosion, and burial histories: employ as many cosmogenic nuclides as possible—stable and

radioactive; can provide framework; depth profile to assess erosion

4. How to find the oldest ice?
    a. Find a hole where the ice is 'dead'
    b. Likely minimizes erosion
    c. Probably degree of mixing in deep ice
    d. Dating methods need to go with oldest ice, because probably not in stratigraphic order

iv. Framing questions: easier to identify negative answers with models. Where did the ice not survive?
    1. Identify areas where models do or do not agree—helps identify locations to collect data: ex. SE corner of Greenland (old ice or frequent deglaciation?), east Greenland highlands

v. Basal characteristics (bedrock, sed, heat fluxes) crucial constraints for models

vi. Logistical problems of drilling with more mobile drills:
    1. Transportation difficult
    2. Rapid access holes—ice chips; could scale up to a few per season (~20 rapid access cores in the time of one deep ice core)
    3. Ideal model constraint: linear array of holes (Ice Cube--similar project around the South Pole)
    4. Moulins are holes? But are not straight
        a. Little camera or sensors (Cryoegg)