Permafrost in a Warming Arctic
Processes and Remote Sensing Data Needs

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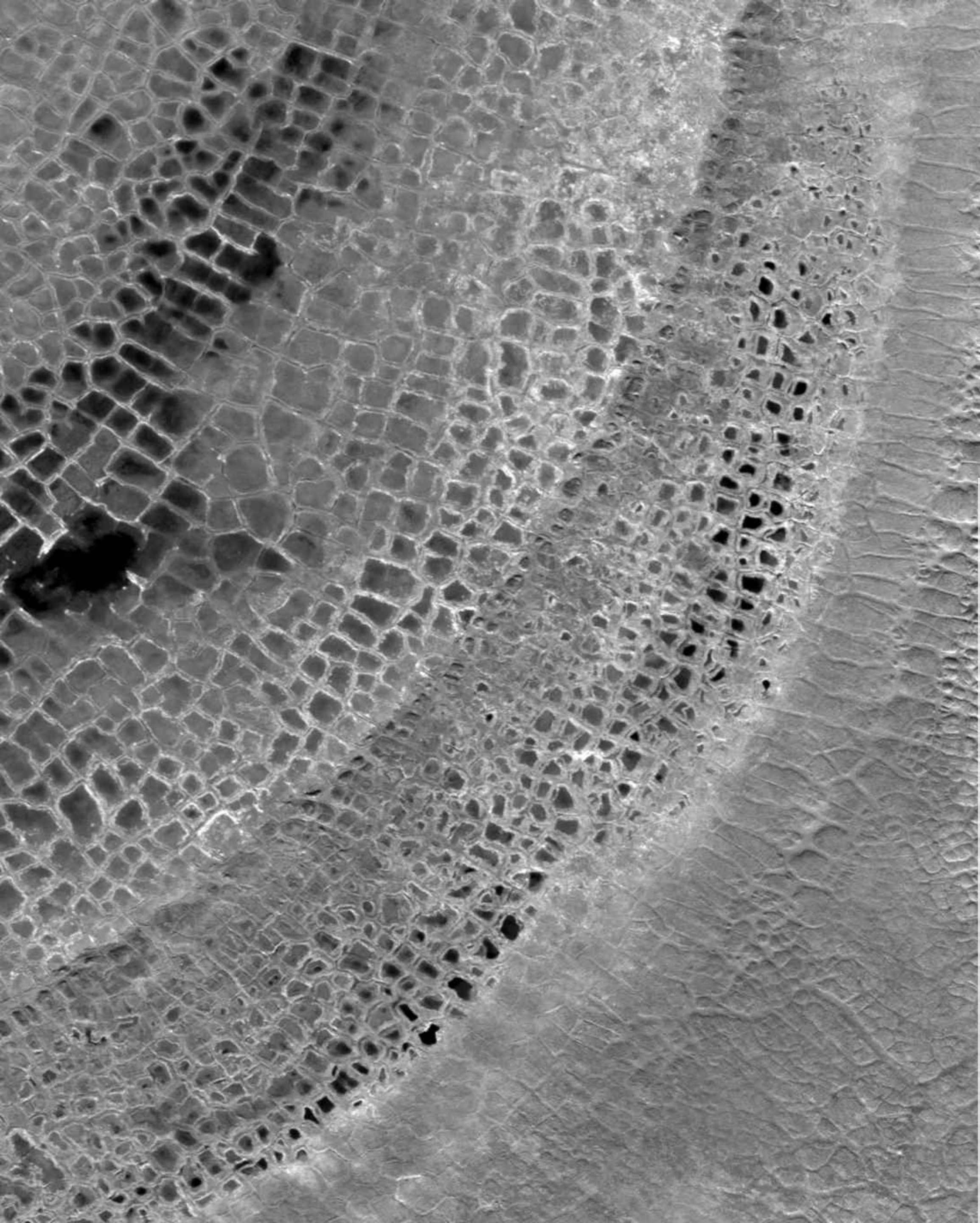
www.permafrostwatch.org



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Historic climate in the Arctic

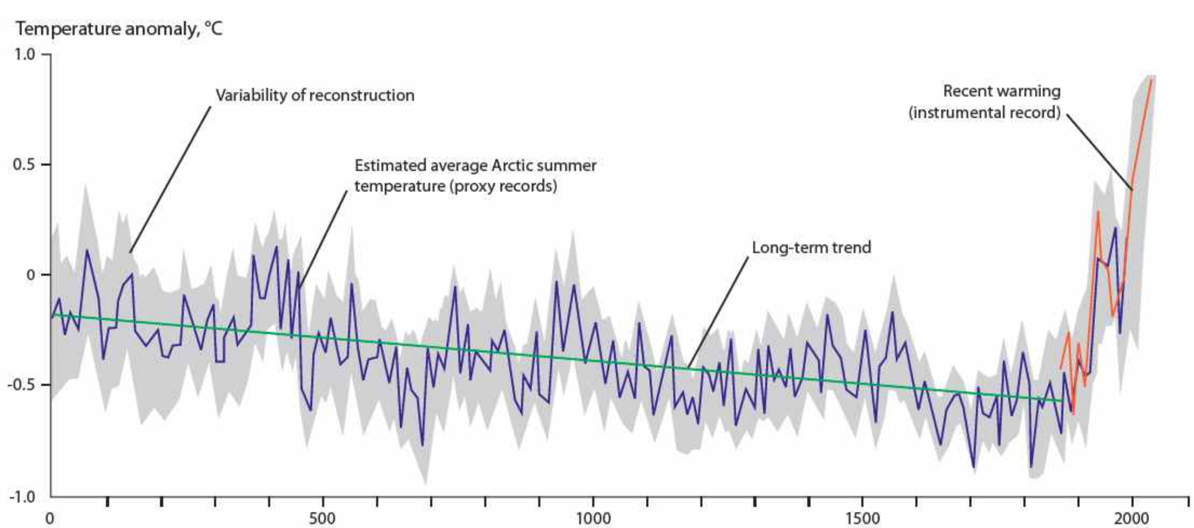
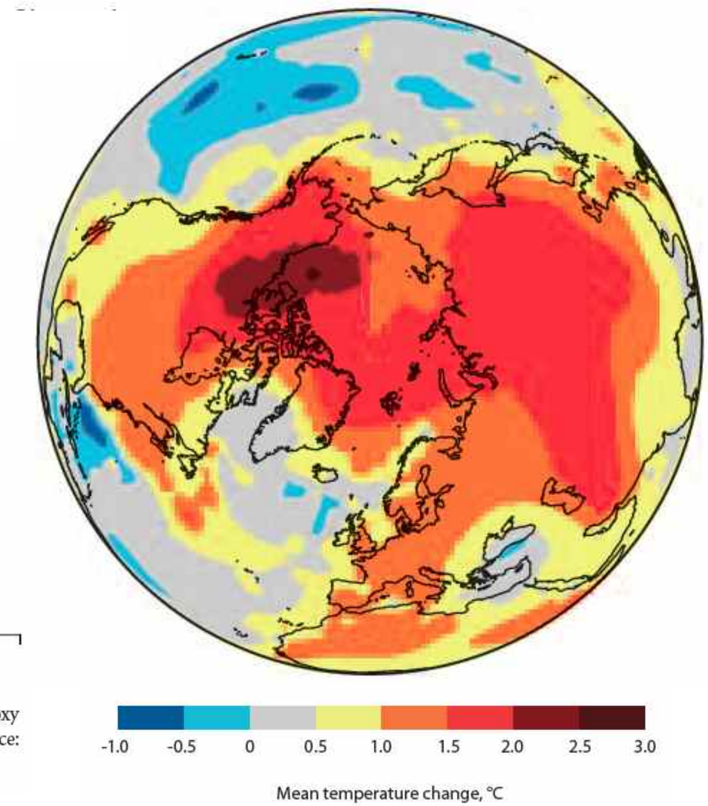


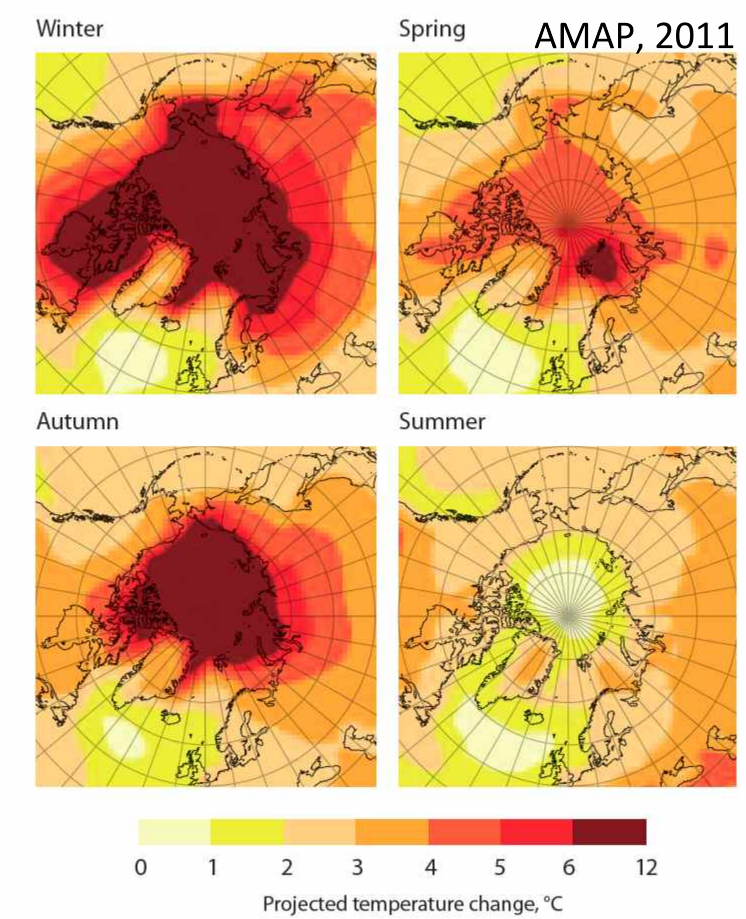
Figure 2.1. Estimated Arctic average summer air temperature anomalies for the past 2000 years (relative to the 1961 to 1990 mean), based on proxy records from lake sediments, ice cores, and tree rings. The shaded area represents variability among the 23 sites used for the reconstruction. Source: Kaufman et al. (2009), modified by UCAR (University for Atmospheric Research).



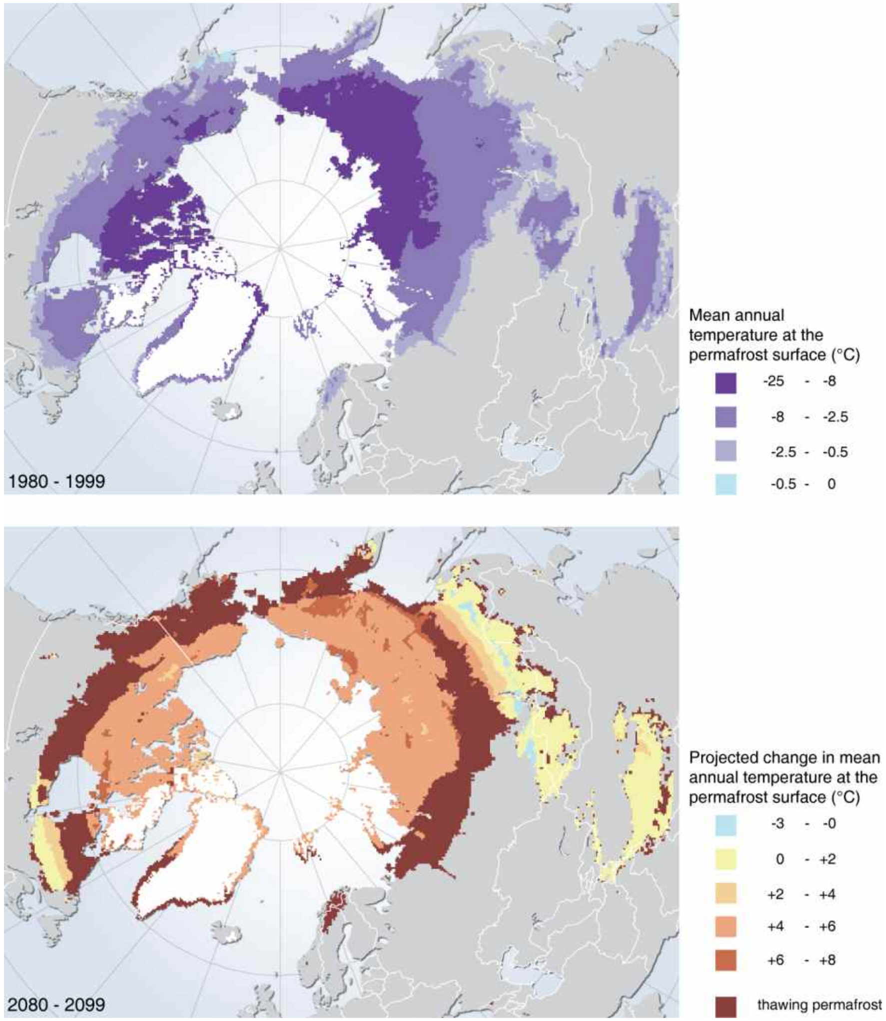
AMAP, 2011

Changes in annual mean temperature over the 50-year period, 1957 to 2006, as observed (NCEP/NCAR re-analysis).

Future Arctic climate and permafrost



Projected changes of seasonal mean surface air temperature for the period 2070 to 2090. Changes are composited over the CMIP3 models forced by the A1B emissions scenario. Fourteen model projections form the composite. Modified from Walsh et al. (2008).

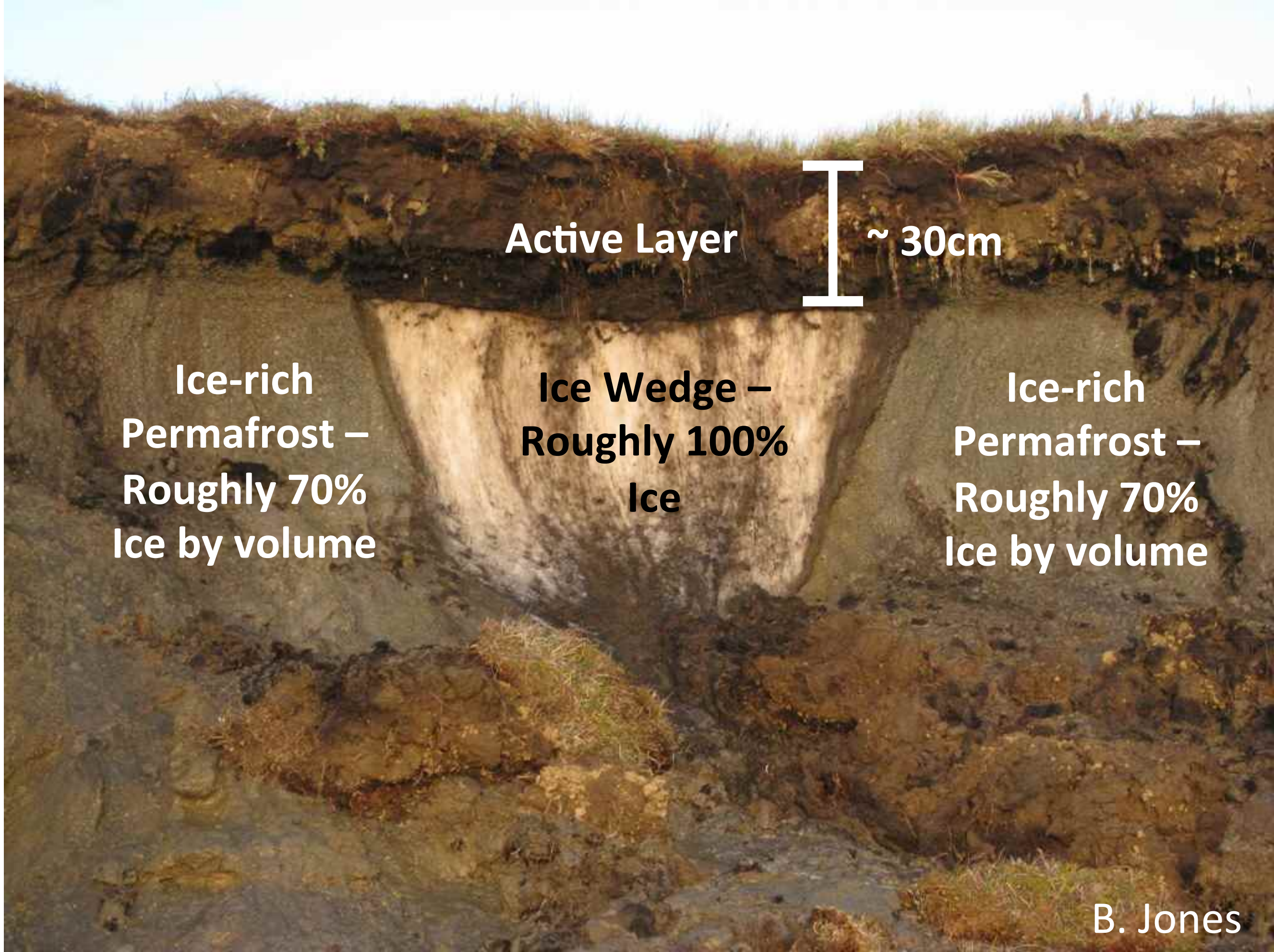


UNEP GRID Arendal, based on Romanovsky et al 2007

Permafrost

- Any ground that has temperatures of <0°C for at least 2 consecutive years.
- Permafrost regions cover 24 % of northern hemisphere land surface
- May consist of bedrock, peat, silt, sand, gravel, ground ice, etc., or a mixture

→ Permafrost does not melt (=liquefying), but it thaws (=warming above 0°C)



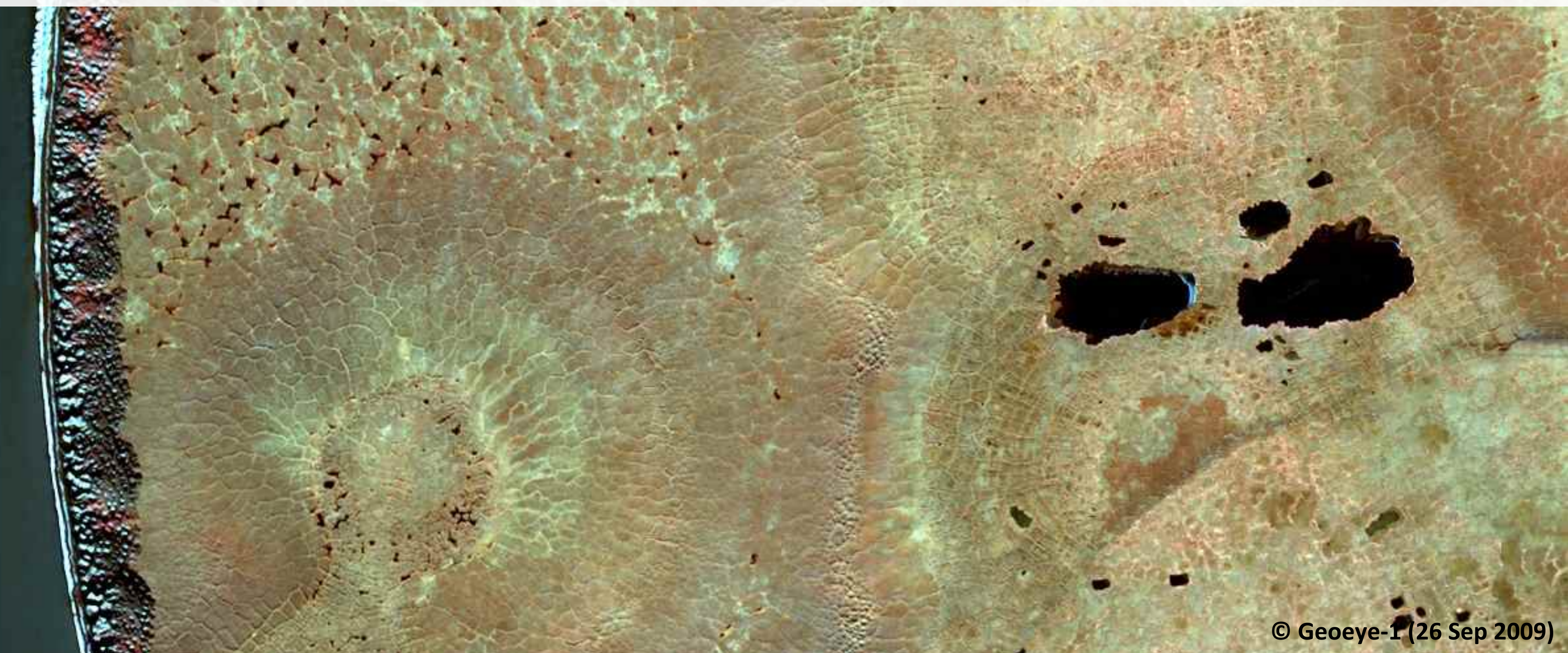
Impacts of Thawing Permafrost

Changes to ecosystems, hydrology, habitats, infrastructure + economic development, subsistence societies

→ Local to regional impacts

Changes to the northern carbon cycle

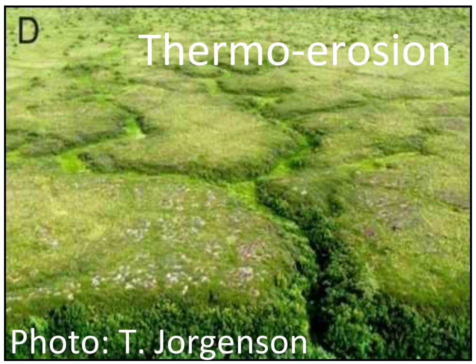
→ Global impact: feedbacks with atmospheric warming

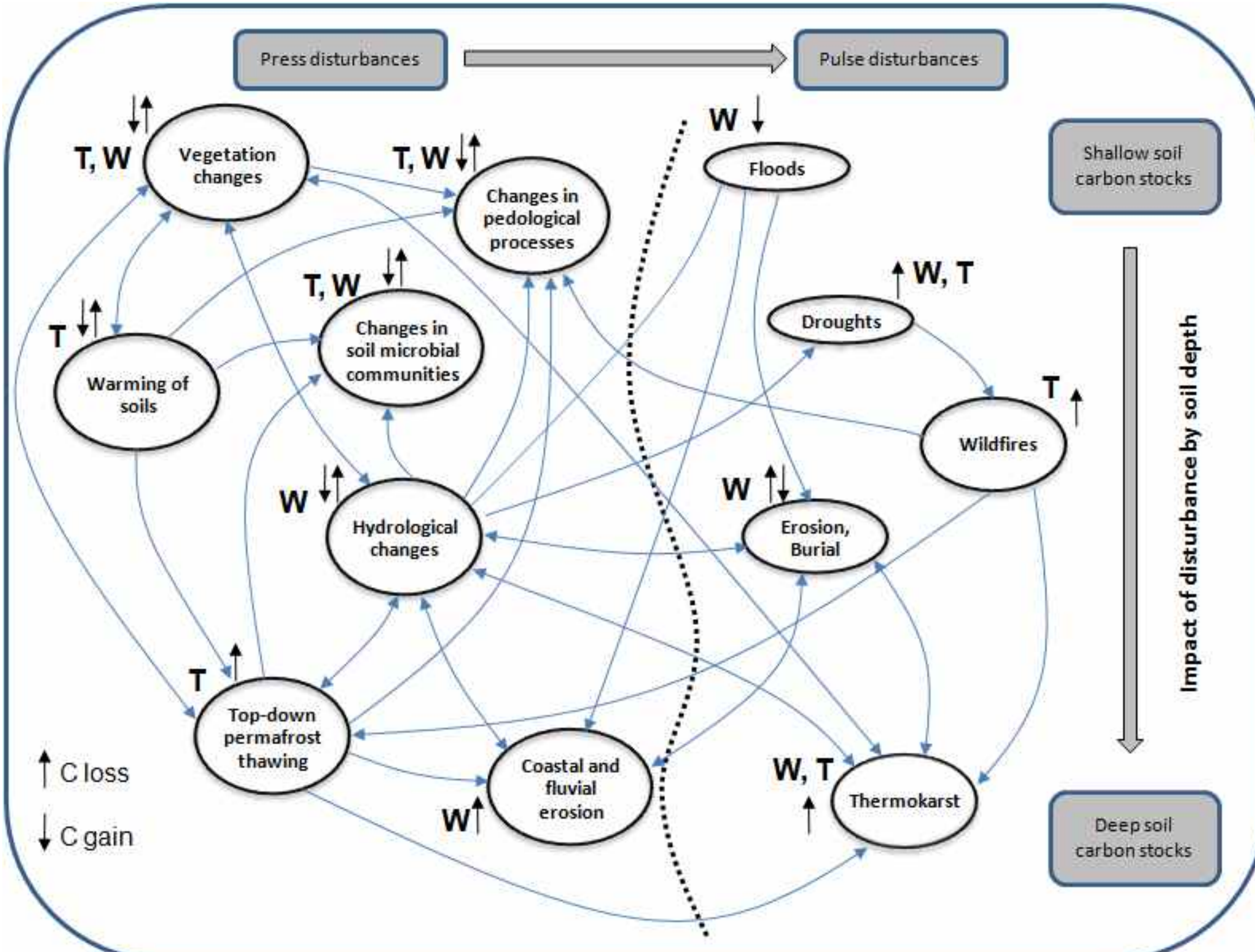


Challenges and Opportunities for (novel) Remote Sensing

- Unlike other components of the Cryosphere permafrost is a subsurface temperature phenomenon (<u>not necessarily connected to ice</u>) and not directly visible from space
- Permafrost distribution is specifically known from boreholes, but for large regions mostly inferred from surface features, geophsyical data, and models
- Many land surface features can indicate permafrost, but some can be ambiguous (i.e., vegetation type) especially in transitional regions and represent a relict state and not the present conditions
- Changes of permafrost in a warming Arctic may
  - progress gradually (top down thaw) or rapidly (thermokarst and erosion)
  - result in warming (cold permafrost) or thawing (warm permafrost) ground
  - manifest in surface expressions (ice-rich permafrost: lakes, basins, gullies, slumps, pingos, etc.) or no surface expression at all (ice-poor permafrost)
  - feed back with surface characteristics (vegetation, hydrology, soils, etc.) and near surface processes (active layer changes and hydrology, energy budget, soil carbon cycling, etc.), whereas feedbacks may occur immediately or with a long temporal lag
- Calibrated remote sensing data may cover large regions and allow extraction of physical information of the land surface and near-surface soils, which can be used to enhance permafrost modeling; high resolution data can observe disturbances

Disturbances impacting permafrost

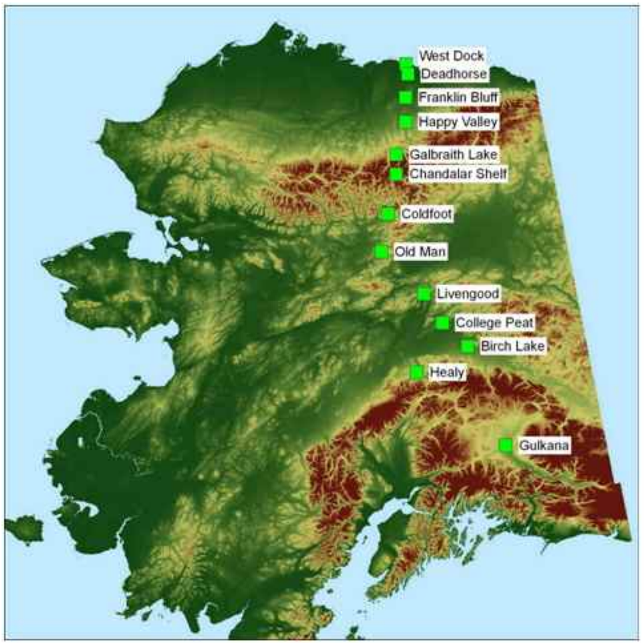


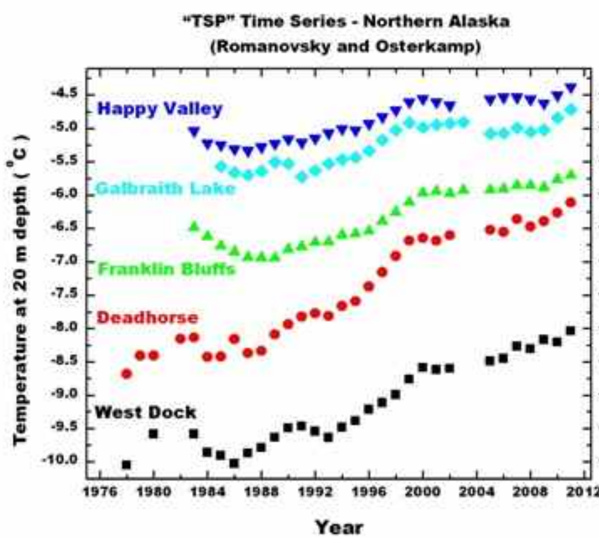


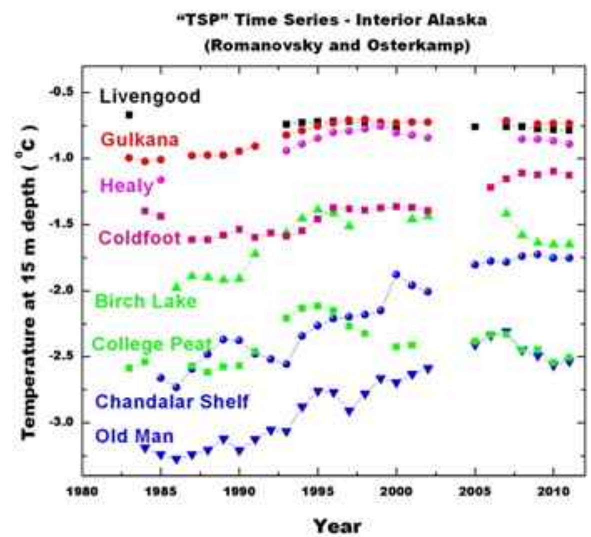
Grosse et al., 2011 (JGR)

Processes and Remote Sensing Needs

- Permafrost warming and thawing

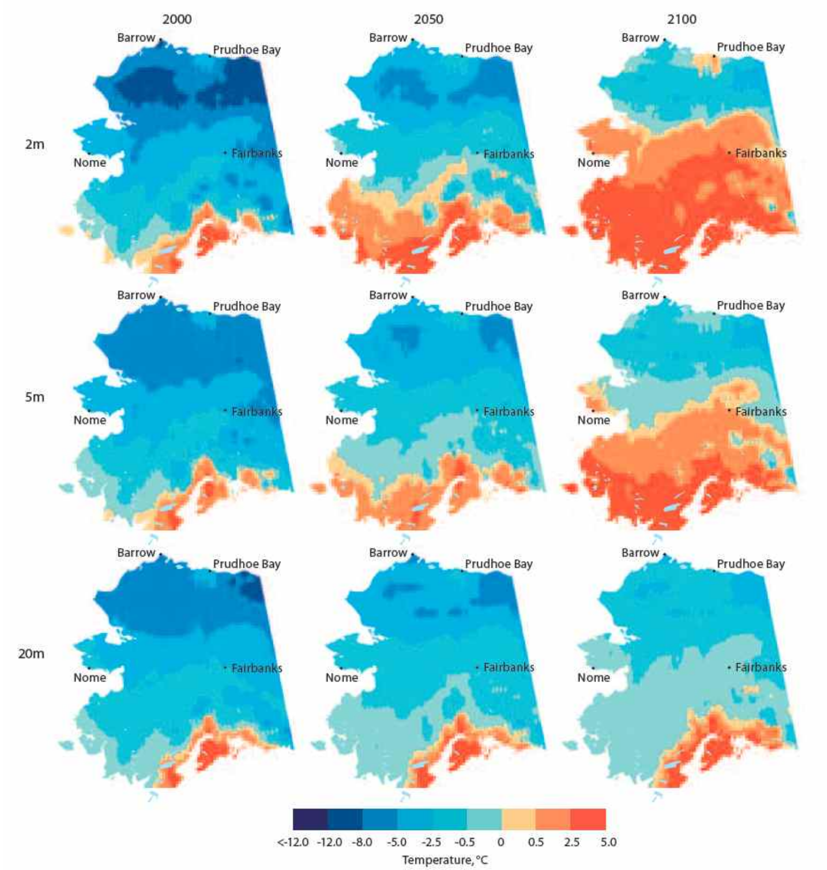






Romanovsky et al. (2011): NOAA Arctic Report Card – Permafrost.

Regional permafrost model projections: Alaska



Source: Marchenko et al. (2008) / AMAP, 2011

Projected mean annual ground temperature at 2 m, 5 m, and 20 m depths in 2000, 2050, and 2100 using the GIPL2 permafrost model with climate forcing from MIT-2D model output for the 21st century.

- Model resolution: 0.5° lat × 0.5° long
- Model period: 1900 to 2100
- Historic climate forcing: CRU2 dataset (Mitchell & Jones, 2005) for 1900 to 2000.
- Future climate scenario: MIT-2D integrated global system model developed at MIT (Sokolov & Stone, 1998), using a gradual doubling of atmospheric CO2 concentration that corresponds to the IPCC A1B emissions scenario.

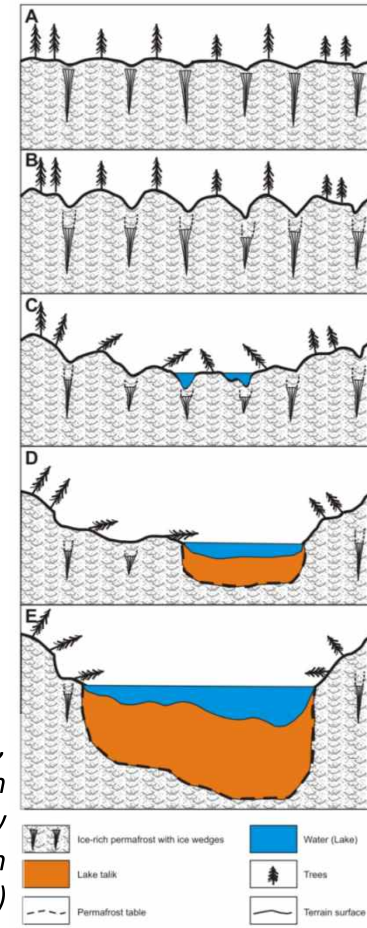
→All regions south of 66°N shift to >0°C at 2m depth by 2100, except high mountains
→Affects 850,000 km^2 (57% of Alaska)
→About 660,000 km^2 may shift to >0°C at 5m depth by 2100

Potential applications:
SMAP → Definition of soil parameters in permafrost models: Soil moisture, freeze-thaw state of the active layer, vegetation maps, organic layer thickness, active layer thickness?
ICESat-2 → Canopy height + density (proxy for snow distribution on ground?), subsidence?

Processes and Remote Sensing Needs

- Thermokarst

- Excess ice present in near surface permafrost (i.e. ice wedge ice)
- Thermal regime changed due to climate or disturbance and ice starts melting
- Strong positive heatflux from surface water into permafrost in any permafrost environment
- Feedback: substrate volume loss (ice:water = 1.0:0.9) → subsidence → can result in either wet thermokarst (TK ponds + lakes) or 'dry' thermokarst (Alas)
- <u>Soil moisture in thermokarst determines aerobic / anaerobic regime: CO_2 or CH_4</u>
- … de … ness threshold



Grosse et al., 2011, Treatise on Geomorphology (based on on Soloviev, 1962)

Potential applications:

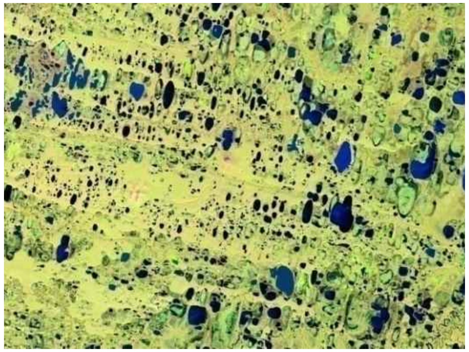
SMAP → Surface water fraction; soil moisture during thermokarst initiation, soil regime

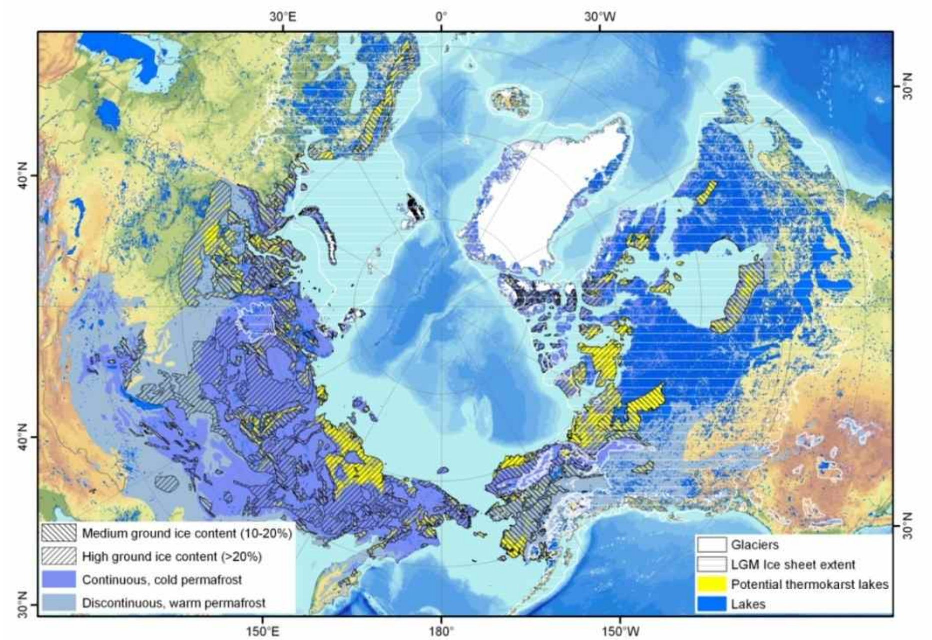
ICESat-2 → Subsidence (single most important parameter to detect permafrost thaw from space)

Processes and Remote Sensing Needs

- Thermokarst lakes

Total potential thermokarst lake area of 252,500-378,200 km^2





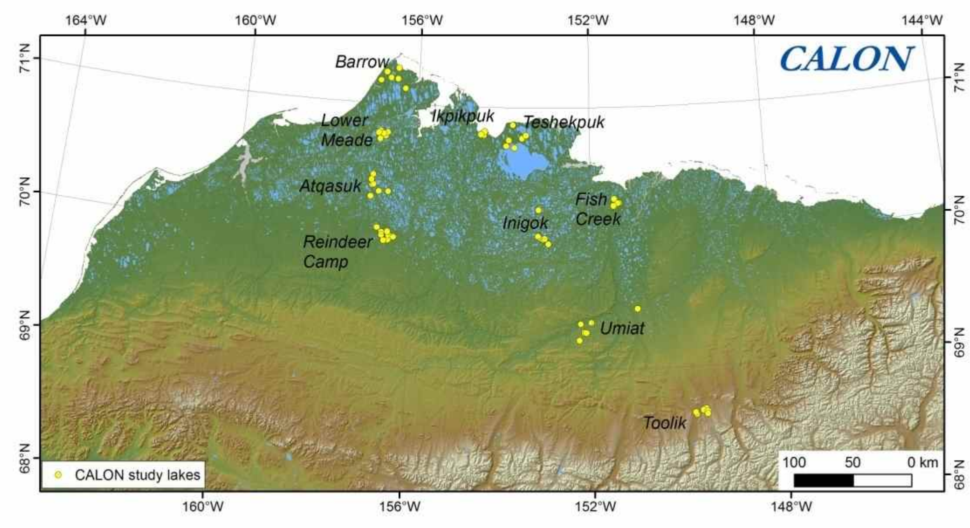
Grosse et al, in press (Elsevier Treatise on Geomorphology)

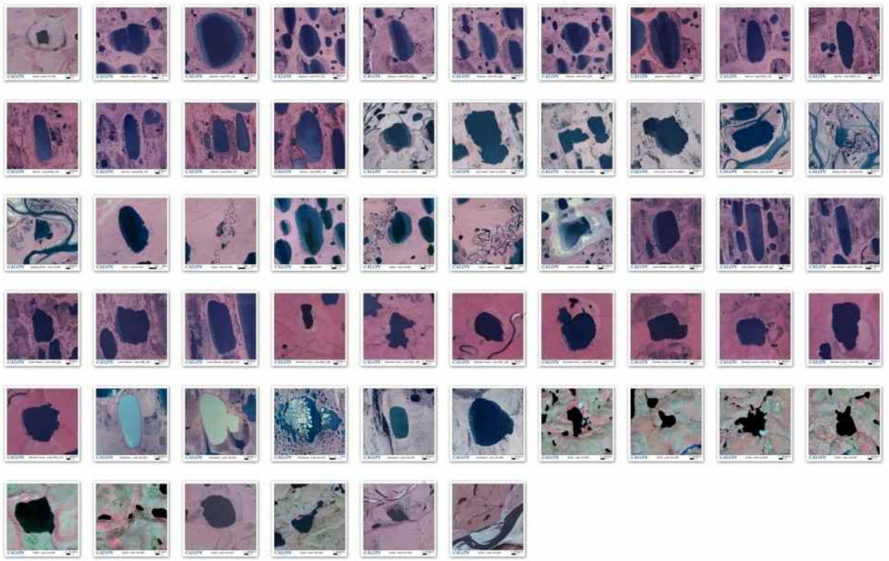
Ongoing projects:
NSF AON: Towards a Circum-Arctic Lake Observation Network (CALON)
Western Alaska LCC: Broad landscape-scale permafrost and lake dynamics in western Alaska

Potential applications:
SMAP → Seasonal surface water fraction; freeze-thaw; water balance of lake watersheds
ICESat-2 → Lake ice/water levels in winter/summer (→changes in lake water balance)

Towards a Circum-Arctic Lakes Observation Network (CALON)

- Currently, 56 lakes monitored on Alaska Arctic Coastal Plain and Arctic Foothills



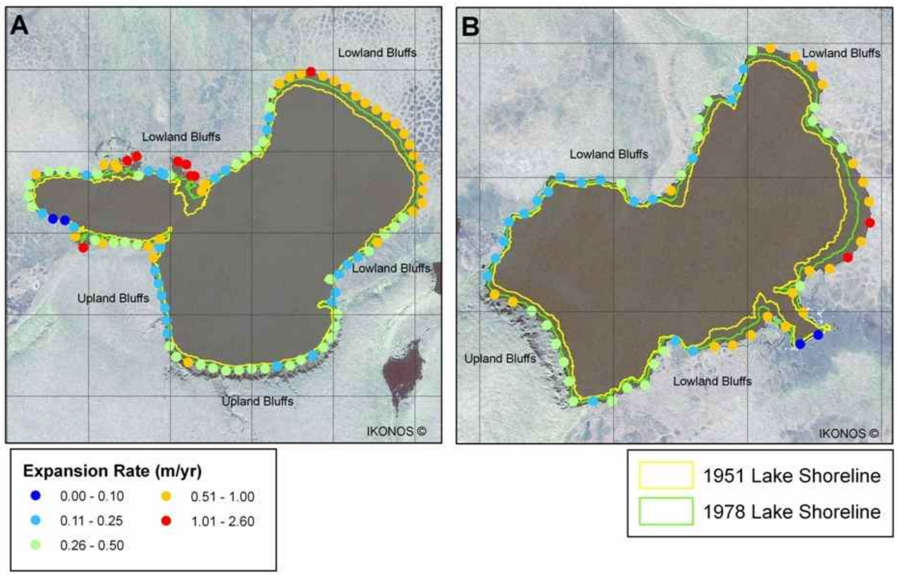


Monitoring Study Design

1. Two foothills to coastal plain transects with four monitoring nodes per transect. Six lake selected within each node (700 km^2) representing gradient in lake size and depth.
2. At each node, four lakes have basic monitoring systems and two have enhanced systems.
3. Basic monitoring lakes: water level, surface and bed temperature
4. Enhanced monitoring lakes: water level, surface and bed temperature (with redundant stations), sediment temperature, DO, SC, Chl-a, turbidity, pH, light penetration + lake surface met station
5. Synoptic surveys in April and August to measure water chemistry, snow-water equivalent, ice thickness, lake level and ice surface (DGPS), and service stations.

https://sites.google.com/a/giesn.com/nsf-

Thermokarst lake expansion and drainage



-Survey of **thermokarst lake dynamics** in ca. 700 km^2 of **typical ice-rich continuous permafrost** on Seward Peninsula, Alaska

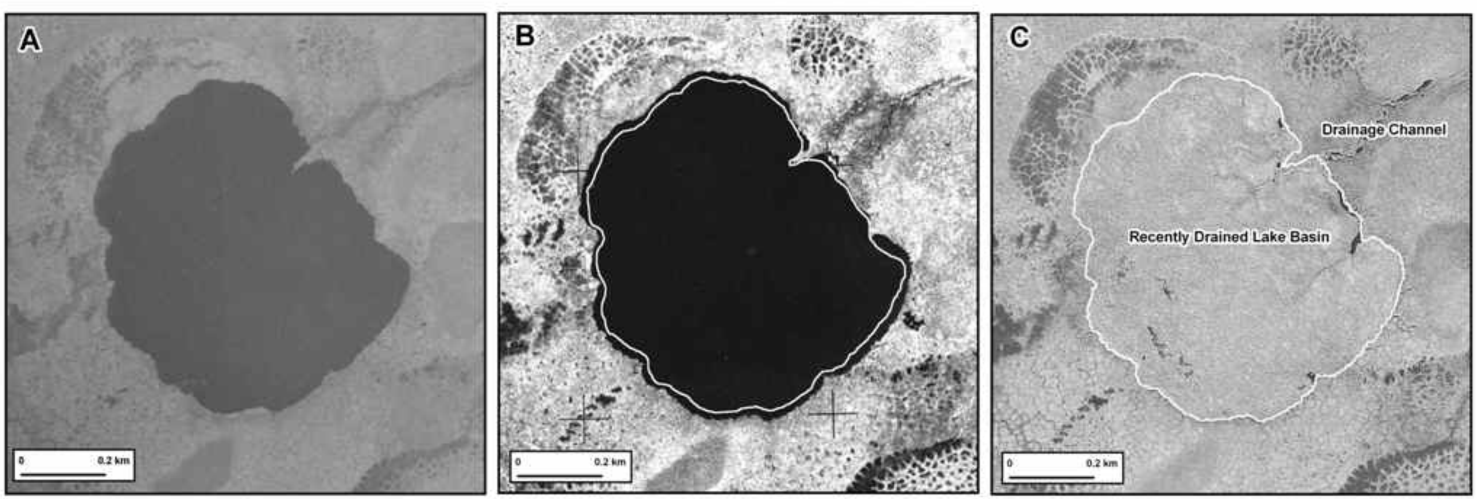
- based on high-resolution optical remote sensing time series 1950-2006

-**Average lake expansion rates of ca. 0.35m/yr** over 56-year observation period; **rate did not change significantly** during that period

-**Expansion resulted in lateral catastrophic drainage of many lakes**, i.e. for large lakes >40 ha

-**Net result is substantial lake area loss**

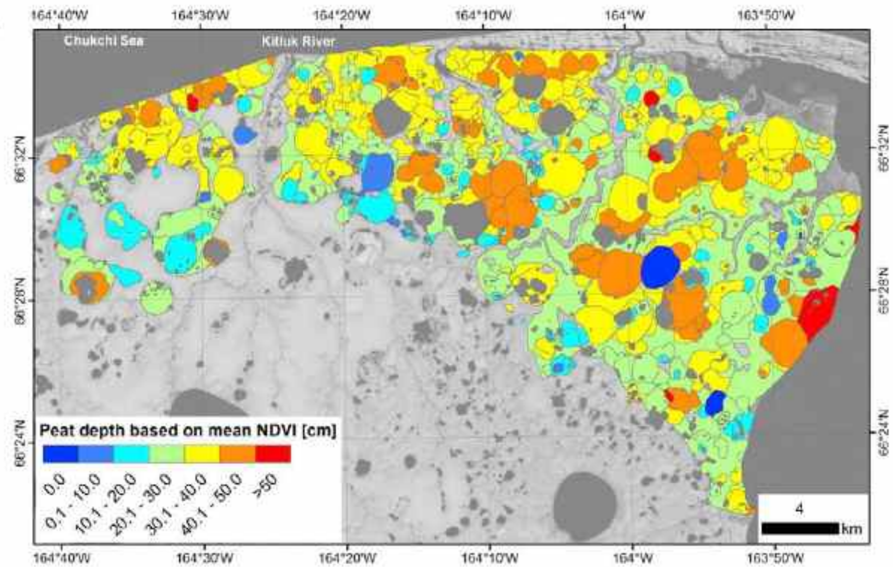
- Implication for Carbon Cycling: Reduction in lake CH4 emissions, sequestration of C in new peatlands, and emission of CH4 from new wetlands.



Jones et al. (2011), Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska, J. Geophys. Res., 116, G00M03, doi:10.1029/2011JG001666

Processes and Remote Sensing Needs

- Thermokarst lake drainage



Jones et al. (2012), Peat accumulation in drained thermokarst lake basins in continuous, ice-rich permafrost, northern Seward Peninsula, Alaska, J. Geophys. Res., 117, G00M07, doi:10.1029/2011JG001766.

Ongoing projects:

NASA Carbon Cycle Sciences: Thermokarst lake feedbacks to carbon cycling in North America

Western Alaska LCC: Broad landscape-scale permafrost and lake dynamics in western Alaska

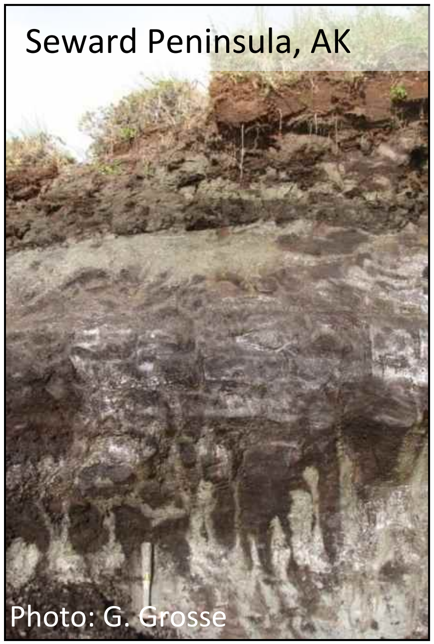
Potential applications:

SMAP → Wetness in drained lake basins (→ peat accumulation rates; habitat character); freeze-thaw

ICESat-2 → Water levels before / wetland elevation after drainage (→ lake volume)

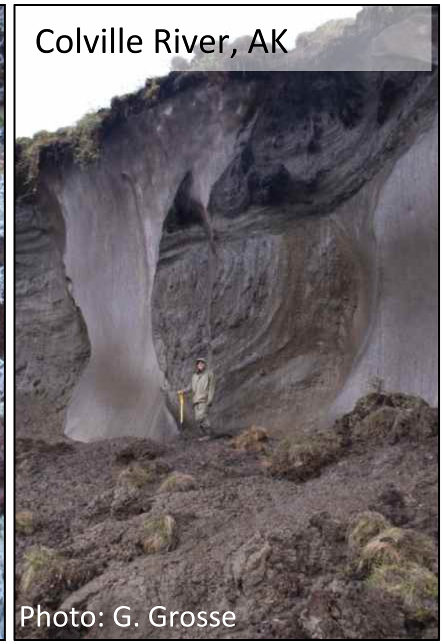
Processes and Remote Sensing Needs

- Soil carbon dynamics



Near-surface (0-3m) soil organic carbon in frozen mineral soils

Near-surface and deep soil organic carbon in frozen organic soils



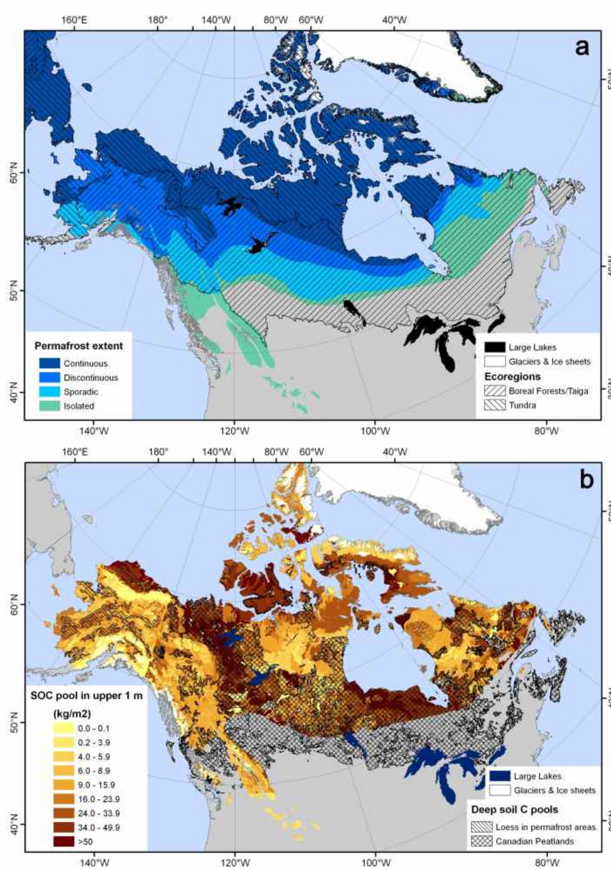
Organic carbon in thick syngenetic Yedoma deposits

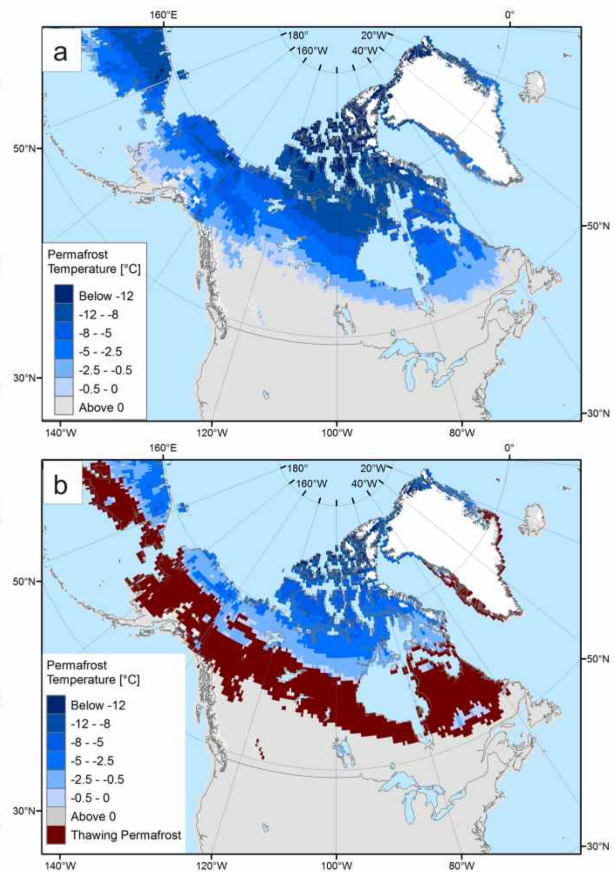
Organic matter (grass stems + roots) thawing on lake bluff

Soils in panarctic permafrost regions store 1672 Pg C
(Atmosphere = 750 Pg C)
(Terrestrial plants = 560 Pg C)
(Fossil fuels = 4130 Pg C)

Potential applications:
SMAP → Soil wetness; freeze-thaw state
ICESat-2 → ?

Vulnerability of high-latitude soil organic carbon in North America to disturbance





-**SOC mass** (0-3m depth) **in North American permafrost region: 387 Pg C**

-**High latitude SOC is highly vulnerable to press (gradual) and pulse (rapid) disturbances:** fire, top-down permafrost thaw, thermokarst, hydrologic changes

-**By 2100, North American regions containing 29 Pg C in upper 1 m of soil will be affected by thawing**; deeper thaw, though highly likely, is not included

Grosse et al. (2011), Vulnerability of high-latitude soil organic carbon in North America to disturbance, J. Geophys. Res., 116, G00K06, doi:10.1029/2010JG001507.

Summary - Research and Data Gaps

- Uncertainties in distribution and physical properties of permafrost (thermal state, ground ice content) and the active layer (thermal state, freeze/thaw state, thickness, water content)
  - Critical to expand and extend field observation programs Thermal State of Permafrost (TSP) and Circum-Arctic Active Layer Monitoring (CALM); Some active layer conditions could potentially be obtained/complemented with SMAP / ICESat-2 <u>remote sensing.</u>
- Thermokarst dynamics from initial subsidence to wetland to lake to drained basin
  - <u>Remotely sensed</u> soil moisture and freeze-thaw state along these transitions are important for understanding thermokarst processes, greenhouse gas feedbacks, and carbon sequestration
  - Thermokarst lake water and ice surface levels are an integration of watershed contributions (inflow, outflow), seasonal and multi-annual wheater conditions (P, E, snowmelt), and thermokarst processes (ground ice melt, subsidence, drainage); <u>ICESat-2</u> remote sensing of water /ice levels would allow better understanding of seasonal and long-term Arctic thermokarst lake dynamics; <u>SMAP</u> may be useful in better determining watershed contributions to lakes and overall fraction of surface water
- Uncertainties in soil organic carbon (SOC) dynamics and vulnerability
  - <u>SMAP</u> may be useful to enhance mapping of soil types and moisture conditions, and observe changes in freeze-thaw, all which are important parameters for SOC dynamics.
  - <u>SMAP</u> may also be useful to assess wetness conditions of drained lake basins and thus aid upscaling of peat accumulation rates and SOC pools.