Remote Sensing of Permafrost Landscape Dynamics

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Lena Delta, 2014
What is Permafrost?

- Ground that stays below 0°C for at least ≥ 2 consecutive years
- 22.8×10^6 km² (23%) of the northern hemisphere land mass

*Brown et al., 1997, IPA*
Typical Arctic tundra landscape with ice wedge polygons

Photo: B. Jones

Wetterich et al. 2014 (modified after Romanovskii, 1977)
Core questions

→ Which regions are impacted by thaw?
→ How fast is permafrost thawing?
→ What are the consequences of thaw?

Global carbon pools

<table>
<thead>
<tr>
<th>Pool</th>
<th>Carbon Pool (GtC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permafrost soils</td>
<td>1330-1580</td>
</tr>
<tr>
<td>Submarine permafrost</td>
<td>?</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>830</td>
</tr>
<tr>
<td>Vegetation</td>
<td>550</td>
</tr>
<tr>
<td>Fossil fuels</td>
<td>4,130</td>
</tr>
<tr>
<td>Global soils</td>
<td>2,300</td>
</tr>
<tr>
<td>Global ocean</td>
<td>38,000</td>
</tr>
</tbody>
</table>

Strauss et al. 2017 (Earth Science Reviews), Hugelius et al. 2014 (Biogeosciences), Walter Anthony et al. 2014 (Nature), Schuur et al. 2015 (Nature)
Key Research Areas in the Arctic

- Herschel Island, Yukon Coast, Canada
- AWI-PEV Station, Ny Ålesund, Svalbard
- Teshekpuk Lake Observatory, North Alaska
- Samoylov Station, Lena Delta, Siberia
**Permafrost variables vs. remote sensing**

**Challenge:** Permafrost is a subsurface temperature phenomenon

**We want to know**

1. Ground temperature
2. Thickness of the active layer (depth to the permafrost table)
3. Thickness of permafrost
4. Spatial patchiness of permafrost
5. Ice content and distribution in permafrost
6. Permafrost thaw and impacts

**Tasks for Remote Sensing:**

- Constraining the presence or absence of permafrost (spatial extent, ground-ice content + distribution)
- Quantifying geo/biophysical characteristics of ground and land surfaces (temperatures, water content, resistivity, vegetation + soil layers)
- Measurement of permafrost change-related dynamics (thaw subsidence + frost heave, erosion, biogeochemical fluxes, energy, water, and matter fluxes)
Very high resolution (VHR) satellite imagery

- Feature detection and mapping
- Stereo photogrammetry
- Change Detection
Thermokarst Lake Dynamics

Global Lake Distribution

- Lenz et al., 2016 (arctos)
- Grosse et al., 2013

Thermo-erosion at lake shore of Teshekpuk Lake, North Alaska

Photos: B. Jones, USGS

Thermo-erosion on lake shore of Peatball Lake, North Alaska

Lenz et al., 2016 (arctos)
Thermokarst Lake Change

- Land area lost was nearly equal to the area gained during the 1\textsuperscript{st} period.
- Land area gained was nearly three times higher due to lakes drainage in 2\textsuperscript{nd} period.
- Lake shore erosion = lake area gain.
- Lake drainage = wetland area gain.

Jones et al., 2011, JGR
**Thermokarst Lakes and Ponds**

TSX-backscatter: excellent for distinguishing floating and bedfast lake ice

Lena River Delta, Arctic Siberia

- bright – floating ice; dark – bedfast ice
- possible to observe spatial progression of ice grounding every 11 days
- different fraction of bedfast ice by the end of winter from year to year
- possible to extract the timing of ice grounding and to estimate the ice thickness from an ice growth model

*Antonova, Duguay, Kääb, Heim, Langer, Westermann, Boike 2016.*

*Monitoring Bedfast Ice and Ice Phenology in Lakes of the Lena River Delta Using TerraSAR-X Backscatter and Coherence Time Series. RS*
Analysis of temporally dense image time series

- Landsat-based time series analysis
  - Seasonal + multi-annual dynamics
  - Surface wetness, brightness, greenness trends; Disturbances (lake change, erosion)
  - Fully scalable: Panarctic mapping possible

Example: 63 Landsat tiles for Lena Delta from 1999-2014

Automated Batch Processing
Data Download
File Operations
Image stacking/redistribution
Atmospheric correction
Index calculation (Tass Cap, NDVI, NDWI, ...)
Subsetting
Trend analysis

Nitze & Grosse 2016, Remote Sensing of Environment
Landsat-Based Land Cover Trend Analysis

~2,700,000 km² @ 30m resolution
Landsat TM, ETM+, OLI
~25,000 Scenes Jul+Aug 1999-2014
~10 TB raw data, 0.6 TB products
Products: Trends + Slope Intercepts
NDVI, NDMI, NDWI, TCB, TCG, TCW

Nitze et al in prep.
Permafrost coasts erode with an annual average of 0.5 m/a.

Observed maximum rates of erosion are up to 50 m/a.

Lantuit et al. (2012)
Thermo-erosion of permafrost coasts

Ortho-image based quantification of coastal erosion in GIS

- Digital Shoreline Analysis System
- Also used for thermokarst lake change detection (Jones et al., 2012)

Günther et al., 2013: Biogeosciences
Coastal erosion and sediment, C+N loss

- Herschel Island, NW Canada
- Erosion rates increased by more than 50% compared to 1970-2000
- Annual release of sediment: 28.2 m³ m⁻¹, TOC: 590 kg m⁻¹ and N: 104 kg m⁻¹

Coastal erosion 2000-2011

Sediment loss 2000-2011

Obu et al. 2016 Polar Research
Impacts of Coastal Erosion

Permafrost coastal erosion surveys with annual repeat LiDAR at 24 sites on Yukon Coastal Plain, Canada

Retrogressive thaw slumps

*Photo: N. Couture*

*Obu et al., 2016 (Geomorphology)*
• Low-elevation ice-rich coasts erode uniformly by up to 20 m a\(^{-1}\).
• Mass wasting causes high erosion variability of high-elevation permafrost coasts.
• Intensive slumping can result in coastline progradation by up to 40 m a\(^{-1}\).
• Short-term coastline movements can impact erosion estimates from aerial imagery.

Obu et al., 2016 (Geomorphology)
Repeat LiDAR to detect post-fire thaw subsidence

Time series of commercial satellite imagery

- Indicates ice wedge degradation between the 4th and 7th years post-fire
- Would be very difficult to quantify this type of change using high-resolution commercial imagery

Jones et al 2015 (Scientific Reports)
Repeat LiDAR to detect post-fire thaw subsidence

Analysis conducted with the Geomorphic Change Detection Tool: http://gcd.joewheaton.org/

Jones et al 2015 (Scientific Reports)
Seasonal thaw subsidence from InSAR

- ERS-1/2 C-band SAR
- Seasonal subsidence in the Alaska Arctic coastal plain
- Continuous permafrost

Liu et al. 2010 (Journal of Geophysical Research)
Needs and Requirements

- **Free data access** (science), long + dense time series, high spatial resolution
- Polar orbiting, frequent revisits
- **VHR imagery** (<1m), stereo, pan, ms
  - Feature and disturbance detection, mapping, change detection, rapid thaw, coastal erosion
- **Moderate resolution** (<30m), ms
  - Frequent revisits (<1 week), VIS, NIR, SWIR; atmospherically corrected
  - Land Cover Change, Arctic-specific vegetation, water, snow, disturbances,
  - Temporal Trends
- **SAR**, different bands, polarisations
  - X-, C-, L-bands
  - Single, dual, quadpol
  - Vegetation, soil moisture, ice conditions (grounded, floating, gas bubble content)
- **Thermal**, high spatial (<1km) and temporal resolution (subdaily)
  - LST as permafrost model input, high accuracy T (<1K)
- **LiDAR, Arctic DEM, WorldDEM**, high resolution (<12m), panarctic coverage
  - Hydrological modelling (high vertical accuracy, cm - dm), feature detection and mapping
  - DSM differencing, quantification of thaw subsidence and erosion
- **InSAR**
  - Seasonal active layer elevation changes (1-10cm)
  - Multi-annual subsidence or heave (cm to m)
Sea Ice Radar Altimetry

Scientific Objective

- Arctic & Antarctic sea ice mass balance
- Retrieval sea-ice freeboard and thickness with satellite radar altimetry (ERS-1/2, Envisat, CryoSat-2, Sentinel-3A)

Activities and Contributions

- Full in-house processing chain for satellite radar altimeter data
- Core activity of Sea Ice Physics Section and AWI research framework
- Production of free and open sea-ice thickness climate data records
  - ESA Climate Change Initiative on Sea Ice, Phase 2 (SICCI-2)
  - Copernicus Climate Change Services (C3S) (feeds in CMEMS: Copernicus Marine Environment Monitoring Service)

User Need

- CryoSat-2 follow-on
  (Sentinel-3x: insufficient orbit inclination for Arctic sea ice)