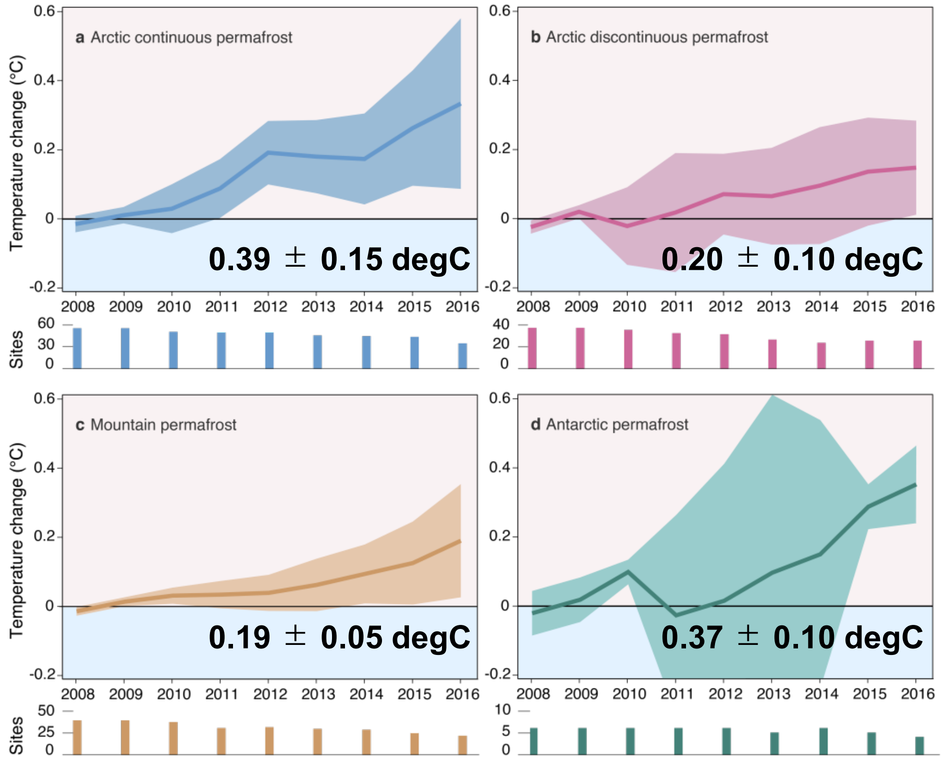
Progress and gaps regarding quantifying and monitoring permafrost thaw dynamics with multi-decadal optical timeseries data

Guido Grosse, Annett Bartsch, Julia Boike, Joerg Brauchle, Matthias Fuchs, Ben Jones, Mark Lara, Anna Liljedahl, Ingmar Nitze, Tabea Rettelbach, Alexandra Runge, Ken Tape, Mathias Ulrich

Lena Delta, 11.08.2014

Permafrost warming and thawing

Permafrost is warming globally

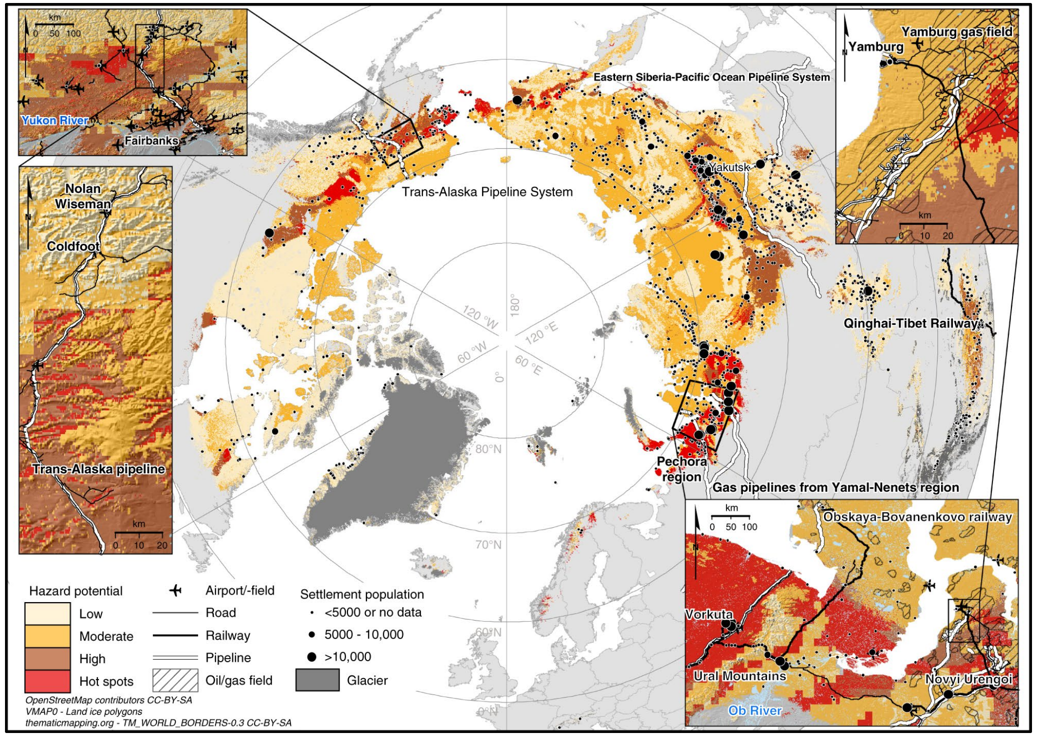


Observed Temperature change in permafrost of the high Arctic (continuous permafrost), Subarctic-Boreal (discontinuous permafrost), Antarctica, and High Mountain regions for 2007-2016:

→ Permafrost was warming globally with ~0.3 degC / decade

Biskaborn et al., 2019, *Nature Communications*

Risk map for 2050



~4 million people and 70% of current infrastructure in the permafrost domain are in areas with high potential for permafrost thaw

Hjort et al., 2018, Nature Communications

Rates of Thaw and Permafrost Carbon Feedbacks

COMMENT · 30 APRIL 2019

Permafrost collapse is accelerating carbon release

The sudden collapse of thawing soils in the Arctic might double the warming from greenhouse gases released from tundra, warn Merritt R. Turetsky and colleagues.

Merritt R. Turetsky, Benjamin W. Abbott, Miriam C. Jones, Katey Walter Anthony, David Olefeldt, Edward A. G. Schuur, Charles Koven, A. David McGuire, Guido Grosse, Peter Kuhry, Gustaf Hugelius, David M. Lawrence, Carolyn Gibson & A. Britta K. Sannel

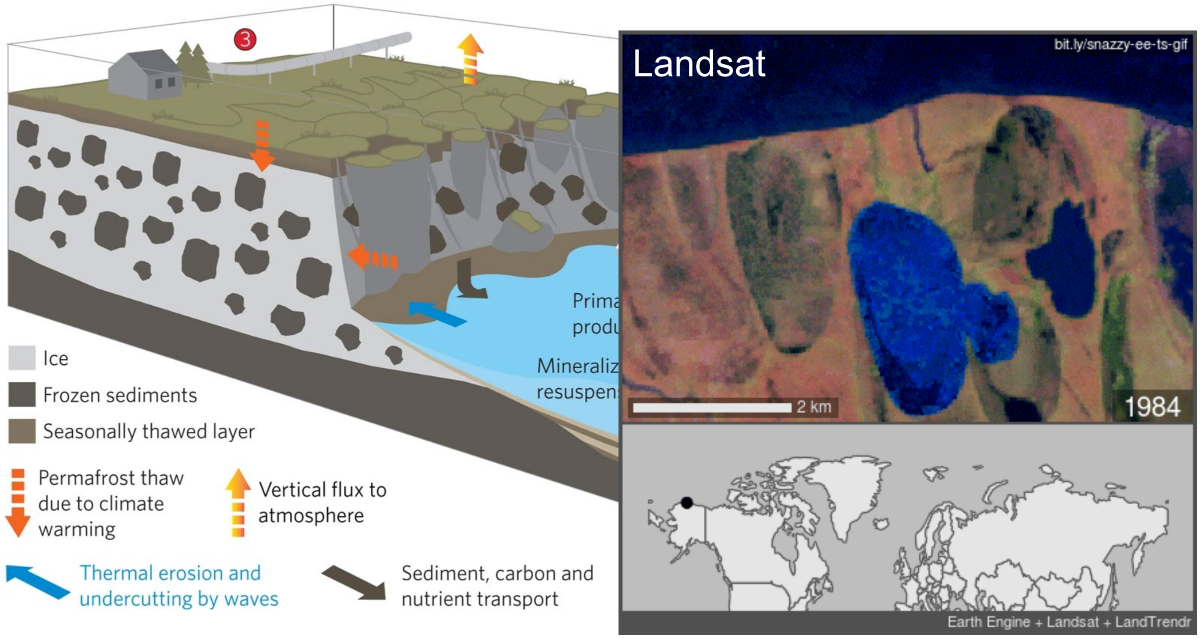
Turetsky et al 2019 (Nature)

Published: 04 January 2017

Collapsing Arctic coastlines

Michael Fritz, Jorien E. Vonk & Hugues Lantuit

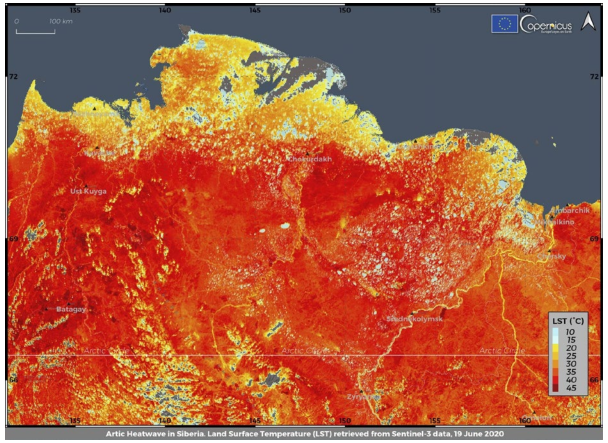
1. **Climatic and biogeochemical impact**
   - Vertical greenhouse gas release
   - Lateral relocation of sediment, carbon and nutrients
   - Sediment, carbon and nutrient burial
2. **Marine ecosystem impact**
   - Increased nutrient supply
   - Ocean acidification
   - Higher turbidity and decreased light transmission
3. **Socio-economic impact**
   - Infrastructure damage
   - Cultural heritage loss
   - Loss of fishing and hunting ground
   - Coastal community relocation



Fritz et al 2017 (Nature Climate Change)

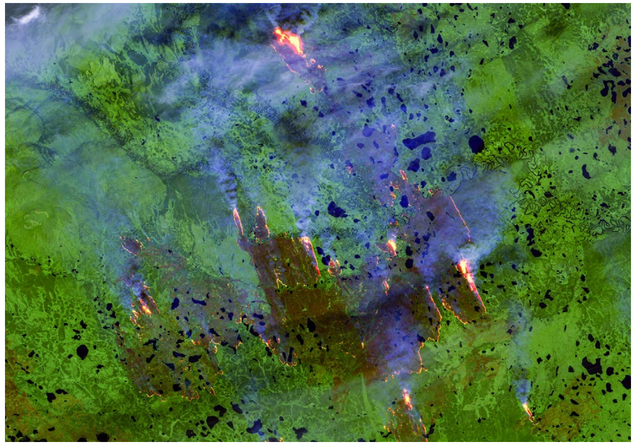
Challenges Ahead

Meanwhile in Siberia, 2020:



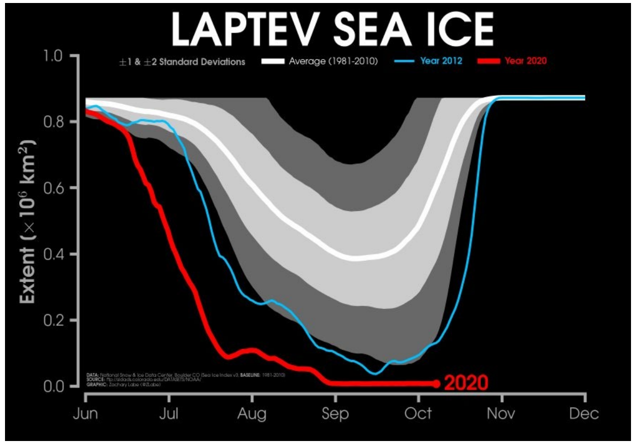
Massive heatwave over Siberia

LST of up to 45 degrees C north of the Arctic Circle on June 2020 (Source: ECMWF Copernicus Climate Change Service via AP)



Massive increase in wildfires

Tundra fires north of the Arctic circle in East Siberia, July 2020 (Source: Modified Sentinel-2 data by Pierre Markuse)



Sea ice loss + lacking recovery

Sea ice in the Laptev Sea, where much of the Arctic Ocean ice is usually formed (Source: Graph by Zack Labe, CSU Department of Atmospheric Science)

Crumbling industrial legacies

Thaw-damaged diesel tank, Norilsk power plant, causing the largest Arctic diesel spill so far (~22,000 t diesel) (Source: AFP)

- Can we still afford, under the current pace of change in Arctic land regions, to only work with snapshots of decadal or multi-annual resolution EO time series?
- Event (e.g., fire, heatwave, rain storm)-driven thaw slumping, coastal erosion, and lake drainages are just a few examples highlighting that we are often not dealing with gradual + linear permafrost thaw anymore
- Urgent need to bump up spatial and temporal resolution in EO

Recent Progress in EO with optical time series

(1) Temporally dense trends of multispectral medium-resolution Landsat/Sentinel-2 data

- Regional / panarctic scope for disturbance mapping with focus on permafrost thaw

(2) Enhanced VHR (0.3 – 3m) availability, temporally dense (annually to near-daily…)

- Coastal erosion, thaw lake dynamics, thaw slumping, ice wedge degradation

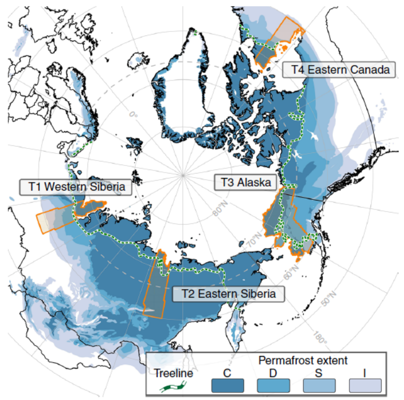
(3) New approaches in quantifying permafrost change with EO

- Machine learning, Deep Learning, AI
- New processing platforms providing extensive data product ecosystem (e.g., GEE)
- Apps featuring near-realtime EO data analysis

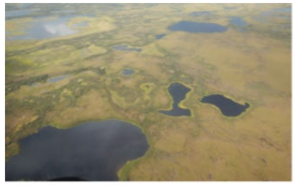
(4) Bridging the scales is key: Satellite EO continues to require field validation with airborne, drone, and/or ground data!

Temporally dense Landsat/Sentinel-2 trend data

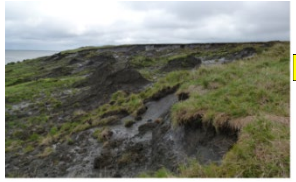
Disturbance trends in panarctic permafrost regions



- Focus on 4 continental transects: E + W Siberia, Alaska, Canada (~2 million km^2); 16 year period (1999 – 2014)
- Based on full Landsat-5/-7/-8 archive with 30 m resolution; processing in GEE and offline
- Multispectral indices (NDVI, NDMI, NDWI, Tasseled Cap, etc.) time series + trend product:
  - Visual Product – Tasseled Cap slopes
  - Trend Product – all indices, trend components
- First spatially consistent mapping of disturbances across large permafrost regions



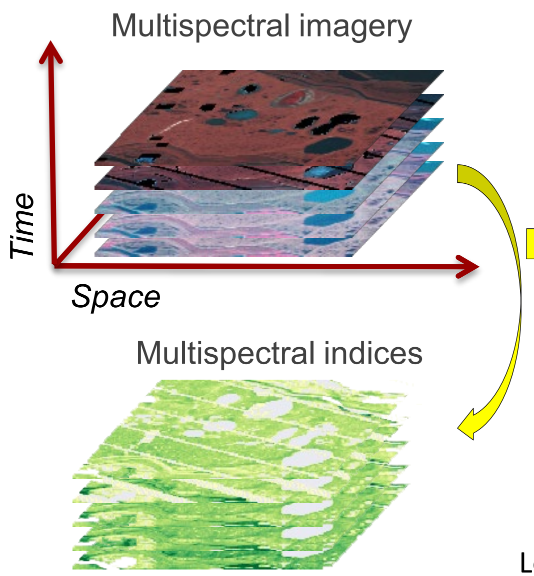
Thermokarst Lakes

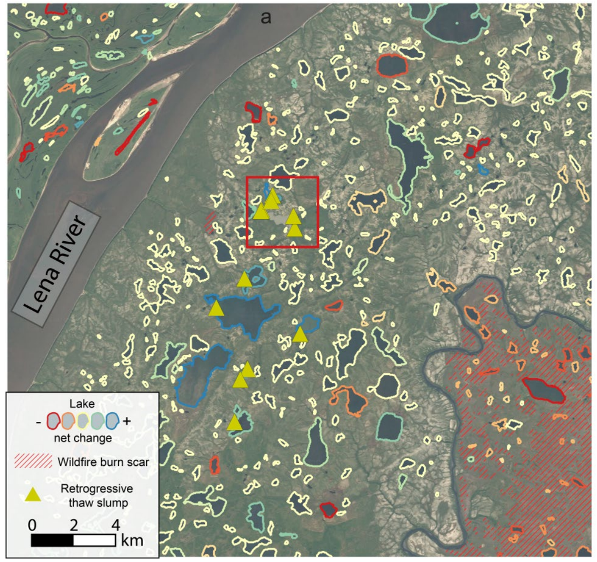


Thaw slumps

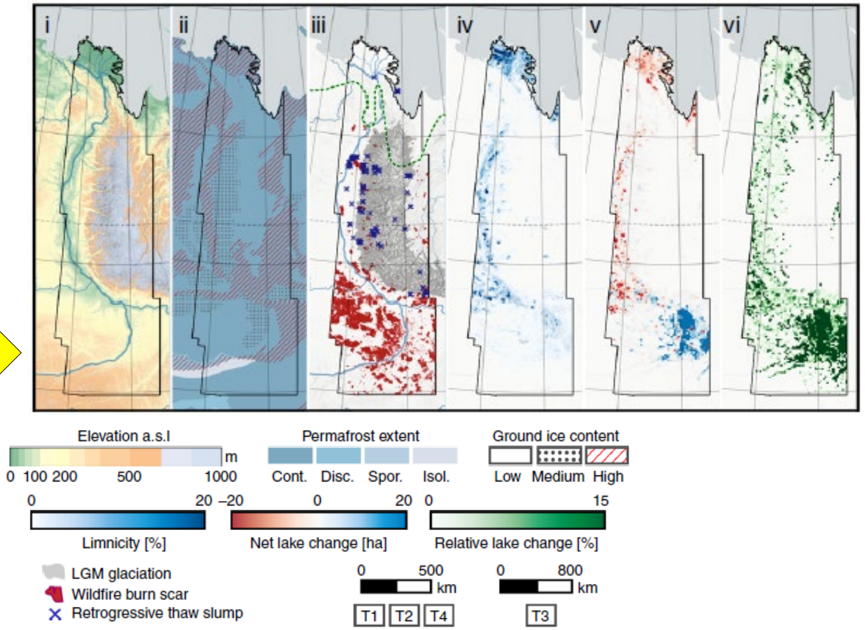
Fires

Multispectral Image Processing





Local example of lake changes, retrogressive thaw slumps and wildfire burn scars along the Lena River, NE Siberia.

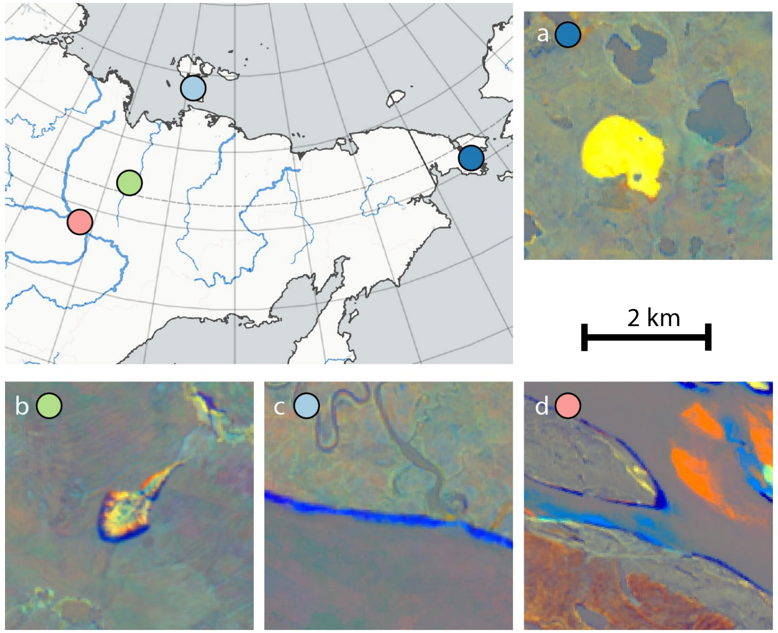


Nitze et al. 2018 (Nature Communications)

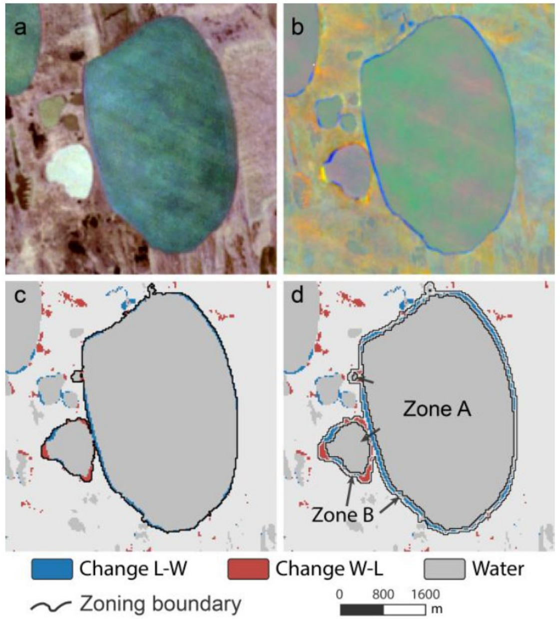
Data available at: https://apgc.awi.de/group/about/persys-hot

Temporally dense Landsat/Sentinel-2 trend data

Next steps: extension of time series to 20 years (2000 to 2019), ML-based disturbance feature extraction



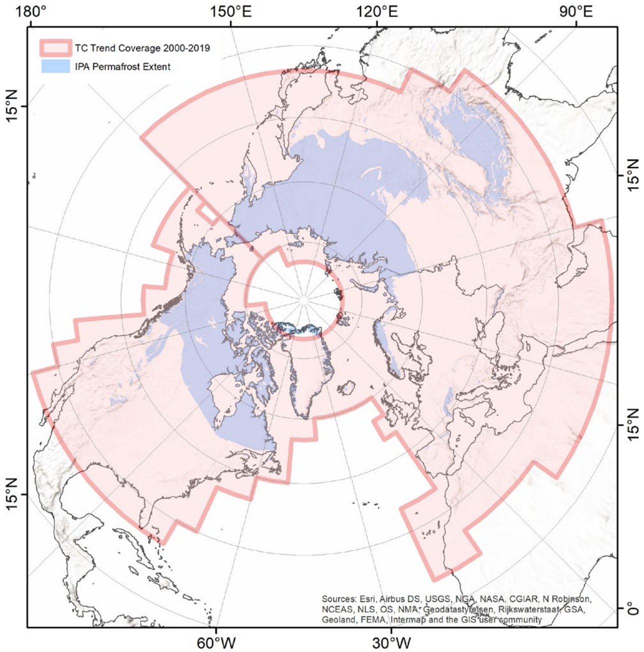
Examples of Tasseled Cap Trend visualization 2000-2019.
a) Lake drainage (~3 km²) on the Chukchi Peninsula.
b) Batagai megaslump with eroding headwall (blue) and revegtation on the slump floor (yellowish).
c) Coastal erosion (blue) at the south coast of Big Lyakhovsky Island.
d) Lena river island and sand bar dynamics with erosion (blue) and accumulation zones (orange), as well as fire impacted area on the southern land surface (brownish).



Machine learning-based extraction and classification of disturbance features (here: lake change)

(a) Raw Landsat satellite image (R-G-B);
(b) RGB-Visualization of Tasseled Cap Index Trends with R: Brightness, G: Greenness and B: Wetness;
(c) Classified trend data and lake object delineation;
(d) Subdivision into stable (A) and dynamic (B) lake zones

Nitze et al. 2017 (Remote Sensing)



Full permafrost region coverage in progress

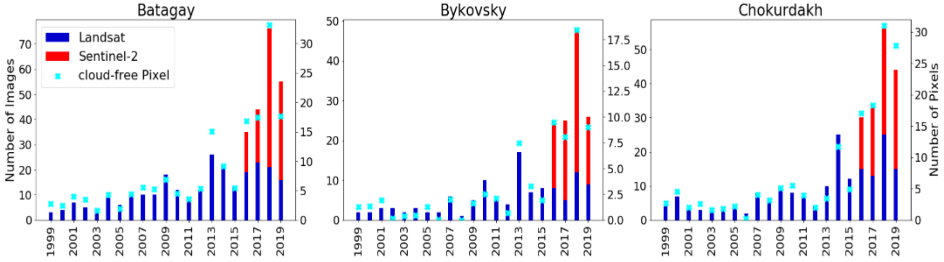
Temporally dense Landsat/Sentinel-2 trend data

Tracking Permafrost Disturbances with detailed LandTrendr analysis

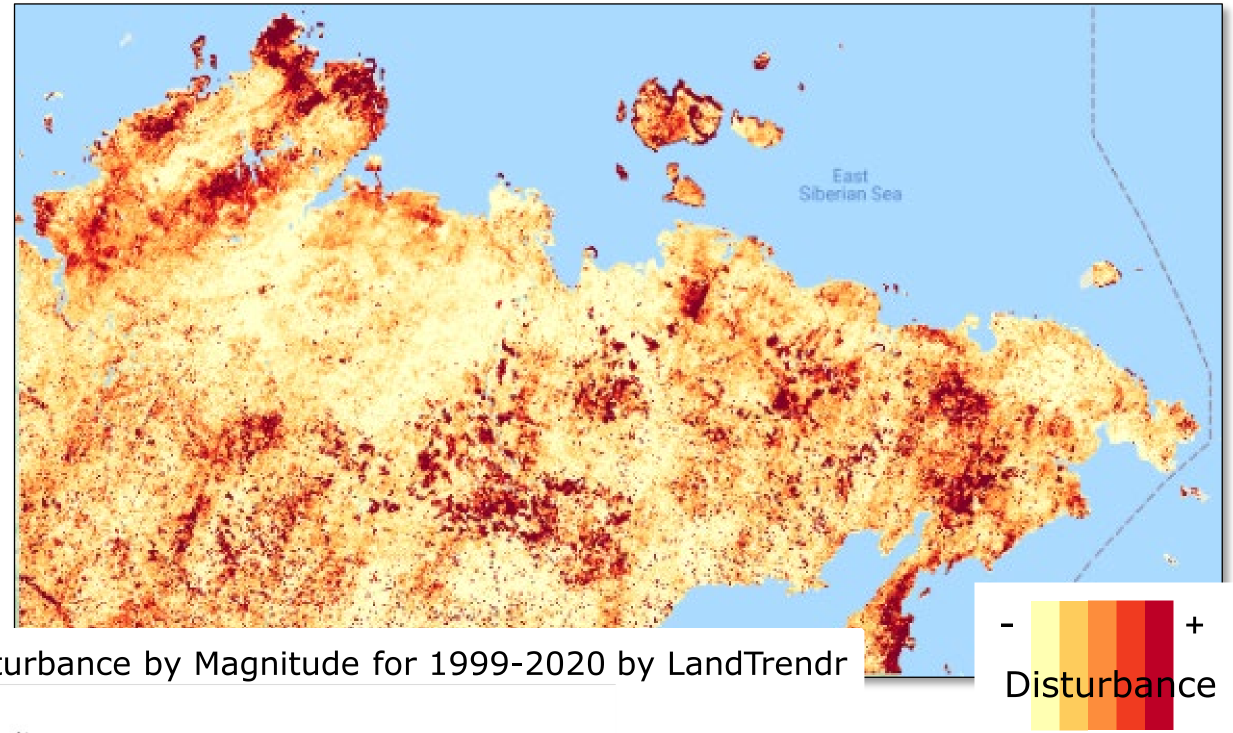
LandTrendr algorithm adapted

- annual Landsat + Sentinel-2 mosaics *(Runge & Grosse 2019 and 2020, both in Remote Sensing)*
- temporal segmentation for biggest changes -> disturbance
- Timing, magnitude, duration of disturbances
- retrogressive thaw slumps, coastal erosion, wildfires

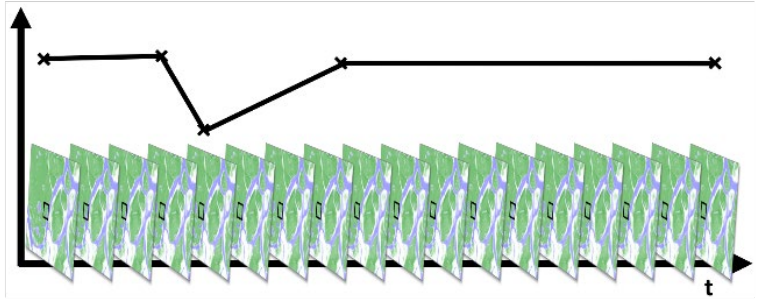
Extending the Landsat-Record with Sentinel-2 for disturbance monitoring with LandTrendr



Runge & Grosse 2019 (Remote Sensing) & Runge & Grosse 2020 (Remote Sensing)



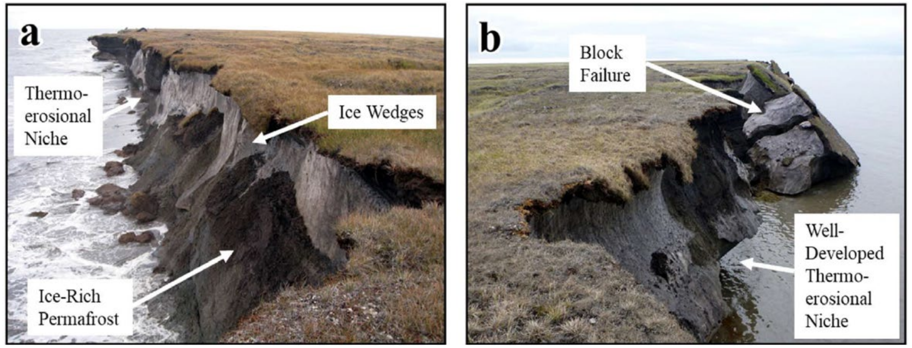
Disturbance by Magnitude for 1999-2020 by LandTrendr

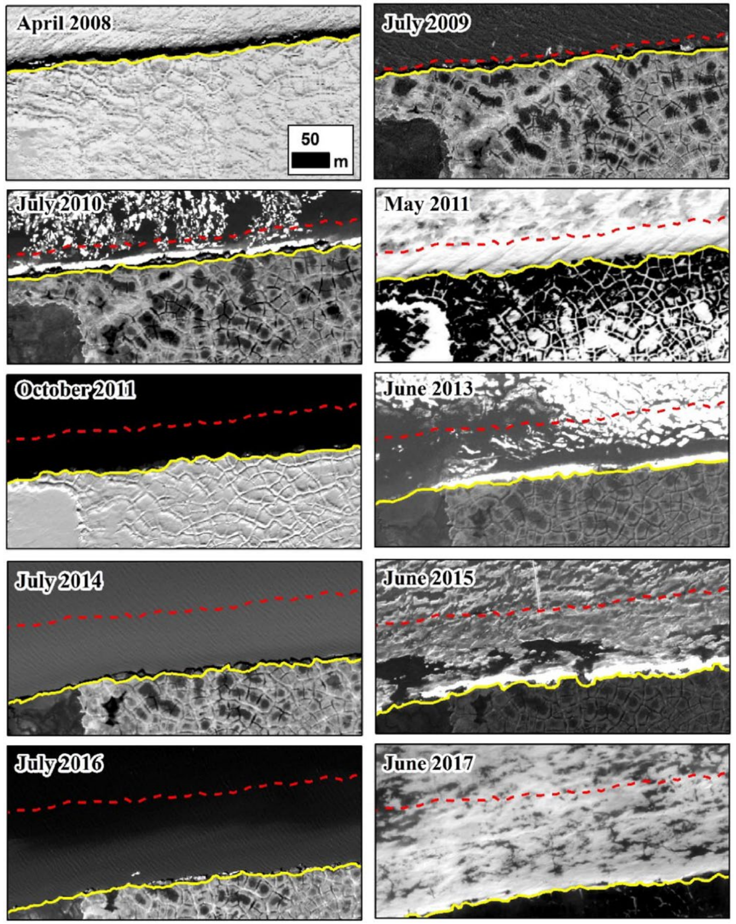


Temporal segmentation by LandTrendr, modified after Kennedy et al. 2010.

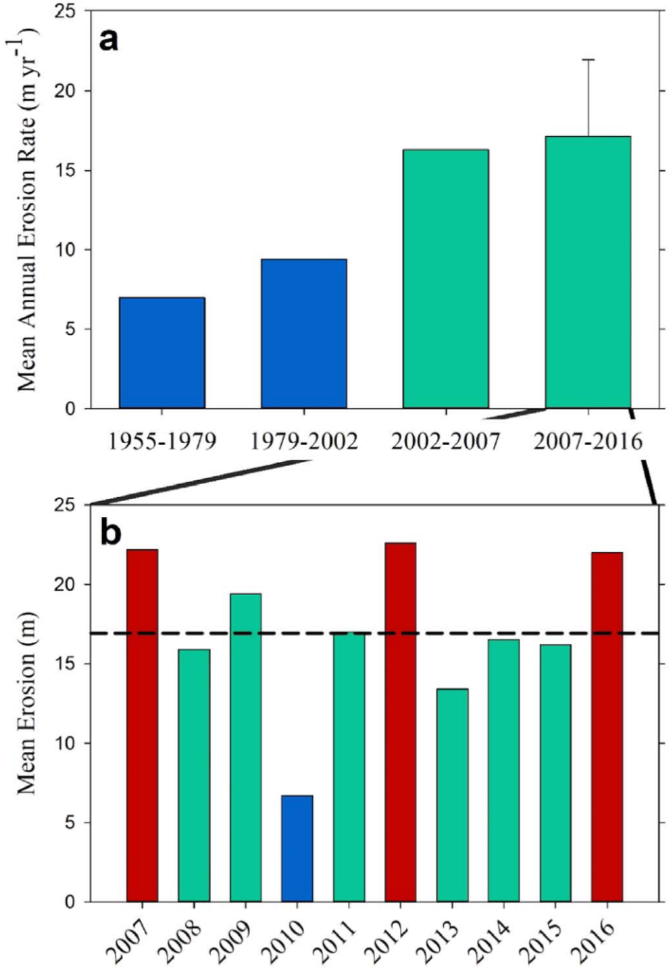
Temporally dense VHR time series: Coastal erosion

Observation of rapid coastal erosion in North Alaska





Images copyright 2008–2017, DigitalGlobe, Inc.



Approach: Annual very high resolution (VHR) satellite images acquired for Drew Point between 2008–2017.

Next goal: Sub-annual temporal resolution at selected sites around the Arctic to better understand seasonal dynamics of erosion and correlation to sea ice, water temperatures, and waves/storms.

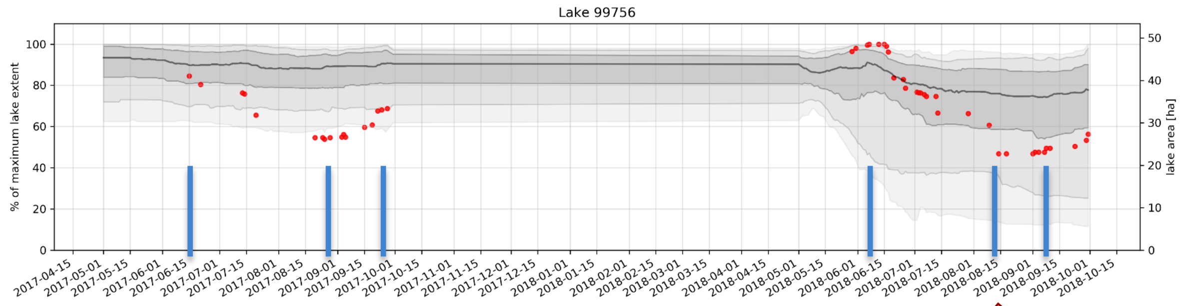
Ideal: Panarctic full-scale automated coastal monitoring…

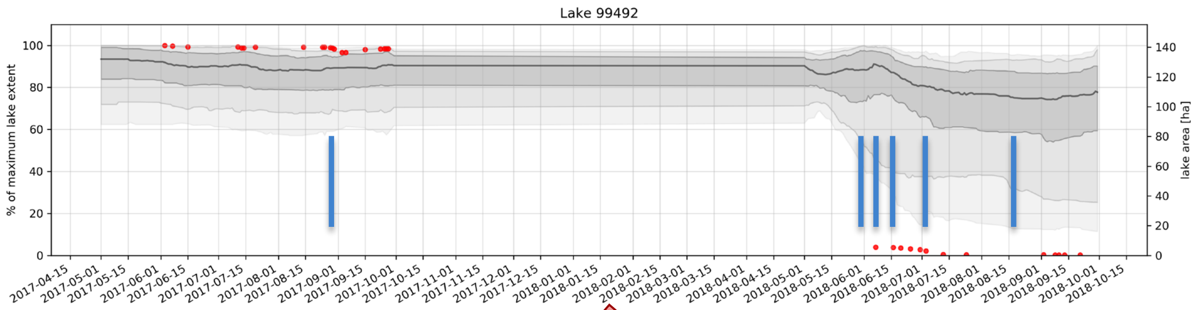
Permafrost Coastal Systems Network (PerCS-Net): https://permafrostcoasts.org

Jones et al. 2018 (ERL)

Temporally dense VHR time series: Lake drainage

Observing thermokarst lake expansion, fluctuation, and catastrophic lake drainage



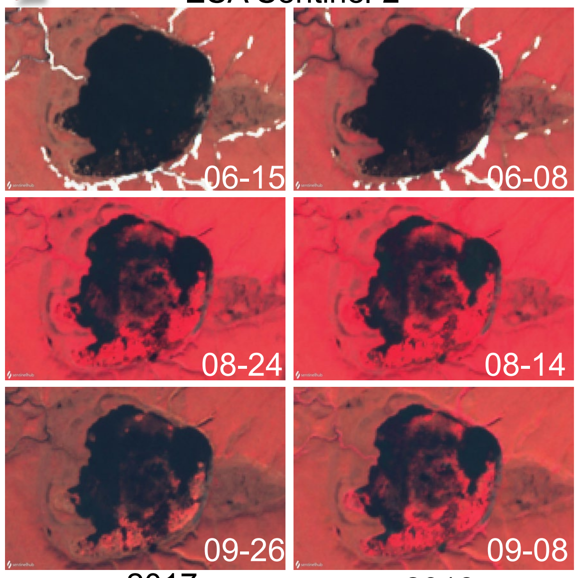


Approach: Sub-annual Planet (3m) satellite images acquired for Northwestern Alaska for 2017/18.

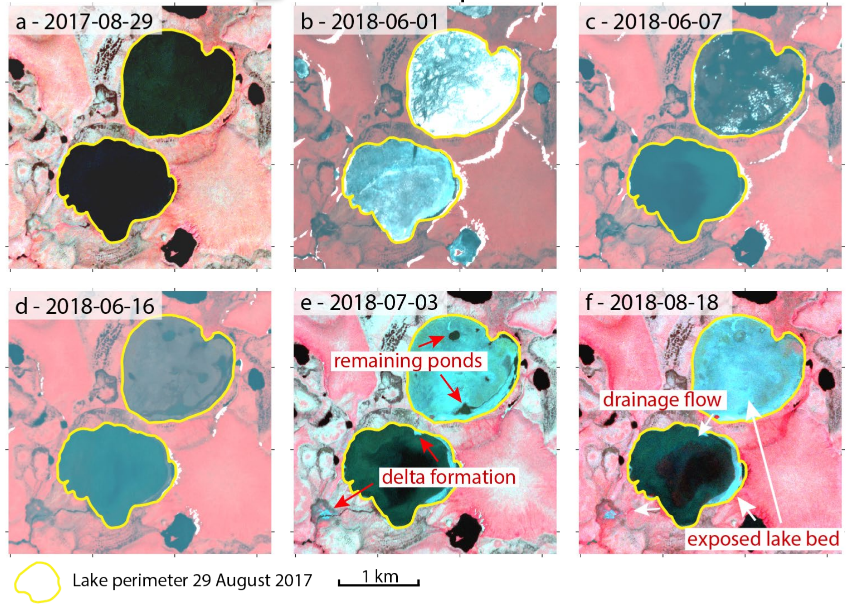
Next goal: ML/DL-guided automated detection and classification of lake drainages in selected Arctic regions to understand seasonal dynamics of catastrophic drainage and correlation to temperature, precipitation, permafrost temperature, active layer thickening, and talik formation.

Ideal: Panarctic full-scale automated lake drainage detection…

ESA Sentinel-2



PlanetScope



HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

AI-CORE

Nitze et al. 2020 (in press): The catastrophic thermokarst lake drainage events of 2018 in northwestern Alaska: Fast-forward into the future. The Cryosphere.

Temporally dense VHR time series: Thaw slumping

Regional detection and monitoring of retrogressive thaw slumps with AI-based methods

- Slope failure resulting from rapid thaw of ice-rich permafrost at coasts + shores
- Result in significant irreversible surface deformation and sediment transport

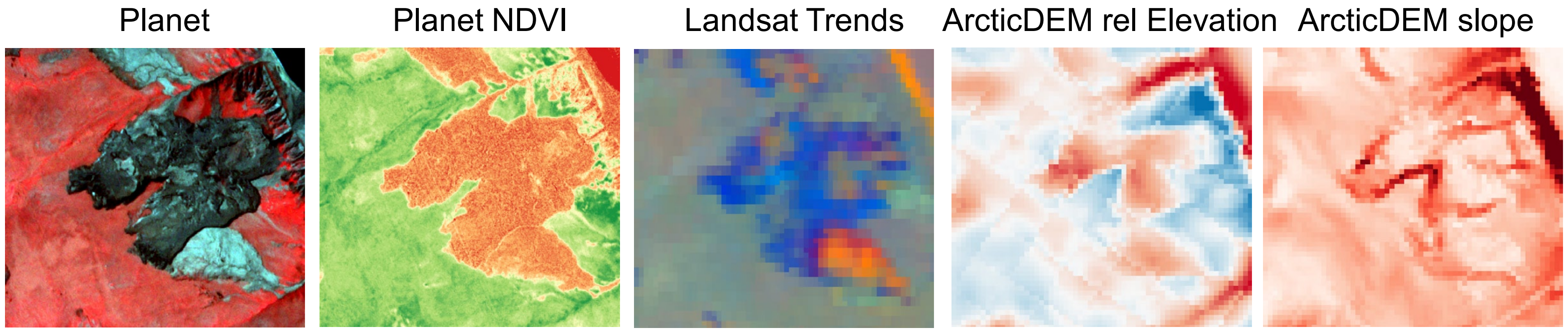
Bykovsky Peninsula, Siberia (Photo: F. Günther)

Herschel Island, NW Canada (Photo: J. Lenz)

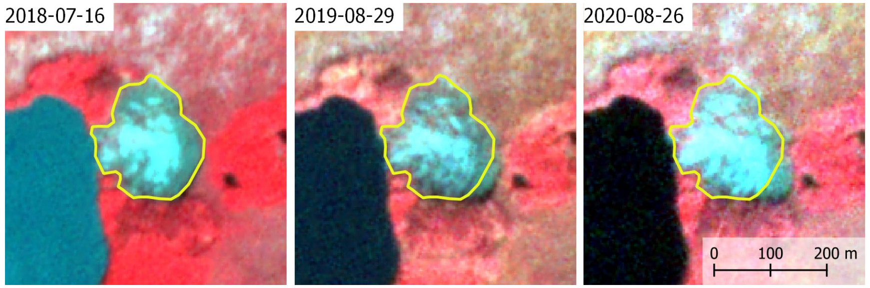
Approach: Sub-annual Planet (3m) satellite images acquired for selected areas in Northeast Siberia.

Next goal: AI-based detection of thaw slumps on selected Arctic regions to understand dynamics of slump activation and stabilization.

Ideal: Panarctic full-scale automated thaw slump detection and monitoring…



Slump characteristics in Planet data and ArcticDEM



Planet time series

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
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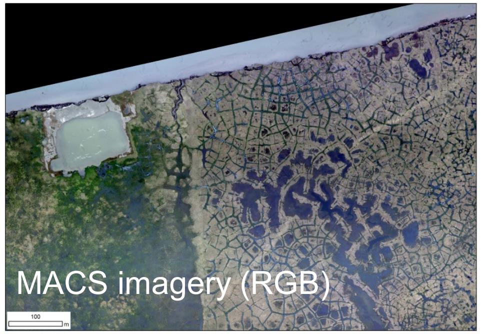
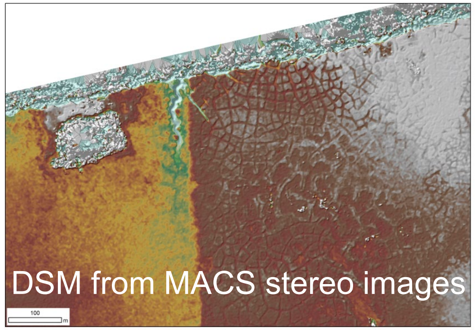
Ground truth: Airborne and ground data collection

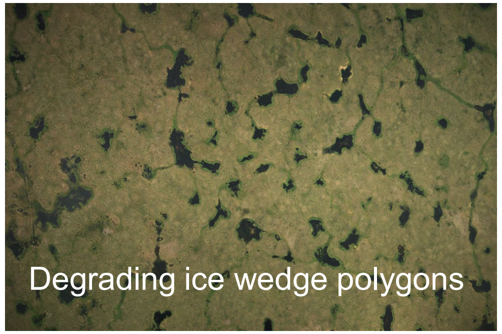
AWI-DLR Permafrost Campaigns: NW Canada 2018, N Alaska 2019

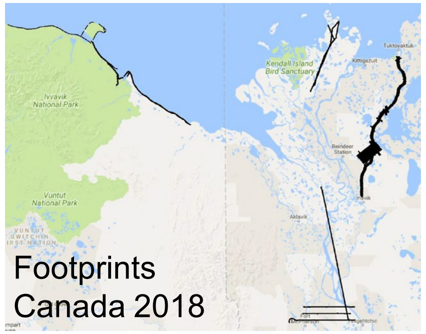
DLR Modular Aerial Camera System:
- Raw: RGB ~ 17MB/image; NIR ~15MB/image
- Footprints @ 1000 m AGL
  • GSD NIR: 15 cm per pixel
  • GSD RGB: 9 cm per pixel → ~120 pixel per m²
  • Overlap @ 3 fps: 93%

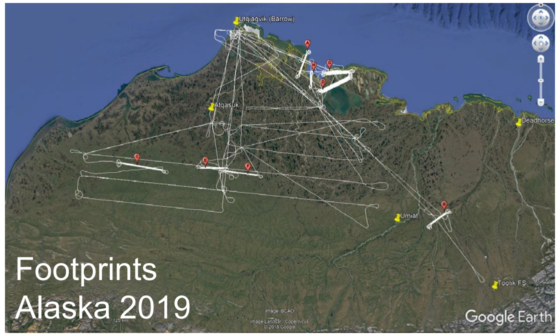
Canada 2018 + Alaska 2019
- ca. 1,070,000 image files
- Raw data: ~23 TB
- TIFF: RGB ~ 90MB/image; NIR ~30MB/image
- additional: LIDAR data











MACS mosaic of the Yukon Coast, NW Canada: Derived from 22 images; MACS DEM draped with RGB @ GSD~12cm

Length of mosaic: ca. 1.3 km

Continuing Challenges

- Need for high temporal and/or high spatial resolution to understand tipping element character of permafrost
- Need to further ease access to Arctic (VHR) EO data, high performance processing and storage platforms
- Need to train new generation of EO scientist and engineers with understanding of permafrost dynamics
- Panarctic work needs close collaboration across nationalities; overarching networking projects help fostering collaboration also in EO (e.g., PerCSNet, T-MOSAiC, Permafrost Discovery Gateway)