Changing Permafrost Landscapes in North Eurasia: Some Remote Sensing Observations and Challenges

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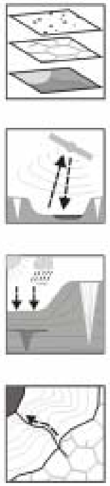
+ many other colleagues from Alaska, Russia, United Kingdom, and Germany

Assessing Climate-Induced Permafrost Degradation in the Arctic (CIPEDIA)



Quo vadis, Remote Sensing of Permafrost?

In Situ Sensing Initiatives

Thermal State of Permafrost (TSP)

Circumarctic Active Layer Monitoring (CALM)

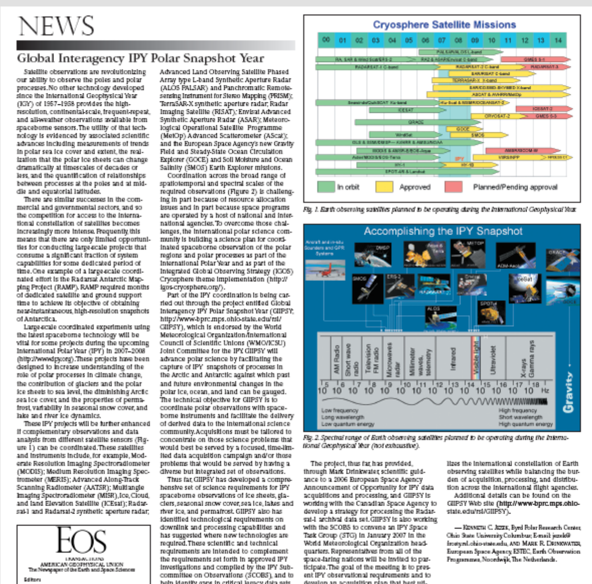
ACCO-Net, AON, etc.

Permafrost

Remote Sensing Initiatives

Integrated Global Observing Strategy (IGOS) *Cryosphere Theme*

Global Inter-agency IPY Polar Snapshot Year (GIIPSY)


NEWS

Global Interagency IPY Polar Snapshot Year

Cryosphere Satellite Missions

Accomplishing the IPY Snapshot

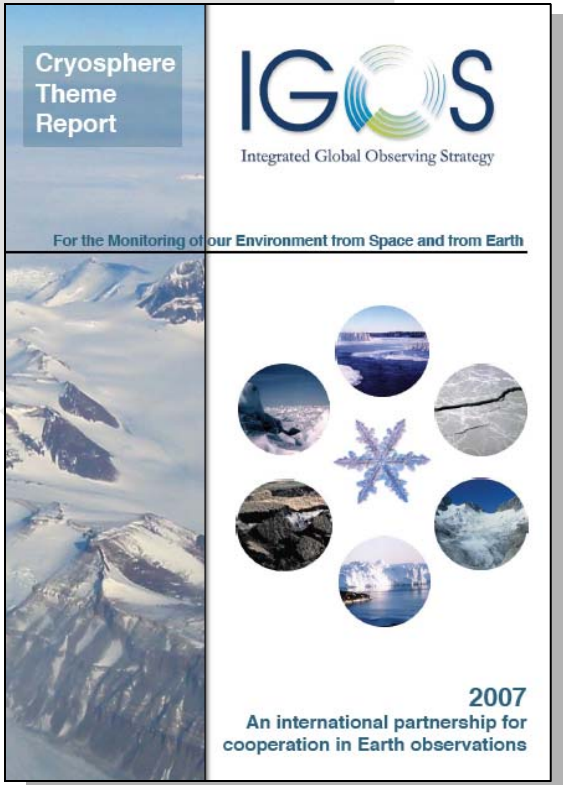
EOS

IGOS

- Status of Observations

- Shortcomings in Current Observations

- Recommendations: Development of Frozen Ground Observations



GIIPSY

-Science Goal and Objectives

-Observation objectives

Definition of ‚Permafrost Degradation‘

A naturally or artificially caused decrease in the thickness and/or areal extent of permafrost *(National Research Council of Canada Technical Memorandum No.142.1988).*

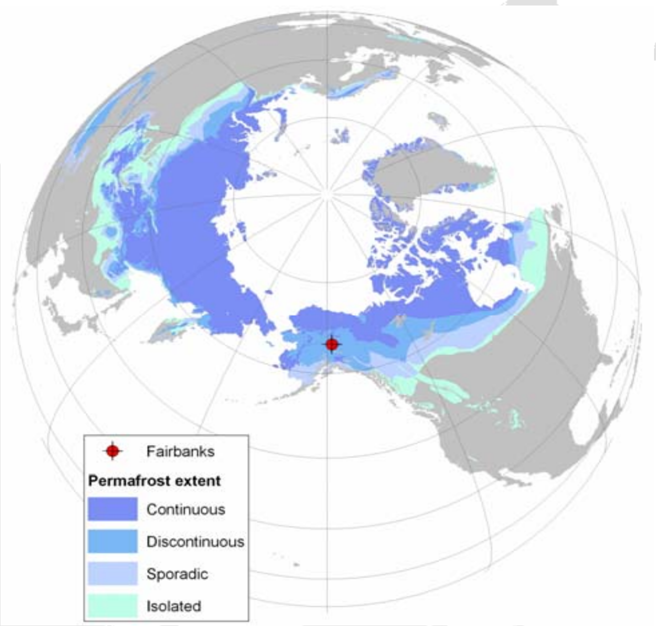
Expressed as

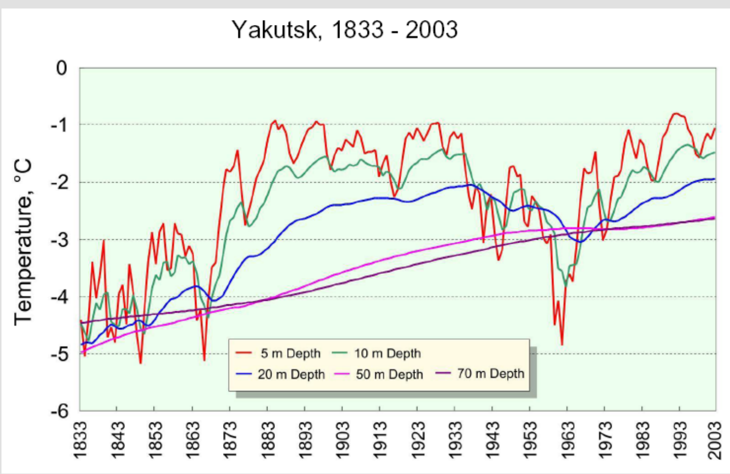
- a thickening of the seasonal active layer

- a lowering of the permafrost table

- a reduction in the areal extent of permafrost

- or the complete disappearance of permafrost.

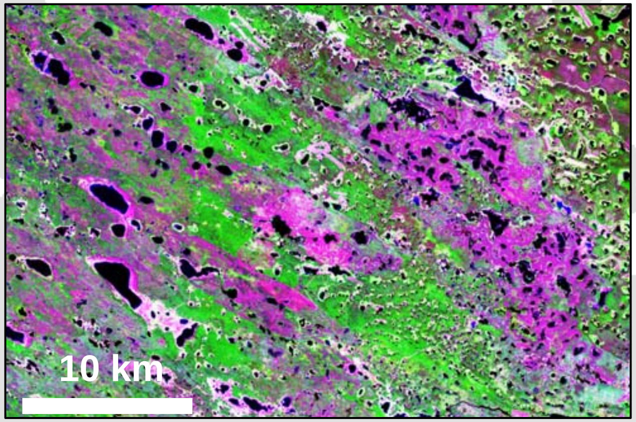




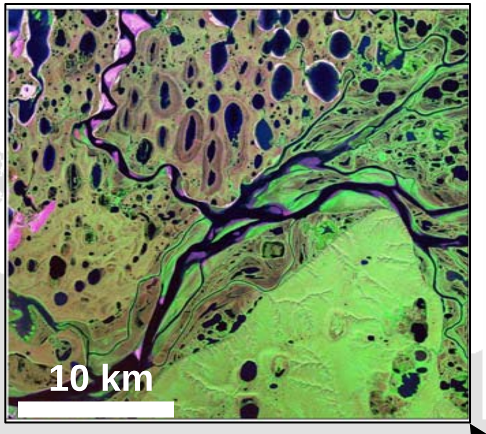
Time scales of permafrost degradation processes and impacts range from years to centuries.

Romanovsky, Marchenko et al.

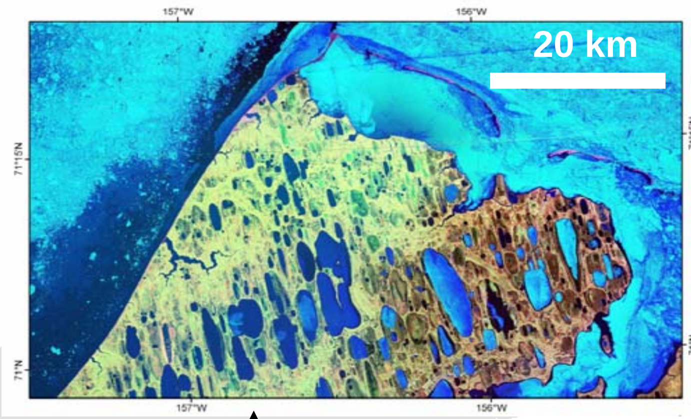
Thermokarst: Processes and landforms resulting from thawing of ice-rich ground, i.e. surface subsidence related to a volume loss due to ground ice melting.



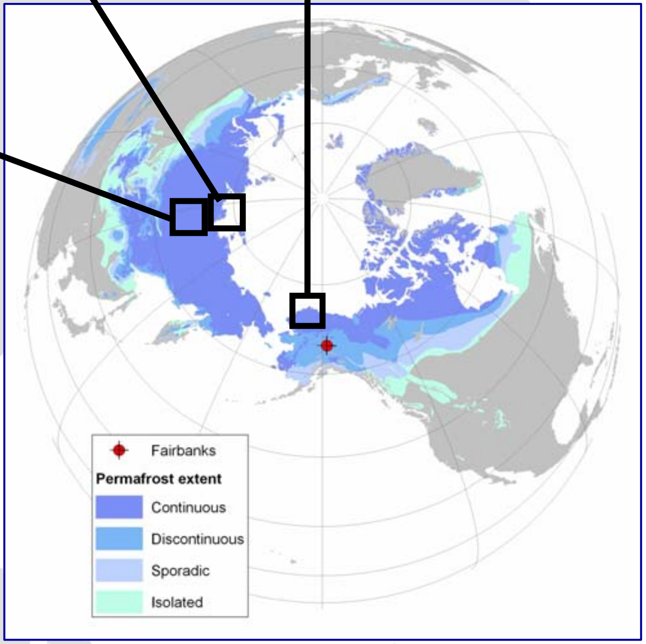
Yakutsk, Central Siberia



Lena Delta, North Siberia



Barrow, North Alaska



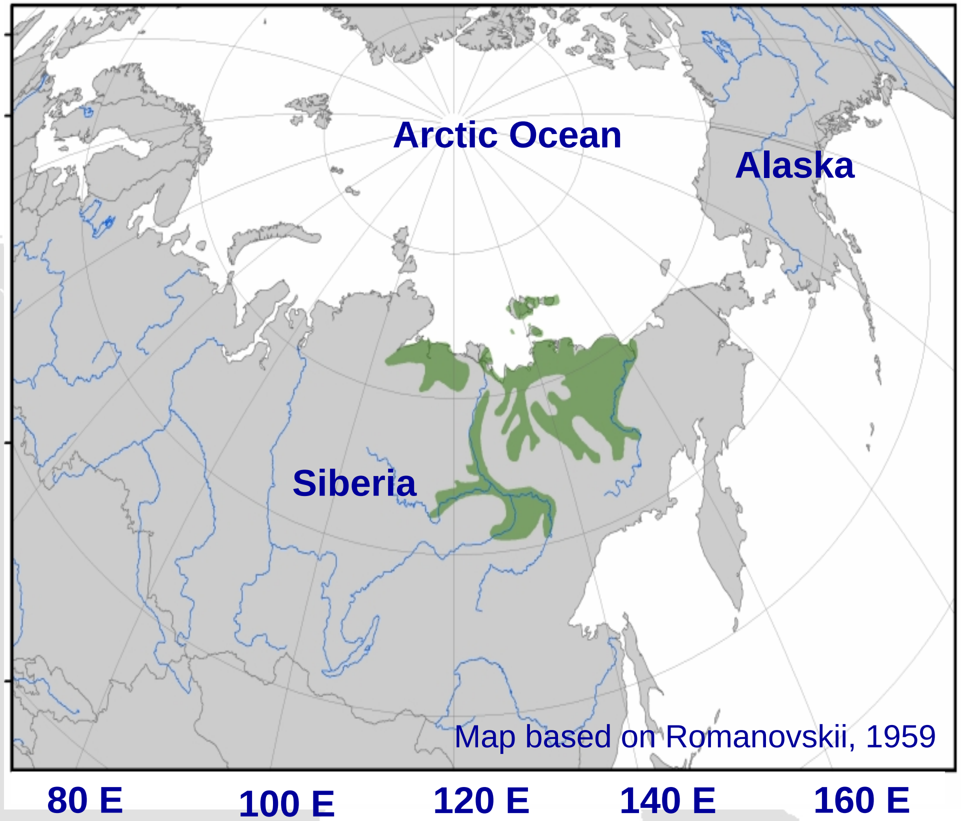
Three Main Messages:

- *Degradation is <u>not</u> restricted to the southern permafrost boundary, where warm permafrost prevails*

-*High impact changes are likely to happen where permafrost is most vulnerable: regions of warm permafrost or high ice content*

- *Degradation is closely related to hydrological + geomorphological change*

Distribution of Ice-Rich Yedoma (Ice Complex) Deposits in North Siberia



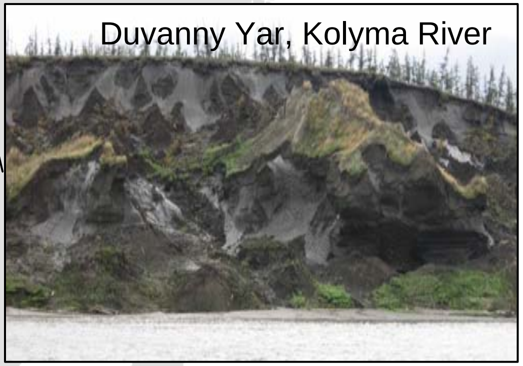
- *Thickness of the deposit is between 5-100m*
- *Present day total coverage is > 1x10^6 km*
- *Gravimetric ground ice contents in the sediments between 60-120%*
- *Including the ice wedges, total volumetric ice content of up to >75%*
- *Organic carbon content averages between 2-5%*
- *Accumulation during several 10 000 years*

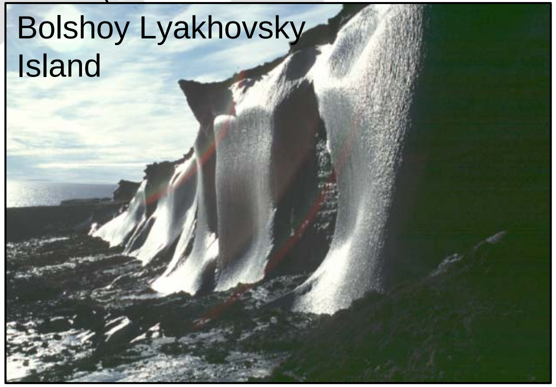
Zimov et al 2006 (Science), Schirrmeister et al., in review

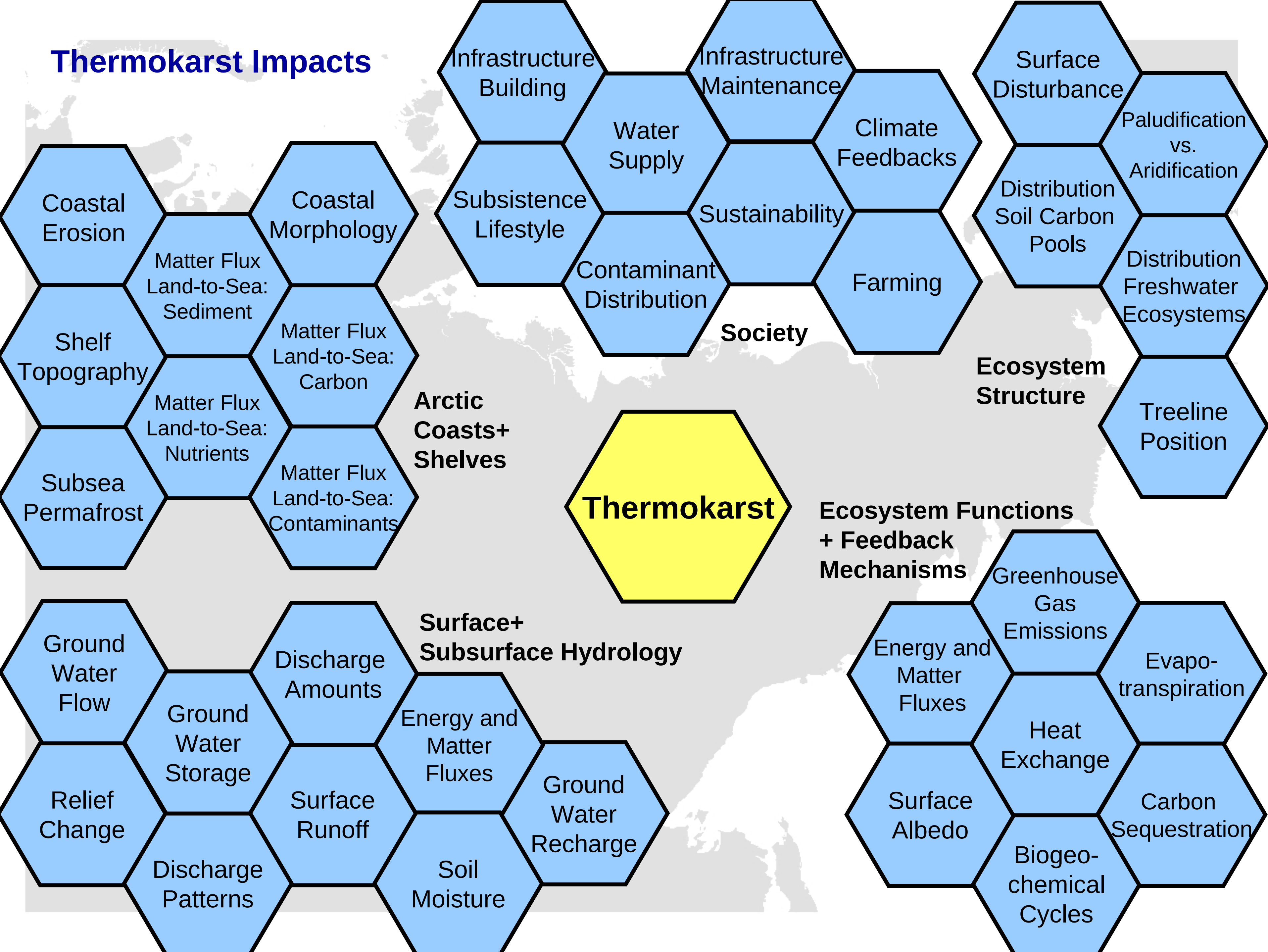
Ice-rich Permafrost in North Eurasia

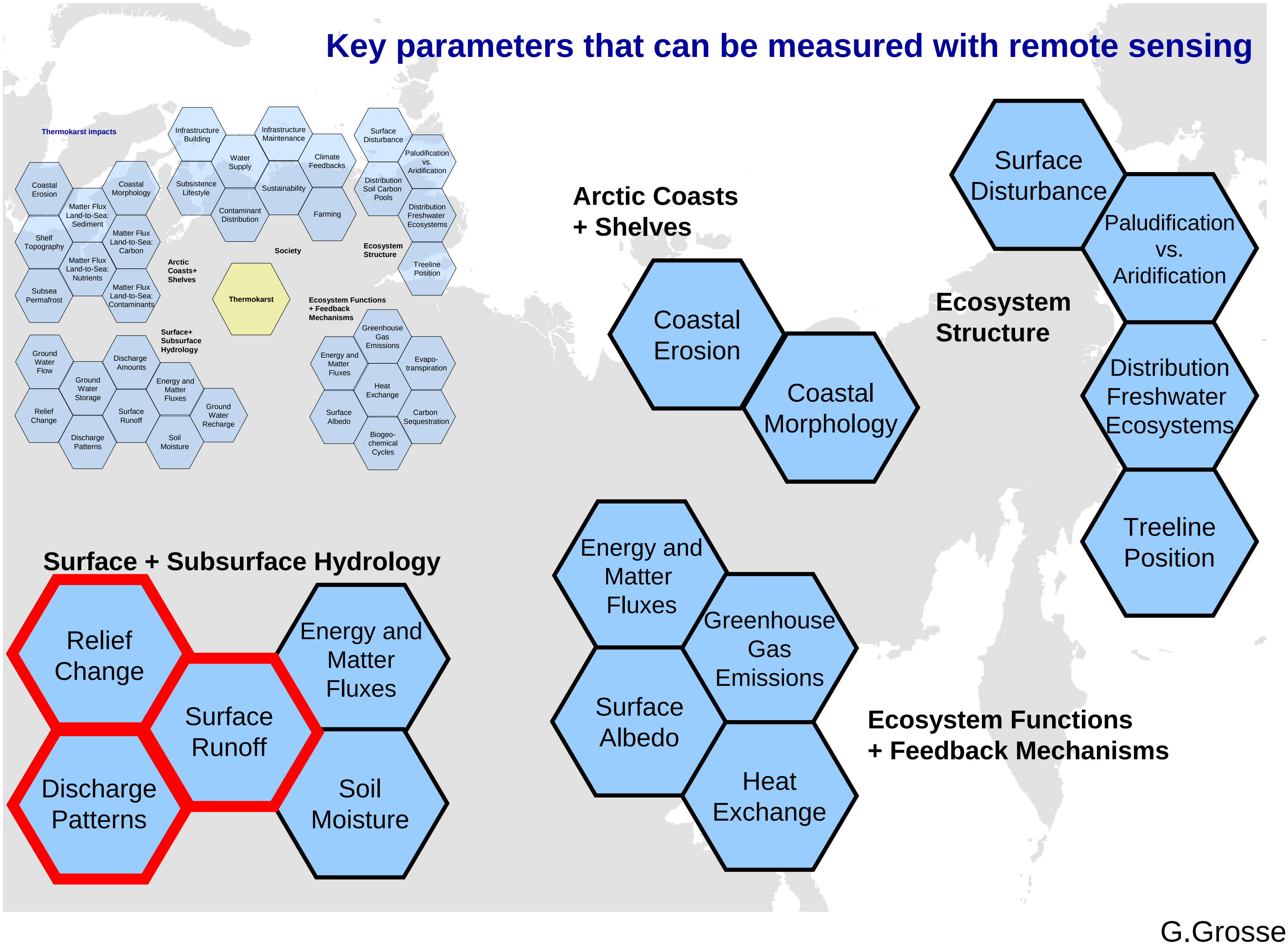
Impacts of thermo-erosion at the coast:
- coastal erosion rates (up to 12m/yr)
- coastal morphology
- sediment and carbon transport
- land loss

Impacts of thermo-erosion inland:
- fluvial erosion rates (several m/yr)
- fluvial morphology
- lake growth and drainage
- sediment and carbon transport






Thermokarst Impacts
Thermokarst
Society
Infrastructure Building
Infrastructure Maintenance
Water Supply
Climate Feedbacks
Subsistence Lifestyle
Sustainability
Contaminant Distribution
Farming
Ecosystem Structure
Surface Disturbance
Paludification vs. Aridification
Distribution Soil Carbon Pools
Distribution Freshwater Ecosystems
Treeline Position
Arctic Coasts+ Shelves
Coastal Erosion
Coastal Morphology
Matter Flux Land-to-Sea: Sediment
Shelf Topography
Matter Flux Land-to-Sea: Carbon
Matter Flux Land-to-Sea: Nutrients
Subsea Permafrost
Matter Flux Land-to-Sea: Contaminants
Ecosystem Functions + Feedback Mechanisms
Greenhouse Gas Emissions
Energy and Matter Fluxes
Evapo-transpiration
Heat Exchange
Surface Albedo
Carbon Sequestration
Biogeo-chemical Cycles
Surface+ Subsurface Hydrology
Ground Water Flow
Discharge Amounts
Ground Water Storage
Energy and Matter Fluxes
Relief Change
Surface Runoff
Ground Water Recharge
Discharge Patterns
Soil Moisture



Key parameters that can be measured with remote sensing
Thermokarst impacts
Coastal Erosion
Coastal Morphology
Matter Flux Land-to-Sea: Sediment
Shelf Topography
Matter Flux Land-to-Sea: Carbon
Matter Flux Land-to-Sea: Nutrients
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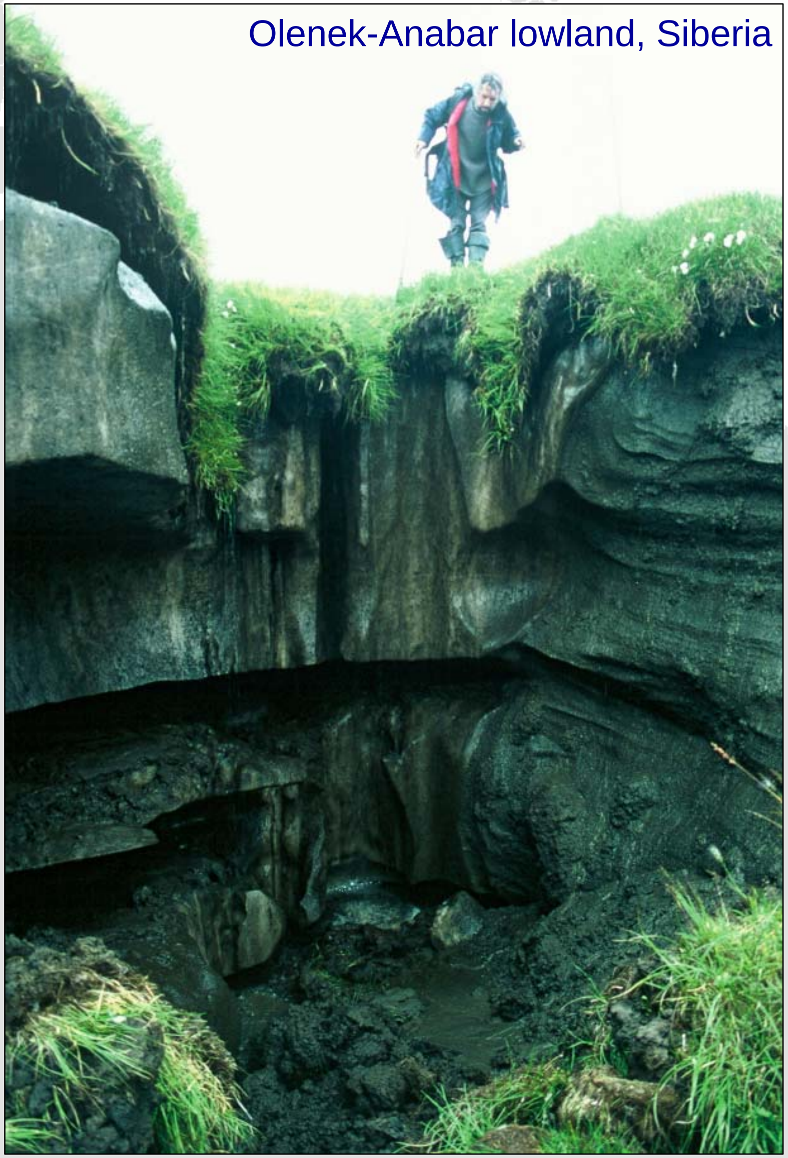
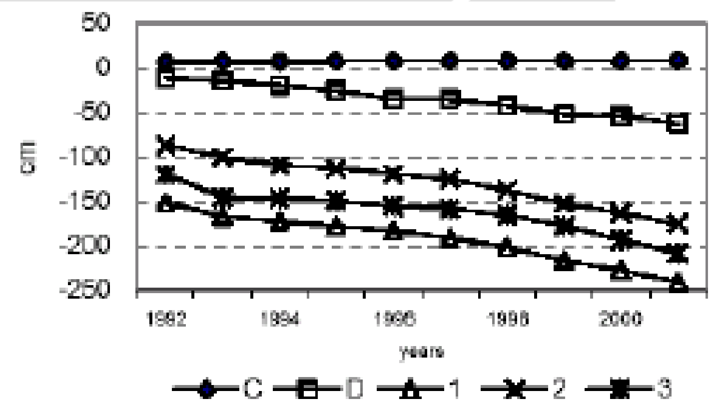
Energy and Matter Fluxes
Greenhouse Gas Emissions
Surface Albedo
Heat Exchange
Ecosystem Functions + Feedback Mechanisms
G.Grosse

Relief change due to permafrost degradation





Fedorov & Konstantinov, 2003

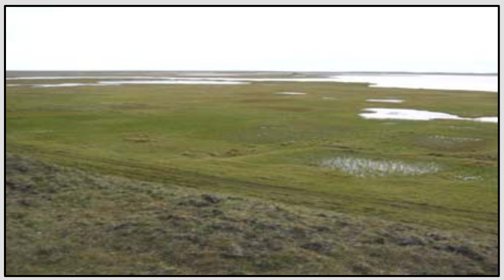
Figure 3. Surface subsidence in thermokarst depression, site 2. C – check point, undisturbed inter-alas area; D – incipient thaw depression; 1-3 – centers of polygons within thaw depression.

Quantification of Thermokarst Terrain with Remote Sensing and a DEM

G. Grosse, L. Schirrmeister, T. Malthus

Study site: Cape Mamontov Klyk

- based on Landsat-7 EMT+ and Corona satellite data, a DEM, cryolithological field data, and terrain surface characteristics
- goal was to quantify the amount of thermokarst-affected terrain



Wet polygonal tundra in thermokarst basin

Riverine floodplain with polygonal tundra

Moist, Edoma-type upland tundra

Riverine barren, Fluvial sand terrace

Wet lowland tundra in Thermo-erosional valleys

Dry slopes with thermokarst hills

Grosse et al, 2006 (Polar Research)

Quantification of Thermokarst Terrain with Remote Sensing and a DEM

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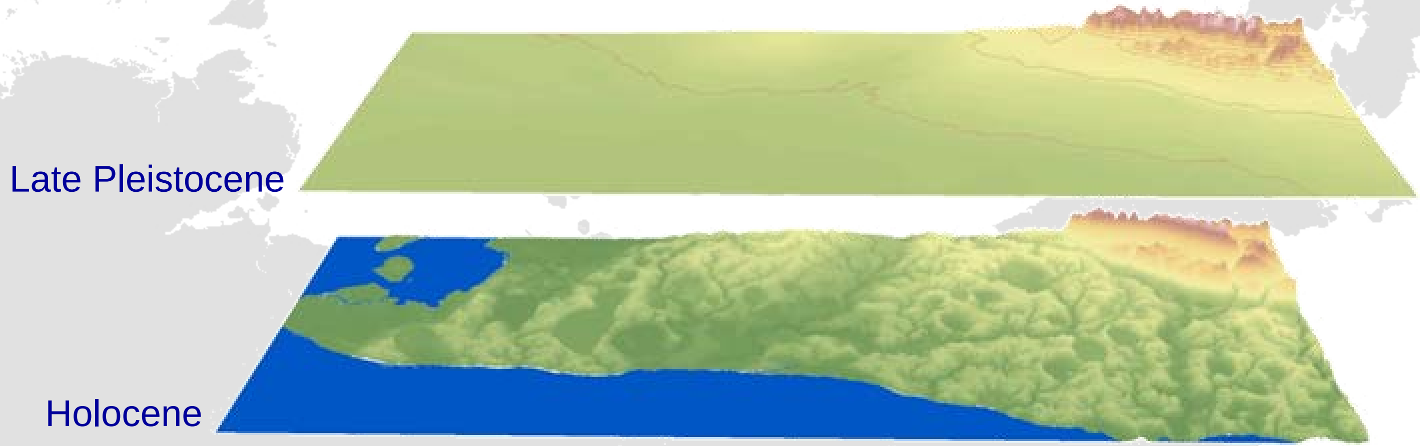
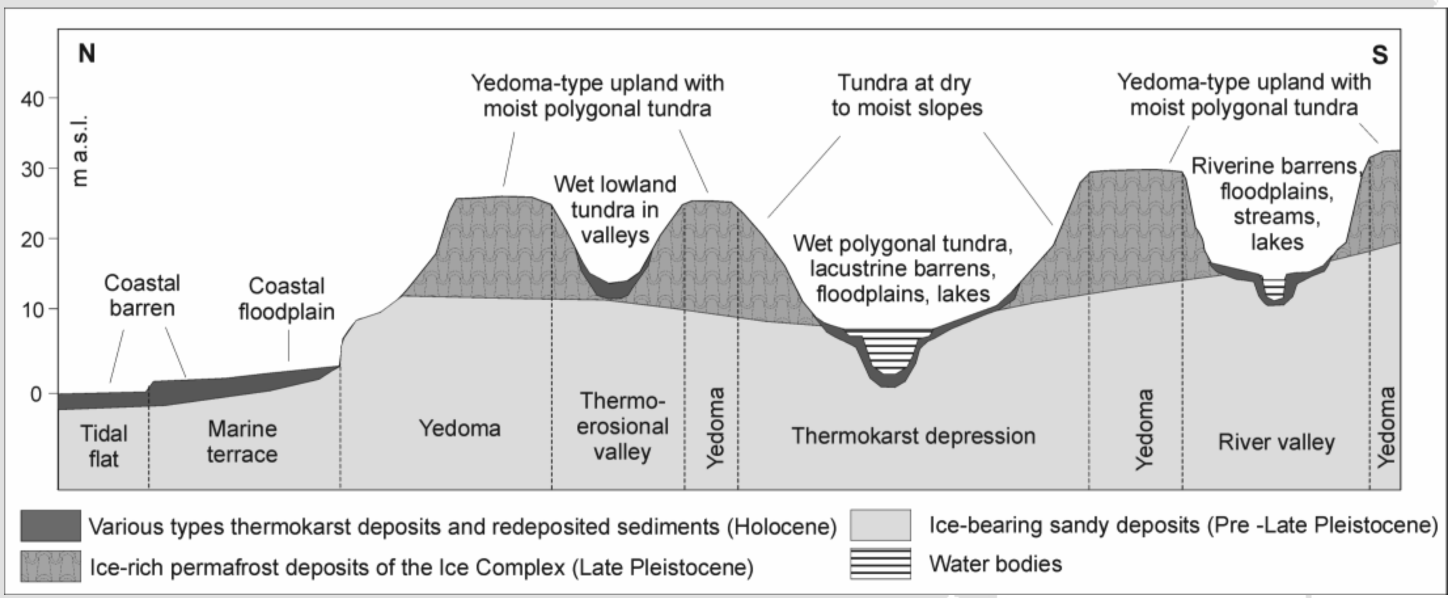
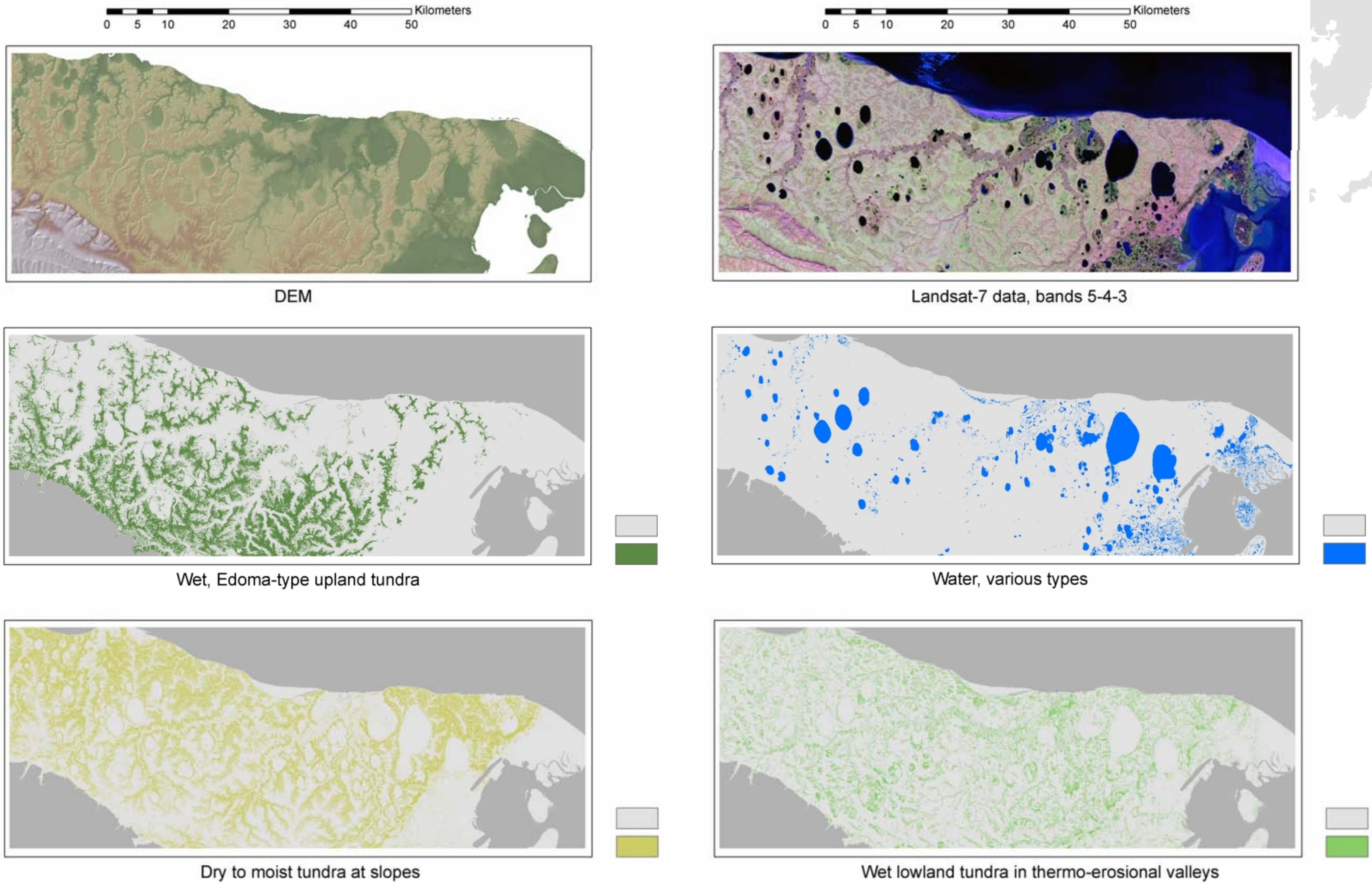




Grosse et al, 2006 (Polar Research)

Quantification of Thermokarst-Affected Terrain with Landsat-7 data and a DEM

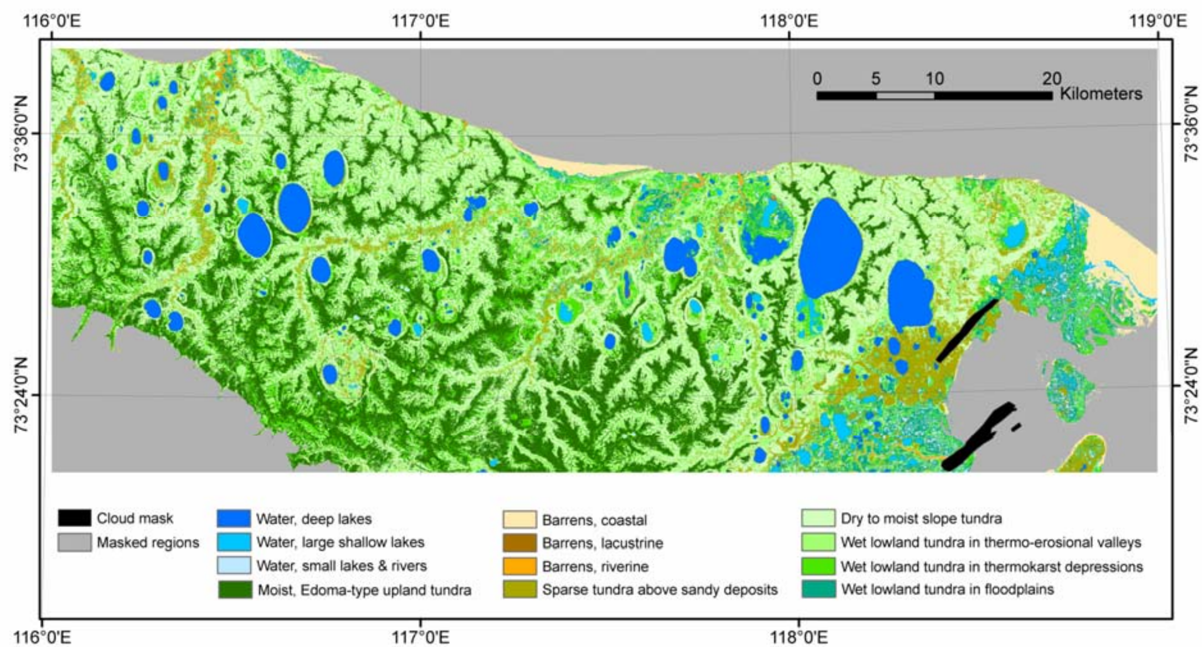
G. Grosse, L. Schirrmeister, T. Malthus



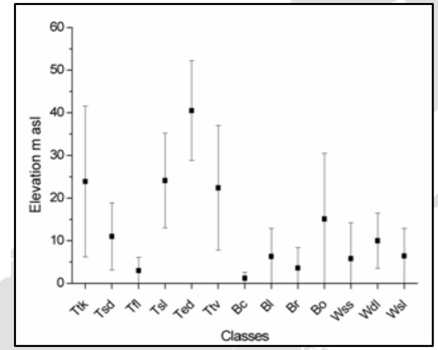
Grosse et al, 2006 (Polar Research)

Classification of Thermokarst-Affected Terrain with Landsat-7 data and a DEM

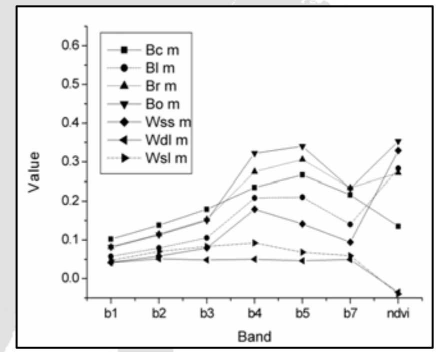
G. Grosse, L. Schirrmeister, T. Malthus

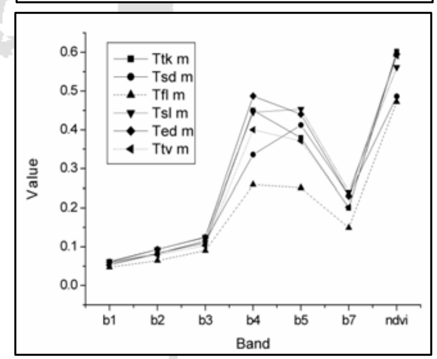


Surface elevation



Spectral bands + NDVI





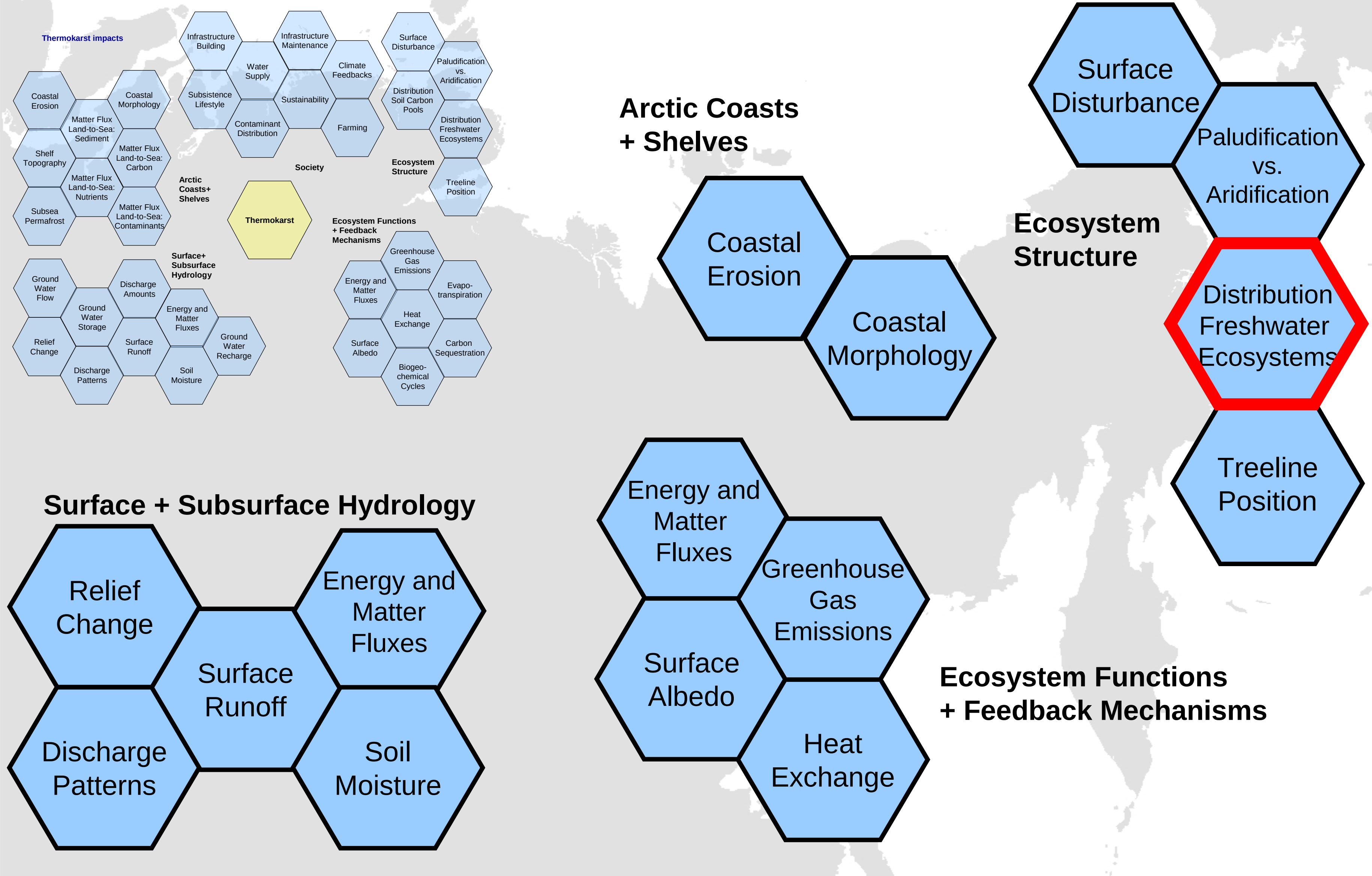
Assumption based on field data: All of the coastal plain was covered by ice-rich deposits.

Degree of degradation in study area (2317.5 sqkm)

- *22.2 % No degradation of ice-rich deposits*
- *31.1 % Partial degradation of ice-rich deposits*
- *14.7 % Strong degradation of ice-rich deposits*
- *11.4 % Complete degradation of ice-rich deposits*
- *20.6 % Complete degradation of ice-rich deposits + deeper*

Grosse et al, 2006 (Polar Research)

Key parameters that can be measured with remote sensing



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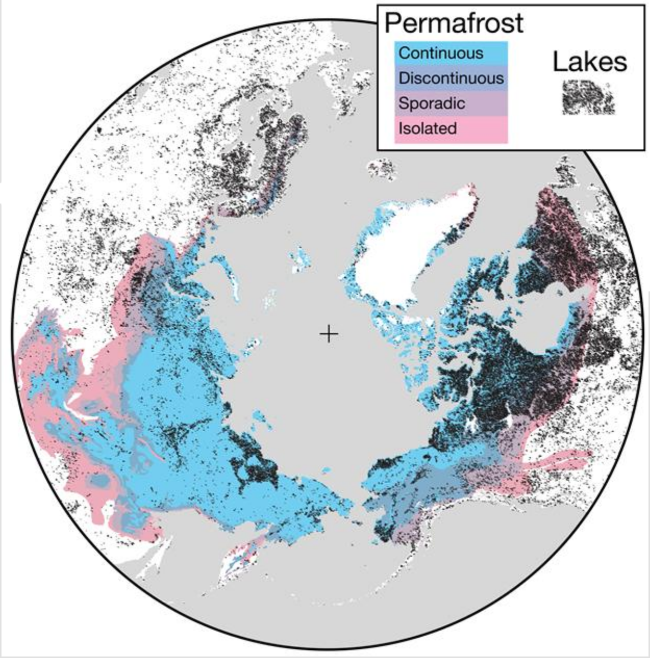
Distribution of Lakes in Permafrost Regions of the Arctic



Smith et al. 2007, Lehner & Döll 2004
Brown et al. 1997, 2001

Smith et al. (2007):

- *High abundance of lakes >0.1 km^2 in Arctic permafrost vs. non-permafrost areas (N of 45.5° latitude)*
- *Relative homogeneous distribution of lakes >0.1 km^2 across different permafrost zones*
- *Unfortunately no classification according to ice content*

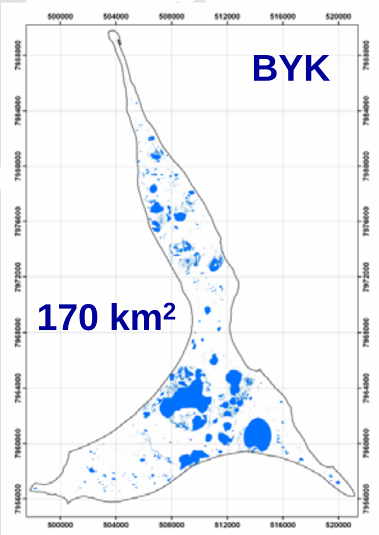
Gutowski et al. (2007):

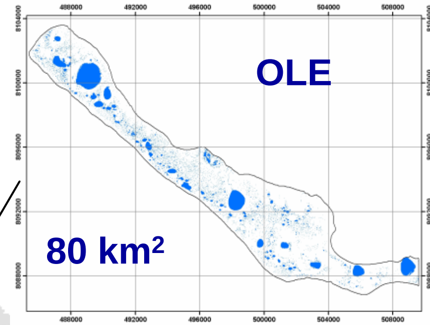
- *Distribution of Arctic wetlands and lakes has impact on atmospheric circulation patterns*

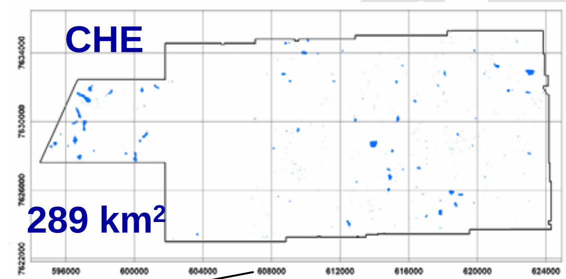
	Land area (km^2)	Number of lakes	Lake area (km^2)	Density (lakes / 100 km^2)*	Lake area fraction (%)**
PF	20 815 400	148 303	414 400	0.712	1.99
No PF	20 490 300	54 453	175 100	0.266	0.85

Includes only lakes >10 ha (0.1 km^2)
** Number of lakes / Land area x 100*
*** Lake area / land area x 100*

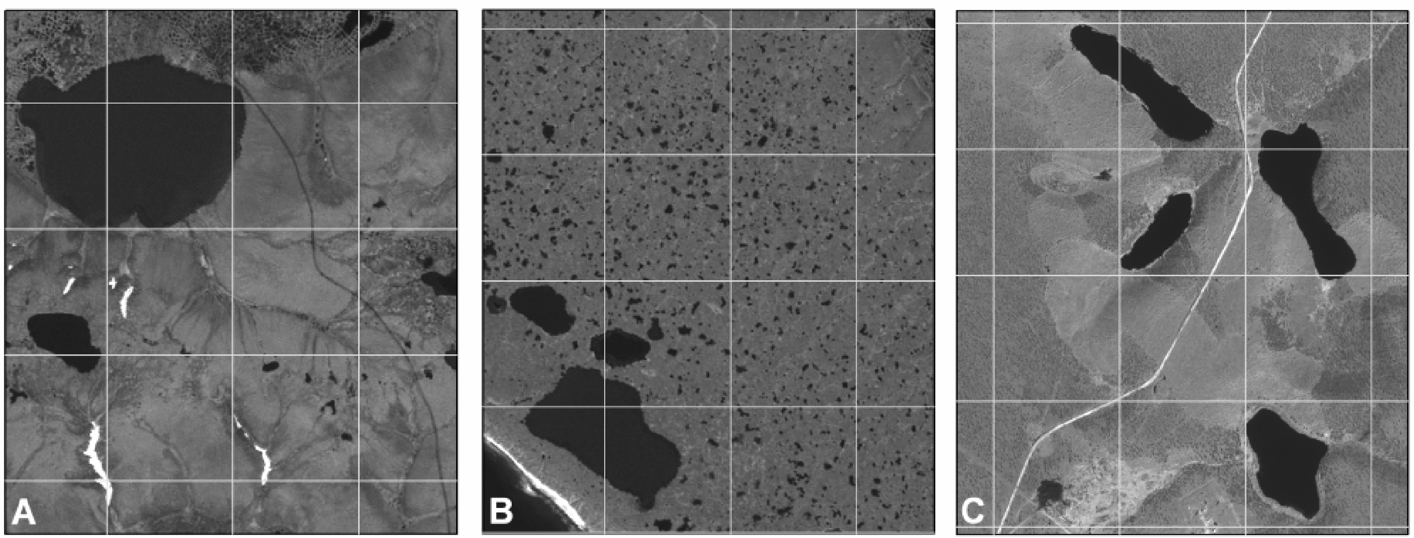
Distribution of Thermokarst Lakes and Ponds in Siberian Yedoma Regions







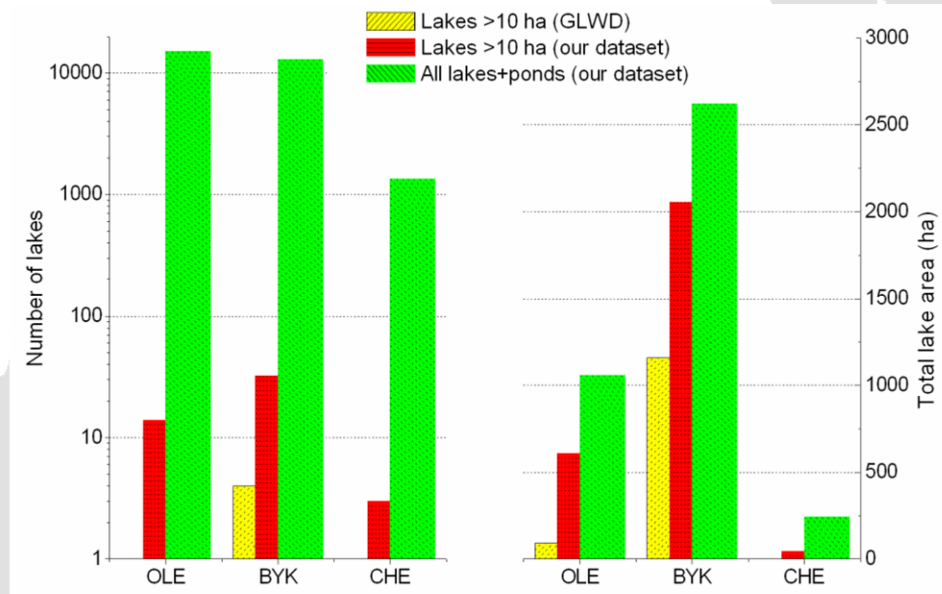
Objectives: *Characterization of the spatial distribution of thermokarst lakes in ice-rich permafrost areas using high-resolution satellite imagery (SPOT-5: 2.5m, IKONOS-2: 1m)*

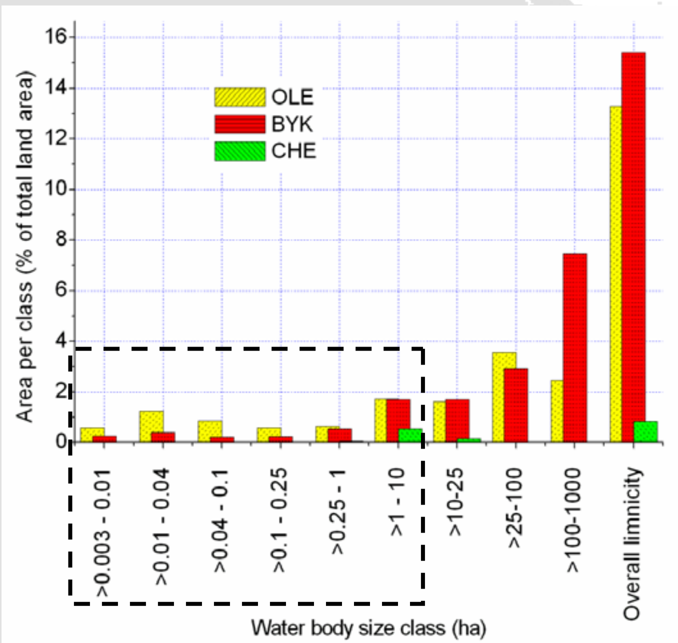


A – BYK (Spot-5)
B – OLE (Spot-5)
C – CHE (Ikonos-2)

Grosse et al, in review

Distribution of Thermokarst Lakes and Ponds in Siberian Yedoma Regions





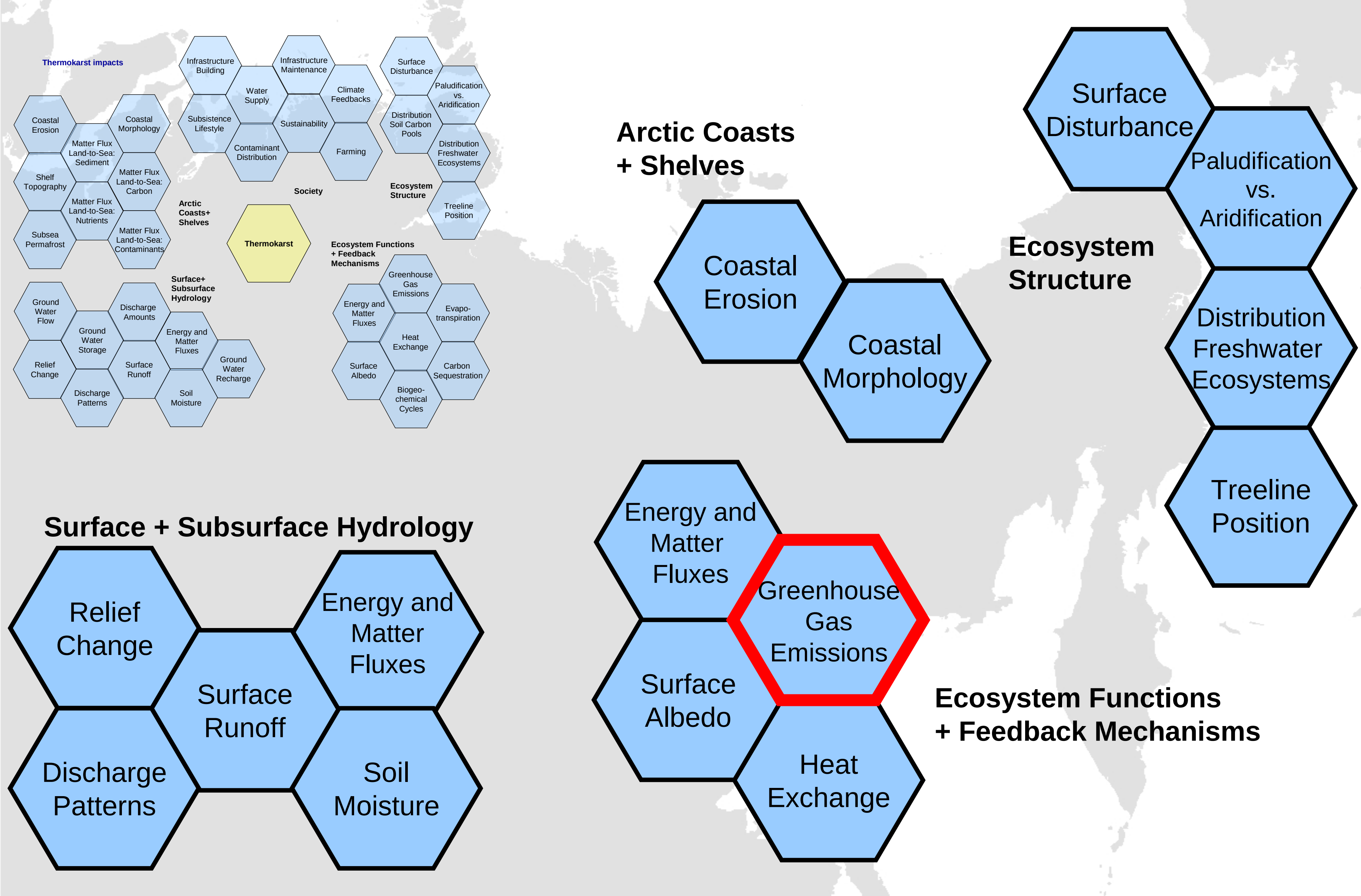
Lakes <10 ha (0.1 km^2) :

OLE: 42.7 % of total lake area per 100 km^2
BYK: 21.6 % of total lake area per 100 km^2
CHE: 82.2 % of total lake area per 100 km^2

These lakes are not considered in current global databases (e.g. GLWD of Lehner & Döll, 2004) or spatial analyses (e.g. Smith et al., 2007)!

Grosse et al, in review

Key parameters that can be measured with remote sensing



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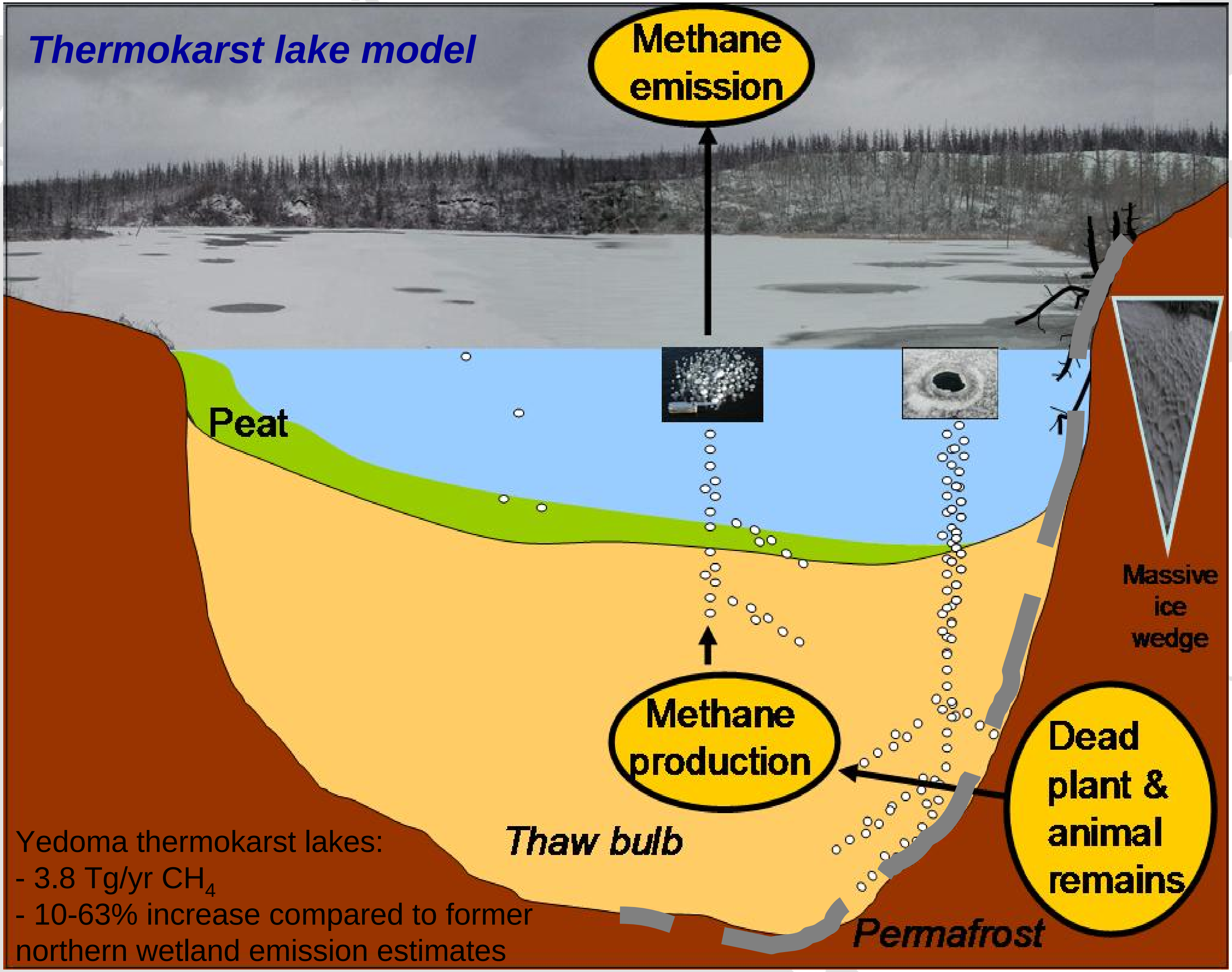
Thermokarst and C-Cycle



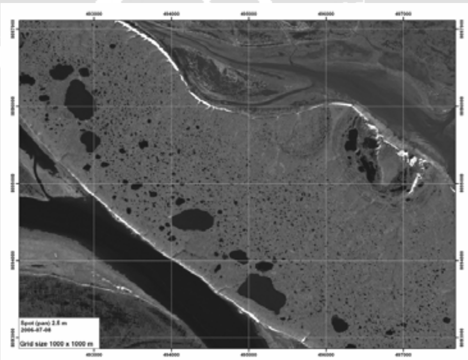
Yedoma thermokarst lakes:
- 3.8 Tg/yr CH_4
- 10-63% increase compared to former northern wetland emission estimates

Walter et al, 2006 (Nature), Walter et al, 2007 (Phil. Trans. Royal Soc. A)

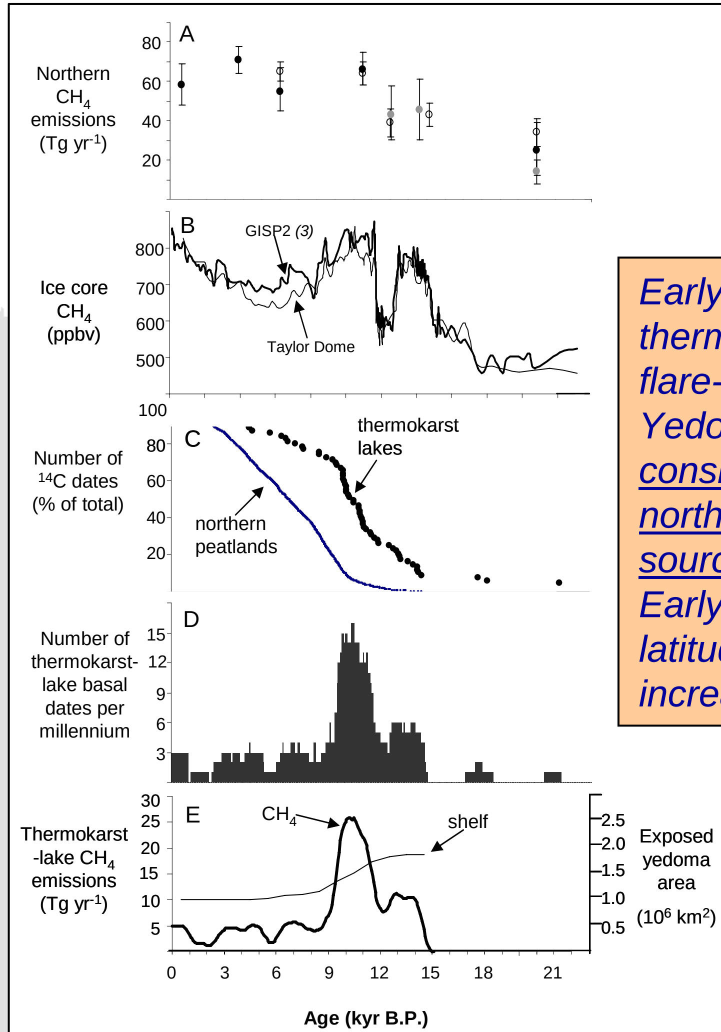
Thermokarst and C-Cycle

Thermokarst Lakes as a Source of Atmospheric CH_4 During the Last Deglaciation

Olenek Channel, Lena Delta



Kolyma Lowland



Early Holocene thermokarst lake flare-up in ice-rich Yedoma was a <u>considerable northern methane source</u> (33-87% of Early Holocene high latitude methane increase).

Walter et al, 2007 (Science)

Thermokarst Lakes: Permafrost Degradation and C-cycling in the Arctic

Carbon Cycle Sciences
2008-2011

National Science Foundation
WHERE DISCOVERIES BEGIN

IPY OPP
2008-2011

Assessing the spatial and temporal dynamics of thermokarst, methane emissions, and related carbon cycling in Siberia and Alaska
G. Grosse (PI), K. Walter (Co-PI), V. Romanovsky (Co-PI)

IPY: Understanding the impacts of thermokarst lakes on C-cycling and climate change
K. Walter (PI), G. Grosse (Co-PI), L. Plug (Co-PI), M. Edwards (Co-PI), L. Slater (Co-PI)

RS-based classification and change detection, GIS-based upscaling *G. Grosse, USA*

Integration into Earth System Models *P. Valdes, UK*

Paleoecology and paleoenvironmental dynamics *M. Edwards, USA+UK*

Thermokarst + Lake Dynamics

Biogeochemistry and Greenhouse Gas Fluxes *K. Walter, USA*

Numerical modeling of lakes and landscapes *L. Plug, CAN*

Geophysics of thermokarst lakes and sediment gas contents *L. Slater, USA*

Permafrost Modeling *V. Romanovsky, USA*

Carbon Cycling *S. Zimov, Russia*

Thermokarst Lakes: Permafrost Degradation and C-cycling in the Arctic

Carbon Cycle Sciences
2008-2011

Assessing the spatial and temporal dynamics of thermokarst, methane emissions, and related carbon cycling in Siberia and Alaska

G. Grosse (PI), K. Walter (Co-PI),
V. Romanovsky (Co-PI)

MODIS, Landsat, Hyperion, ALOS PRISM+AVNIR-2, Spot, Ikonos, Corona, aerial imagery

ALOS PALSAR
Radarsat
TerraSAR-X

Thermokarst characterization, classification, up-scaling to regional scales, quantification, and change detection

Greenhouse Gas Emissions from Thermokarst Lakes

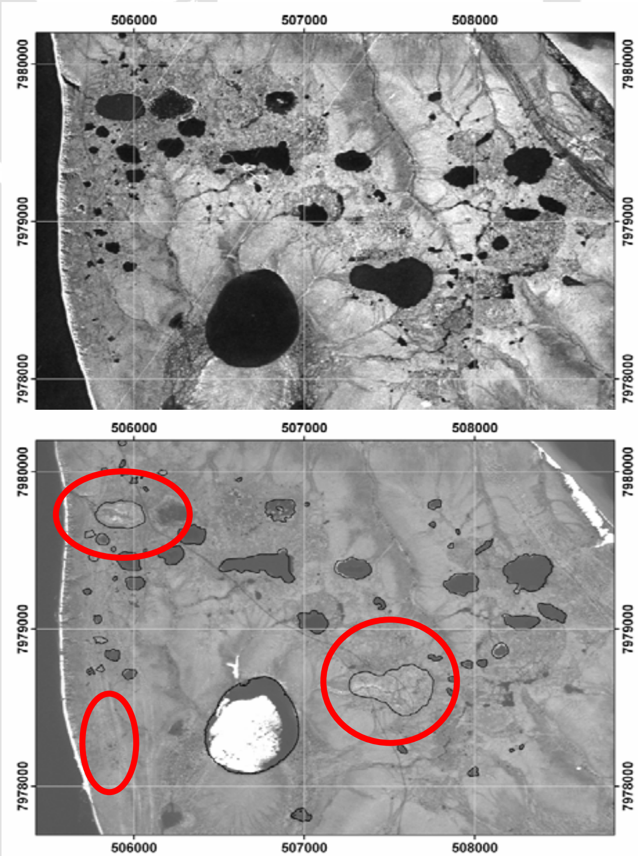
Thermokarst + Lake Dynamics

Primary study areas:
Seward Peninsula, Alaska
Kolyma Lowland, Siberia

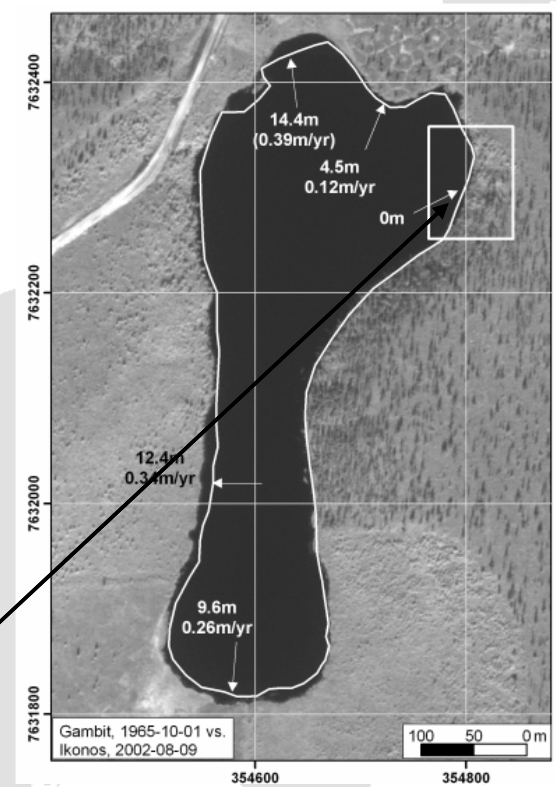
Secondary study areas:
Bykovsky Peninsula & Yakutsk region, Siberia
Toolik Field Station & Fairbanks region, Alaska

Temporal Changes of Thermokarst Lakes in Siberian Yedoma Regions

G. Grosse, V. Romanovsky, K. Walter, S. Zimov



Bykovsky Pensinsula:
- of 308 randomly selected lakes, 244 indicate shrinkage, 44 growth, and 20 lakes drained completely
- Net shrinkage is 24.4 ha (-2.9%)



Bykovsky Peninsula (Corona KH-4B 1969 vs. Spot-5 2002) (2.5m ground resolution)

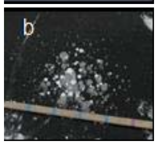
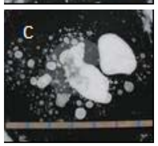
New thaw slump
in September 2007

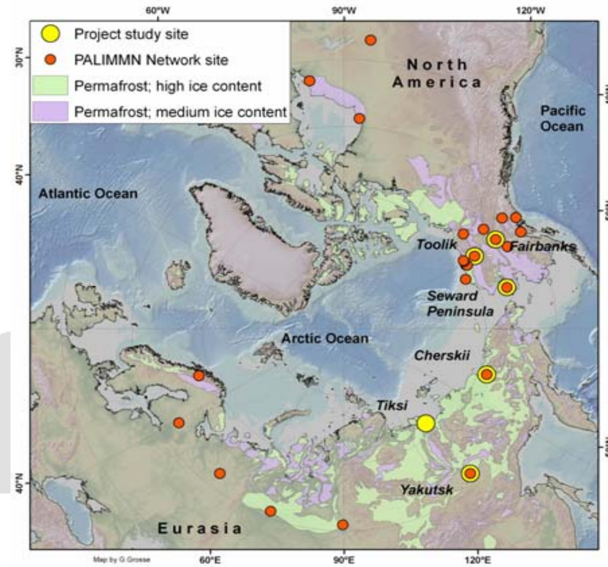
Thermo-erosion along shore bluffs of thermokarst lakes near Cherskii (Gambit 1965 vs. Ikonos-2 2002) (1 m ground resolution)

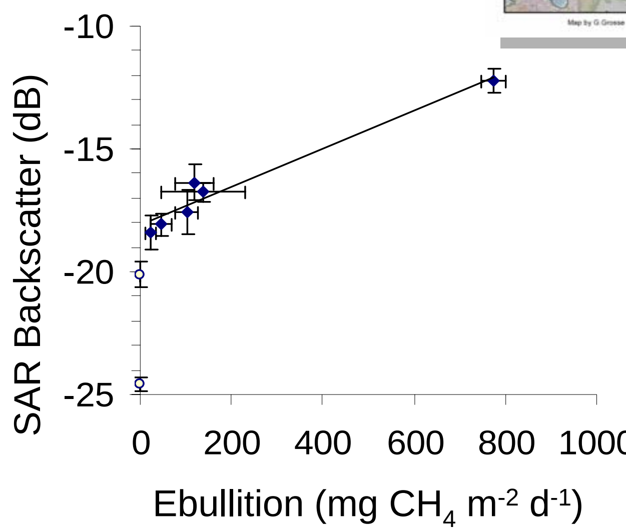
Grosse et al, in prep

PALIMMN - Pan-Arctic Lake-Ice Methane Monitoring Network

An open network to quantify methane emissions from northern lakes using field and SAR data (K. Walter & G. Grosse)

	Bubble category on ice transects	Description	Average flux (mg CH_4 d^{-1})
 a			
 b	kotenok	stacks of small individual, unmerged bubbles	25 ± 12
 c	koshka	merged bubbles clustered in multiple layers of ice	190 ± 172
 d	kotara	single large pockets of merged bubbles in ice	825 ± 348
 e	hotspot	open-hole in lake ice	2,175 ± 1,195





Collaborators so far:

C. Duguay, T. Christensen, D. White, R. Striegl, A. Larson, M. Wilmking

Challenge #1: The Remote Observation of Permafrost

How do we monitor something that is not a single object itself, sits invisible under the land surface, and is solely defined by temperature?

Present:

Young in situ monitoring networks

Good Modeling capabilities

Limited study areas

Limited availability of sensor types (resolution vs. coverage vs. spectral characteristics)

Indirect RS observation of land surface features and parameters

Goals:

- *Expand in situ monitoring coverage, parameters, temporal resolution, and network lifetime*
- *Expand to regional / hemisperical scale monitoring of general surface properties using existing sensors*
- *Annual or multi-annual RS snapshots of complete permafrost region*
- *Further develop modeling capabilities*
- *Develop new focused sensors capable of*
    - a) *sensing physical surface parameters relevant to permafrost modeling (e.g. T, snow)*
    - b) *direct observation of subsurface conditions*

Challenge #2: Data Availability and Access

Present:

Poor spatial coverage of Arctic regions
Poor temporal resolution of time series
Classification of RS data and restricted use in some countries
High costs for high-resolution data

Goals:

- *Succeed with IPY multi-sensoral snapshot (GIIPSY) and repeat*
- *Increase of temporal monitoring frequencies*
- *Develop scaling rules to bridge gaps between high and low resolution sensors*
- *Better and cheaper access to RS data*
- *Unrestricted scientific data exchange*
- *Provide RS software tools ready to use for end users*

Challenge #3: Precise Elevation Data

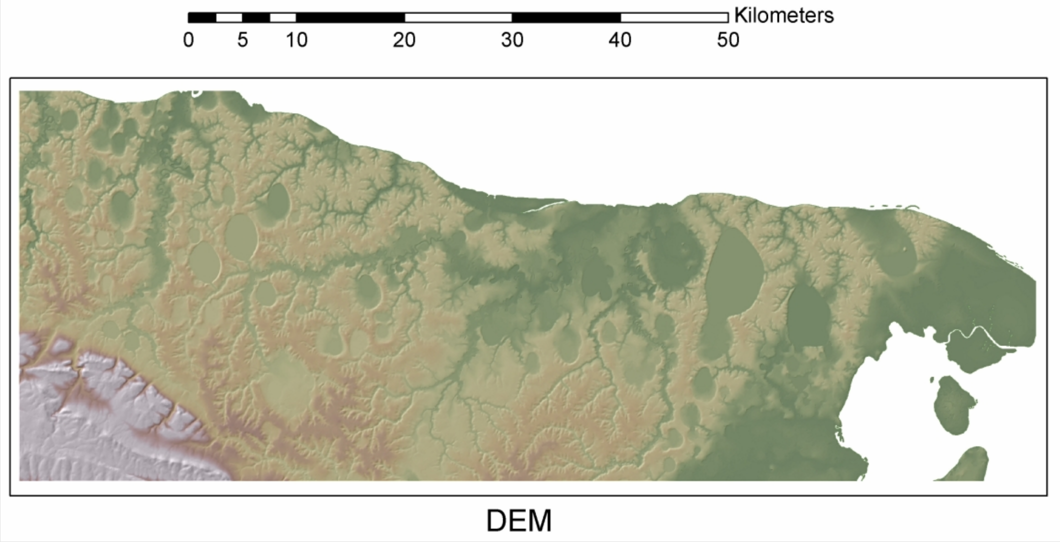
Present:
Local LIDAR or InSAR coverage (e.g. in Alaska)
DEM from analogue topographic maps 10-200m
SRTM 90m (south of 60°N only, excluding the majority of permafrost regions)
GLOBE 1km

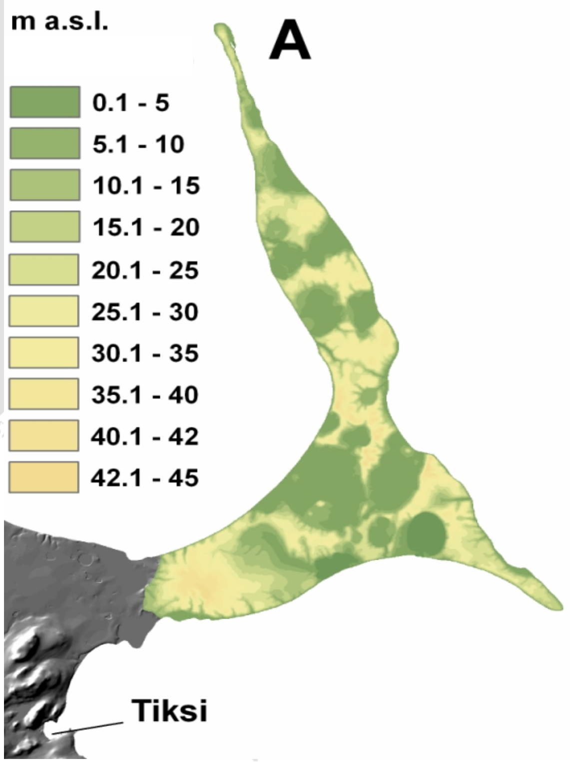
High-potential new methods:
Optical high-resolution stereo imagery
InSAR / DInSAR
LIDAR

Goals:

-Quantifying of past+future thaw subsidence (few cm / yr)

-Modeling of permafrost hydrology





Thank You

Recommendations

- *Monitoring in high detail: surface relief and thaw settlement, hydrological dynamics, coastal and fluvial dynamics, etc.*

- *Hemispherical monitoring of permafrost-relevant parameters with RS can be done with medium to coarse resolution sensors (important variables are: Temperature, snow, soil moisture, vegetation cover, incoming solar radiation, etc.)*

-*The expansion of RS capabilities with Arctic coverage and sufficient funding of ground truth networks is necessary*

- *Upscaling and modeling will play a major role in bridging the spatial and temporal gaps in understanding and predicting permafrost degradation: Delivering physical parameters from RS for modeling will be key to permafrost monitoring*