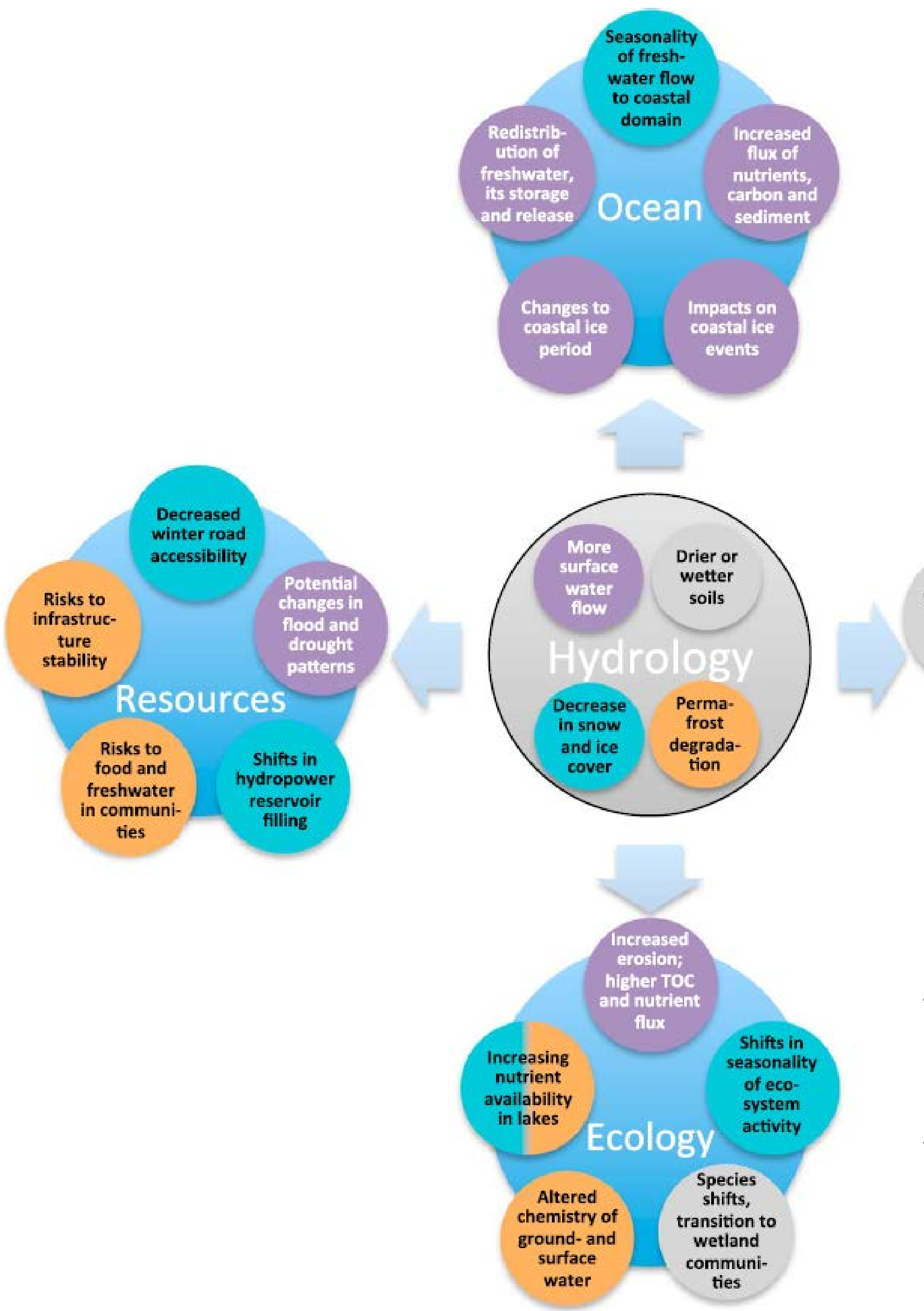
Arctic hydrology and cryospheric change

Olga Makarieva
St. Petersburg State University
Melnikov Permafrost Institute
Russia
omakarieva@yandex.ru

CRYOSPHERE 2022 REYKJAVÍK ICELAND

Support of research: Saint Petersburg State University – project 75295776, RFBR – projects No. 20-05-00666 and 19-55-80028

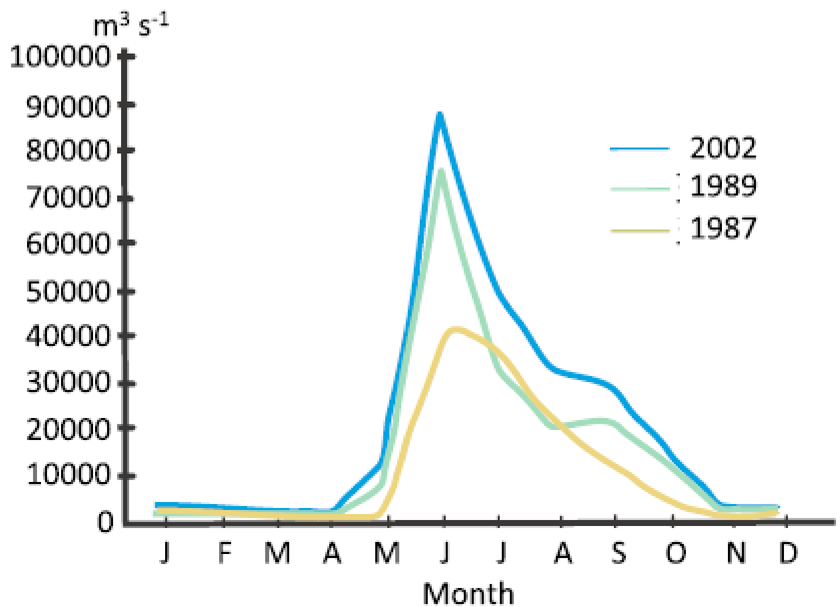
Links between terrestrial hydrology and other components



Links are colored depending on whether they are primarily pertaining to permafrost degradation (orange), decrease in snow and ice cover (blue), more surface water flow (purple), or drier or wetter soils (gray) [Bring et al., 2016]

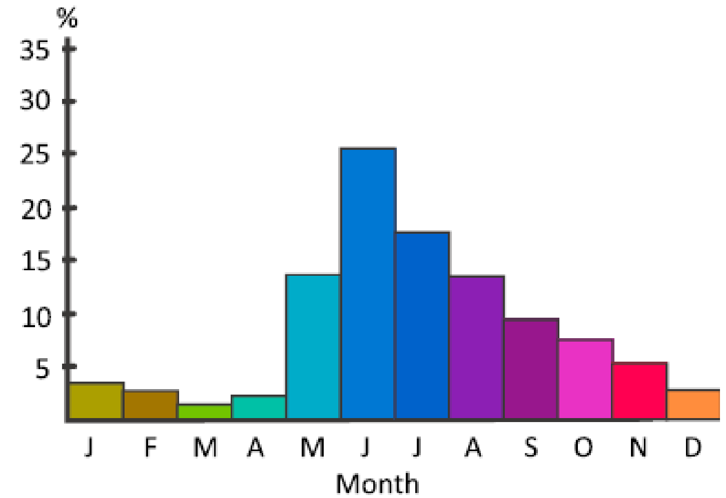
River streamflow

- There are examples of both increases and decreases in river discharge to the Arctic Ocean, but for the Arctic as a whole, flow has increased both from Eurasia and North America [Holmes et al., 2013].
- The total river flows, calculated from averages of reanalysis and in situ data, have likely increased from 3900± 390km^3 during 1980–2000 to 4200 ± 420km^3 during 2000–2010 [Haine et al., 2015], with errors assumed to be about 10%.



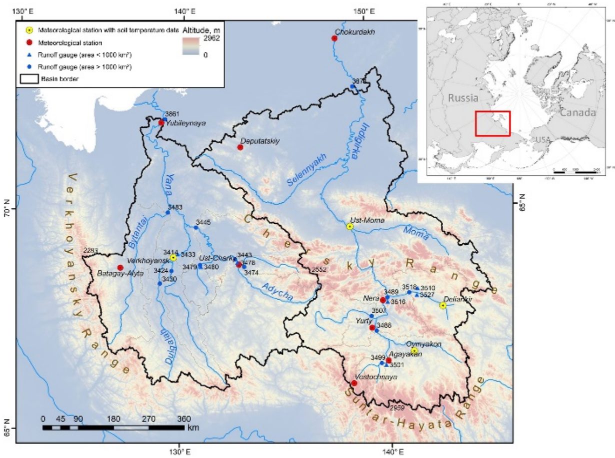
Monthly average discharge for the combined Eurasian Arctic drainage [Bring et al., 2016]

- Interannual variability is high, and the total water flow in a wet water year can be twice the flow in a dry year.

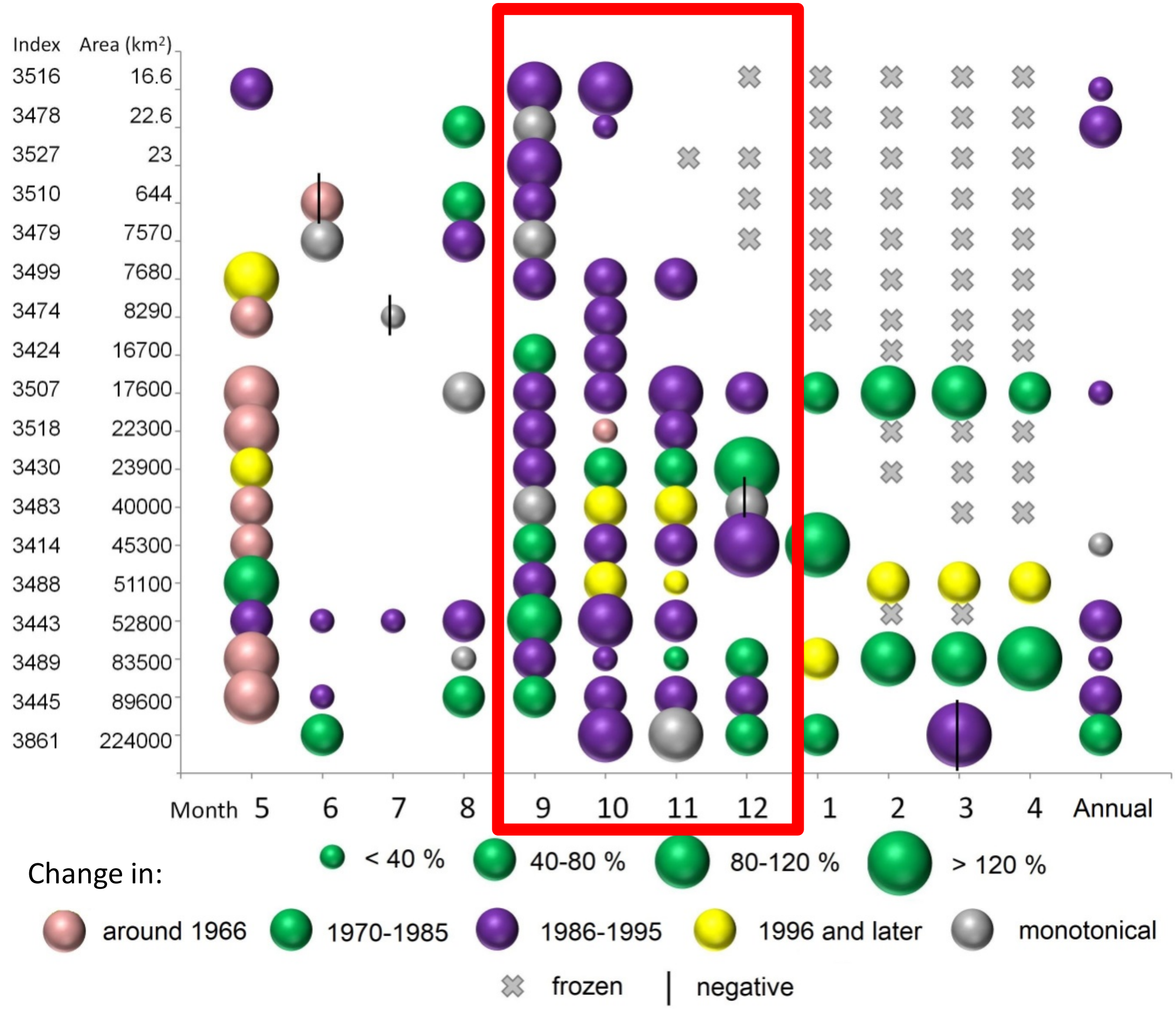


Differences in discharge between a dry and a wet year for the Lena River [Bring et al., 2016]

River streamflow



The Yana and Indigirka River basins, 1936-2015



- mountainous, continuous permafrost, 22 gauges
- positive trends in the monthly streamflow during the autumn–winter period for most of the gauges
- streamflow increases in a stepwise pattern (post-1981)
- September – 58 % or 9.8 mm, October – 61 % or 2.0 mm
- November (54 %, 0.4 mm)
- December (95 %, 0.15 mm).

[Makarieva et al., 2019]

River streamflow

The Lena River basin
1936-2015

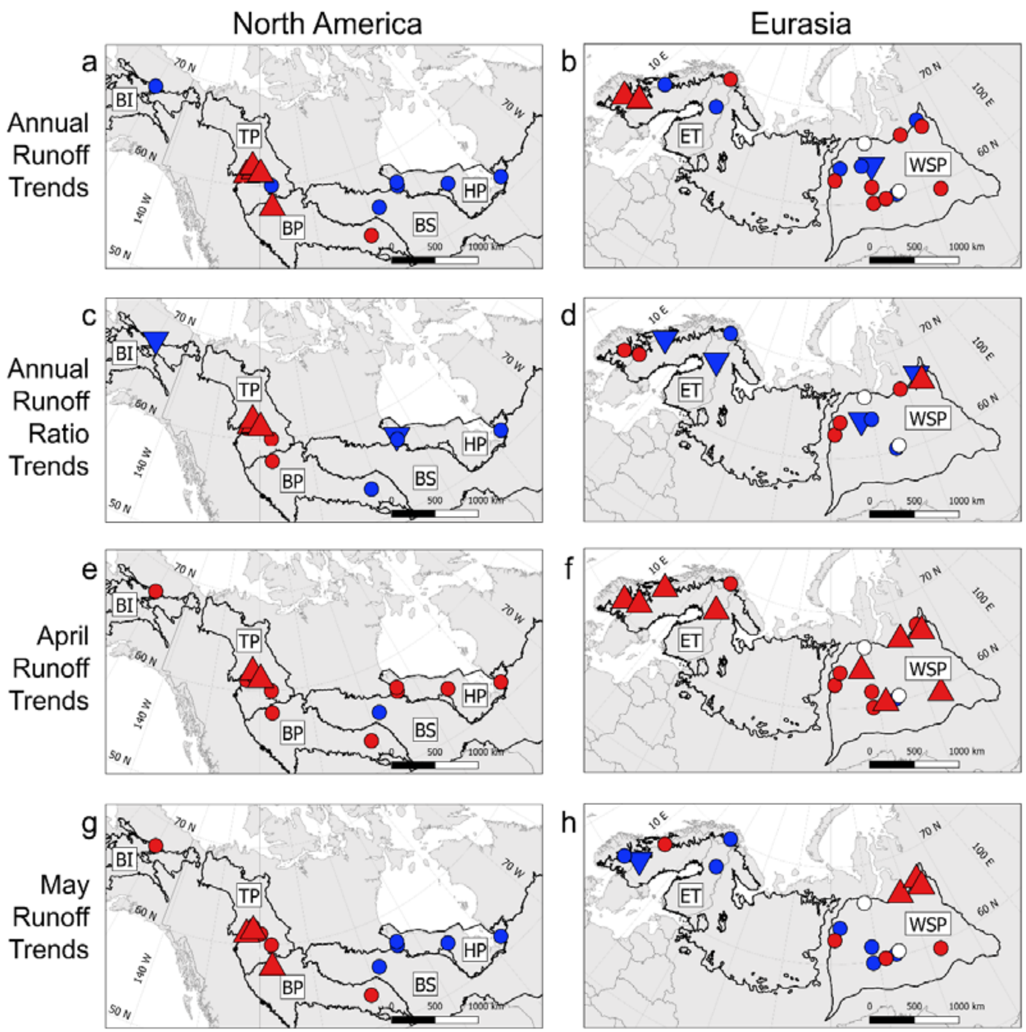
32 of the 96 studied time-series showed significant trends in mean annual daily flow (2 negative, 30 positive).

Positive trend magnitude varies from 14.3% to 184.2%, and all-records average is 40%.

31 of the 48 records showed trends in Q_{min} (2 negative and 29 positive).

[Tananaev et al., 2016]

River streamflow



△ positive and significant trends, ● positive trends, ▽ negative and significant trends, ● negative trends

Taiga Plains (TP), Hudson Plains (HP), Boreal Shield (BS), Boreal Plains (BP), Boreal Interior (BI), European Taiga (ET), and Western Siberian Plain (WSP)

Peatland-dominated basins in discontinuous and sporadic permafrost, 1970-2016

- Increased annual runoff ratios occurred exclusively in basins overlying permafrost.
- Streamflow during winter increased significantly in all ecoregions and occurred independently of the areal extent of permafrost, although the magnitude of these increases was small compared with those of April and May.

[Mack et al., 2021]

River and lake ice cover

- Lake and river ice grow to cover 1.7×10^6 km^2, an area approximately equal to the Greenland ice sheet. The peak volume of 1.6×10^3km^3 roughly matches the Northern Hemisphere snowpack on land [Brooks et al., 2013].

- Shortening duration, with the time of breakup generally changing more rapidly than the freeze up [Benson et al., 2011].

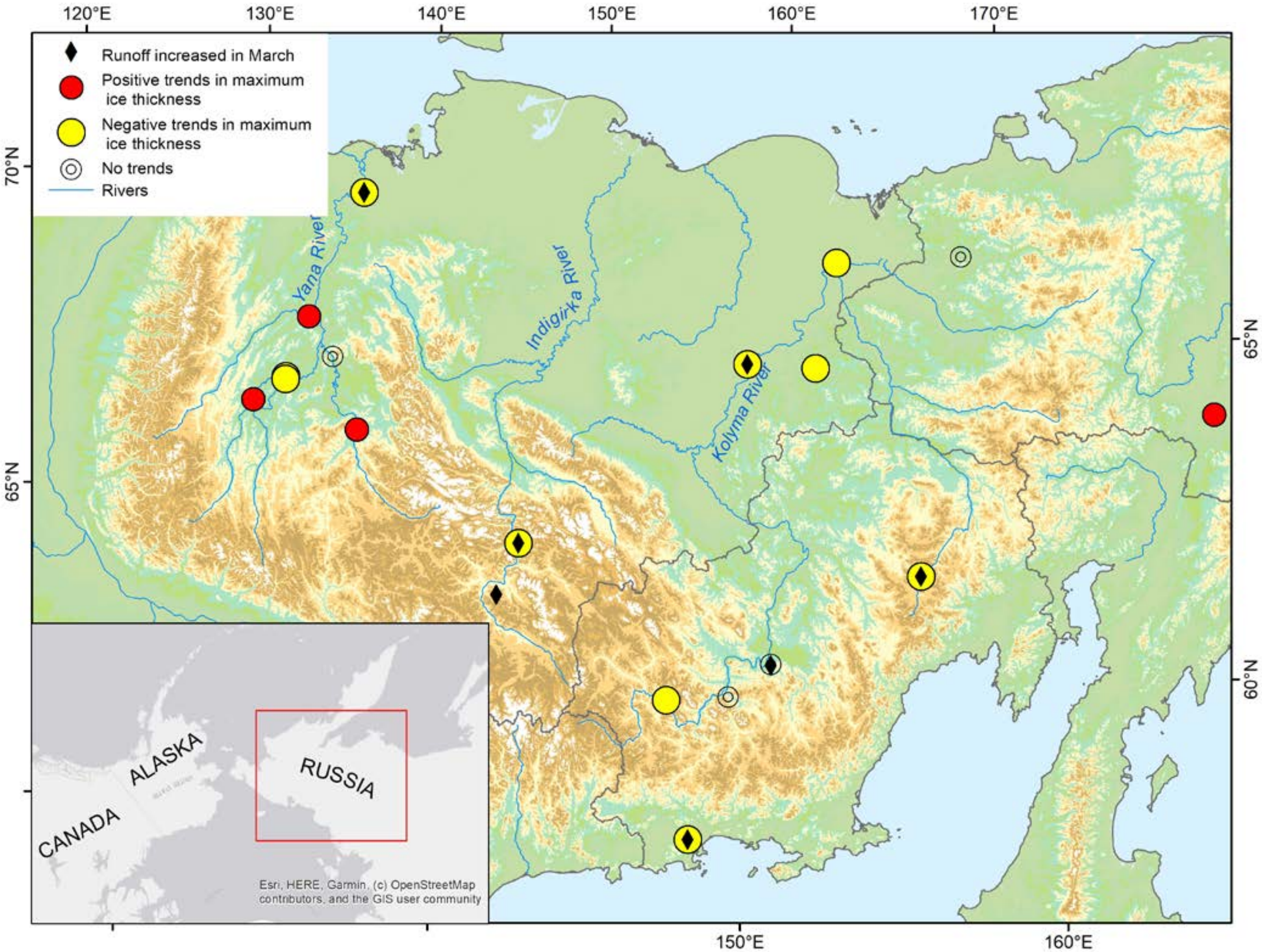
- The most rapid changes occurred in the most recent 30 year period, with freeze up 1.6 d/decade later, breakup 1.9 d/decade earlier, and ice duration 4.3 d/decade shorter.

- Although ice cover tends to be more sensitive to air temperature variations at lower than at higher latitudes [Livingstone et al., 2010], remote sensing observations indicate that ice cover loss seems to be more rapid in very high latitude lakes [Latifovic & Pouliot, 2007].

- In terms of river ice observations, there is almost universal trend toward earlier breakup dates but considerable spatial variability in those for freeze up.

- Changes are often more pronounced during the last few decades. There is a 10 to 15 day advance in breakup and delay in freeze up, respectively [Beltaos & Prowse, 2009; Lique et al., 2016].

River and lake ice cover. NE Russia



North-East of Russia
1970-2020

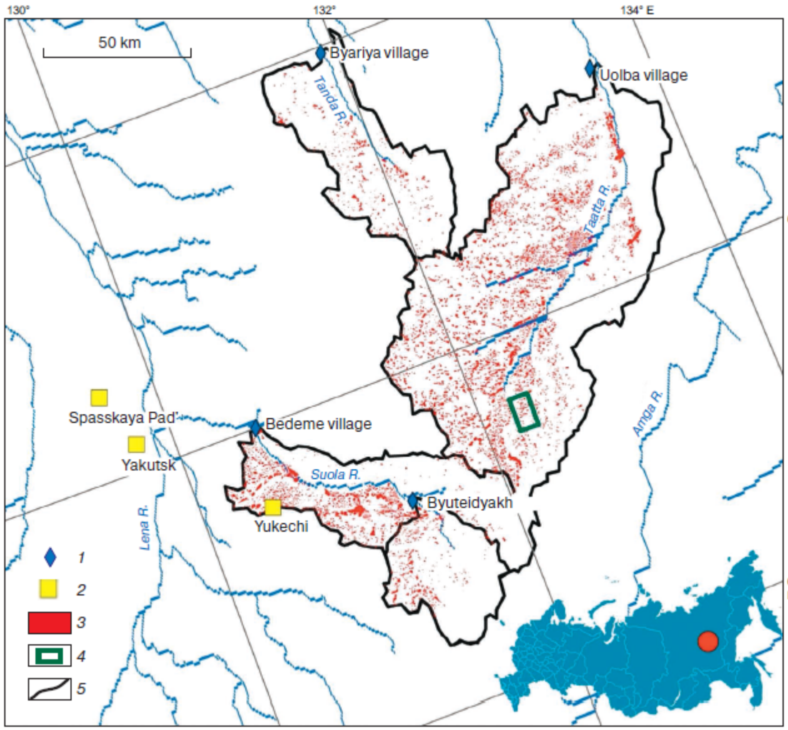
- On average, the decrease of river ice cover maximum depth was **39 cm (27%)**
- The period of formation of river ice with a thickness of 60 cm (necessary for using winter roads for passenger cars) has shifted to later period **by 7-40 days**.

Wetlands and lake area

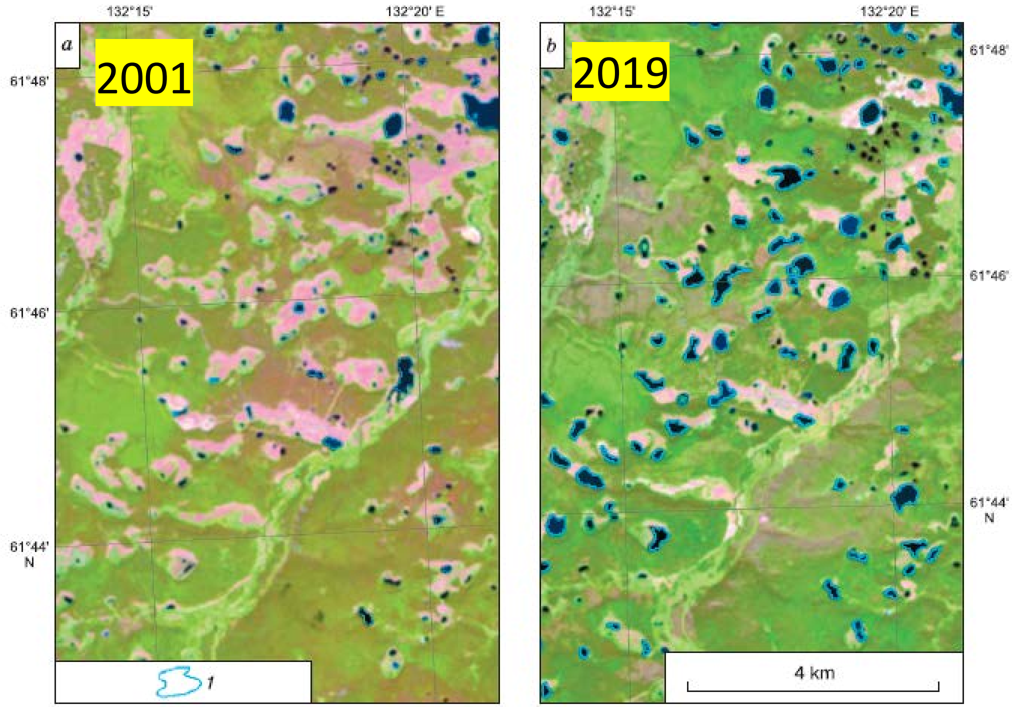
- Generally, the changes in number and area of wetland lakes and ponds depend on the local permafrost and hydrological conditions.
- Lakes have mostly decreased in size and number in areas where discontinuous and sporadic permafrost thaw is in progress [Andresen and Lougheed, 2015].
- In these areas, flow paths and water tables are becoming deeper, and lakes may also drain as the permafrost substrate is breached.
- In contrast, increases, decreases, or no change in lake size and number are reported from areas in continuous permafrost [Kirpotin et al., 2008; Jones et al., 2011; Andresen and Lougheed, 2015].
- A significant decrease in the area of thermokarst lakes in the northwestern part of Alaska has been noted due to an increase in the intensity of thermoerosion processes [Jones, Arp, 2015; Swanson, 2019].
- In the Northwestern Territories of Canada, the total area of thermokarst lakes generally increased between 1978 and 1992 and decreased between 1992 and 2001 [Plug et al., 2008].
- In Russia, multidirectional changes in the area of thermokarst lakes have been revealed only in 8 out of 20 reference areas located in different parts of the cryosphere [Kravtsova, Bystrova, 2009].

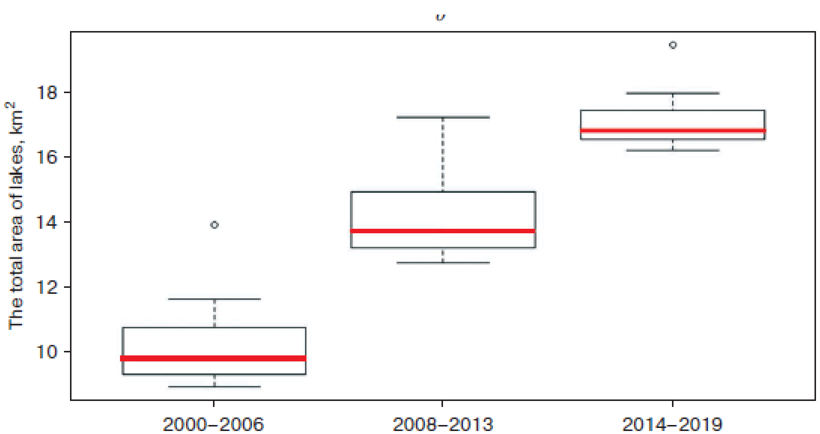
Thermokarst lakes,Central Yakutia

Study area



Landsat images

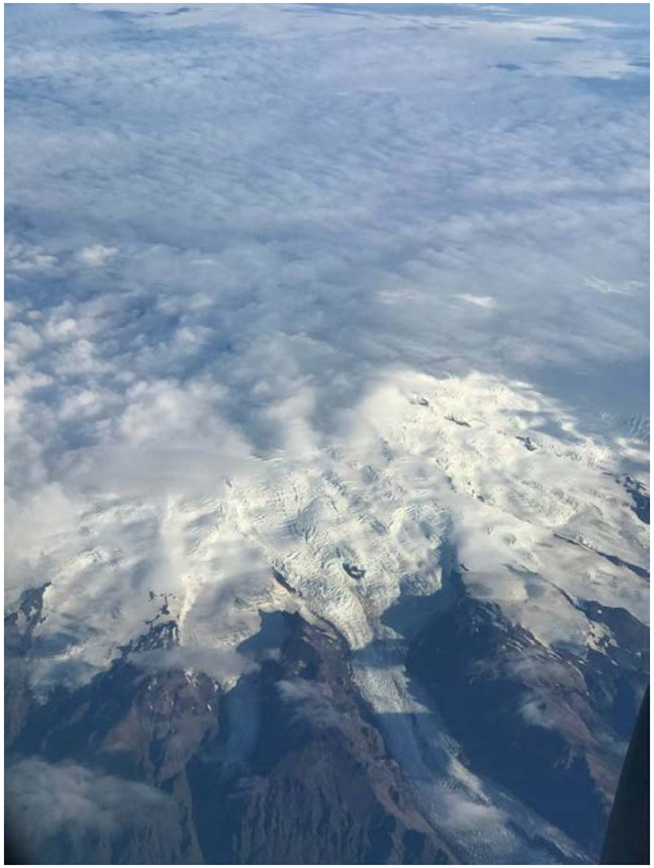




Changes of lake area

- Central Yakutia, the area of the lakes doubled over the 20-year period
- The increase occurs in a step-wise manner
- The main factor leading to disturbance of the stable state of the thermokarst lakes is the short-term (1–3 years) periods of the anomalous increase in the temperature of the seasonally thawed layer.

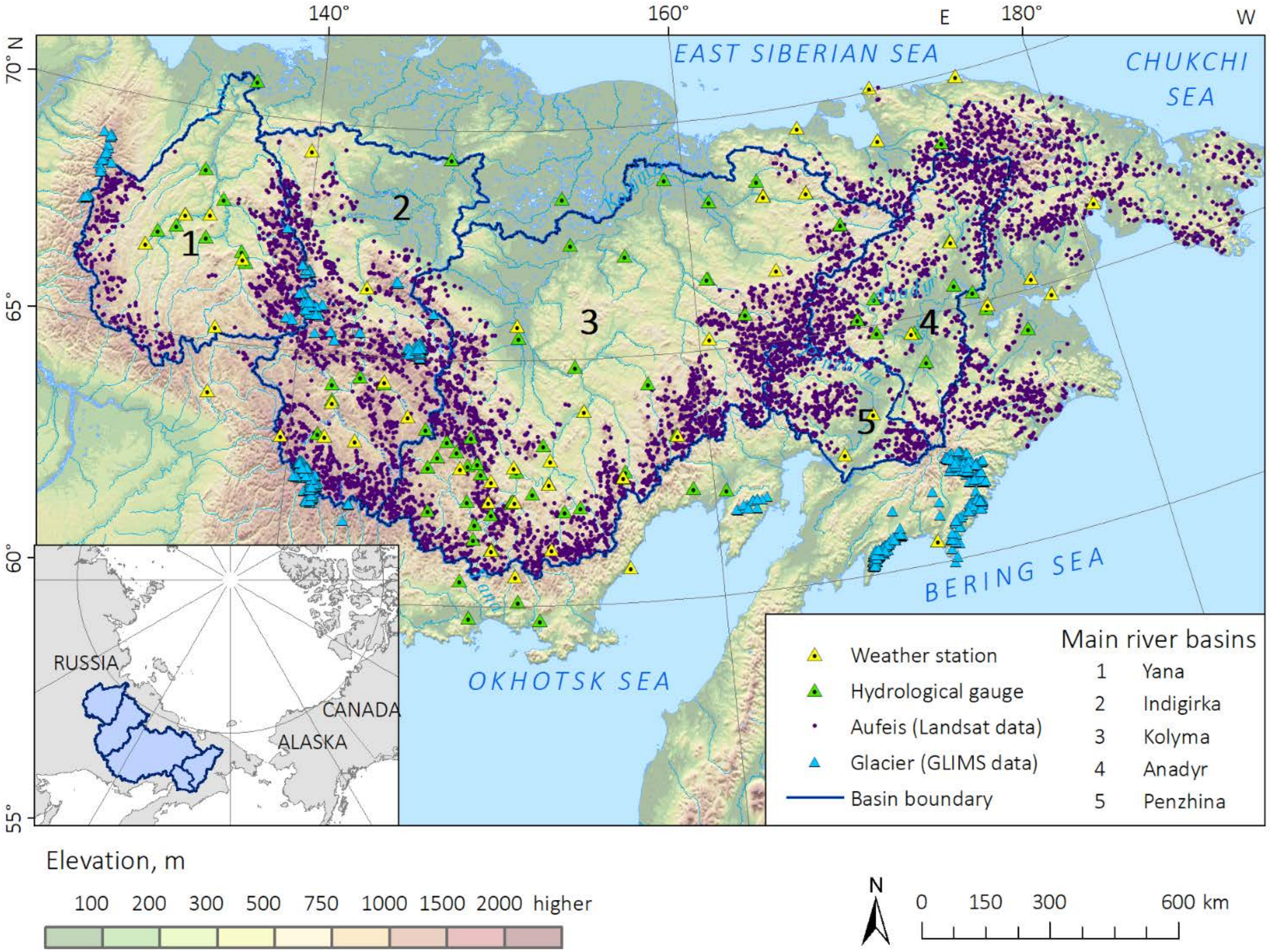
Glaciers

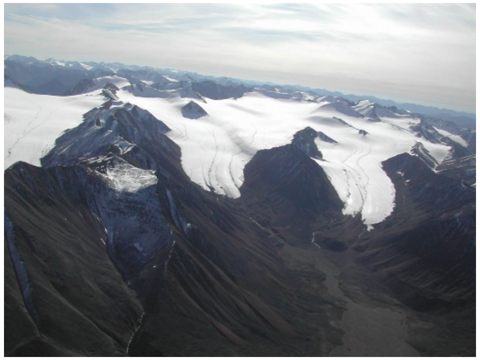


- Of the several thousands of glaciers that are located in the pan-Arctic, only ~25–30 have ongoing operational mass balance programs to quantify glacier mass balance conditions and change [World Glacier Monitoring Service, 2013].
- Since the early 1990s, the increasing glacier and Greenland ice sheet (GrIS) net mass loss and surface runoff have followed atmospheric warming [Mernild et al., 2014; Lique et al., 2016].
- Mass loss from the GrIS has increased rapidly, with recent estimates of 375 ± 24 $km^3 yr^{-1}$ for 2011–2014 [Helm et al., 2014].
- For Greenland, runoff was estimated to 481 ± 85 km^3 yr^{-1} for 1960–2010 [Mernild and Liston, 2012].
- For some smaller basins, mass balance change constitutes a substantial share of river runoff. For example, about 35% of runoff from the Mittivakkat Glacier basin in southeast Greenland originates from net mass balance loss [Liston and Mernild, 2012].

Glaciers

North-East of Russia

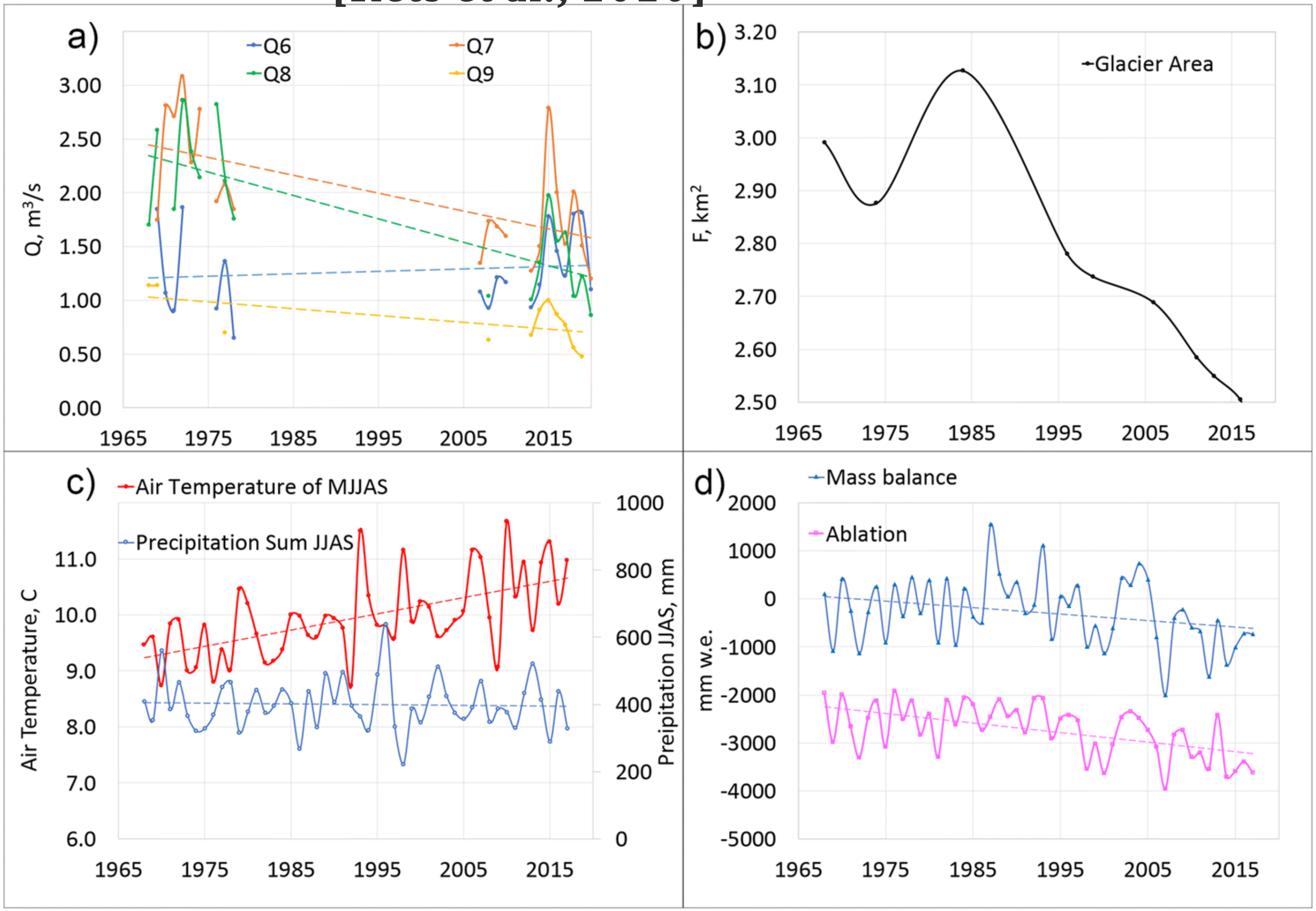




- The loss of glacier ice volumes for the Suntar–Khayata and Chersky ranges are 1.7 and 1.4 km^3 for the periods 1945–2003 and 1970–2003 [Ananicheva, 2014]
- The annual maximum input of glacier runoff to streamflow in the Indigirka River basin was passed in the period 1980–2010 and is expected to decline in the future [Huss & Hock, 2018]

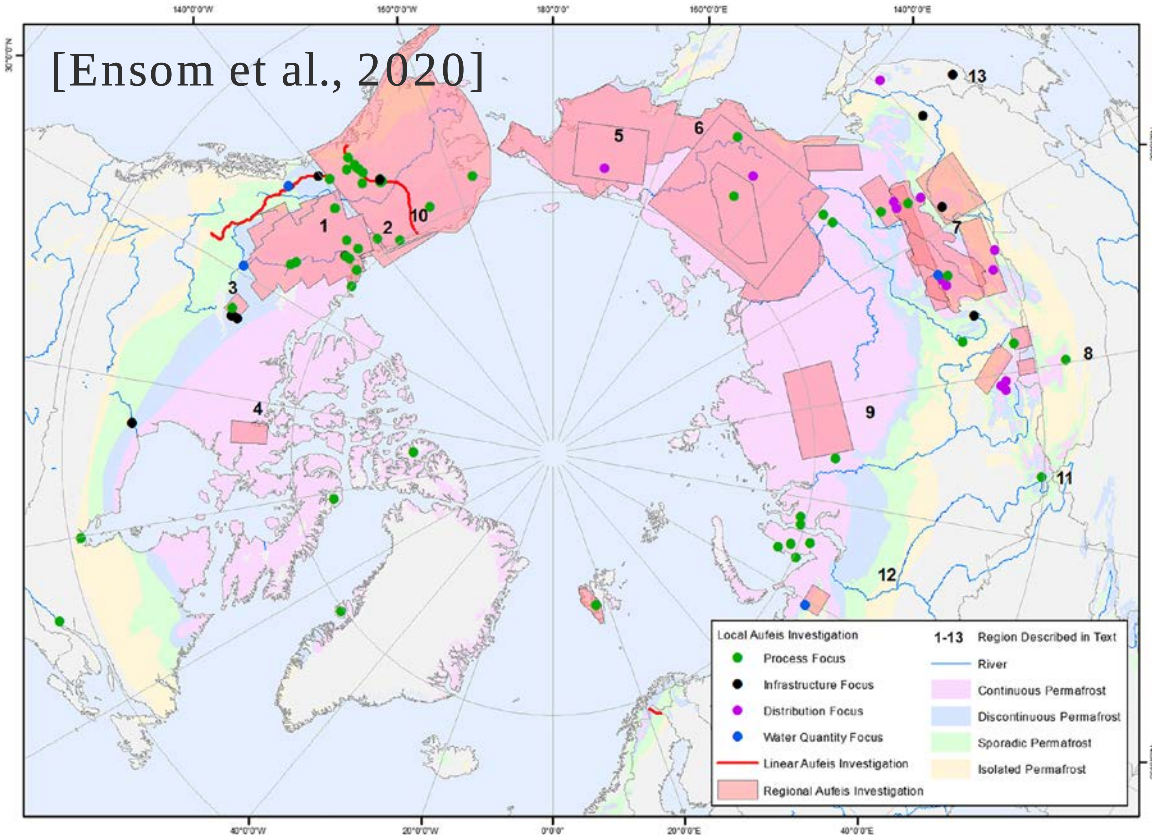
Glaciers

It is likely that the peak water of glacial runoff has already been passed in <u>the central North Caucasus</u> [Rets et al., 2020]



Long-term dynamics of monthly runoff of the Djankuat river (June – Q_6, July – Q_7, August – Q_8, September – Q_9; dashed lines show linear trends) (**a**) in comparison with oscillation of the Djankuat glacier area (Glacier area) (**b**), mean air temperature from May to September measured at the Terskol weather station (Air Temperature MJJAS), precipitation sum from June to September (Precipitation Sum JJAS) (**c**), and specific mass balance (mass balance) and annual ablation (Ablation) of the Djankuat glacier (**d**)

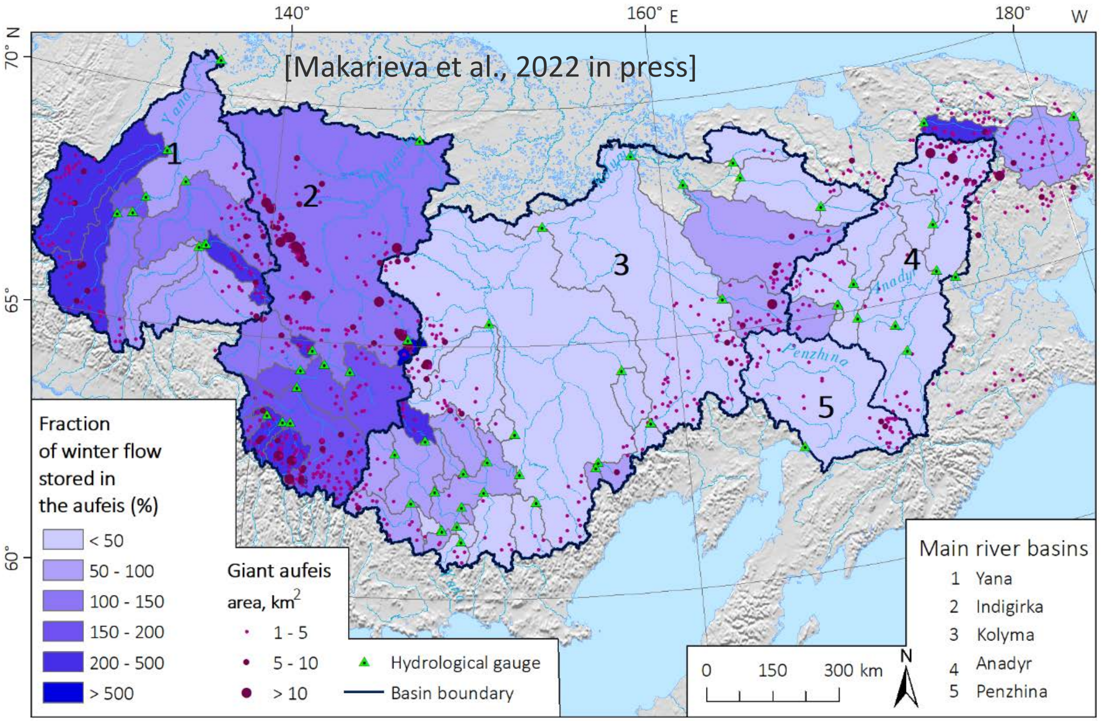
Aufeis



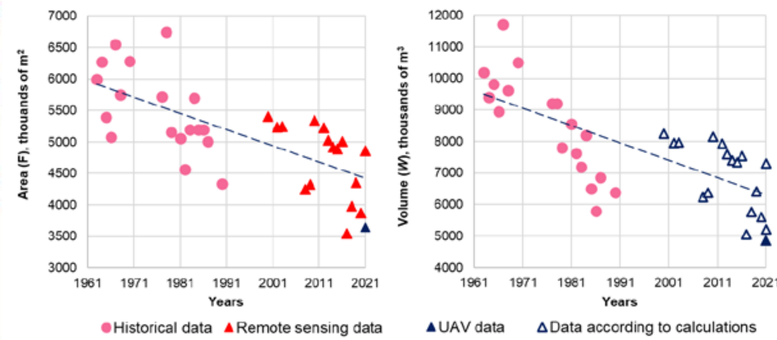
Aufeis, (icing or naled), is an accumulation of ice that forms primarily during winter when water is expelled onto frozen ground or ice surfaces and freezes in layers.

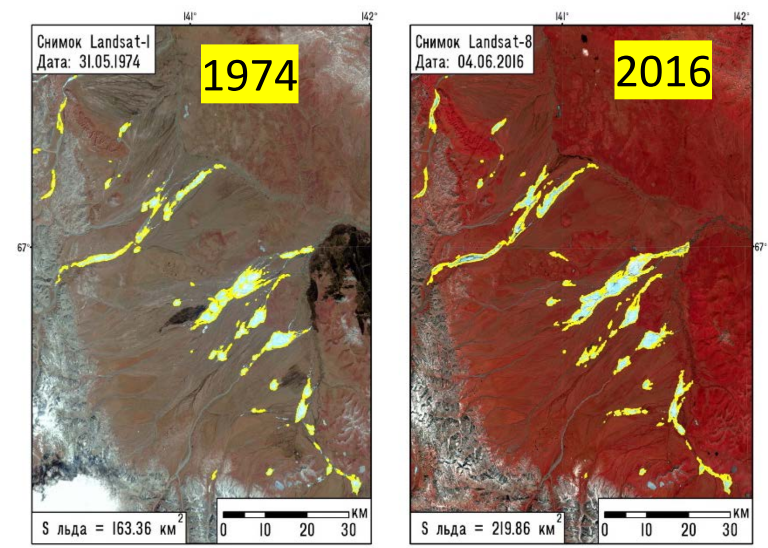
The result of the interaction of surface and ground waters in permafrost conditions.

Spring aufeis – underestimated resource



[Zemlianskova et al., 2022 in press]
The Anmangynda aufeis area and volume decreased by 25-30% in 1962-2021

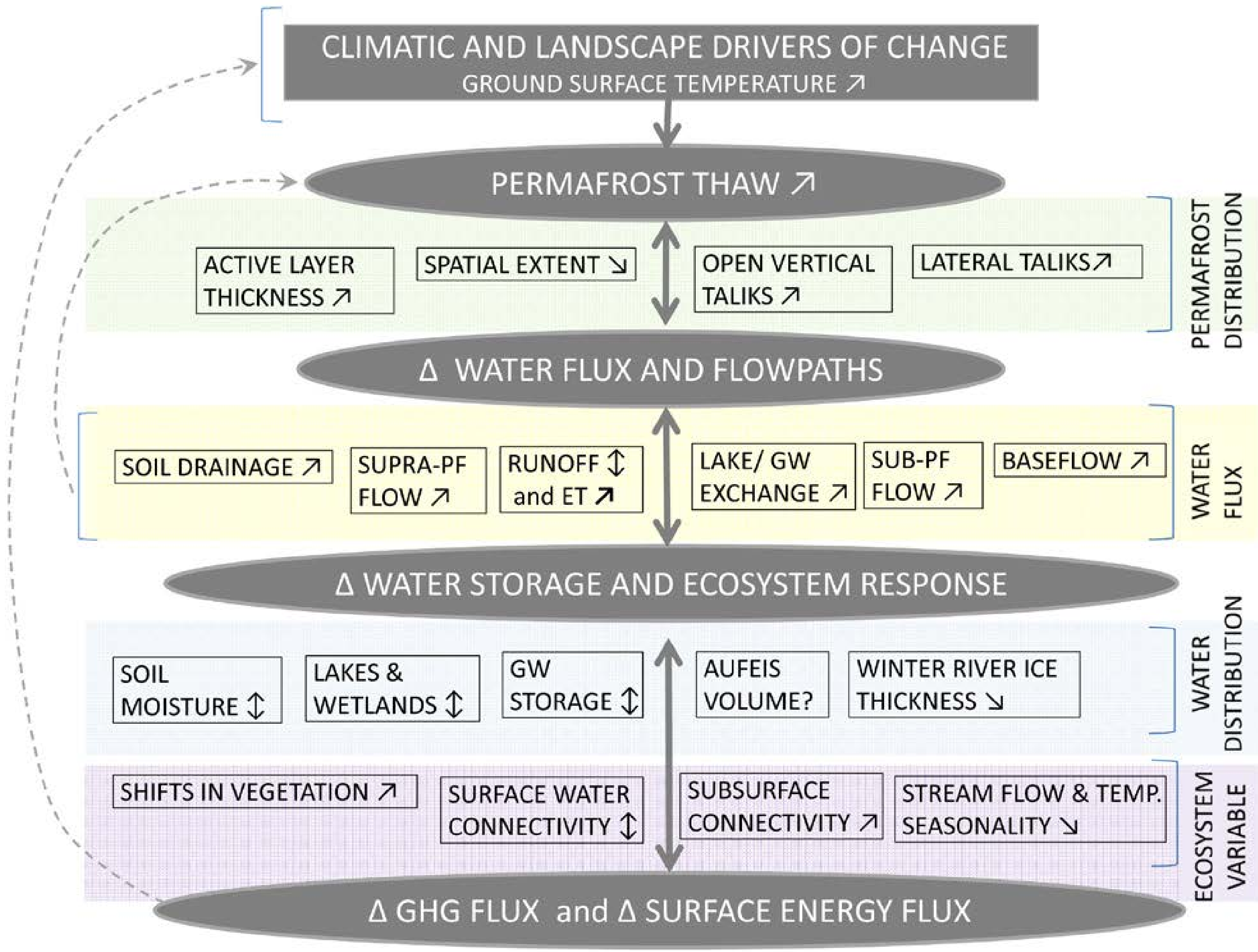




- The number of aufeis has increased by 1.4 times, the total area has decreased by 1.6 times (1958-2019).
- The aufeis resources are at least 10.6 km^3 or 5 mm of aufeis runoff per year.
- The estimate of aufeis impact in the runoff: annual runoff – from 0.3 to 29 mm (0.1 – 22% with the average value 3.8%); winter runoff – from 6 to 712 % (average 112%); spring freshet runoff – from 0.2 to 43% (average 7.1%).

Some giant aufeis fields (individual area may reach up to 72 km^2) have not changed since 1950s. This phenomenon has not been studied so far.

Permafrost



Overview of impacts and feedbacks of permafrost thaw on water fluxes and distribution [Walvoord & Kurylyk, 2016]

Permafrost

- Permafrost thaw has changed the hydrological regime in some basins, particularly through altered surface and subsurface interactions through the transformation of landscapes.

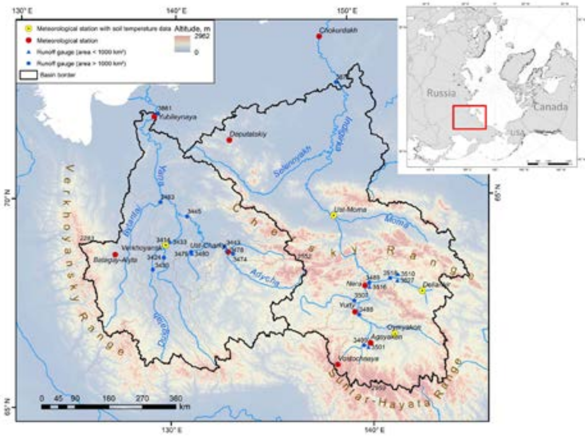
- For example, Connon et al. [2014] report observed increases of annual runoff in the lower Liard Valley (NWT, Canada) by between 112 and 160 mm over the period of 1996–2012, mainly due to increase of plateau runoff contributing areas and a change in the relative proportions of the major land cover types, such as peat plateaus, channel fens, and flat bogs.

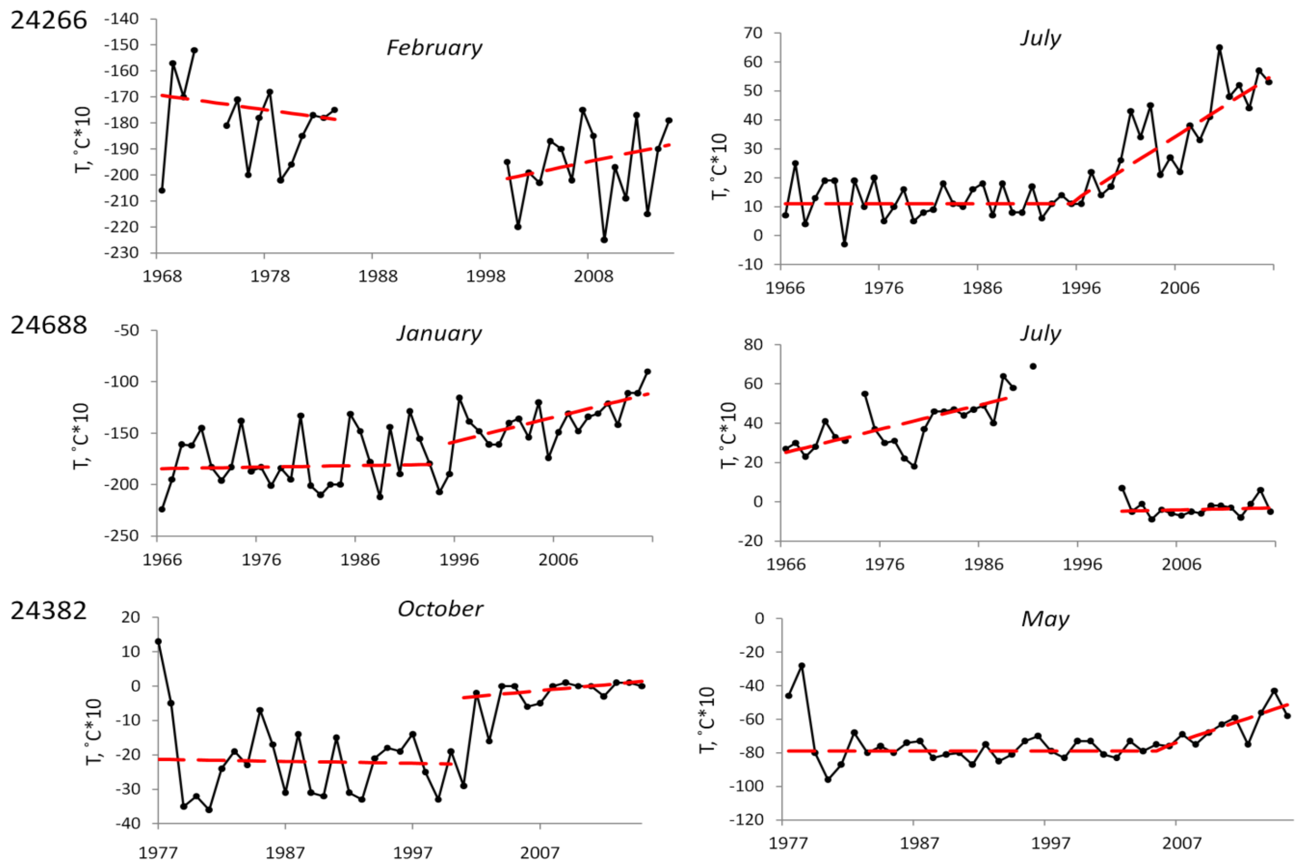
- In contrast, ground ice melt has not been responsible for any significant contribution to historical streamflow increases [McClelland et al., 2004; Pavelsky & Smith, 2006; Zhang et al., 2013], although an exact quantification remains uncertain.

Permafrost data

Very few meteorological stations of Russian Hydrometeorological Service monitoring ground temperature at 0.8 – 3.2 m depth in **2008**

Permafrost. North-East Russia





Overall, there is an increase in the annual soil temperature at a depth of 80 cm by +1.7 °C

Limited observations

Observation errors

Multidirectional trends

[Makarieva et al., 2019]

Precipitation

- Northern Hemisphere snow cover extent decreased by 2.2% per decade, averaged for March and April, and by 14.8% per decade for June, over the period 1979–2012 [Vaughan et al., 2013].
- Both positive and negative regional trends are distributed throughout the pan-Arctic, however, including spatially distinct areas of increasing and decreasing snow water equivalent or snow season length [Callaghan et al., 2011].
- As winter air temperature increases, observations of rain-on-snow events become more common in Arctic regions where they were rarely seen before [Vihma et al., 2016; Instanes et al., 2016; Wrona et al., 2016].
- Overall, a number of reanalysis, modeling, and observation-based studies show that increased atmospheric moisture transport, due to higher temperatures and changing atmospheric circulation, is likely the principal driver of long-term increases of streamflow [Zhang et al., 2008, 2013; Rawlins et al., 2009; Troy et al., 2012; Vihma et al., 2016].

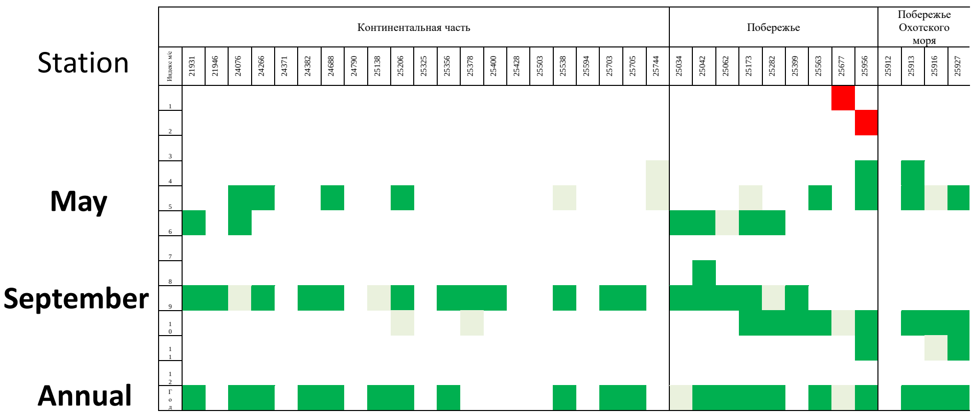
Precipitation. NE Russia

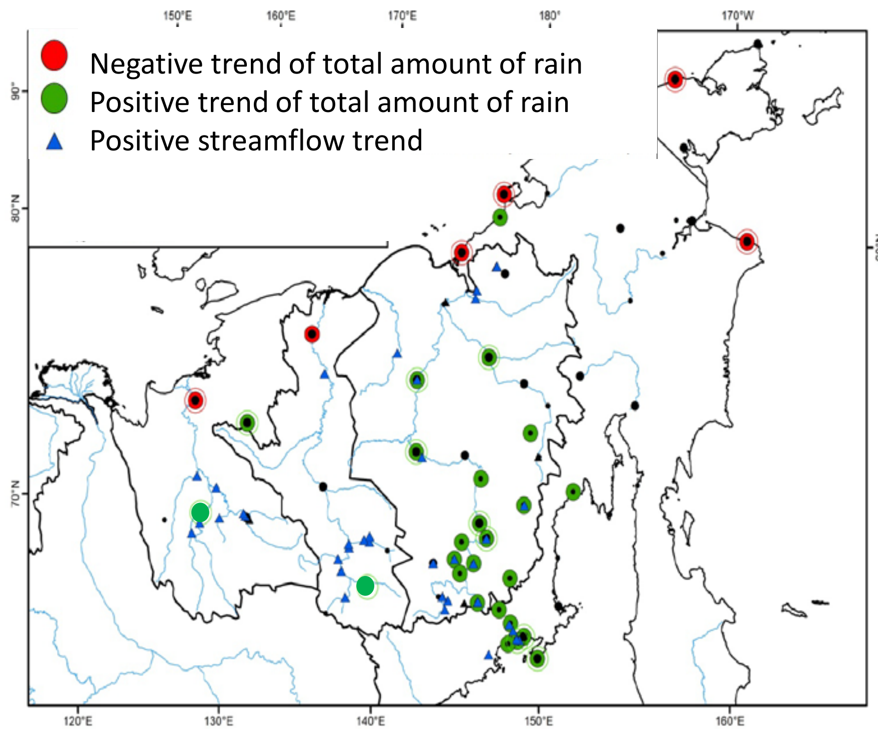
Increase in the proportion of liquid precipitation in the transition months

Total amount of rain is increasing in August and September

The increase in air temperature led to a change in the ratio of "rain-snow"

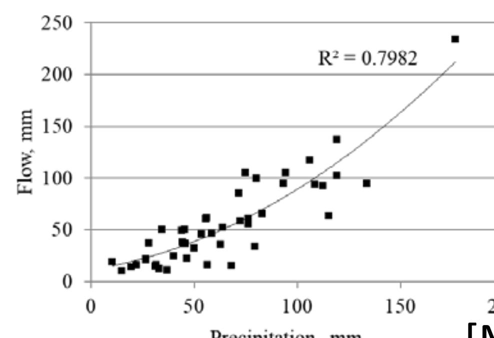
Share of rain is increasing in September and annually





- The amount of solid precipitation has decreased by about 20-25 mm, half of which falls as rain, and the other half is the result of a decrease in precipitation at the end of winter.

- The increase in low-water runoff is due to the transition of the precipitation type from solid to liquid and the corresponding increase in runoff in September, which continues in the following months.



[Makarieva et al., 2019]

Nutrients and sediments flow

The total delivery of water constituents such as nutrients, sediment, and carbon is less known than that of the freshwater itself [Bring & Destouni, 2009],

but recent estimates indicate fluxes in the Arctic such as:

- total nitrogen amounting to 1.3 Tg N yr^{-1} [Holmes et al., 2011],
- total phosphorus 73 Gg P yr^{-1} [Holmes et al., 2011],
- sediment 324–884 Tg yr^{-1} [Hasholt et al., 2006],
- inorganic carbon 57± 9.9 Tg C yr^{-1} [Tank et al., 2012],
- dissolved organic carbon 34–38 Tg C yr^{-1} [Holmes et al., 2011].

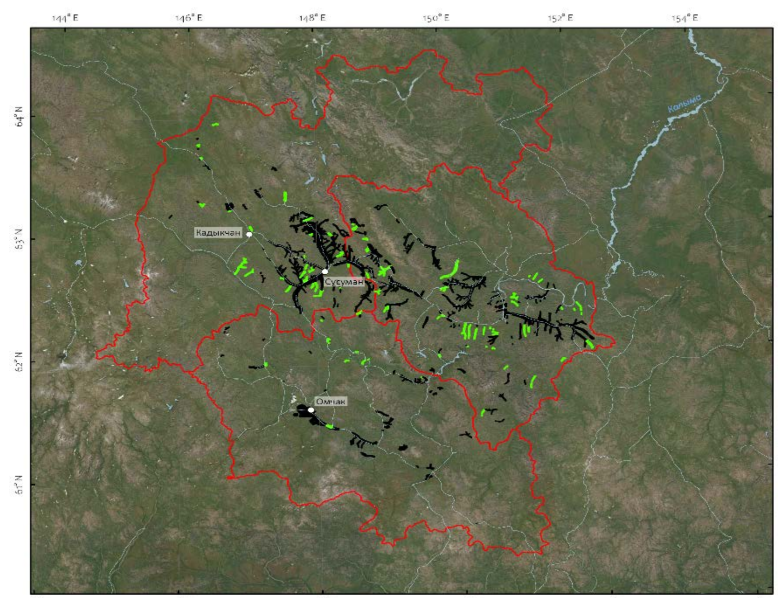
Carbon from rivers is a key input to near-coastal and ocean acidification [Carmack et al., 2016].

Teragram=10^9 kg, Gygagram=10^6 kg

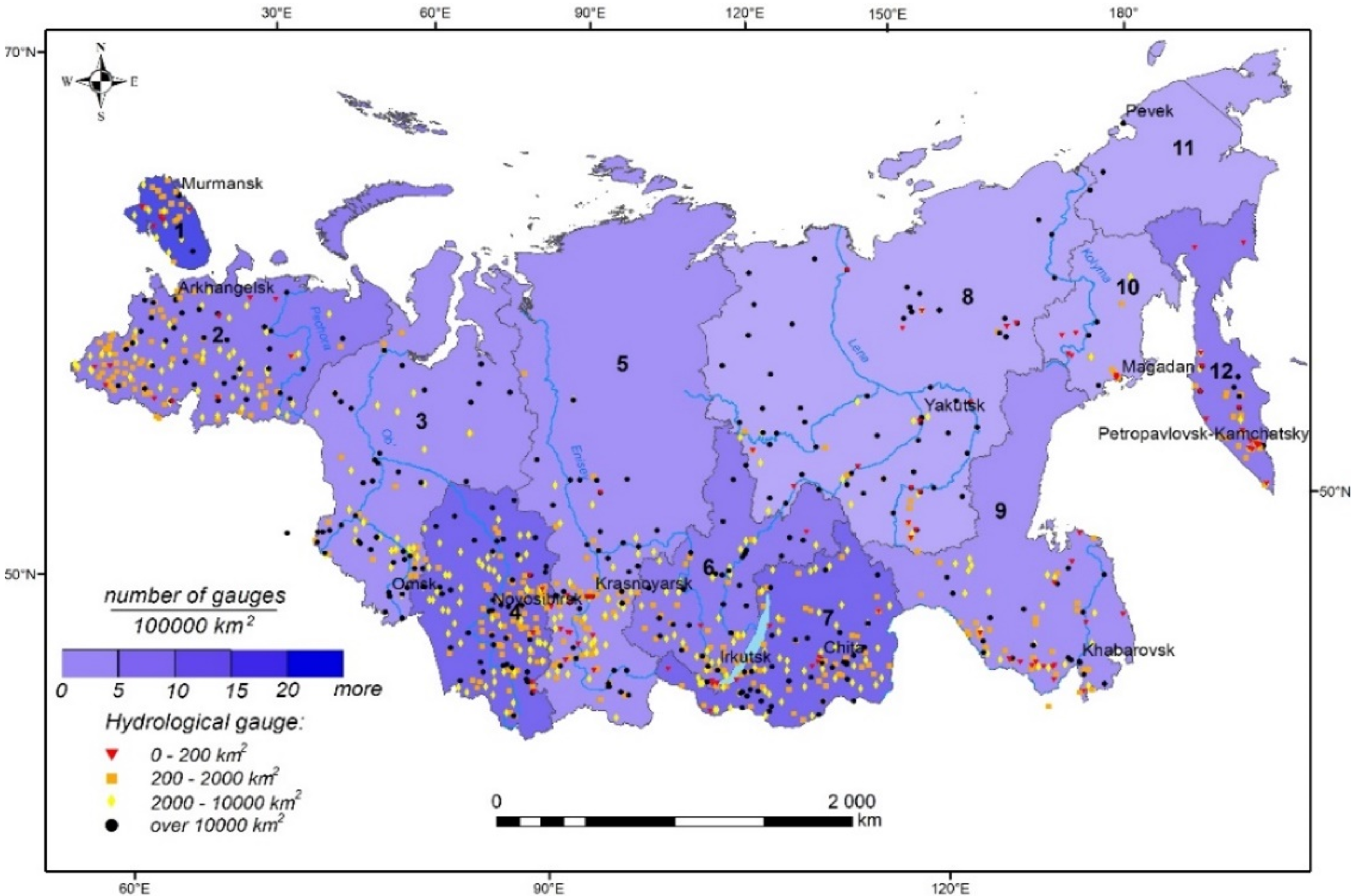
Anthropogenic landscape disturbance. NE Russia

Images of active gold mining sites (a) and mined-out areas (b)

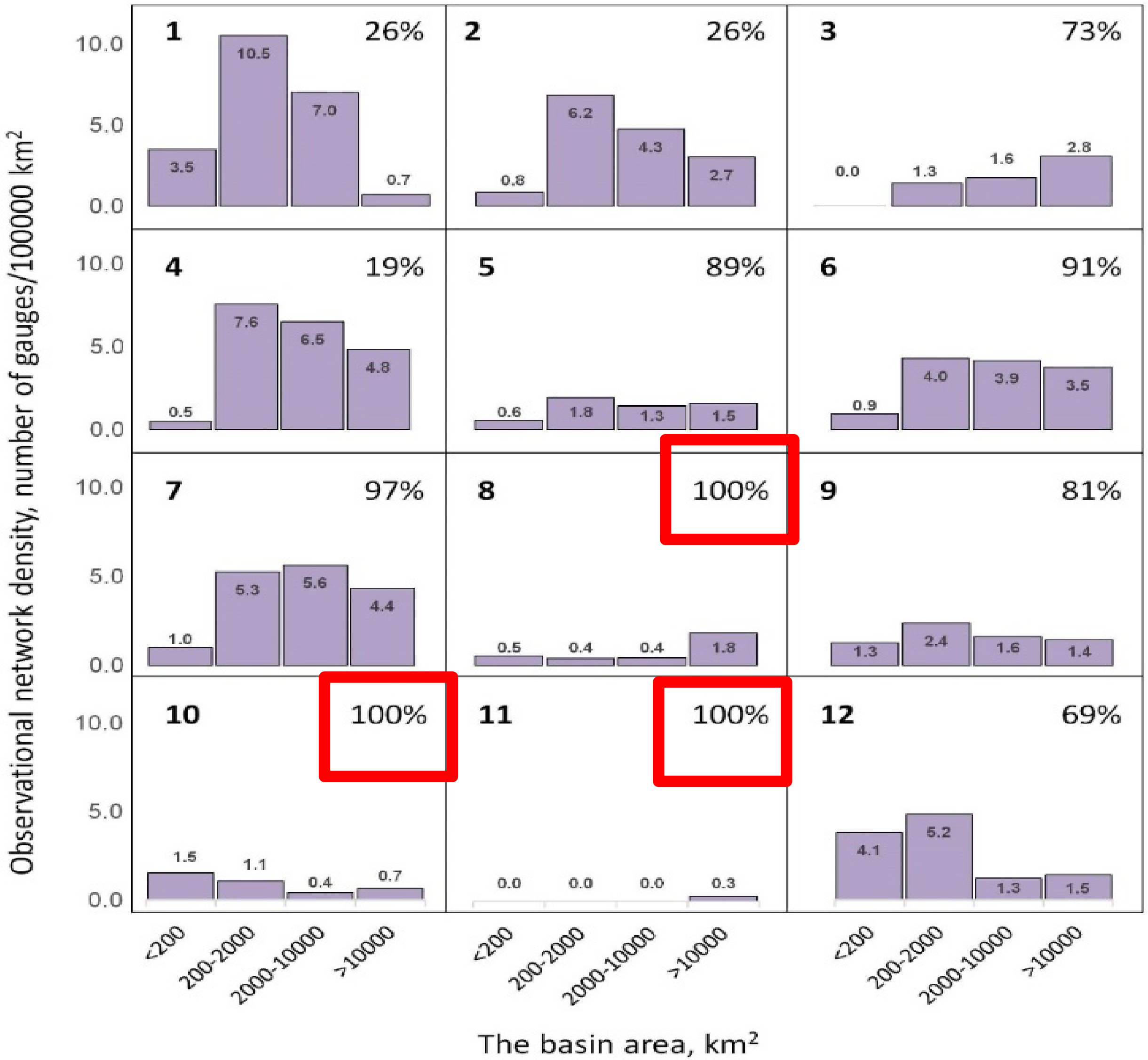
- About 2% of the Upper Kolyma River basin has been disturbed as a result of gold mining, of which only 10% are experiencing vegetation restoration processes.
- At some territories, there is an increase in the area of disturbed lands by more than 7 times over the period 2001-2021.
- Suspended matter concentration increase by 2-16 times depending on a season.



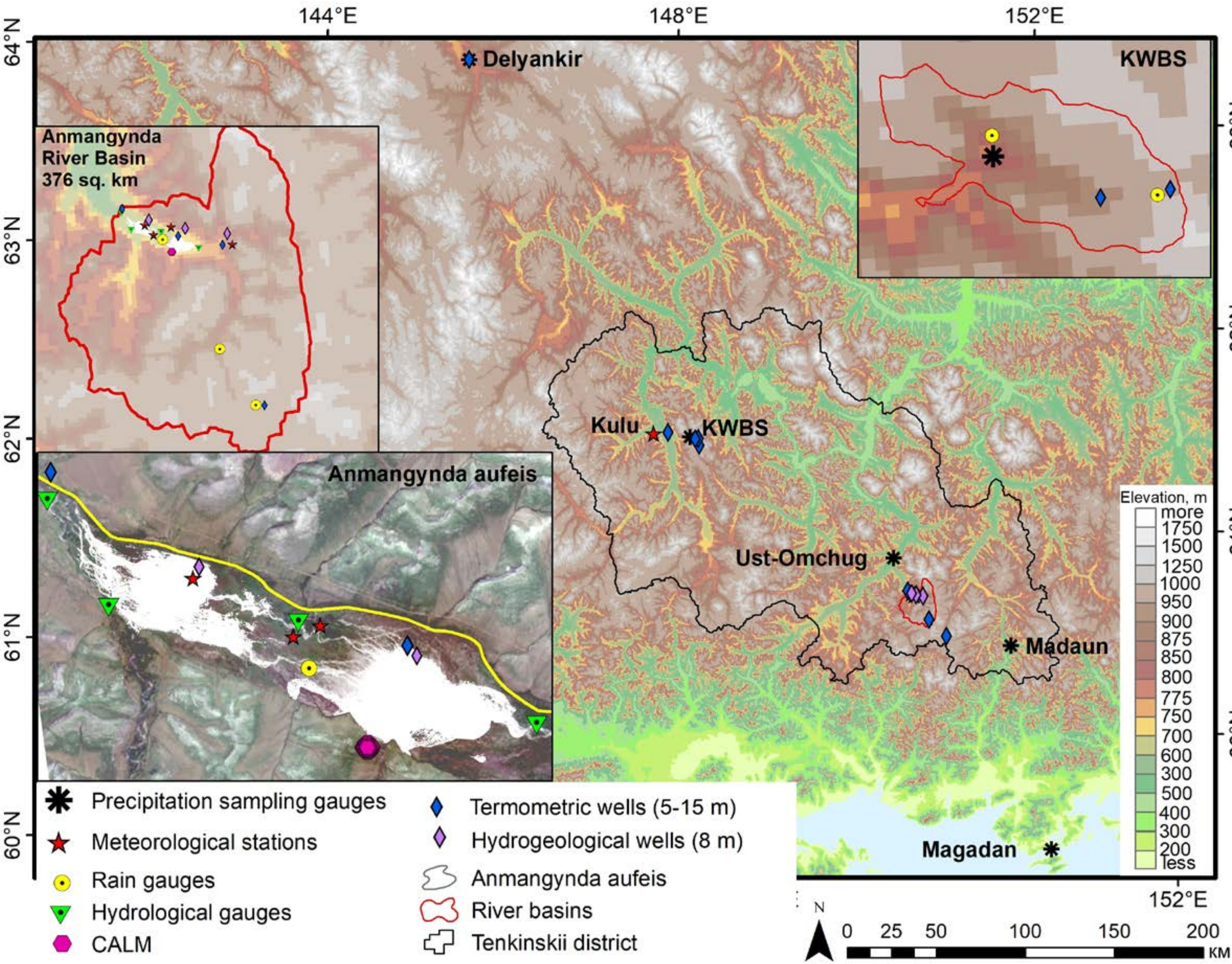
Hydrological network in permafrost zone of Russia



Density of hydrological gauges in the regions with different proportion of permafrost coverage, Russia



Developing research network, NE Russia, 2020-2022



2 meteorological stations

5 rain gauges

4 hydrological gauges

10 thermometric wells (5-15 m)

3 hydrogeological wells (5-12 m)

CALM plot (2022)

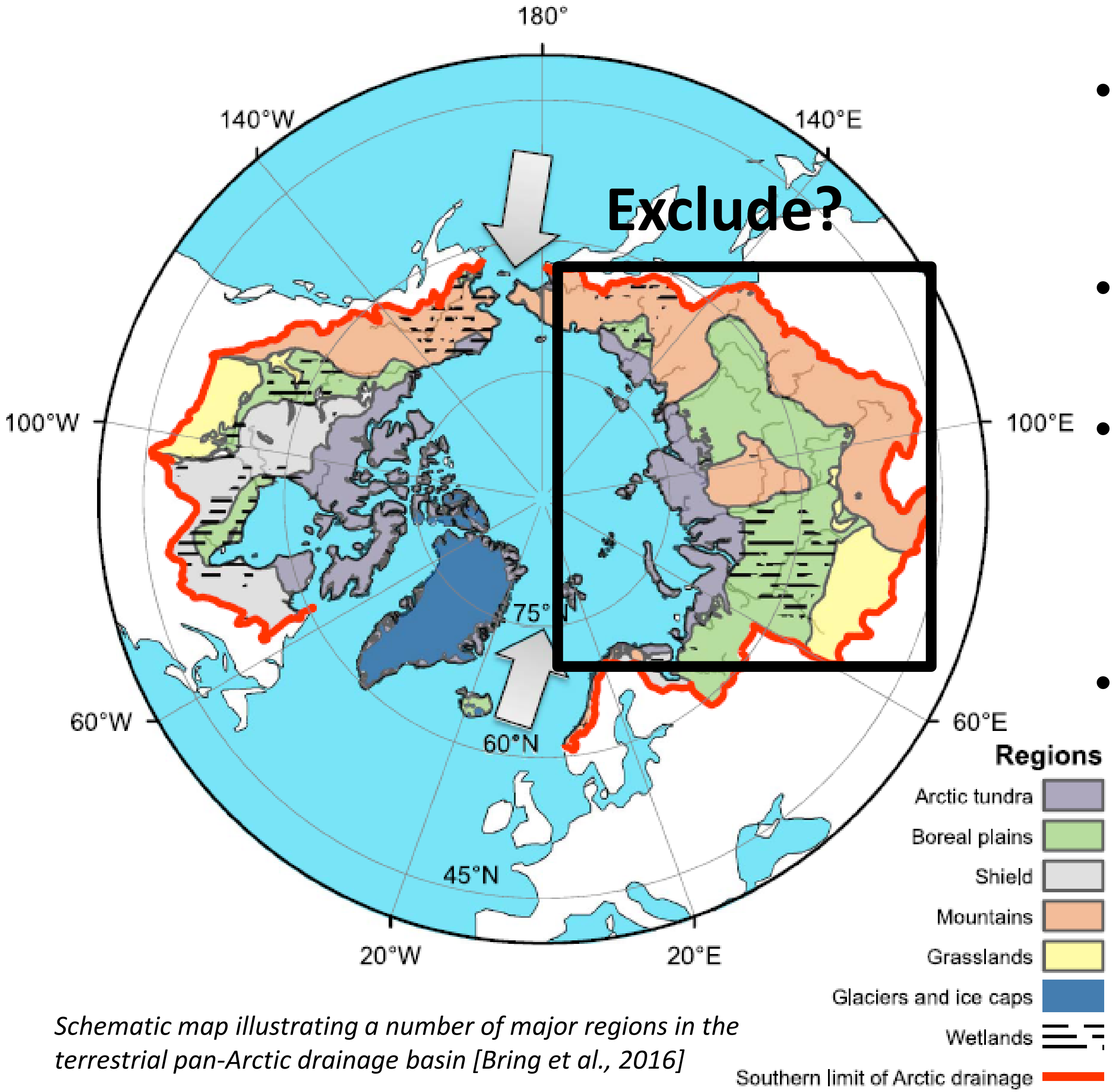
Landscape study profiles

5 precipitation isotope sampling gauges

Conclusions

- Terrestrial freshwater pathways have a central role in water, material, and energy exchanges between components of the Arctic freshwater system. They connect the atmosphere and ocean over large distances, along which ecosystems and resources are affected by varying geographical characteristics of the terrestrial freshwater systems.
- We are still lacking a comprehensive picture of evapotranspiration across Arctic regions and how it will interact with climate and landscape changes.
- Mot of the territory of the Arctic are essentially ungauged.
- As some parts of the Arctic increasingly become subject to settlement and natural resource extraction, it will become more important to separate anthropogenic effects from underlying environmental changes.
- Concerted efforts at studying water, solute, and energy fluxes on various scales will remain important to detect, understand, and project water system changes.
- Despite a growing potential of remote sensing, it remains critical to at least maintain the current ground-based capacity to observe Arctic terrestrial hydrology.

Cooperation in the Arctic



Schematic map illustrating a number of major regions in the terrestrial pan-Arctic drainage basin [Bring et al., 2016]

- Earth system is unite and unique. It is the home for all humans.
- The physical processes are beyond the politics.
- Scientists should have their civil position to ignore biased political demands and decisions.
- Progress in Earth Science can be achieved only in cooperation.

Deepest gratitude to

- the conference organizers for this opportunity and hospitality
- conference participants for listening and exchanging the science
- my scientific team who shares the difficulties and joy of taken research path (Nataliia Nesterova, Andrey Shikhov, Anastasiya Zemlianskova, Andrey Ostashov)

CRYOSPHERE 2022 REYKJAVÍK ICELAND