Climate change and the carbon cycle of frozen floodplains.

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River plain carbon cycle

Transport / emission of dissolved carbon species
Erosion, transport and re-sedimentation of particulate carbon
depends on river regime, morphology / channel mobility
climate-dependent

How do changes in water balance, discharge affect permafrost and the floodplain carbon cycle?
Berelegh floodplain, NE Siberia

Methods:

Interferometric SAR surface movement mapping

Multi-year high resolution satellite image study thaw pond development and river flooding

Geomorphological mapping

Active layer thickness data

4 km
Recent high river water and snow

2017 flood (Tei et al., 2019):
- High early flood peak early June
- Prolonged extreme flooding June and July
- Flood probability <= 1 in 49 years
Results

1. The floodplain wetlands are
   a hotspot of CH$_4$ emission
   stores of carbon in sediments

2. Extreme floods expand the floodplain:
   permafrost thaw, subsidence
   capture of thaw lakes

Future projections: increased flooding of Siberian rivers
(Shkolnik et al. (2016): 2-5% increase in flood area by 2050 - 2059)

3. INSAR surface movement data:
   Subsidence in poorly-drained areas
   Well drained areas: no significant subsidence, or ice gain
   Sedimentation: on floodplain, peat accumulation in alases

See next slides also!
Permafrost rivers: carbon cycle diversity

Nival or glacier-fed discharge regime, sensitive to drainage basin permafrost cover

Erosion processes linked to permafrost thaw
  channel bank stability, thaw lake development

Diverse floodplain morphology affects:
  carbon storage in sediments
  wetland environments

Nutrient supply by floodwater
Carbon cycle significance: $\text{CH}_4$

Wet floodplain vegetations:

1. Higher $\text{CH}_4$ fluxes than comparable sites (water level, vegetation) on oligotrophic tundra see e.g. FW2 and TW1 class above: both are sedge meadows with same vegetation composition and above-surface water table. Nutrient conditions cause higher primary production on floodplain FW2 class (Van Huissteden et al., 2005, 2009)

2. Evasion of $\text{CH}_4$ from river flood water in spring is an important process (Morozumi et al., 2019)
Carbon cycle significance: Organic sediment

Active carbon sedimentation and burial:
- carbon in vegetation horizons in floodbasin sediment
- peat growth in floodbasin sediments
- particulate carbon deposition
Local floodbasin sedimentation rate: $0.5 \pm 0.3$ cm yr$^{-1}$

Carbon storage in floodplain sediments is poorly quantified (Hugelius et al., 2014; Van Huissteden, 2020)
River spring flood height

Low stand, end of summer (August 2010):
  Thaw lakes:
    If not connected with river: ± stable water level
    River connected: water level follows river, drained in autumn

At receding, ± normal spring flood mid July 2015:
  Channels are bank-full
  All river-connected lakes filled
  Floodbasins without lakes are partly flooded

Extreme spring flood, mid July 2017 (Tei et al., 2019)
  after high winter precipitation, rain on snow, ice jams
  Complete floodplain flooded except river terrace
  River water invades normally non-flooded
    drained thaw lake basin (DTLB) surfaces
  One thaw lake invaded by river water, another nearly
    (arrows)
INSAR data

Method: Persistent scatter interferometric SAR using Sentinel 1
Persistent scatterer: pixels that are not affected by surface property changes
3 year velocity rates from 2017-2019, flooding year 2017, uncertainty +4 mm/yr

Processes affecting velocities:
- permafrost ice gain / loss (frost heave / thaw subsidence)
- slope and fluvial erosion
- sedimentation (peat growth / fluvial / colluvial deposition)
- tectonic movements (not considered here)

Data interpretation supported by geomorphological mapping and flood mapping based in high resolution Geoeye and Worldview satellite images
Sampling bias

Cross-image requirement of coherence: may exclude dynamic surface types (vegetation change, flooding)
INSAR comparison with geomorphology, high resolution images

Low-lying pond-rich thaw lake basins (alas) areas: subsiding
Well-drained Yedoma and alas areas: not subsiding or heave
Higher pond density and higher NDWI water index: more subsidence (p<0.01)
Higher elevation: less subsidence

NDWI = normalize differential water index = (green - near infrared) / (green + near infrared)

velocity vs. elevation

velocity vs NDWI

Outliers: fluvial sedimentation
Examples drainage effect, peat growth, frost heave

- Incised river channel in alas: better drainage along banks + ice gain after ice loss in 2017 flood?

- Pingo complex: heave?

- Polygon areas in alas: spectral signature in satellite images indicates peat growth in ice wedge polygons

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Flooding affects active layer thickness

Active layer depths in July 2018 along transects at ± right angle to 2017, 2018 flood limits

- **Transect 1, 2, 3**: Mesic (dry-moist) tussock tundra
  - increased active layer thickness in flood-affected areas

- **Transect 4**: Wet *Sphagnum*-dominated tundra
  - no clear effect of flooding

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Subsidence after flooding
INSAR time series 2017-2019

INSAR seasonal time-series surface changes in drained thaw lake basins are compared for alas point affected by the 2017 flood, and alas points that were not flooded in 2017.

flooded DTLB:  n = 14
non-flooded DTLB:  n = 432

- After flood 2017: early, rapid subsidence during flooding
- Nonflooded areas 2017: later subsidence progressing with thaw season
- Effects appear to continue in 2018 (more subsidence at 2017 flooded points)
- In 2019 no statistically significant difference
Flooding effects on vegetation

- Dwarf shrubs (*Betula*, *Vaccinium*), *Sphagnum*, *Eriophorum* tussocks
- Advantage of flood-resistant willow
- Tei et al. (2019) report forest browning

Immediate and longer-term effects of flooding on vegetation and carbon cycle need quantification!
Floodplain expansion into thaw lake basin

Visible at low water level (2010):
expanding channel + floodplain vegetation (high willow, grasses) into alas

thaw lake captured in the past by river bank erosion,
drains at river low stand

Early summer 2015 ± normal flooding:
flood water does not enter the alas at this location

2017 extreme flood
flood water enters the alas at this location and makes contact with thaw lake
subsidence + channel erosion may widen the connection of the alas to the river, and potentially drain the thaw lake
Discussion

Subsidence on poorly drained sites and floodplain:
  is it driven by more surface water - ponding/flooding in wet years?
  longer INSAR time series + field observations on changes needed

Well drained sites - no subsidence, some heave:
  do wet years contribute to ice accumulation at top of permafrost in wet years?
  quantification of ice content over the years necessary

Other positive surface movement:
  peat accumulation (areas with *Sphagnum*)
  floodplain sedimentation
  colluvial deposition on lower slopes of Yedoma remnants

Extreme river flooding drives floodplain expansion by:
  subsidence
  thaw lake capture

What are effects on the carbon cycle, ecological changes, Arctic browning/greening?

Factors affecting the floodplain carbon cycle at a large scale:
  Vegetation stress / die-back in areas affected by unusual flooding
  Higher vegetation productivity on floodplain
  Higher CH$_4$ emission in floodplain environments
  Floodplain expansion creates accommodation space for carbon-rich fluvial sediment
Conclusions

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   - a hotspot of CH$_4$ emission
   - carbon storage in sediments

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3. INSAR surface movement data show:
   - Subsidence in poorly-drained areas
   - Well drained: no significant subsidence, or ice gain
   - Sedimentation: floodplain, peat accumulation