River and Lake Ice:

Quantification, Extremes and Historical Trends;

Advances under IPY cryosphere/hydrology & ArcticNet

Terry Prowse	W-CIRC (EC/UVic)
Katrina Bennett	PCIC -UVic
Rheannon Brooks	UVic - Geomatics
Laurent de Rham	W-CIRC (EC/UVic)
Holly Goulding	UVic - Geography
Simon von de Wall	UVic - Geography
Barrie Bonsal	EC-NHRC
Charles Cuell	EC-NHRC
Yonas Dibike	W-CIRC (EC/UVic)

IP3 Workshop #3, 12-15 November 2008, Whitehorse, Yukon

Environment Canada Environnement Canada

W-CIRC WATER AND CLIMATE IMPACTS RESEARCH CENTRE

University of Victoria

Outline

1. Quantification of Freshwater Ice: Areas and Volumes in the Northern Hemisphere
2. River Ice and Hydrologic Extremes: Mackenzie River Basin
3. River Ice and Hydrologic Extremes: Mackenzie River Delta
4. Atmospheric Linkages
5. Lake Ice Phenology and Composition

1. Quantifying freshwater ice: area & volumes

Issue:

- Of all cryospheric components: no estimates exist as summarized by IPCC 2007
- Required to understand past variability and future change

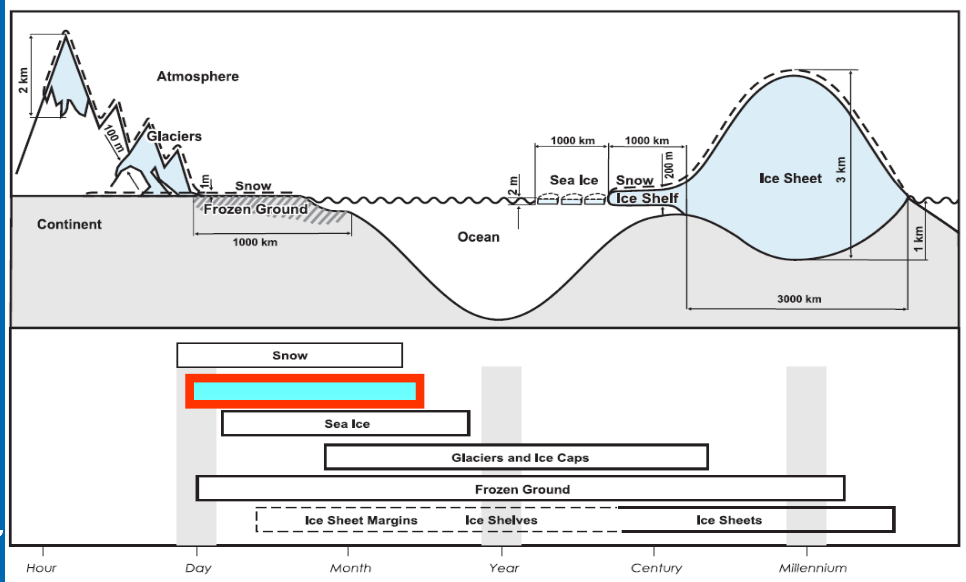


Figure 4.1. *Components of the cryosphere and their time scales.*

From Lemke et al. 2007

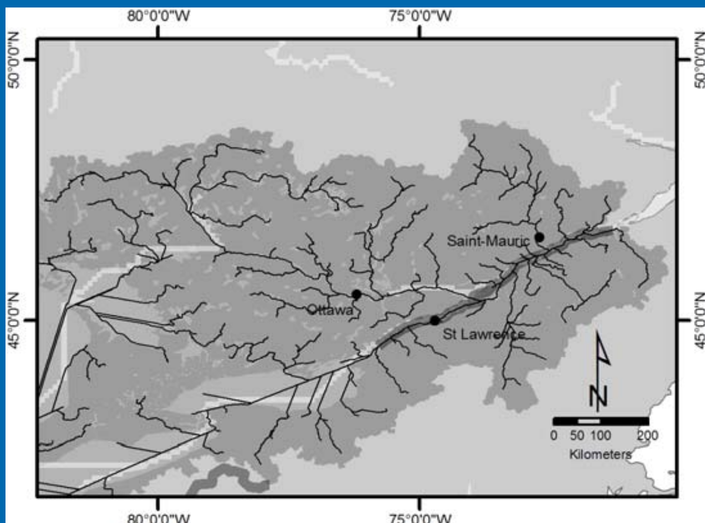
Table 4.1: *Area, volume and sea level equivalent (SLE) of cryospheric components. Indicated are the annual minimum and maximum for snow, sea ice and seasonally frozen ground, and the annual mean for the other components. The sea ice area is represented by the extent (area enclosed by the sea ice edge). The values for glaciers and ice caps denote the smallest and largest estimates excluding glaciers and ice caps surrounding Greenland and Antarctica.*

Cryospheric Component	Area (10^6 km²)	Ice Volume (10^6 km³)	Potential Sea Level Rise (SLE) (m)[g]
Snow on land (NH)	1.9–45.2	0.0005–0.005	0.001–0.01
Sea ice	19–27	0.019–0.025	~0
Glaciers and ice caps			
Smallest estimate[a]	0.51	0.05	0.15
Largest estimate[b]	0.54	0.13	0.37
Ice shelves[c]	1.5	0.7	~0
Ice sheets	14.0	27.6	63.9
Greenland[d]	1.7	2.9	7.3
Antarctica[c]	12.3	24.7	56.6
Seasonally frozen ground (NH)[e]	5.9–48.1	0.006–0.065	~0
Permafrost (NH)[f]	22.8	0.011–0.037	0.03–0.10
Freshwater ice; lakes and rivers	?? - ??	???? - ????	????????

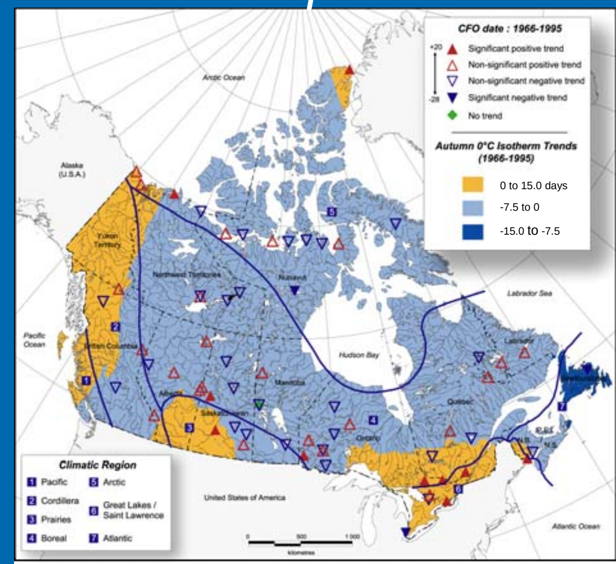
Objective:

- Quantify the spatial extent, distribution, and volume of river ice across the Northern Hemisphere

GIS river networks



Gridded temperature & 0C isotherms

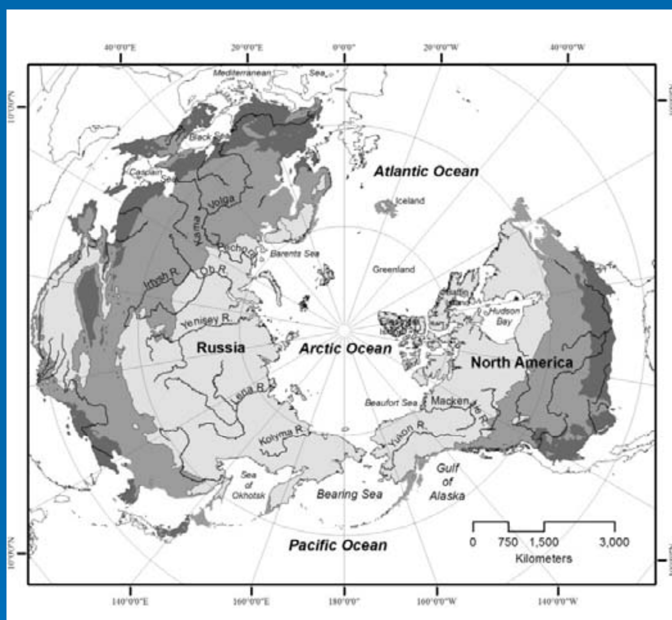


Methods:

- Analyzed using overlapping gridded temperature and river network data sets in GIS
- current (~last ½ century) river-ice extent and volumes were quantified
- Spatial extent f: of 0°C isotherm for Jan, Oct-Mar & Annual air temp.
- Volume: temperature index modelled using AFDD

Results:

- 54, 46 and 27% of NH river networks are ice affected in the coldest month, three-month and six-month periods
- Maximum Area covered by river ice in the Northern Hemisphere is 231 x10^3 km^2.
- Peak Volume of river ice in the Northern Hemisphere is 120 km^3



Cryospheric Component	Area (10^6 km^2)	Ice Volume (10^6 km^3)
Snow on land (NH)	1.9–45.2	0.0005–0.005
Sea ice	19–27	0.019–0.025
Glaciers and ice caps		
Smallest estimate[a]	0.51	0.05
Largest estimate[b]	0.54	0.13
Ice shelves[c]	1.5	0.7
Ice sheets	14.0	27.6
Greenland[d]	1.7	2.9
Antarctica[c]	12.3	24.7
Seasonally frozen ground (NH)[e]	5.9–48.1	0.006–0.065
Permafrost (NH)[f]	22.8	0.011–0.037
Freshwater ice; rivers (NH)	**0.23 - ???**	**0.00012 - ????**
; lakes (NH)	**?????**	**?????**

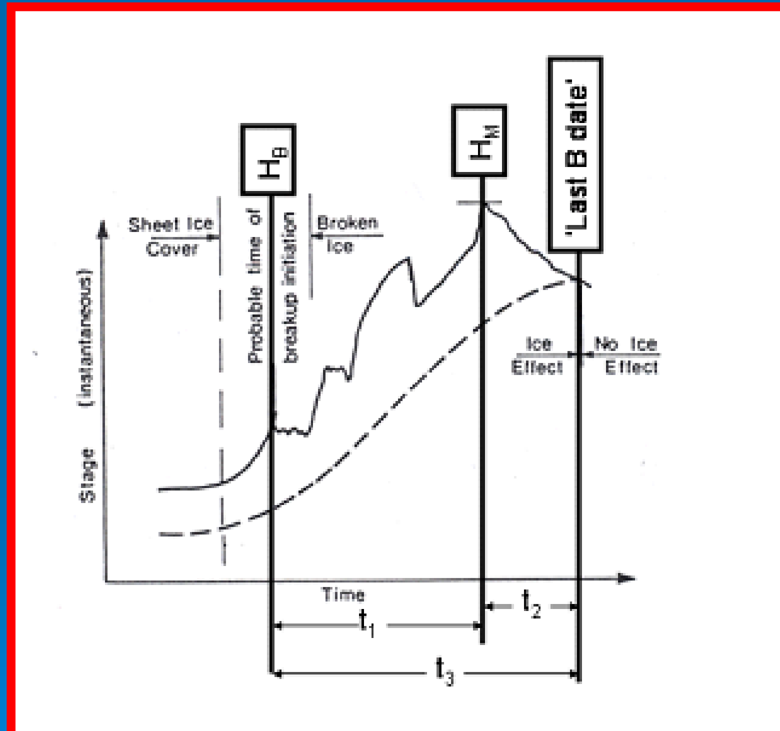
Future Research:

- Quantification of Northern Hemisphere lake ice
- Examination of past trends/ variability
- Assessment of climate-change on future ice extent & volume

2. River Ice: Hydrologic Extremes for the Mackenzie River Basin

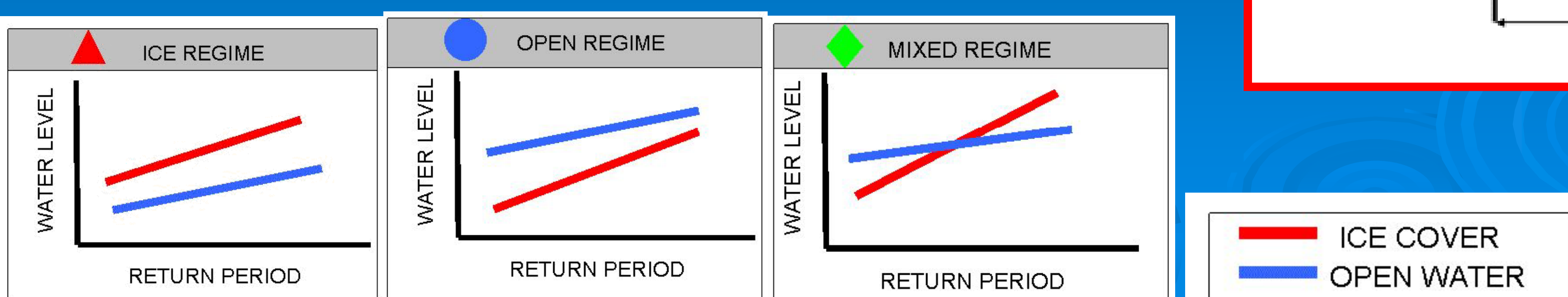
Issue:

- Virtually all break-up and ice jam flood studies are site-specific case studies
- No quantification of spatial and temporal patterns of break-up season at the watershed scale

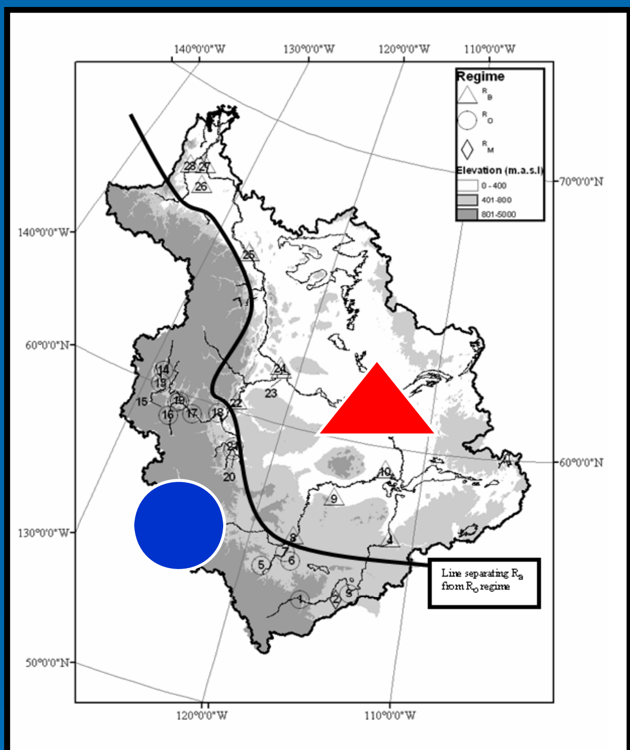


Methods:

- Extraction and calculation of spring break-up variables (timing and magnitude) from WSC (1913-2002):
- Mann-Kendall trend analysis (1970-2002)
- Return Period assessment (H_M and H_O)

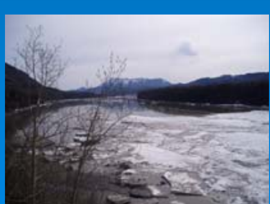


Results:



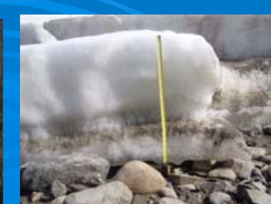
Regime classification

- ice effects evident at <u>all</u> locations
- 13/28 sites dominated by ice events (i.e. break-up flooding)
- some distinct hydro-climatic regimes





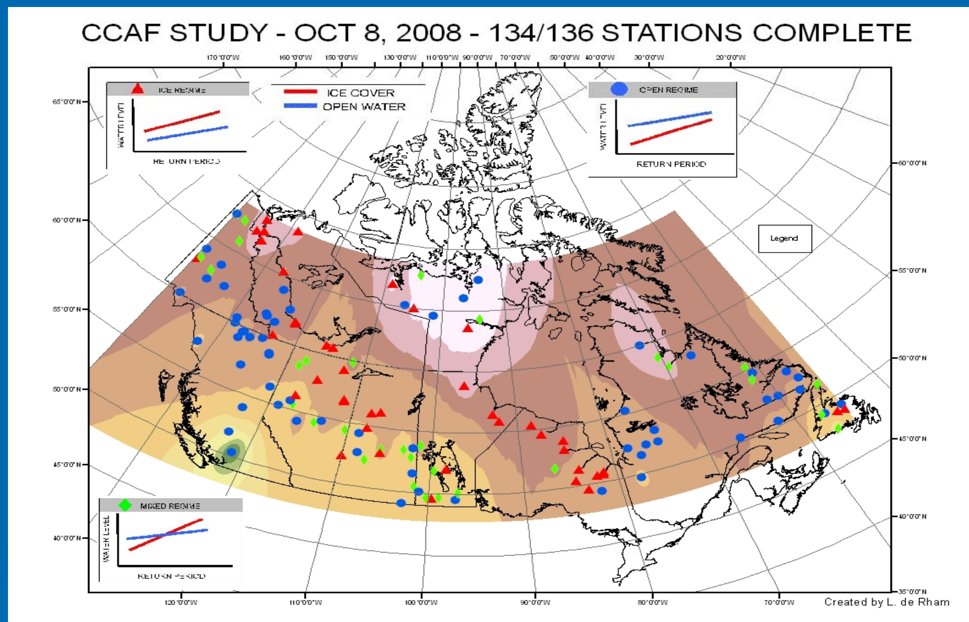




References:
de Rham LP, Prowse TD, Bonsal BR. 2008a. Temporal variations in river-ice break-up over the Mackenzie River Basin, Canada. Journal of Hydrology 349: 441-454
de Rham LP, Prowse TD, Beltaos S, Lacroix MP. 2008b. Assessment of annual high-water events for the Mackenzie River basin, Canada. Hydrological Processes 22: 3864-3880

Conclusions and Future Research:

- Break-up dominates peak water level events for Mackenzie basin
- Currently analyzing similar data across Canada to evaluate broader range of hydro-climatic regimes; eventually circumpolar beginning with Russia



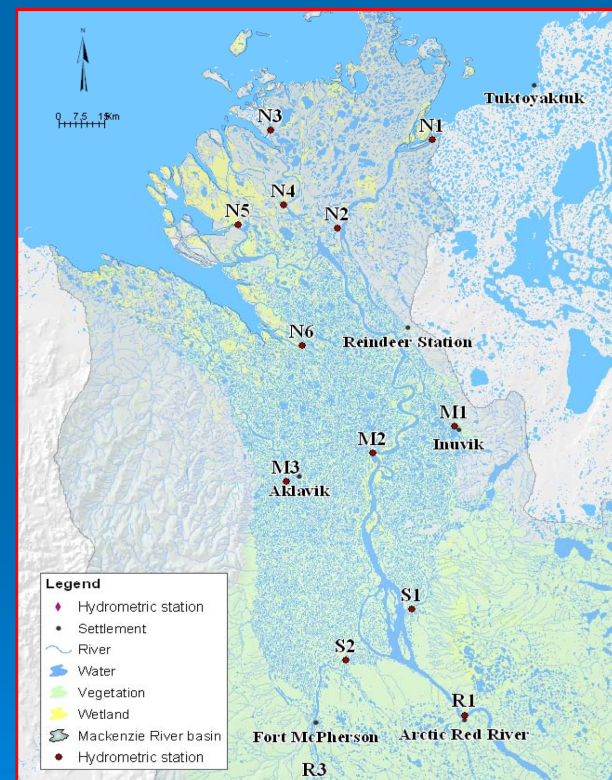
- Also assessing physical and climate controls of regimes; further analysis will also evaluate effect of freeze-up levels on break-up – a variable likely to change with increasing climate-induced autumn flows
- Future goal to assess effects of changes in driving (e.g., flow) and resisting forces (e.g., ice thickness) under changing climatic conditions

3. River Ice: Hydrologic Extremes for the Mackenzie River Delta

Objective:

Characterization of ice break-up in the Mackenzie Delta

- emphasis on break-up patterns and hydro-climatic controls for extreme events



1) Create a chronology of breakup in the delta, characterizing spatial and temporal patterns

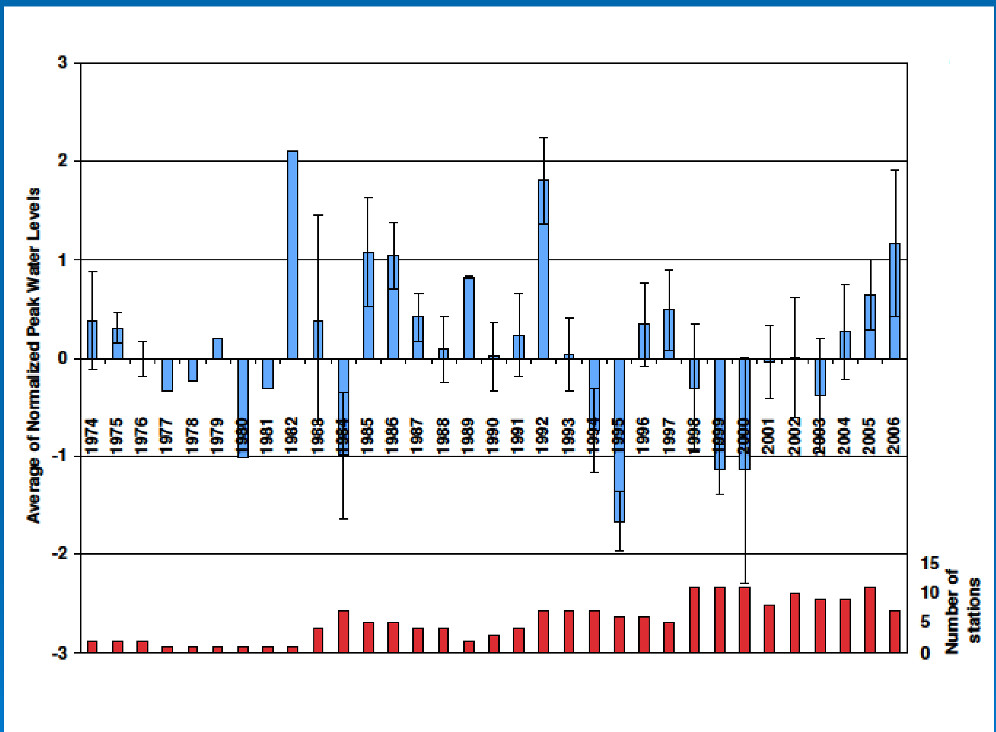
2) Quantify basin-wide and intra-delta hydroclimatic controls and assess their influence on break-up timing & severity

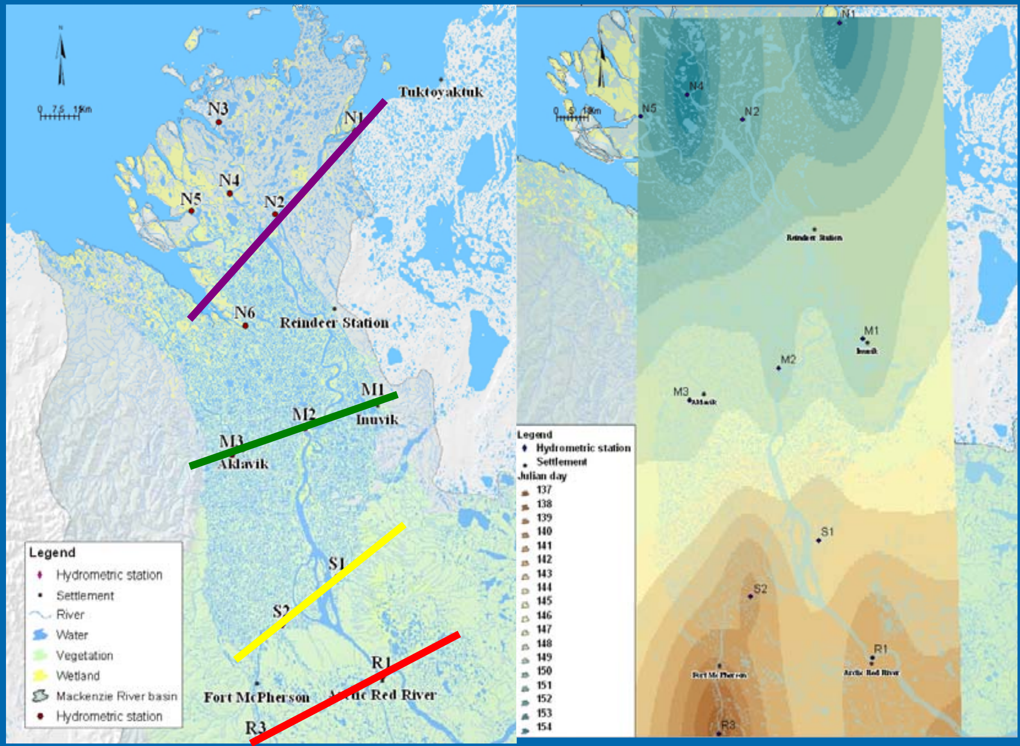
Snowpack size, rate of melt = Size and 'shape' of spring hydrograph

Ice cover resistance = Ice thickness, strength, & support boundary conditions

Results:

- Severity of break-up most influenced by <u>upstream discharge</u> related controls
- Timing most influenced by <u>downstream ice</u>





Two extreme event types:
Discharge-driven and *ice-driven*

<u>Spatial Patterns</u>:

Increase (decrease) in peak water levels moving northward through the delta for discharge (ice) events

<u>Temporal Patterns</u>:

Later (earlier) break-up in the delta for discharge (ice) events

Conclusions:

- Spatial and temporal patterns of break-up associated with different types of high peak stage events: *ice-driven* and *discharge-driven*

- Break-up severity most influenced by upstream discharge, but ice conditions also important

- Other Trend Analysis: earlier break-up trends, longer prebreak-up melt interval and smaller upstream and downstream factors
  - more frequent occurrences of low peak stage events in the future?

Future Research:

- **Multi-variate analysis of factors affecting extreme events**

- Quantification of upstream controls, i.e., basin snowpack and trigger tributaries

- Relationship of upstream and downstream controls to large-scale controls, i.e., mid-tropospheric synoptic patterns

4. Atmospheric Linkages

Issue/Objective:

- Obtain better understanding of past & future climatic relationships with freshwater ice
- Synoptic typing of atmospheric circulation patterns associated with observed ice variability

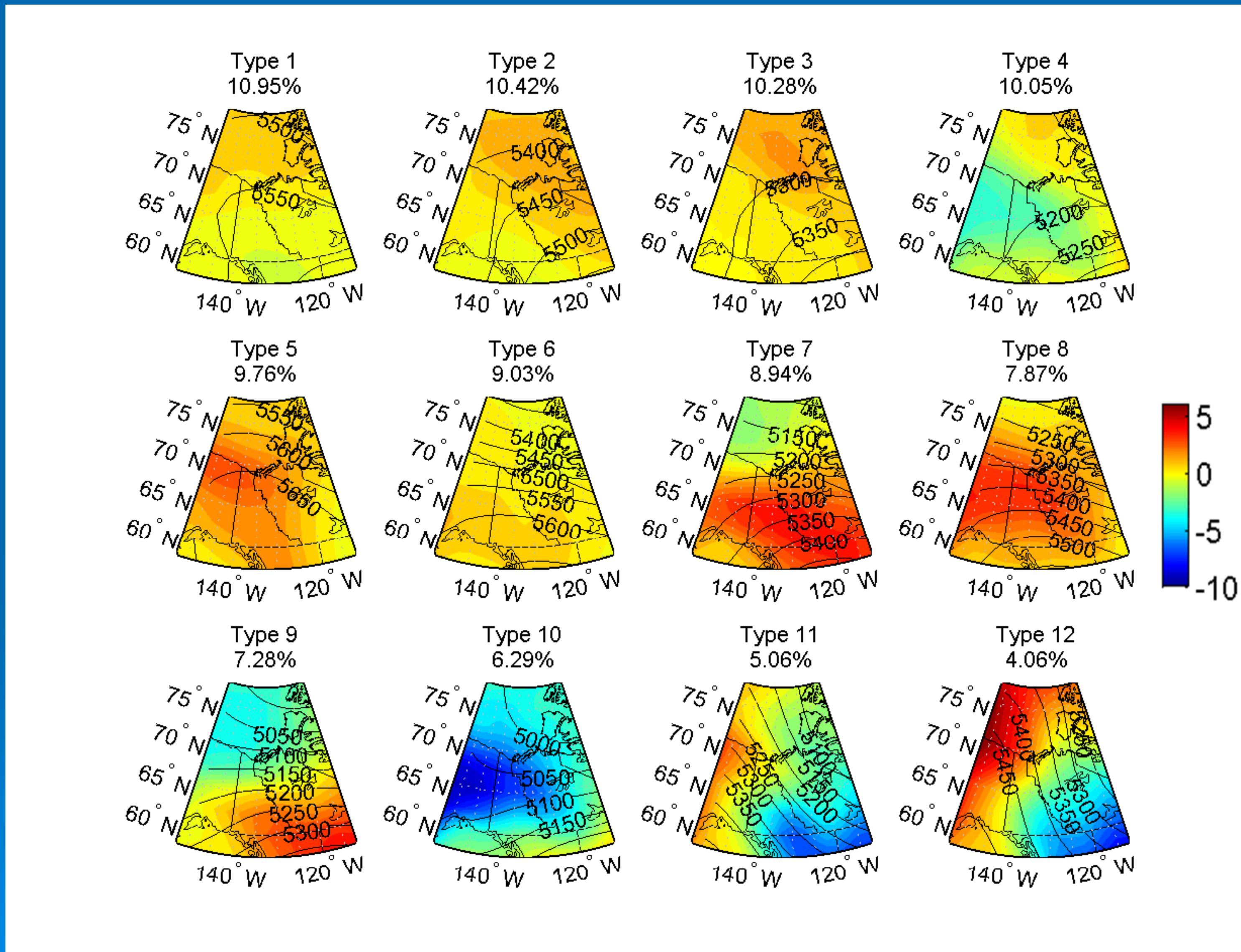
Methods:

- Synoptic typing of daily 500mb geopotential heights over northwestern Canada from 1948-2008.
- Assessment of synoptic patterns as they relate to cryospheric variability and extremes
- Examination of long-term trends and variability in relevant synoptic types

Results:

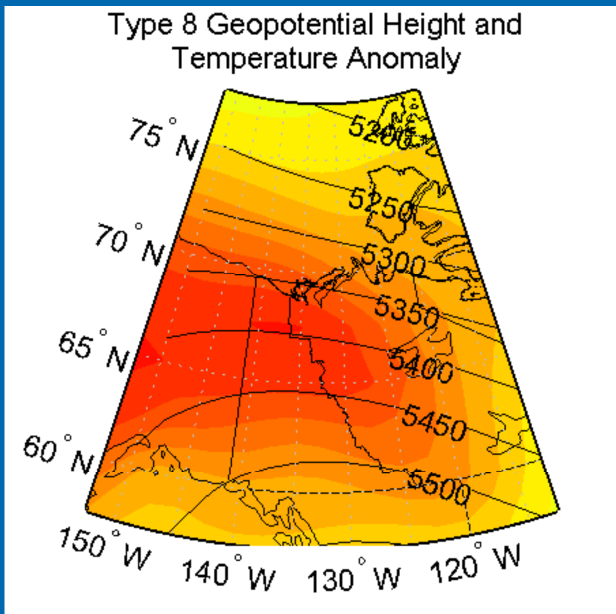
Synoptic Types: *cold*, *warm* and *normal* defined by linking with NCEP reanalysis of surface air temperature

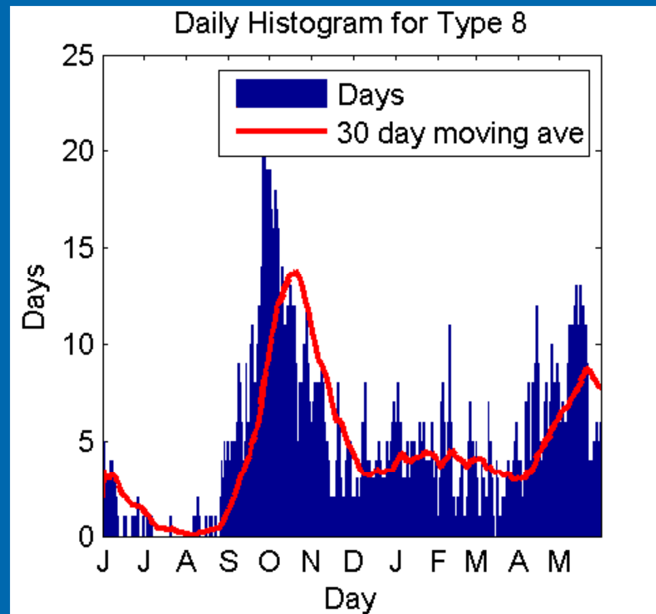
- **Cold northerly flow; types 10,11,12**
- **Warm southerly flow, types 7 & 8**

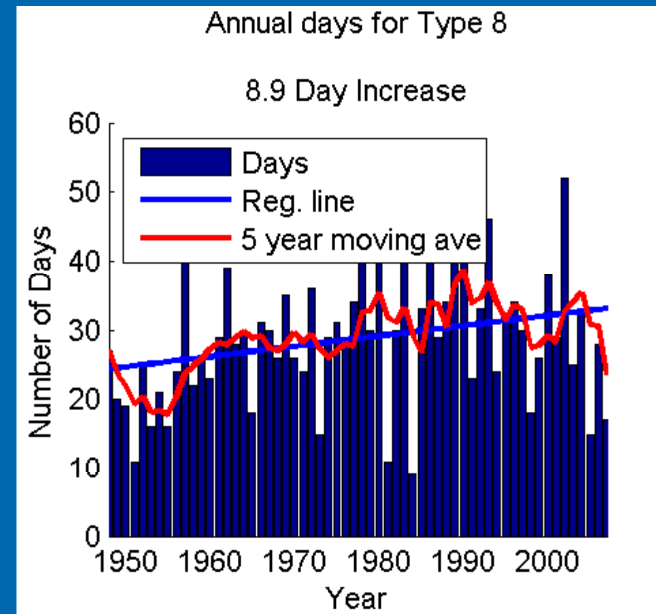


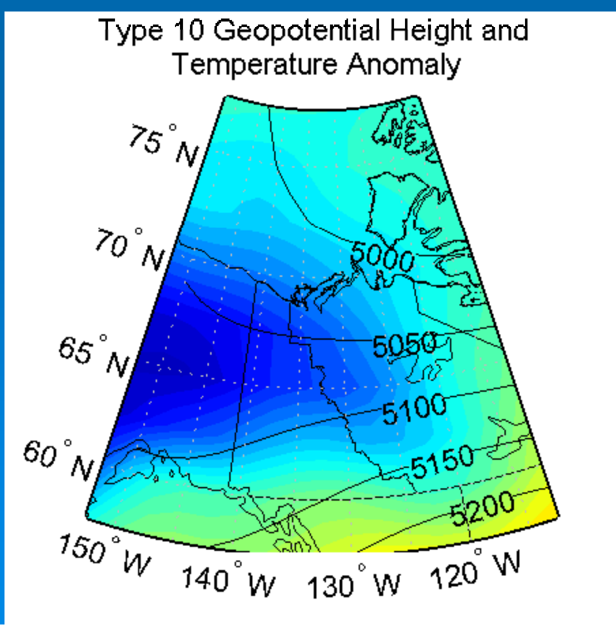
Frequency/Trends: trends leading to cold-season warming in the lower Mackenzie region, e.g.,

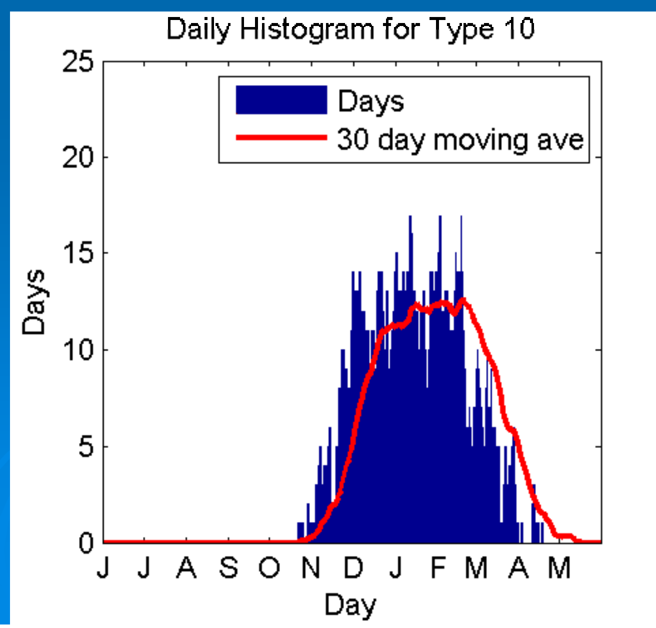
- warm 8: most common in fall and spring of cold season; trend = +8.9d/60yr
- cold 10: exclusive to winter; -11d/60yr

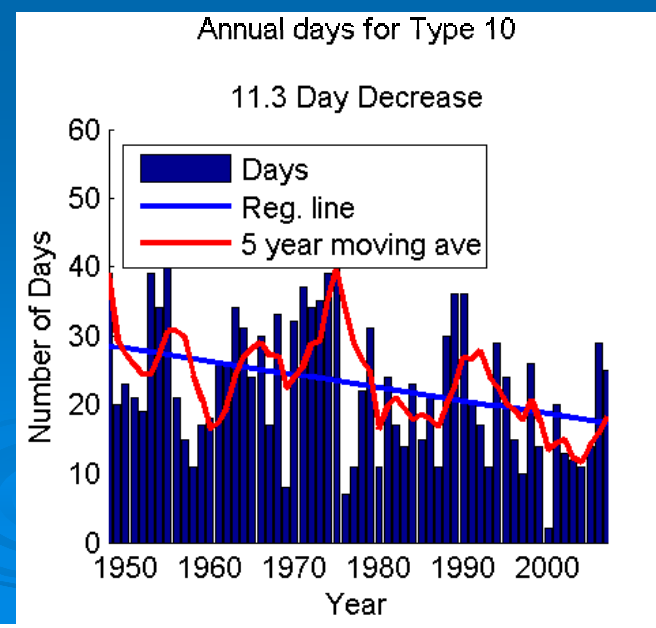












Future Research:

- Relating synoptic types to aforementioned observed ice extremes
- Continued assessment of past trends and variability in key synoptic types
- Relationships to large-scale teleconnections and circum-polar circulation features
- Assessment of changes to future synoptic types based on GCM/RCM data

5. Lake Ice Phenology and Composition

Issue:

- How will climate change affects North American lake-ice phenology and composition at a continental scale?

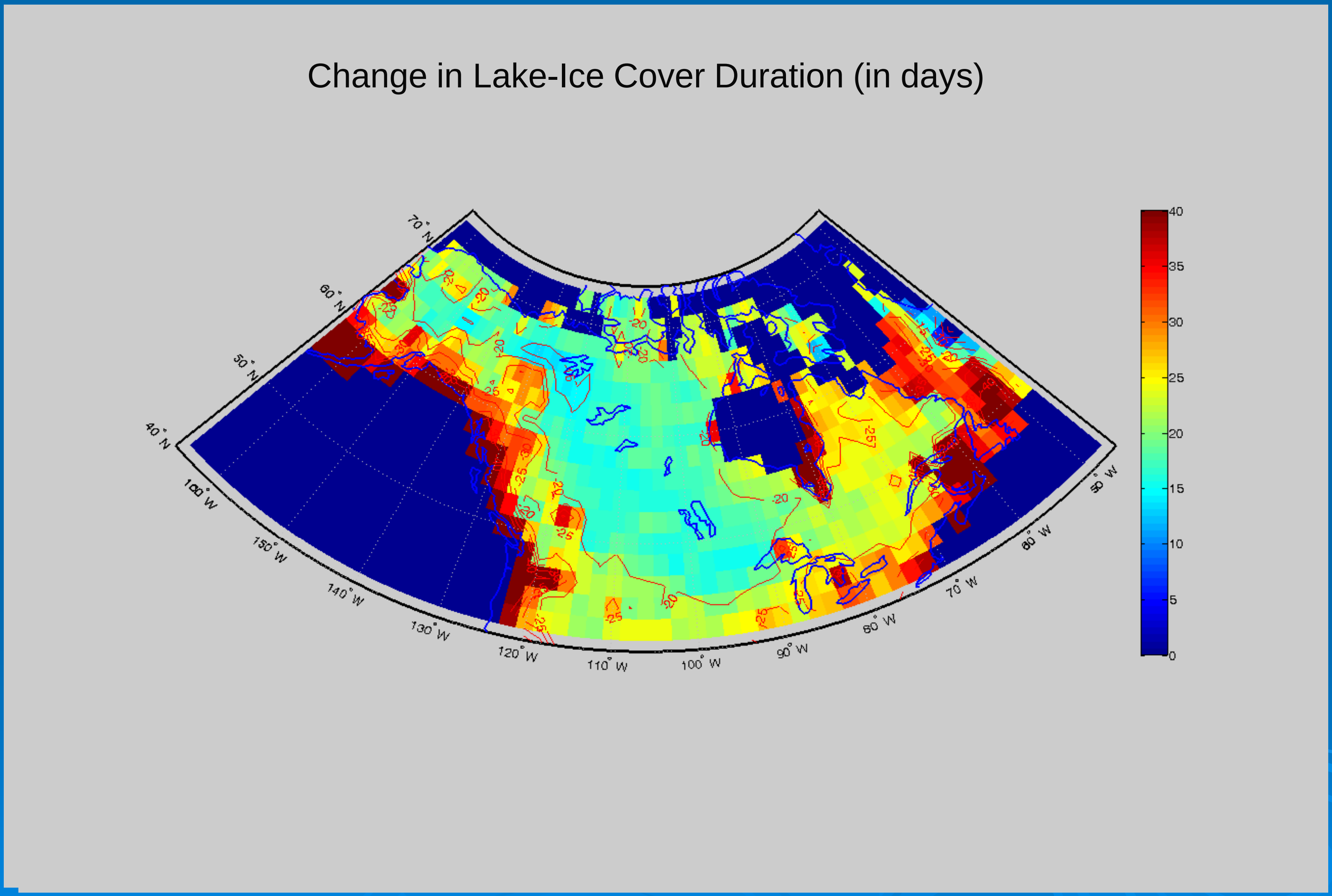
Objectives:

- Simulation of lake ice phenology and composition for current and future climate over North America
- Analysis of climate change impacts to ice (longer term: thermal structure, aquatic habitat)

Methods:

- Simulate vertical distribution of lake water temperature and evolution of seasonal lake ice and snow cover using 1-D, process based model (MyLake) *(Saloranta and Andersen, 2004)*
- Inputs: Daily gridded air temperature, cloud cover, relative humidity, surface air pressure, wind speed and precipitation (*from NARR 0.3^o and CRCM 4.2/Class 2.7 0.4^o data sets)*
- Conduct simulation using hypothetical lakes of 5m, 20m and 40m depths located at each 2^o data grid point

Results



CRCM-A2 Climate Change Scenario (2050s Vs 1970s)

Results:

- Maximum lake-Ice thickness on average 10 to 30cm thinner in 2050s compared to 1970s
- Greater change in lake-Ice thickness at high latitudes
- Lake-ice break-up dates are earlier by around 10 to 20 days
- No significant difference in the future change in break-up dates with different lake depths
- Lake-ice freeze-up dates are delayed by up to 10 days
- Future change in freeze-up date is more significant for deeper lakes
- Lake-ice duration is decreased by around 15 to 35 days

Conclusions:

- Future climate will result in reduction of lake ice thickness and ice-cover duration
- Lake depth has significant influence on ice thickness, phenology and composition
- Elevation and magnitude of precipitation have greater influence on lake ice composition than latitudinal effects
- Relative increase in snow-ice thickness at northern latitudes may be attributed to increase in winter precipitation events

Future Research:

- Extending the grid-based lake-ice simulation study with different climate inputs corresponding to different RCM models and emission scenarios
- Field verification of simulation results for lake ice phenology and composition

Thank you!