Lake ice cover and surface water temperature I:

Role and response in lake-atmosphere interactions

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1. Role of lakes in climate and weather

2. Response of lakes to climate

3. Implications of changing ice cover and temperature of lakes

4. Water properties

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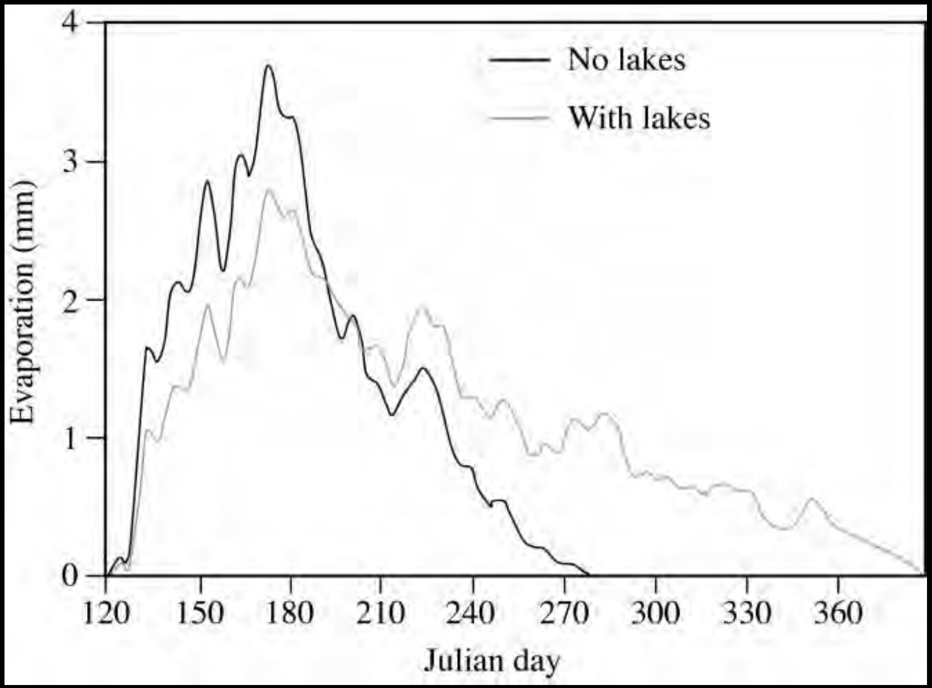
Acknowledgements

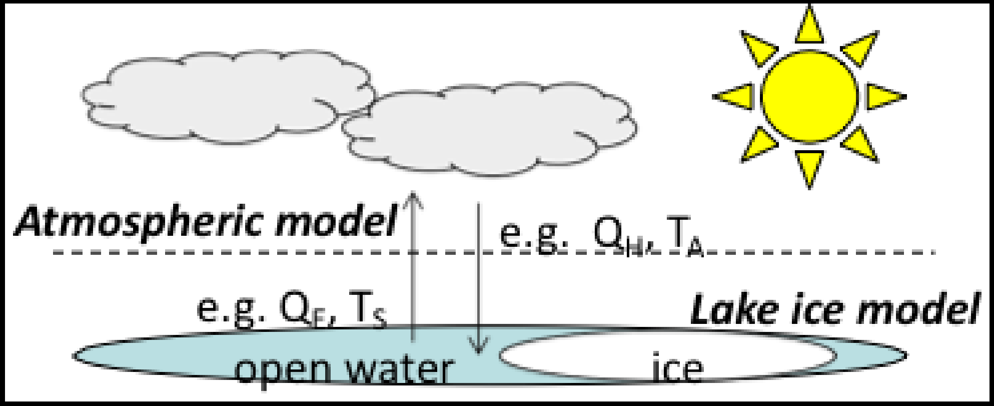
Thanks to L. Brown for provision of some of the figures used in this lecture.

Role of lakes in climate and weather

- Understanding lake processes and interactions with climate is essential for climate modelling, weather forecasting
  - Ice free season affects evaporation in the summer/fall



Average evaporation patterns for a region with no lakes and a region with lakes Source: Rouse et al. (2008)

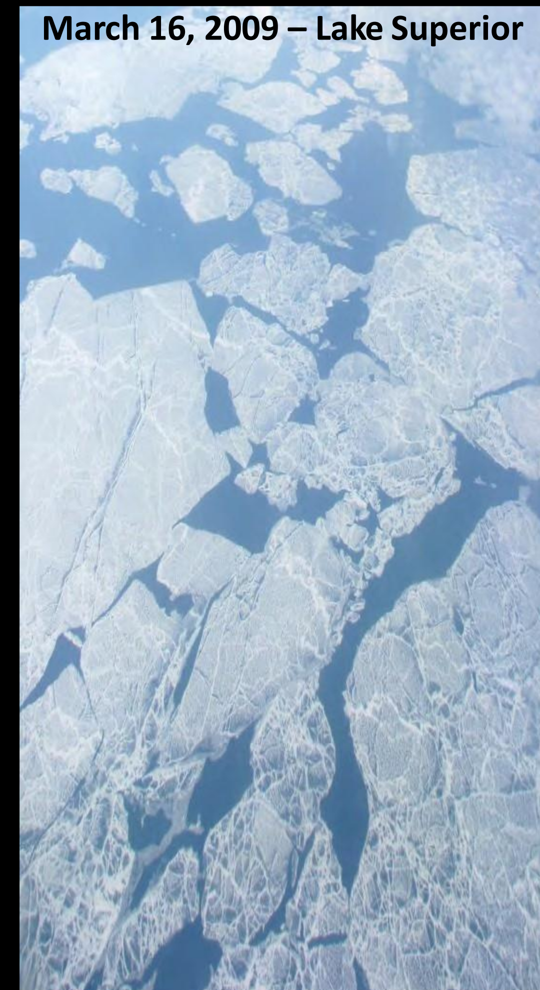


Brown and Duguay, 2010

Role of lakes in climate and weather

- The presence (or absence) of ice cover on lakes in winter has effect on the surrounding climate
  - Surrounding land can freeze before lakes, results in lake becoming heat source
  - Lakes that freeze over completely essentially put a ‘lid’ on turbulent fluxes
  - Lakes that do not freeze completely continue to interact with atmosphere throughout winter (e.g. Laurentian Great Lakes)

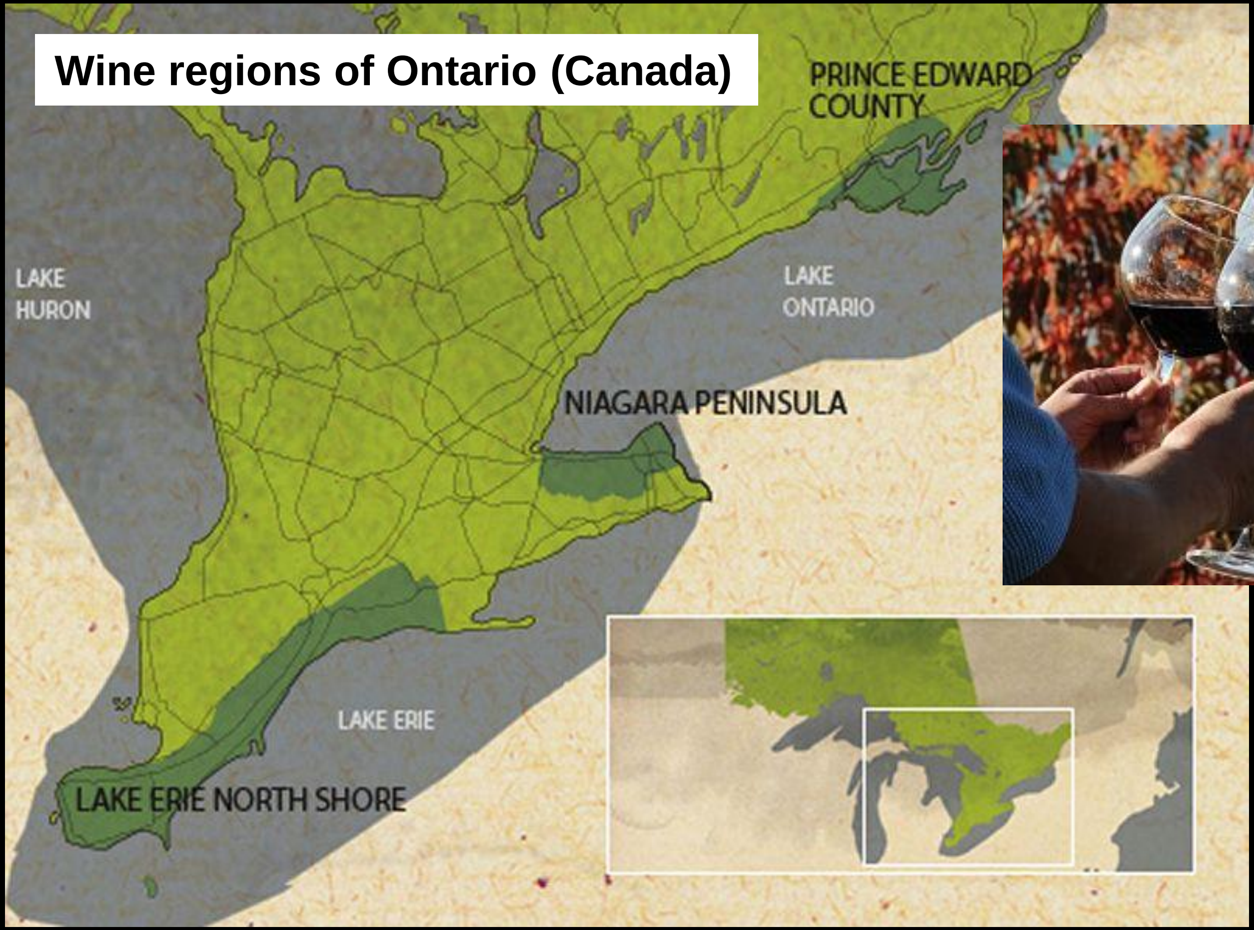
March 16, 2009 – Lake Superior



Brown and Duguay, 2010

Role of lakes in climate and weather

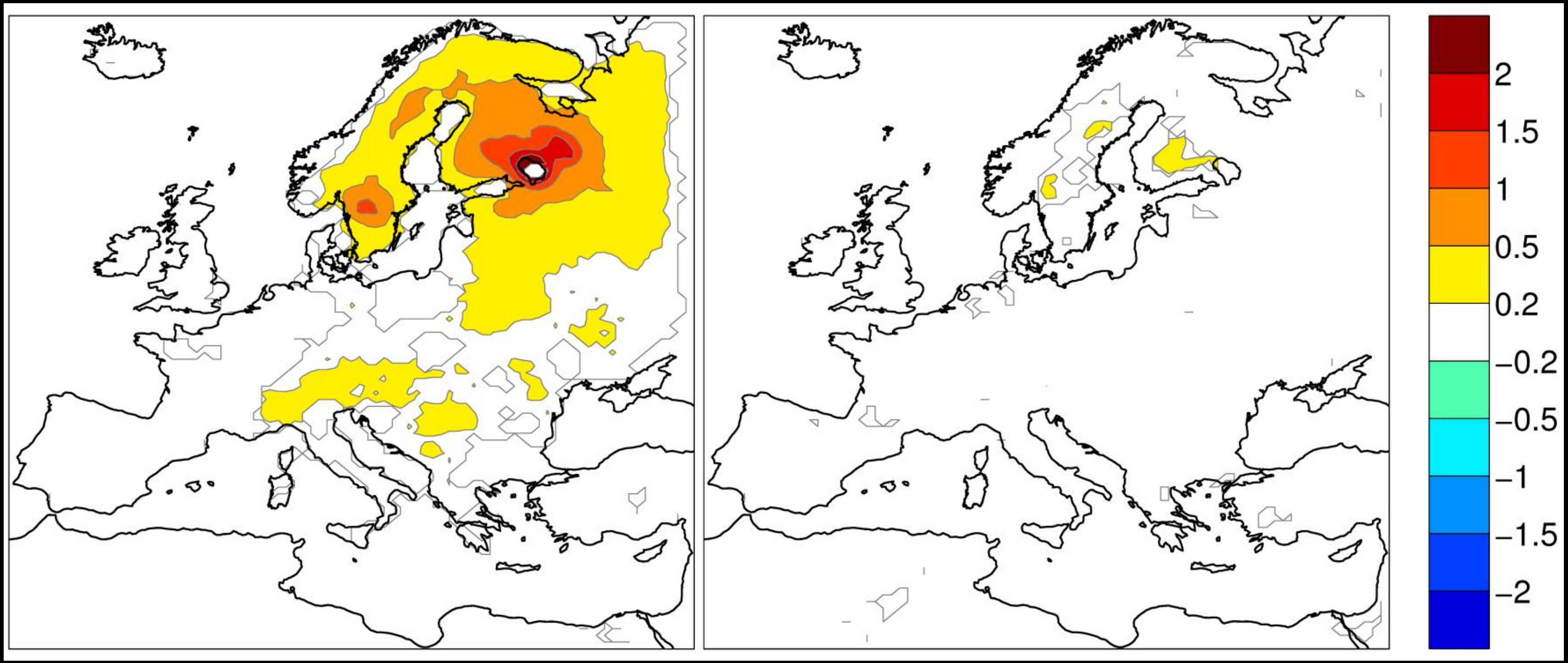
Thermal moderation effect of lakes



Source: http://www.winesofcanada.com/shore.html

Role of lakes in climate and weather

Thermal moderation effect of lakes

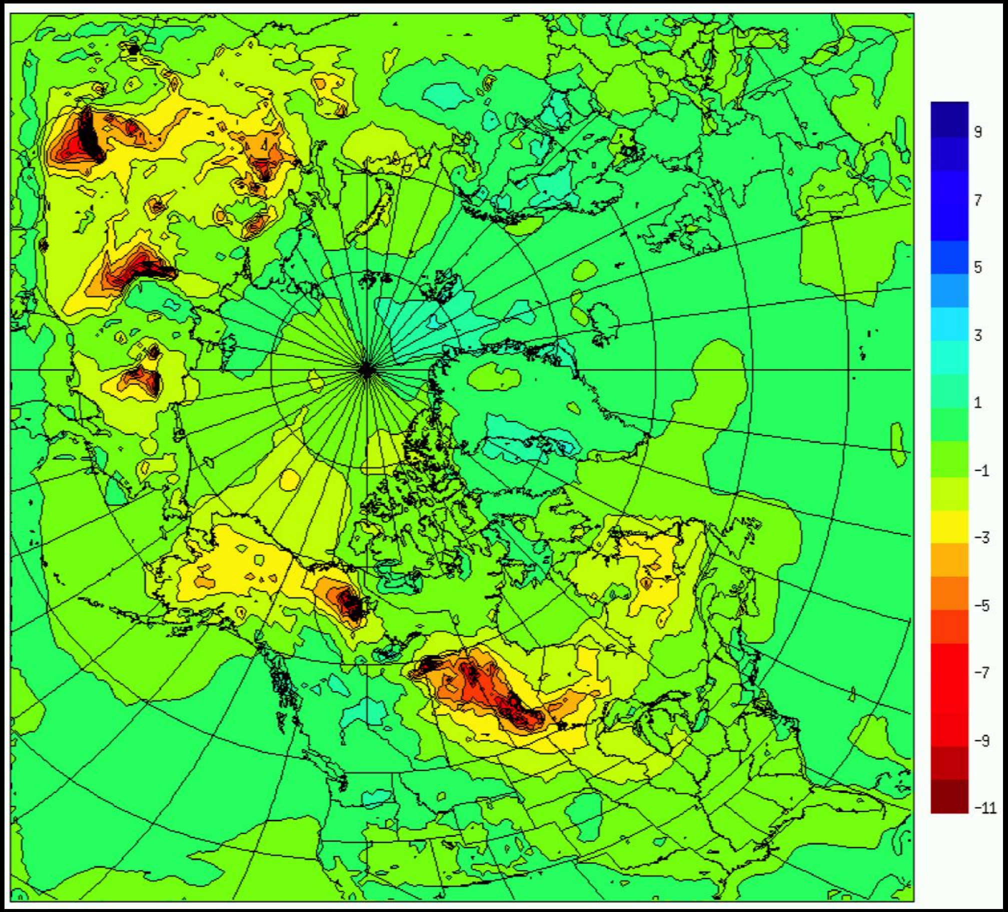


Differences in simulated air temperature (° C) 2 m from RCA model over northern Europe with lakes (coupled with FLake lake model) and without lakes (open land) for winter (left) and spring (right) 1961-1990.

Source: P. Samuelsson

Role of lakes in climate and weather

Thermal moderation effect of lakes



Mean winter temperature difference (^{o}C)
(with ice – no ice)

Improper representation of lake ice can lead to substantial errors in weather and climate models (e.g. air temperature, lake effect snowfall).

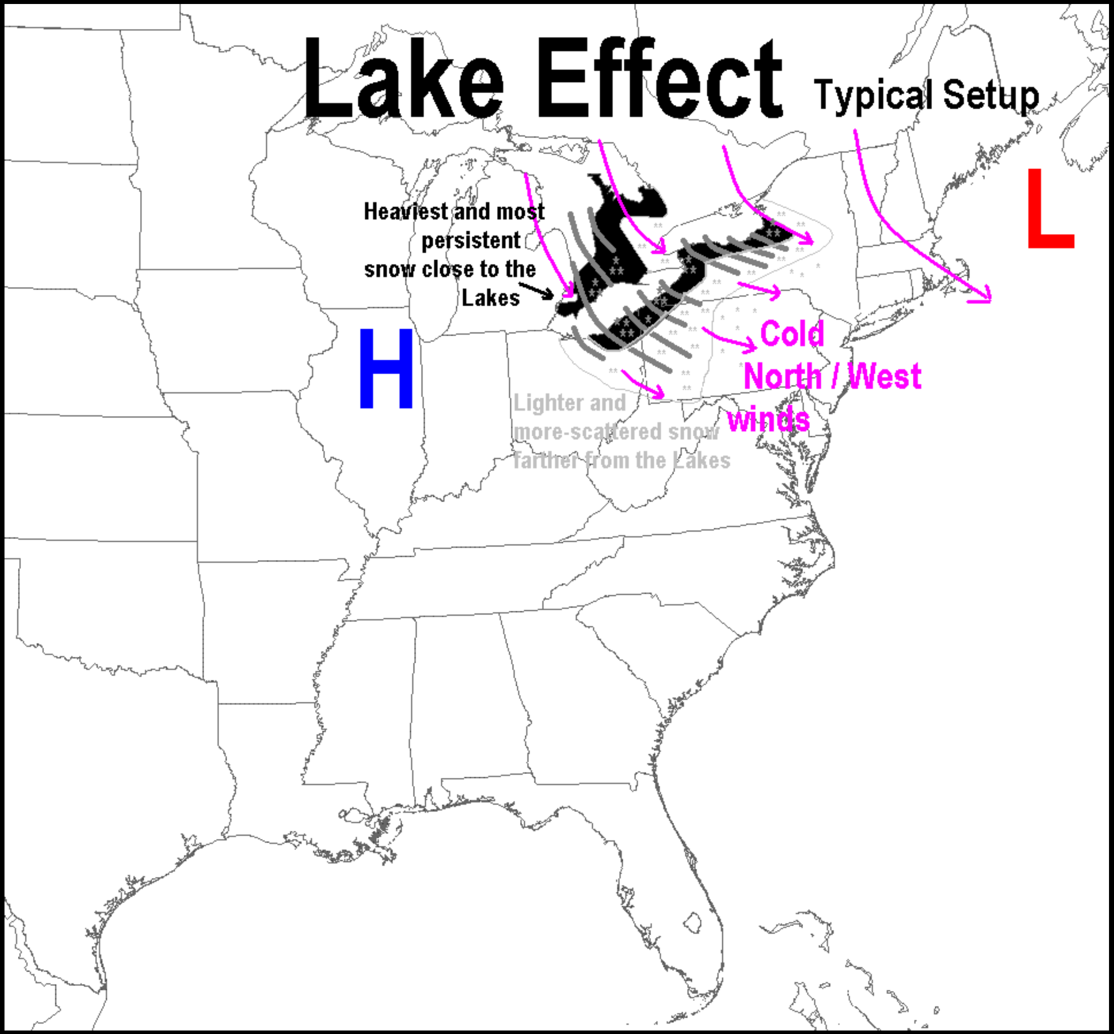
Source: Winger and Brown, pers. comm., 2008

Role of lakes in climate and weather

Lake effect snowfall in Great Lakes region

Role of lakes in climate and weather

Lake effect snowfall in Great Lakes region



Role of lakes in climate and weather

Lake effect snowfall in Great Lakes region

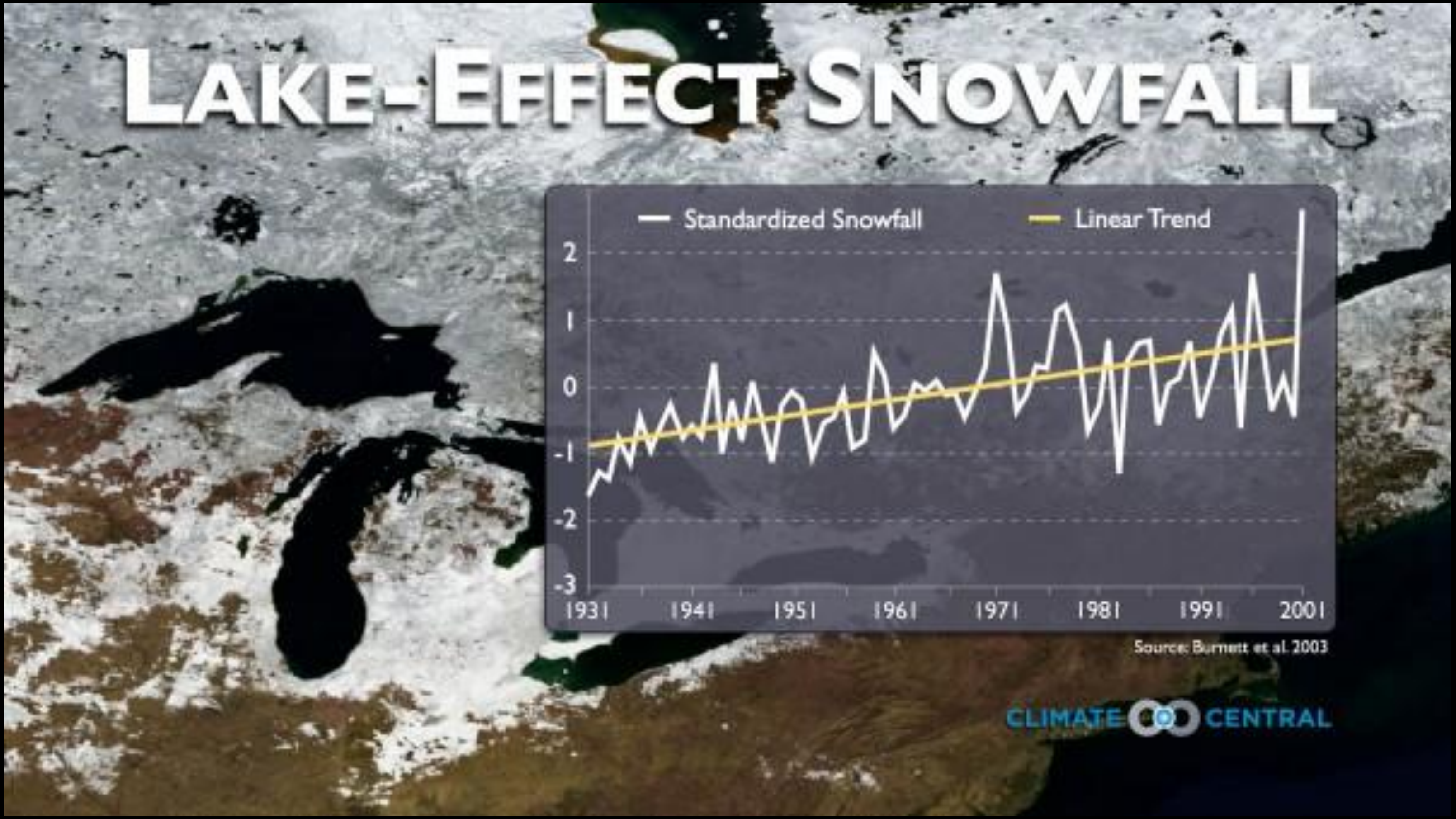
"8 Days, 10 Feet and the Snow Isn't Done Yet"

Workers tackling snowbanks around homes in Mexico, a community in Oswego County, N.Y.
February 12, 2007

Sylwia Kapuscinski - *The New York Times*

Role of lakes in climate and weather

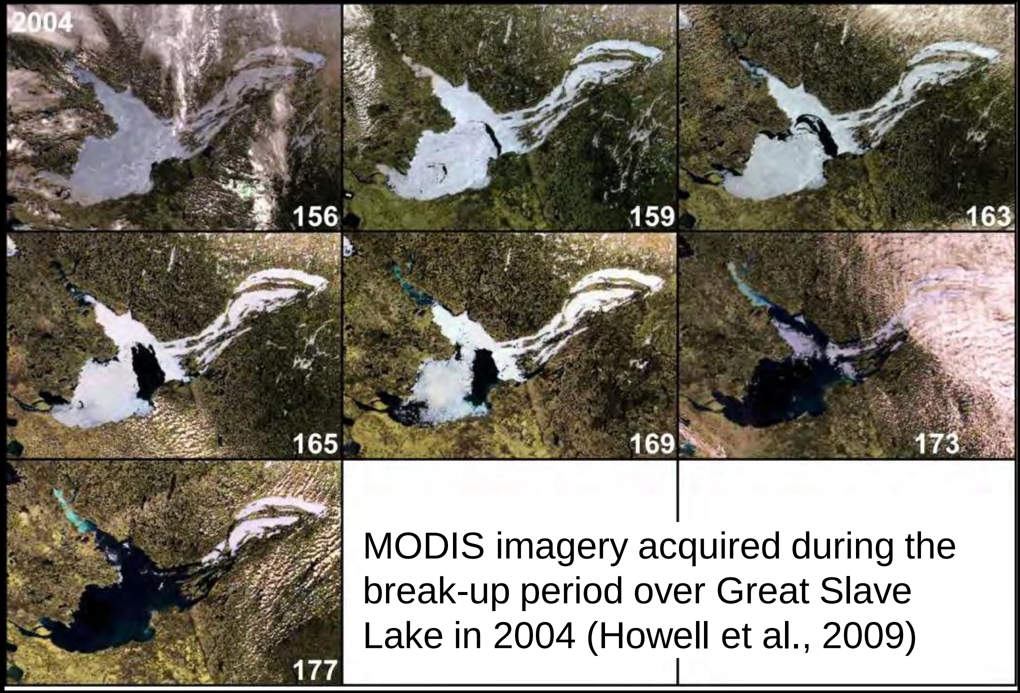
Lake effect snowfall in Great Lakes region



Response of lakes to climate

- The timing of lake ice phenological events (e.g. freeze up, break-up, water clear of ice, melt onset and freeze onset) can be a useful indicators of climate variability and change
  - Trends in ice cover changes have been observed in the northern hemisphere and related to climate variability

- Factors that affect phenology
  - Climatic
    - Air temperature (and radiation)
    - Precipitation
    - Wind speed and direction
  - Terrestrial (non-climatic)
    - Morphometry (depth, shape, size)
    - Inflows (streams, runoff)

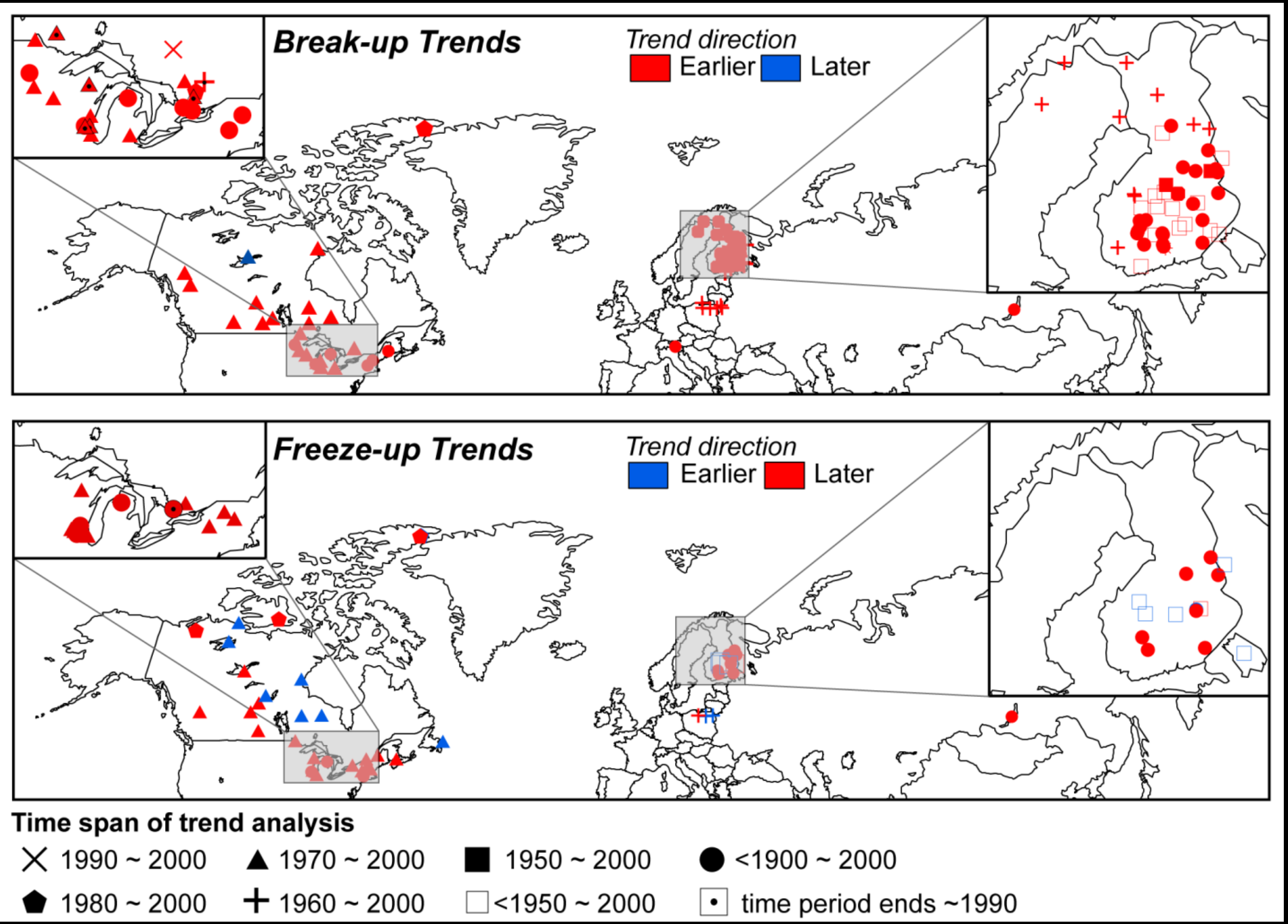


MODIS imagery acquired during the break-up period over Great Slave Lake in 2004 (Howell et al., 2009)

Brown and Duguay, 2010

Response of lakes to climate

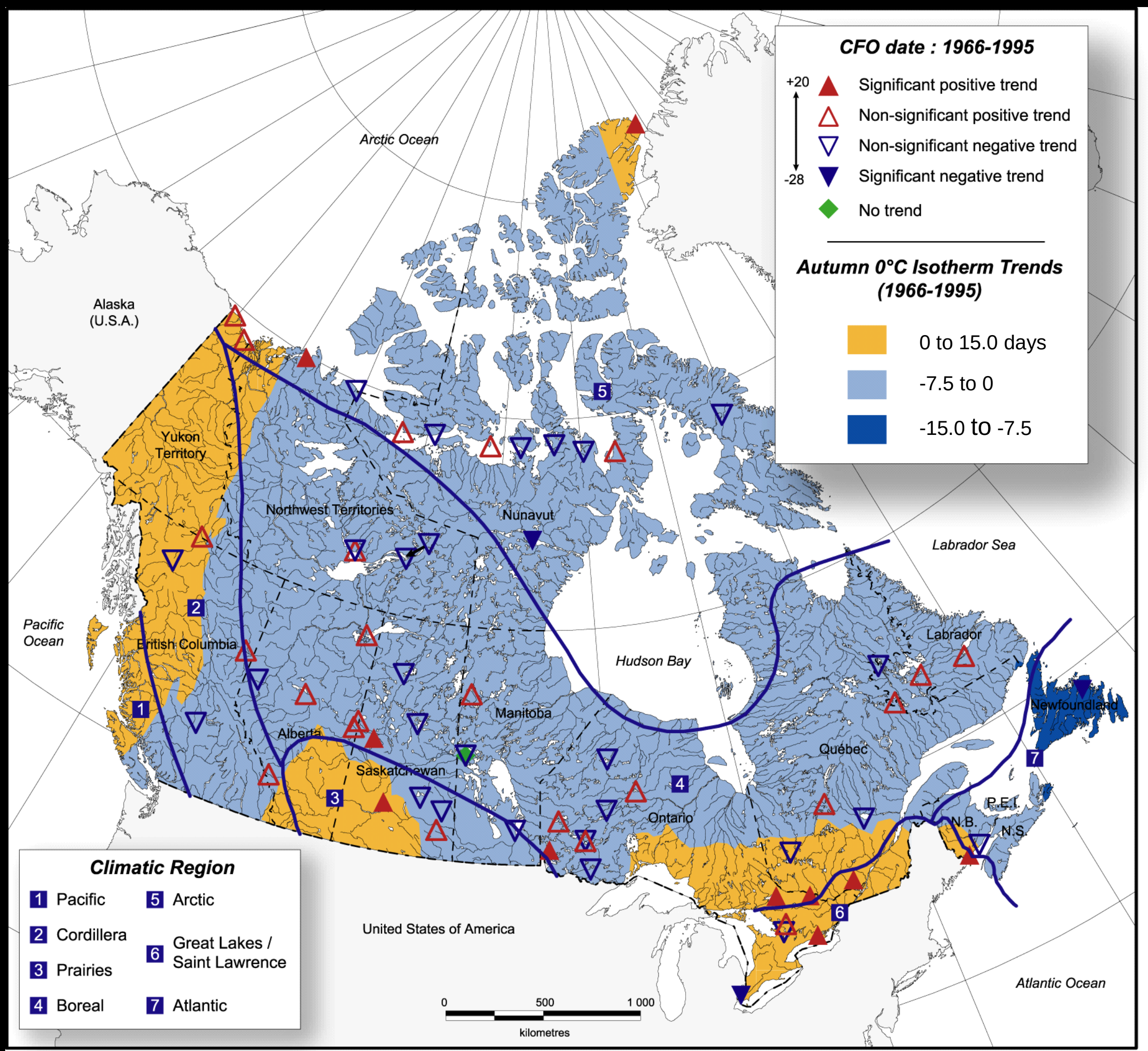
Freeze-up (ice-on) and break-up (ice-off) trends for lakes of the Northern Hemisphere



- Freeze-up/break-up dates (and ice cover duration) are robust indicators of climate variability and change

Brown and Duguay, 2010

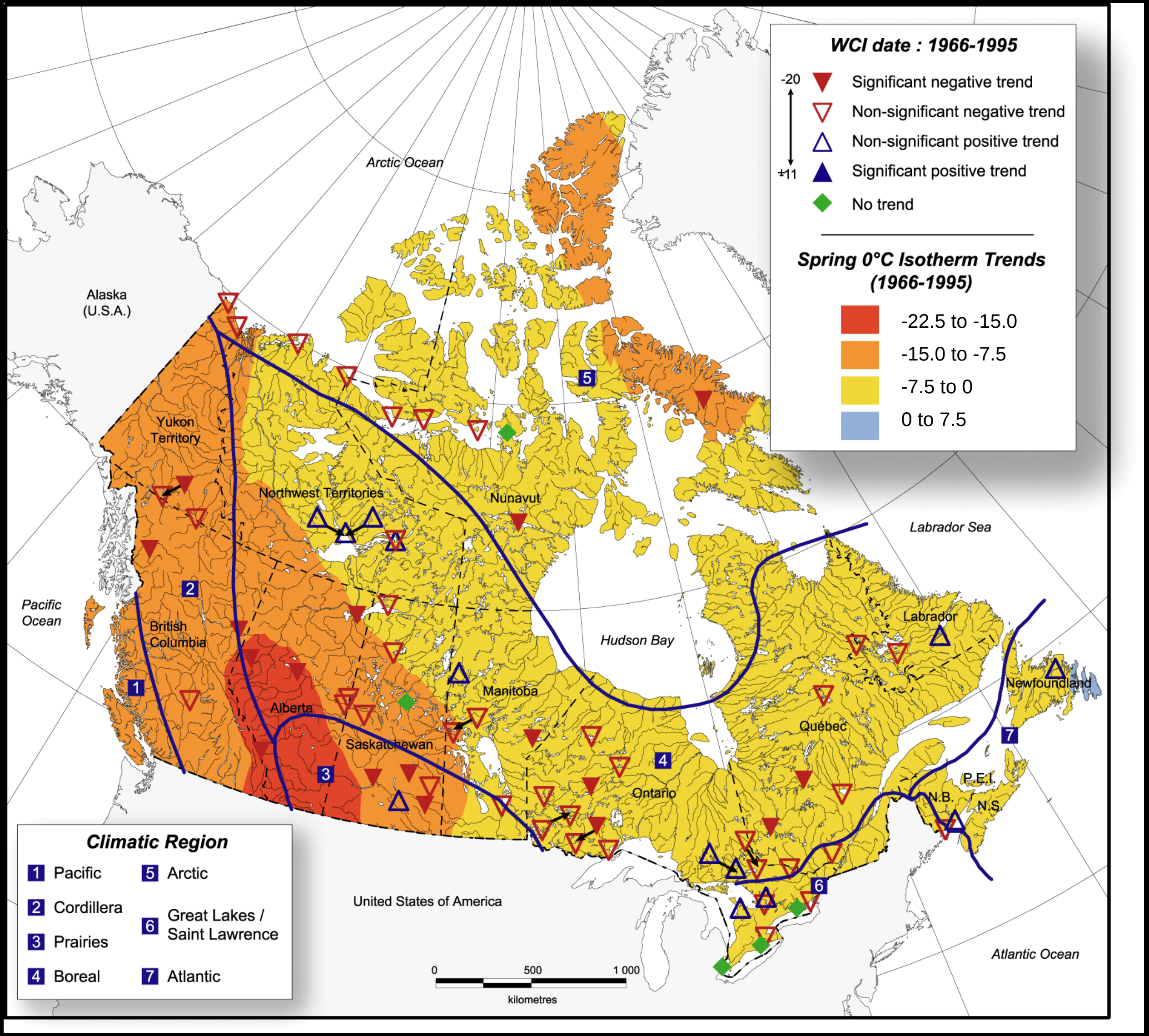
Response of lakes to climate



Trends in freeze-up and autumn 0ºC isotherm dates

Duguay *et al.*, 2006

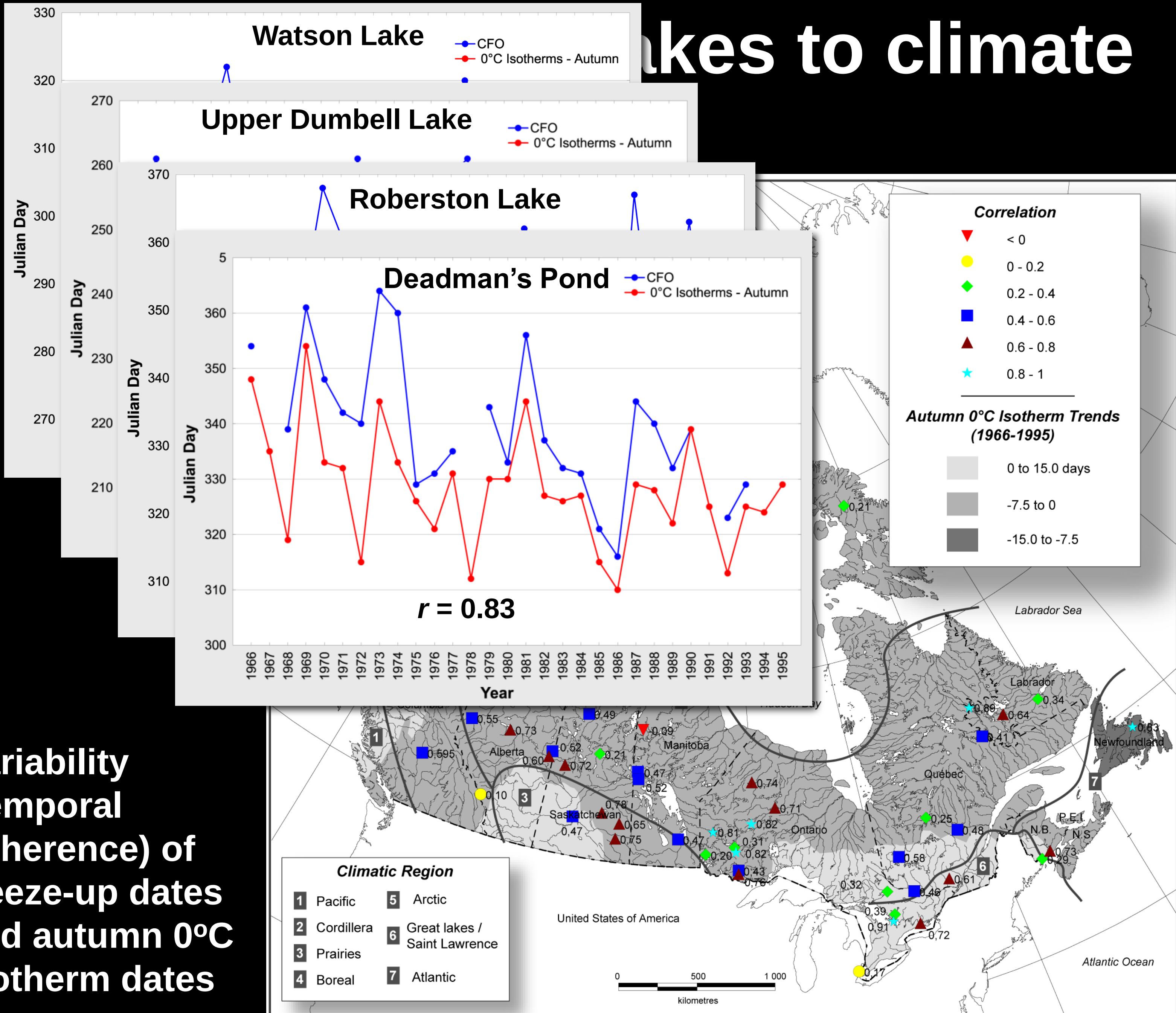
Response of lakes to climate



Trends in break-up and spring 0°C isotherm dates

Duguay *et al*., 2006

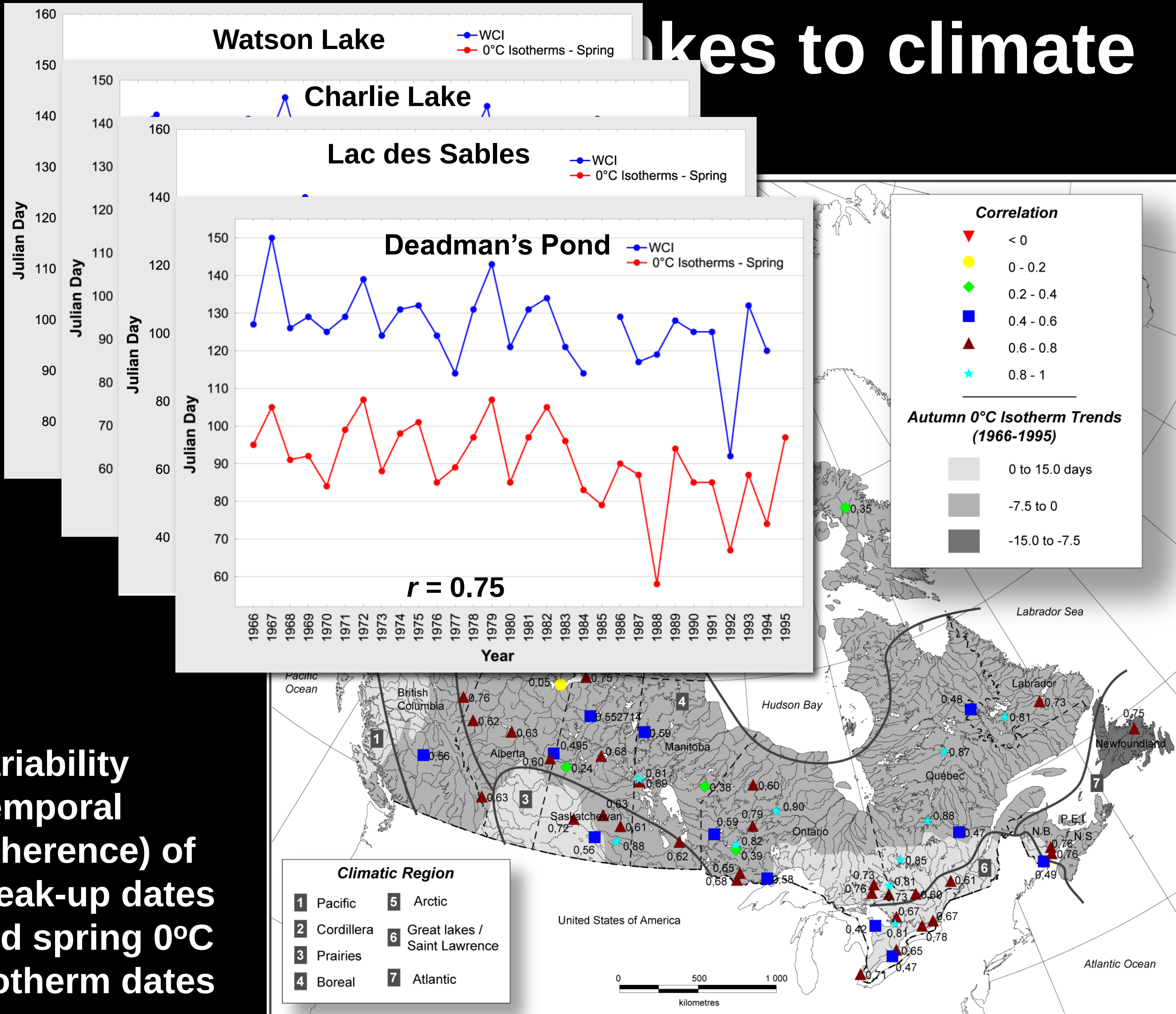
kes to climate



Variability (temporal coherence) of freeze-up dates and autumn 0ºC Isotherm dates

Duguay *et al.*, 2006

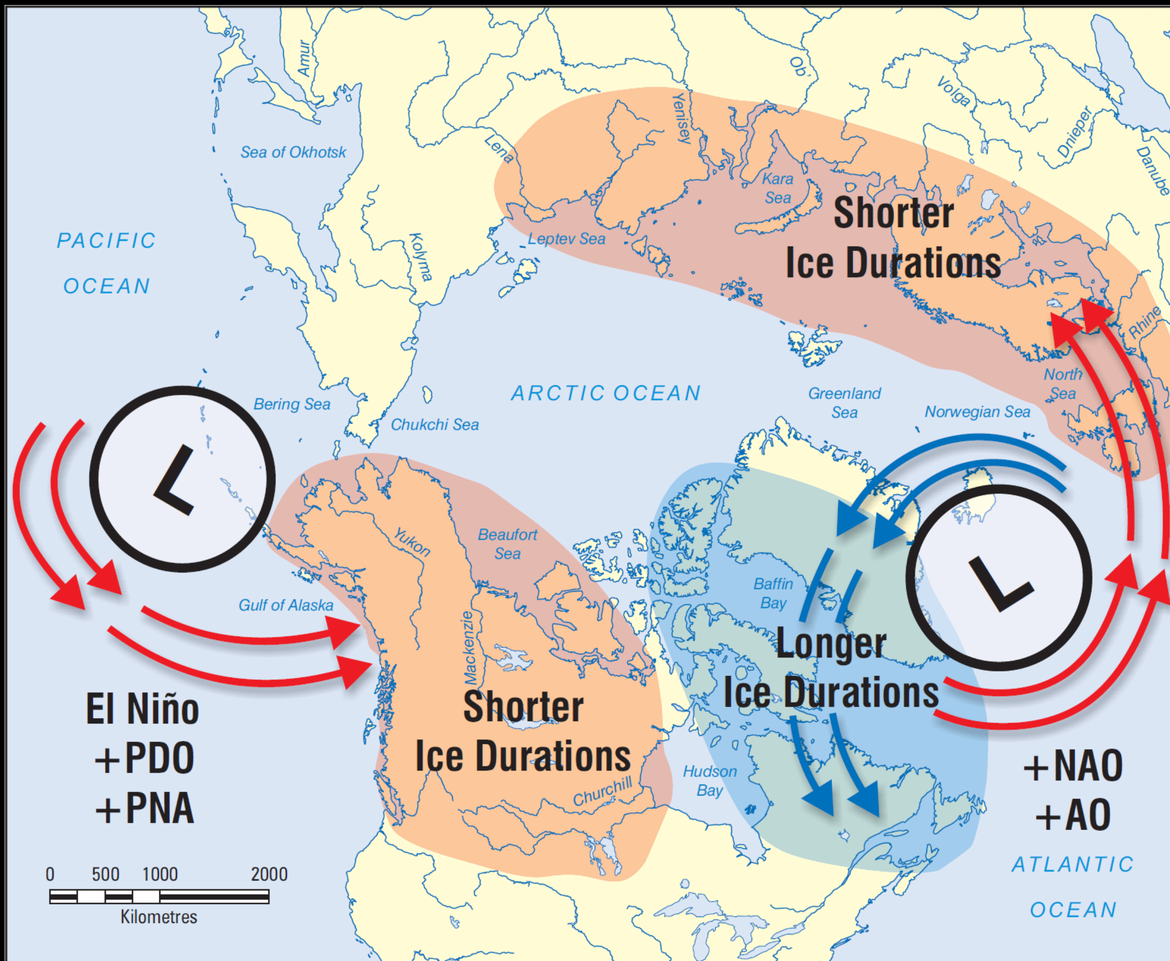
kes to climate



Variability (temporal coherence) of break-up dates and spring 0ºC Isotherm dates

Duguay *et al.*, 2006

Response of lakes to climate



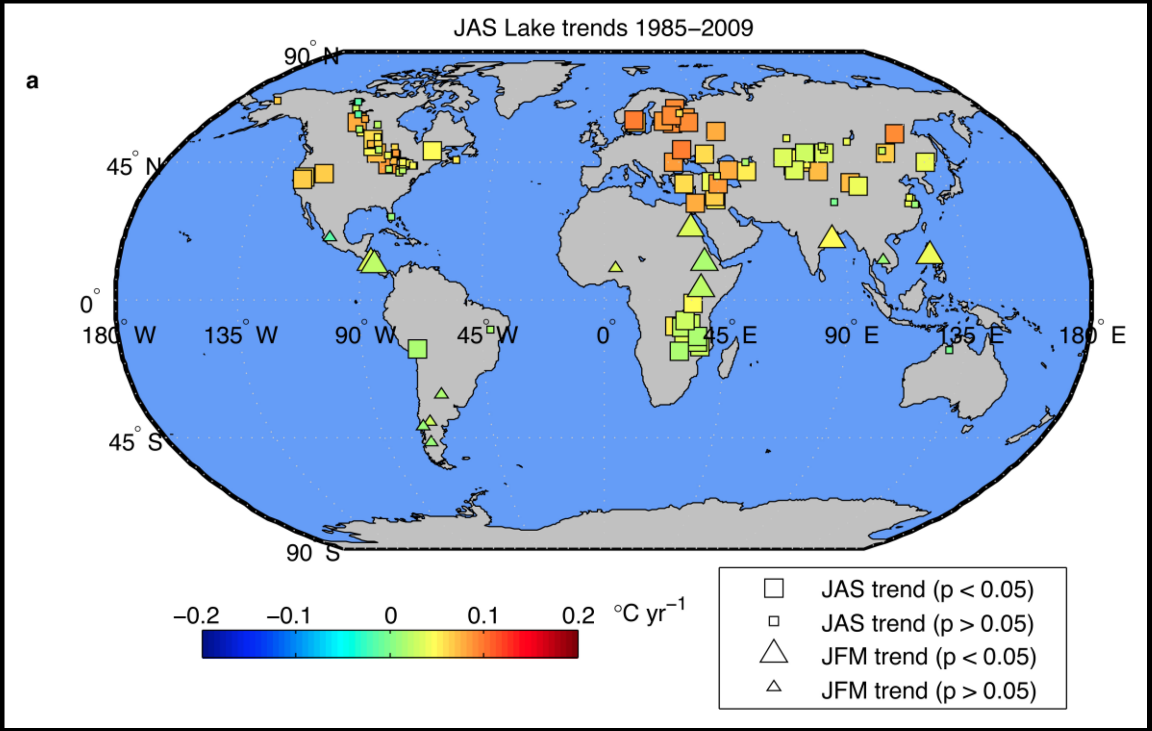
- Positive phases of ENSO (El Niño), the PDO, the PNA, and the NAO/AO are shown.
- Negative phases of these oscillations are associated with opposite temperature changes and lake ice durations.

Prowse *et al.*, 2011

Response of lakes to climate

Global lake temperature trends

- Average warming rate of 0.45 degrees Celsius per decade, with some lakes warming as much as 1 degree per decade.
- The warming trend is global, and the greatest increases are in the mid- to high-latitudes of the Northern Hemisphere.

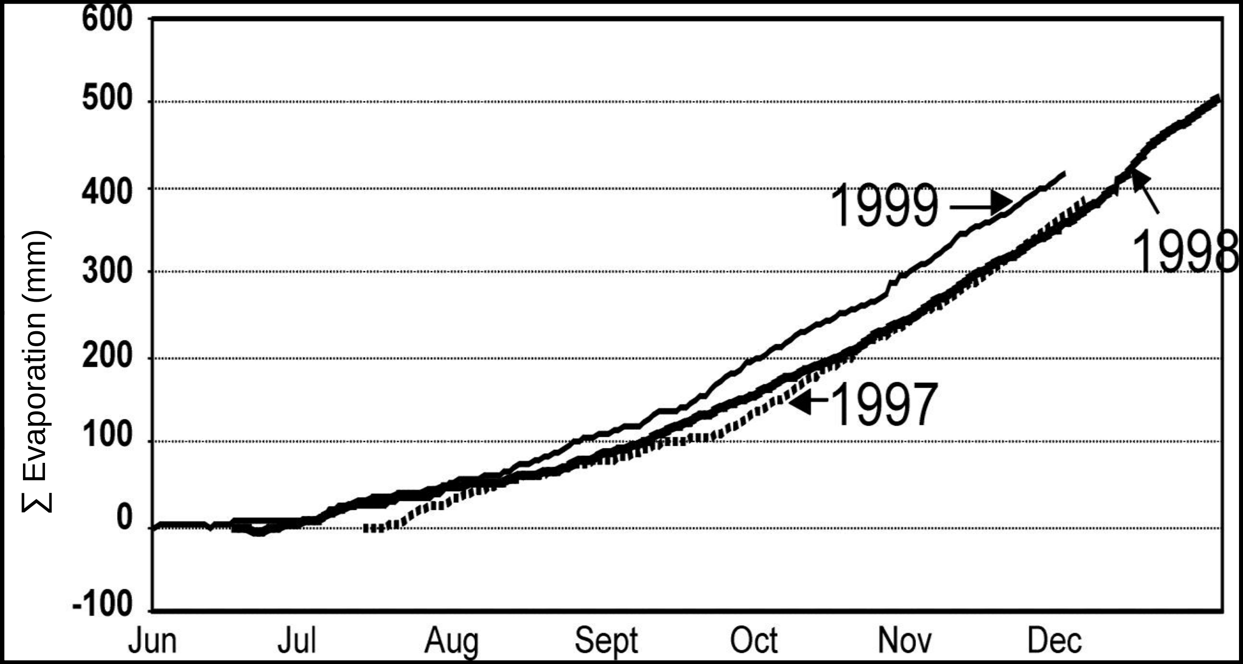


167 large lakes from NOAA AVHRR

Schneider and Hook, 2010

Implications of changing ice cover and temperature of lakes

Impact of earlier break-up on the energy balance of Great Slave Lake, N.W.T., Canada (Source: Rouse et al., 2003)

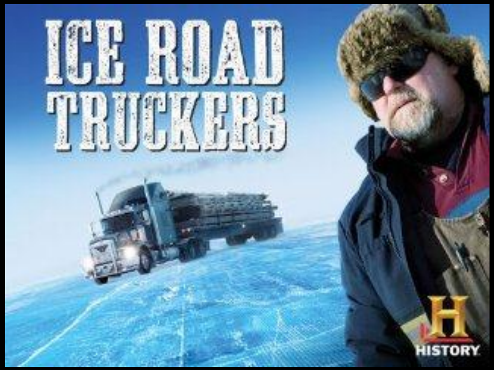


An analogue for climate change?

Earlier break-up date (one month from normal) during the El Niño year of 1998 greatly enhanced evaporation totals compared to 1997 and approached average values for the lower Laurentian Great Lakes (Schertzer, 1999).

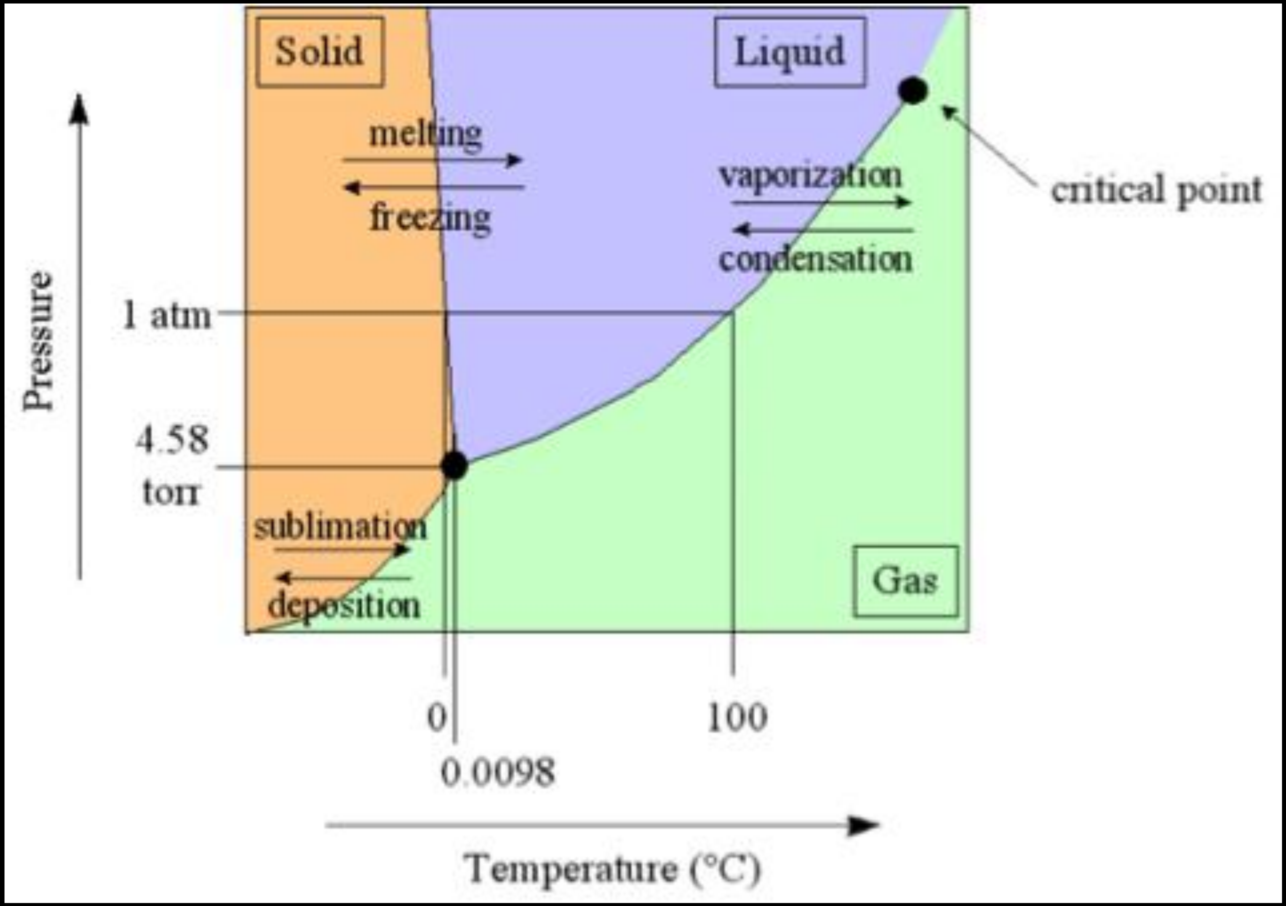
Implications of changing ice cover and temperature of lakes

- Timing of ice events important for many aspects
  - E.g. High Arctic, changes in the ice phenology are resulting in some perennial covered lakes changing to an annual ice regime and longer ice free seasons resulting in species shifts within the lakes
- Changes in ice cover (phenology, thickness and composition) and water temperature affect water resources, recreation, ecology, transportation



Water properties

Phase diagram of water and ice



The plot shows the phase diagram of water.

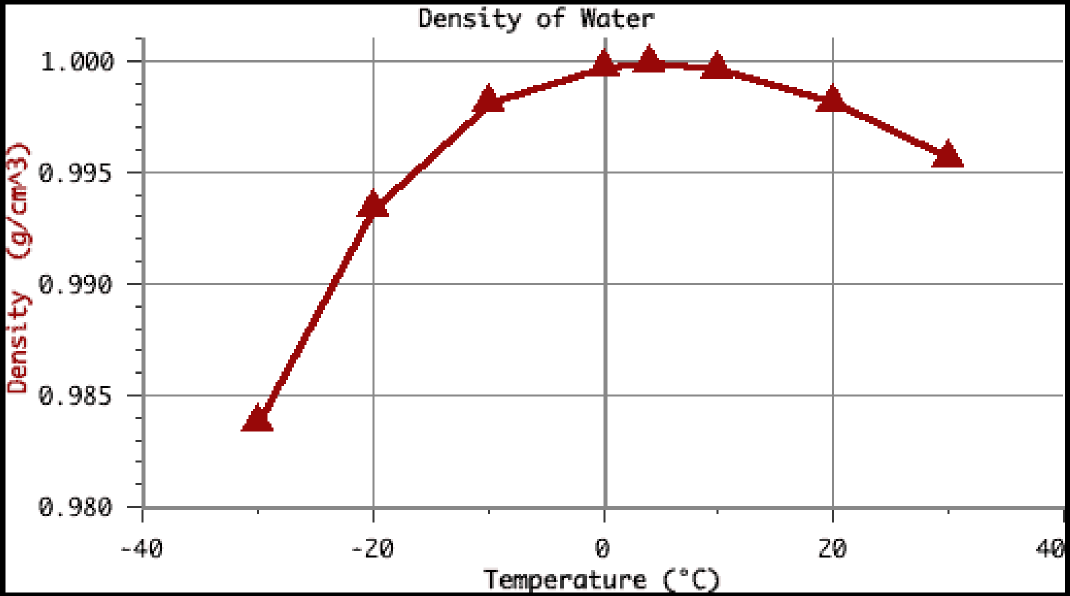
The triple point of water - when ice, water, and water vapor can coexist - is at a temperature of 0.01ºC (0ºC = 273.16 K), and a pressure of 6.1 mbar.

Water is the only substance which we commonly experience near its triple point in everyday life.

Source: http://www.its.caltech.edu/~atomic/snowcrystals/ice/ice.htm

Water properties

Density of freshwater



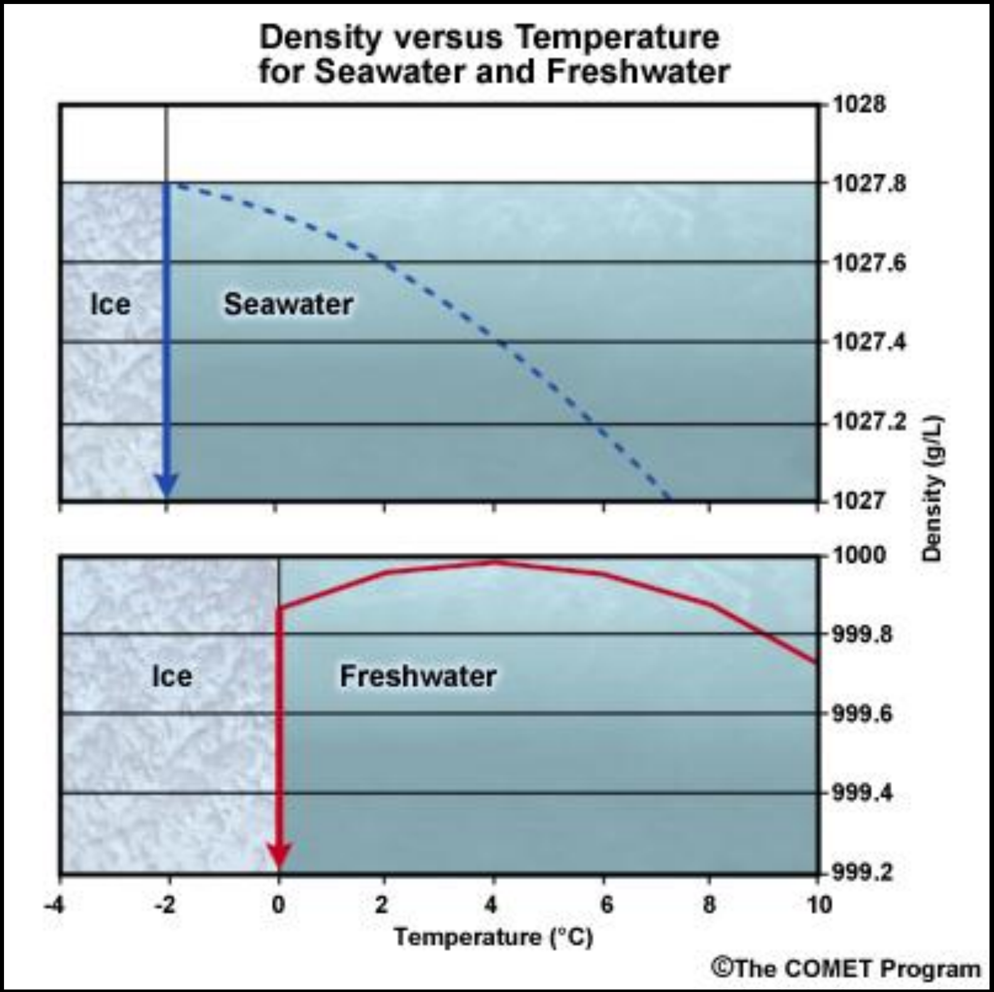
The graph shows the density of liquid water vs temperature.

The density of water increases as the temperature is lowered, but below 4ºC this trend is reversed.

The reason it can show liquid water below 0˚ C is that water can be supercooled.

Water properties

Density of freshwater and seawater



In fresh water, the maximum density occurs at a temperature of 4° C. In the autumn, as surface water cools, it becomes denser and sinks. Warmer water from below replaces it. As freshwater cools below 4° C, it becomes less dense and convection ceases. This allows the surface water to freeze without cooling the entire body of water to the freezing point.

Seawater is different. Dissolved salt interferes with the freezing process, lowering the freezing point to -1.8° C. Seawater also gets denser as it cools, right down to its freezing point. However, this does not mean that the entire ocean must cool to -1.8° C before the surface can freeze.

Water properties

Thermodynamic properties of water/ice/snow

Table 2.1
Physical Properties of Snow and Ice at 0°C

Property	Freshwater	Ice	Sea Ice[a]	Snow[b]		Firn
				Fresh	*Settled/Wet*	
Density ($kg\ m^{-3}$)	1000	917	720–940	20–150	250–550	550–830
Albedo	0.1	0.1–0.6	0.1–0.7	0.8–0.9	0.4–0.6	0.3–0.4
Thermal conductivity ($W\ m^{-1}\ °C^{-1}$)	0.56	2.11	1.91	0.03–0.06	0.1–0.7	0.7–1.5
Heat capacity ($J\ g^{-1}\ °C^{-1}$)	4.218	2.12	2.12	2.09	2.09	2.09
Thermal diffusivity ($m^2\ s^{-1}$)	0.13	1.09	1.06	0.22	0.30	0.69
Latent heat of fusion ($J\ g^{-1}$)	334					
Latent heat of sublimation ($J\ g^{-1}$)	2834					

[a]Thermal properties for a temperature of −2°C, a salinity of 5 ppt, and a density of 850 $kg\ m^{-3}$.

[b]Thermal diffusivities calculated for densities of 100, 400, and 700 $kg\ m^{-3}$.

Marshall, 2012

Lake ice properties

Lake Ice Types

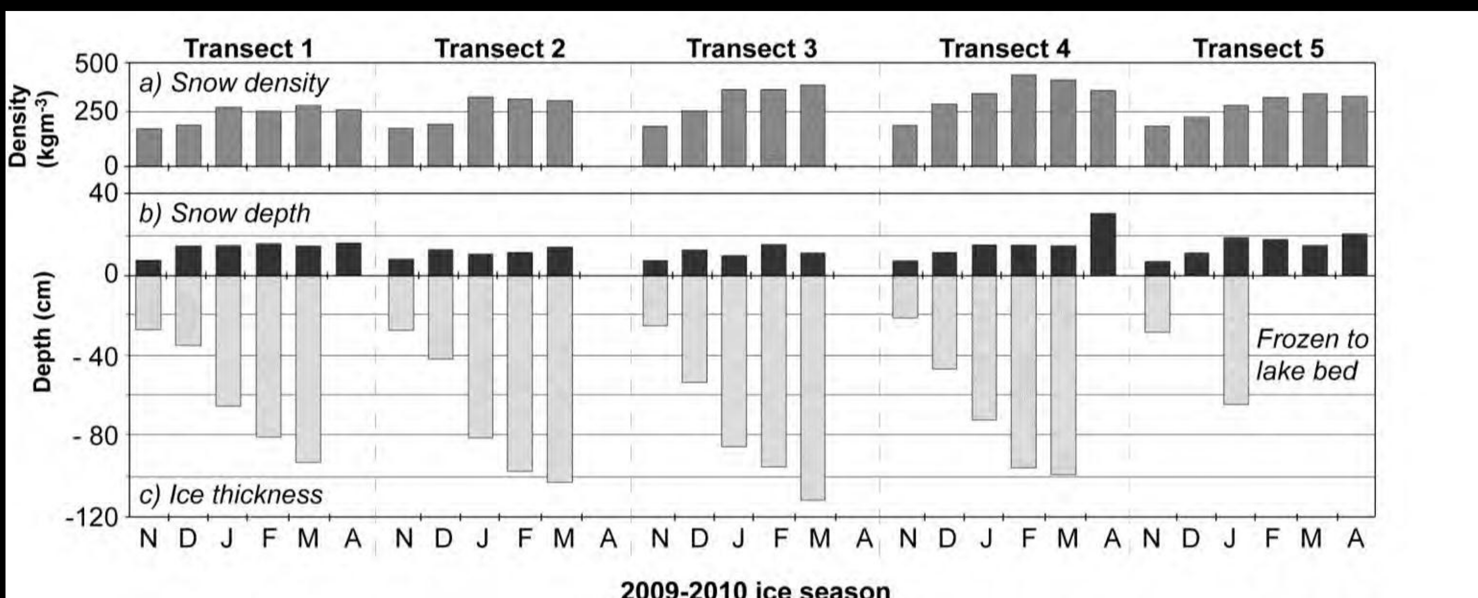
- **Clear/Black Ice**
  - Appears black as the ice is clear and you can see down to the darker water and/or bottom
  - Snowcover provides insulation and slows growth

- **Snow/Slush/White ice**
  - Weight of the snow presses ice below hydrostatic level, water floods surface through cracks, or percolates from melt. Forms slush layer that refreezes as white ice
  - Redistribution of snow key for snow ice development
    - Tends to develop near shorelines more than in centre of lakes
  - *Albedo different from black ice due to light scattering from bubbles and small ice crystals (appears white, high albedo)*

Lake ice properties

Lake Ice Thickness

- Lake ice thickness can be highly variable across a lake
- Heavily influenced by the overlying **snow depth** and **density**



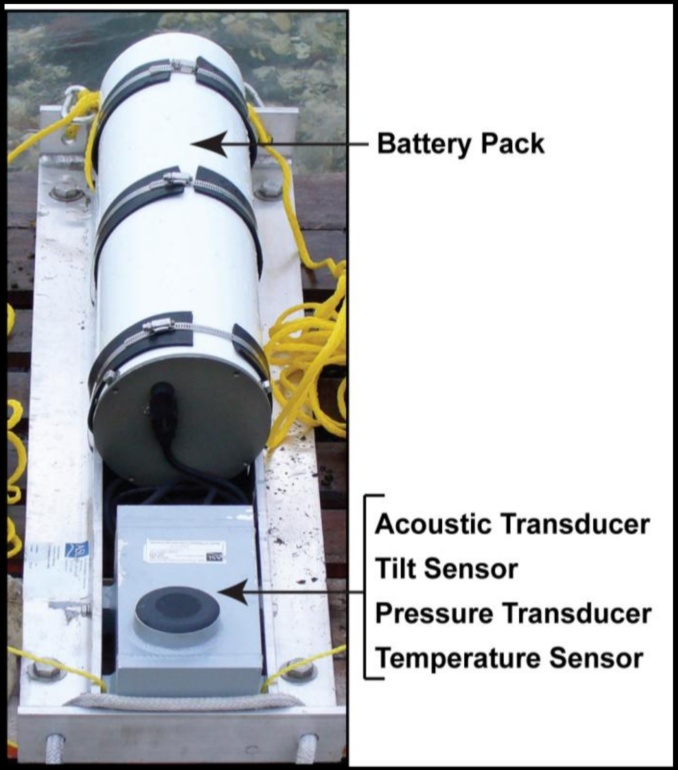
(a) Monthly average density (gcm^{-3}), (b) snow depth (cm) and (c) ice thickness (cm) from sampling transects on the lake ice surface 2009/10.

Brown and Duguay, 2011

Lake ice properties

Monitoring ice phenology and ice thickness automatically (in situ)

Malcolm Ramsay Lake, Churchill, MB



Shallow Water Ice Profiler

Brown and Duguay, 2011

Lake ice properties

Monitoring ice phenology and ice thickness automatically (in situ)

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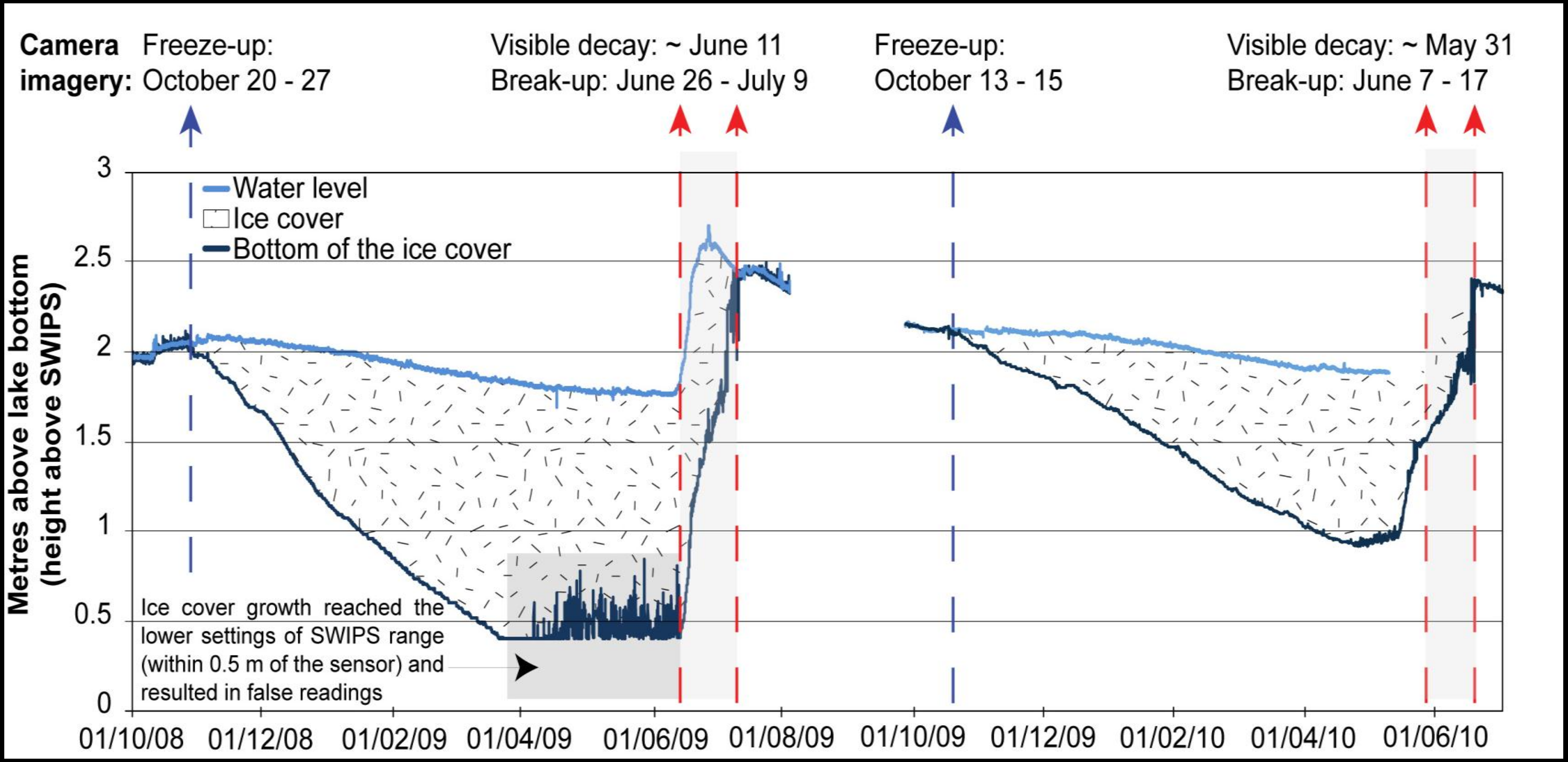


Brown and Duguay, 2011

Tomorrow

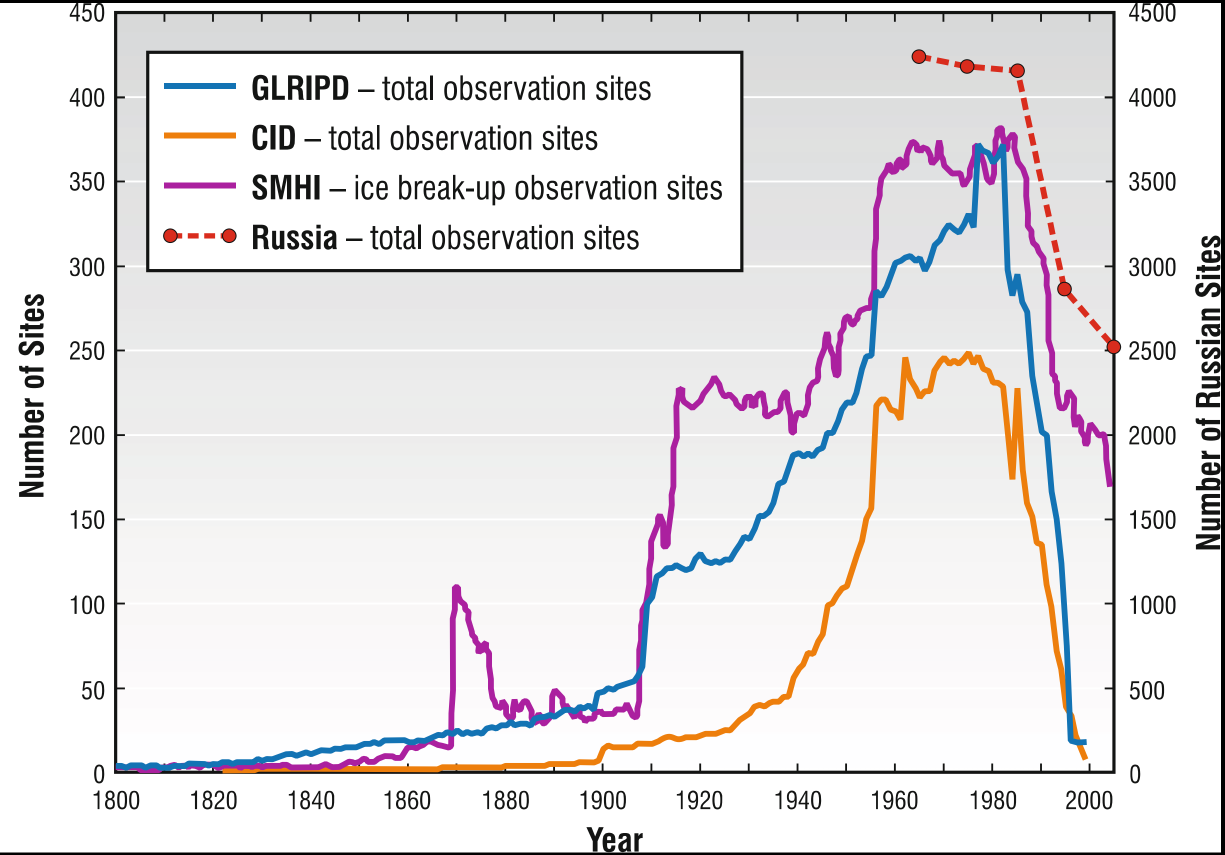
Lake ice cover and surface water temperature II:

Satellite remote sensing

Why remote sensing?

Ice monitoring networks have nearly disappeared in the last 30 years

Historical evolution of the number of in situ lake-ice and river-ice observation sites recorded in various databases.



Source: Prowse et al. (2011)

Why remote sensing?

GCOS: Lakes as terrestrial ECV

- Lake water level
- Lake surface area
- Lake surface temperature
- Lake freeze-up and break-up?

*"Changes in **lake volume, level, and area** may be indicators of changes in climate.*

Analysis of temporal and spatial variability of lake levels and lake surface areas is important to global climate research and the planning and management of regional resources.

***Lake temperature** affects freeze-up and break-up dates, which are markers used in regional climate monitoring."*

Stitt, S., Dwyer, J.L., Dye, D.G., Josberger, E.G., 2011. Terrestrial essential climate variables at a glance. *U.S. Geological Survey Scientific Investigations Map 2011–3155*, 1 plate.