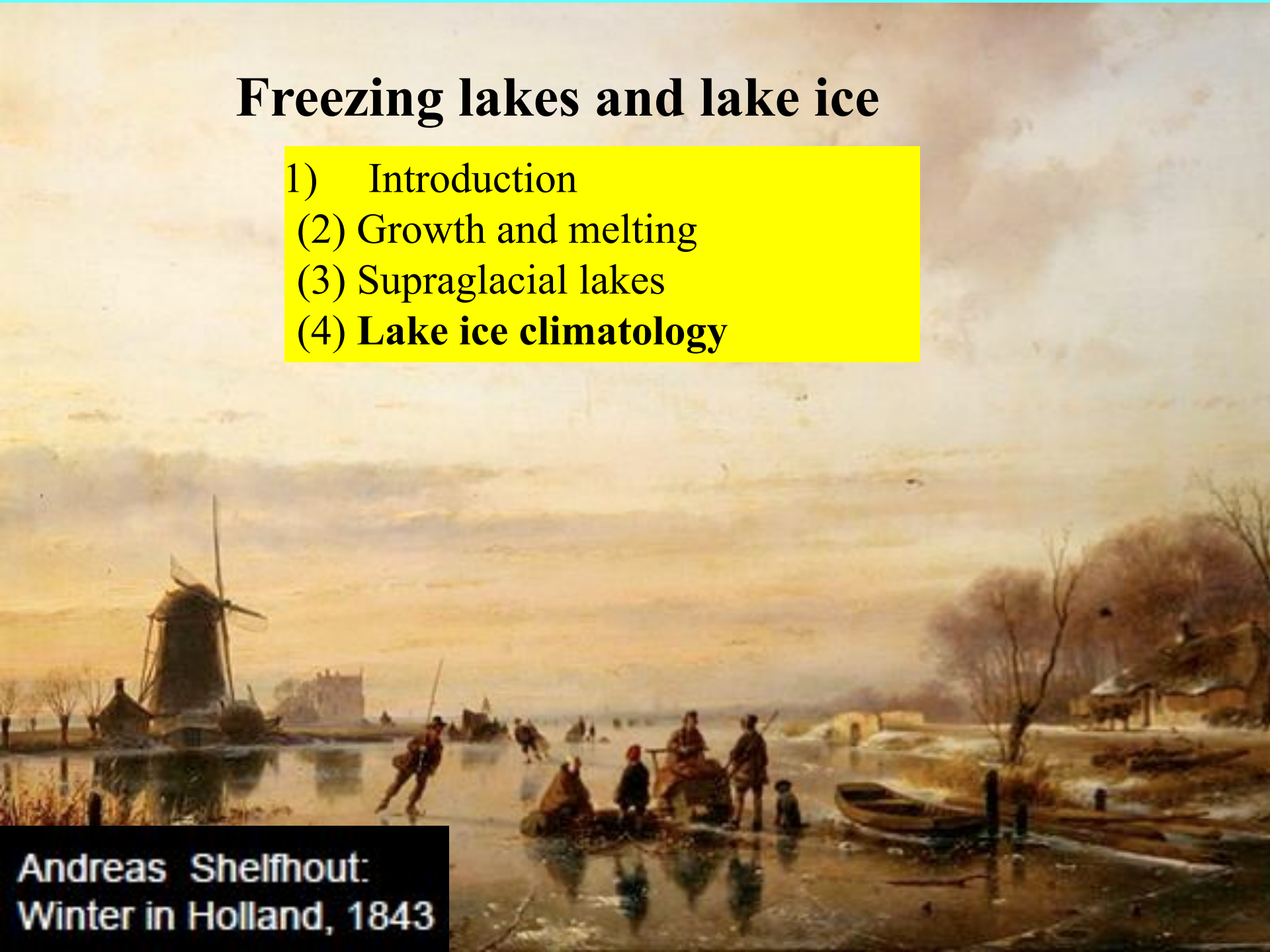


Freezing lakes and lake ice

- 1) Introduction
- (2) Growth and melting
- (3) Supraglacial lakes
- (4) **Lake ice climatology**

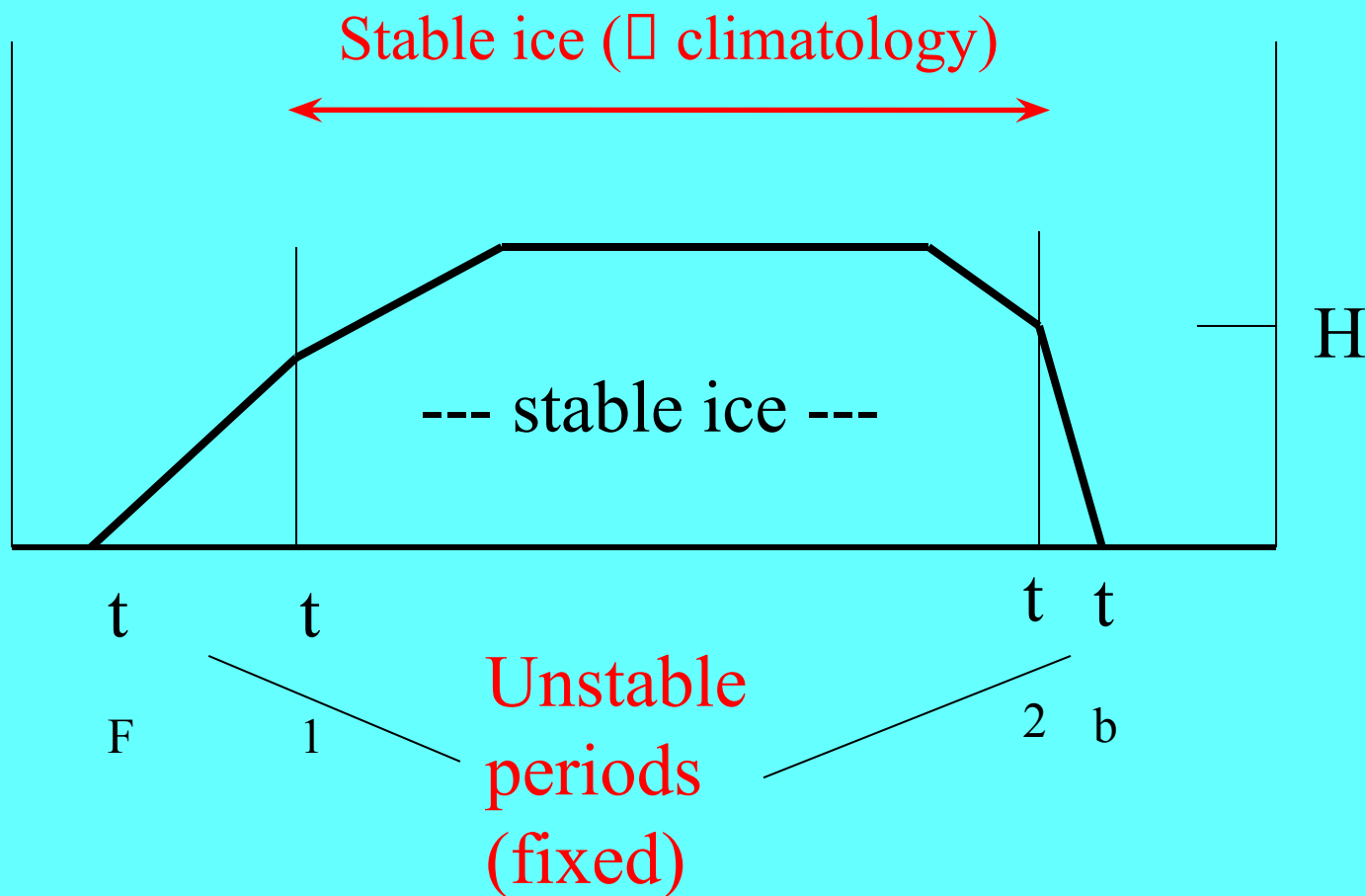


Andreas Schelfhout:
Winter in Holland, 1843

Lake ice season

H = min thickness
for stable ice,
10 cm (small lakes)—
50 cm (large lakes).

Ice thickness



Warming climate □ ?

- Will the lake freeze in future ?
- How much are freezing date and break-up date affected ?
- How much is ice thickness affected ? And ice quality?
- Ice cover stability ?
- Ice coverage ?

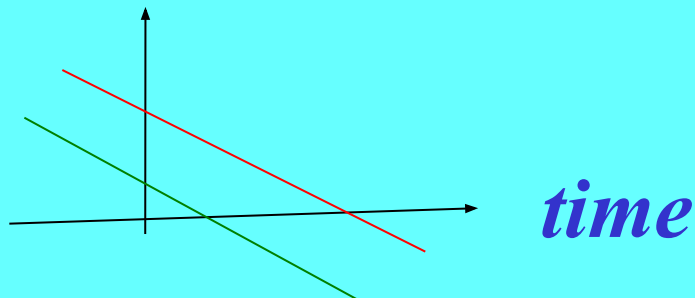
Ice phenology

- **Freezing date**

- Strongly connected to air temperature (long-wave radiation, turbulent fluxes)
- Connection depends on lake depth
- Freezing after 0°C downcrossing
- Air temperature falling rate major factor

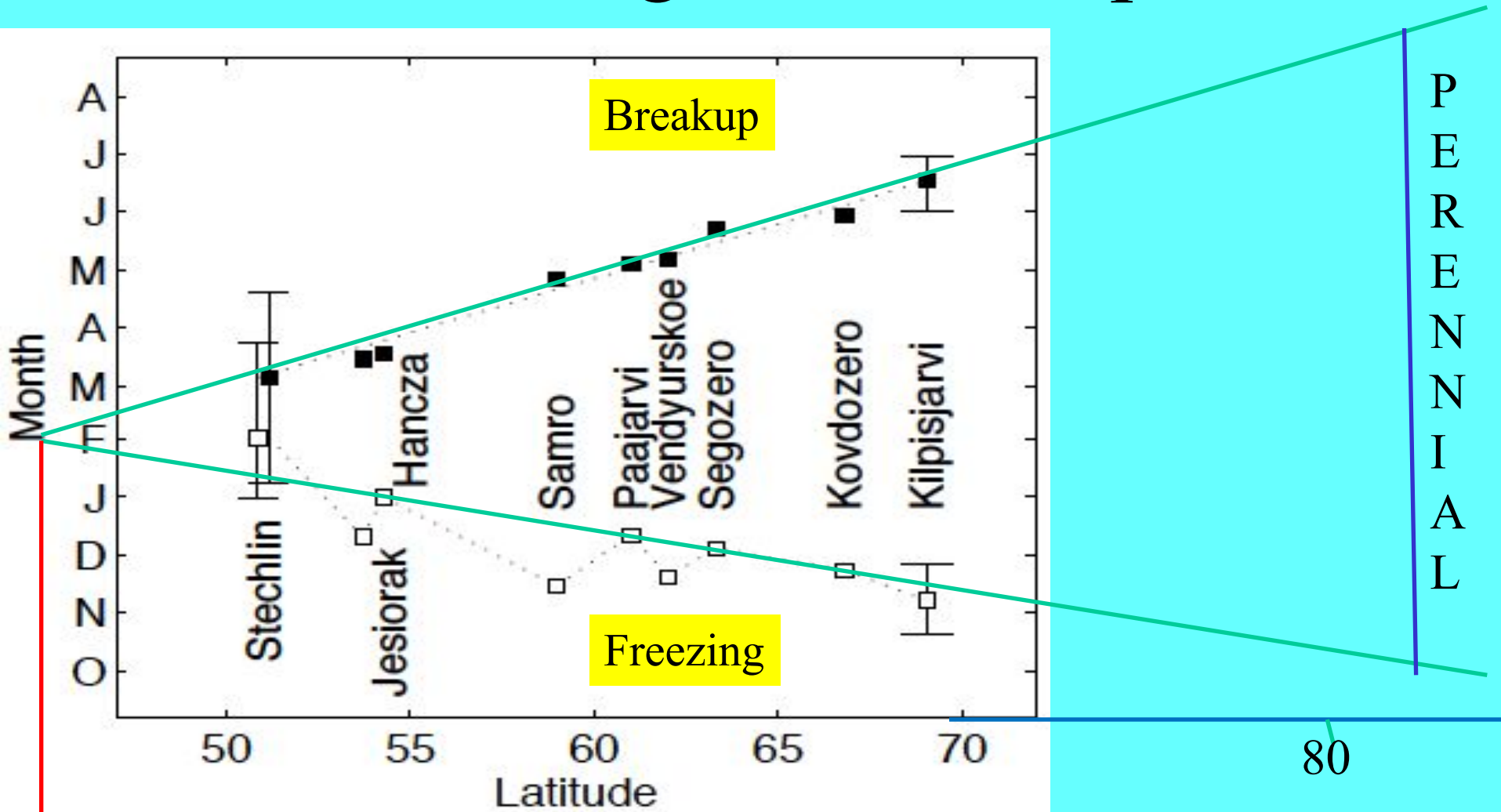
- **Breakup date**

- Solar radiation driving force – no long-term trend
- Ice and snow thickness – weak positive trend
- Turnover day from negative to positive heat balance key factor
- Degree-days correlate with net solar flux



Thickness ~ ✓
freezing-degree-days

Freezing and breakup



No ice

Extrapolated from Kirillin et al. (2012)

Lake ice time series

Ice phenology

- freezing date
- breakup date

How to define?

Ice cover properties

- Ice thickness – max annual value
- Ice concentration (large lakes)

Variability

- independent winters
- interannual variability externally forced

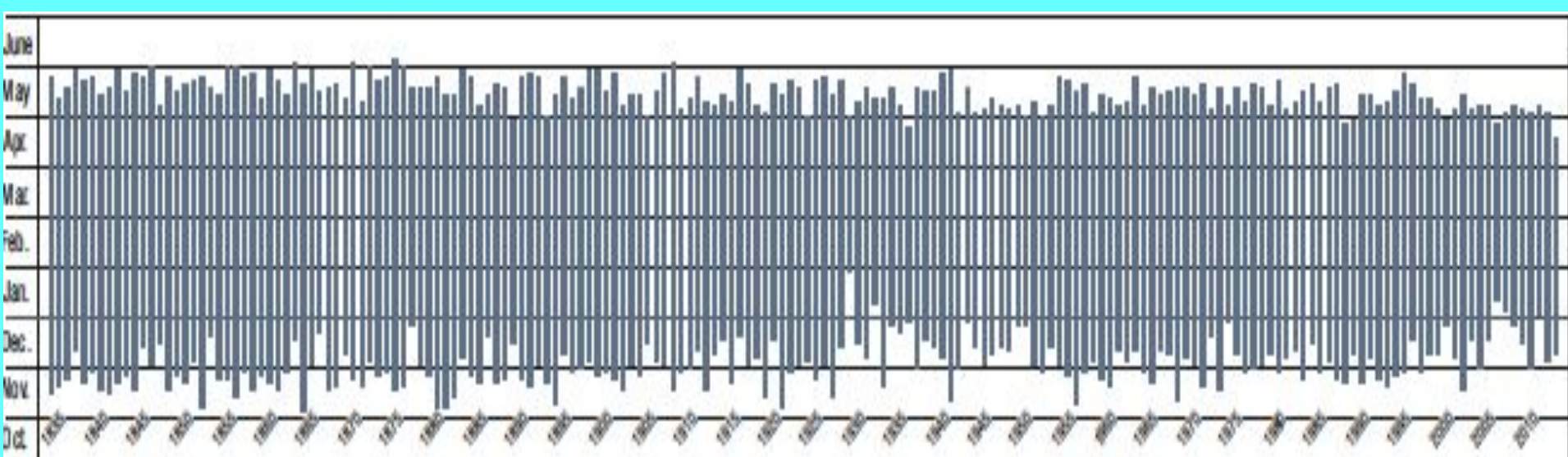
□Aperiodic time series outcome

- weak intra-seasonal connections

Lake Kallavesi, Finland 1830 – 2014

Breakup

- Trend 10 days/100 years
- Aperiodic
- Variability 45 days

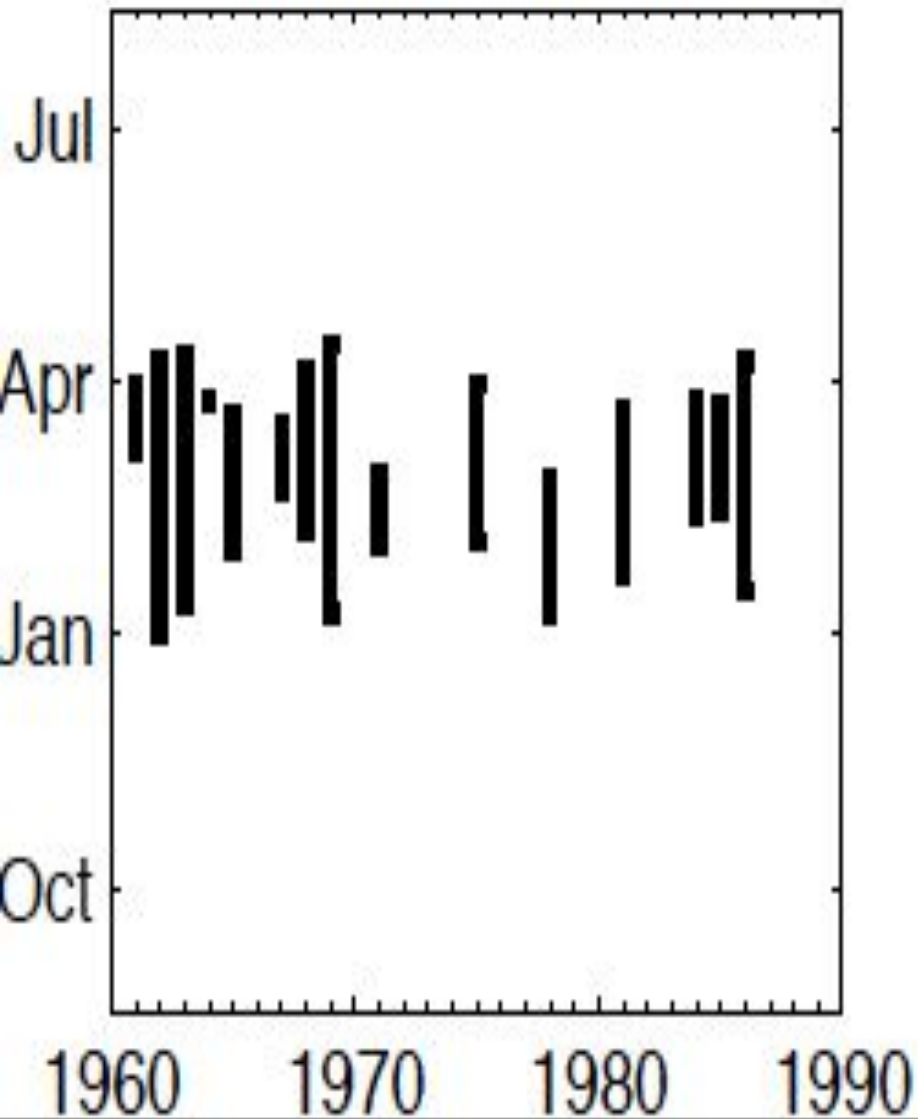


Freezing

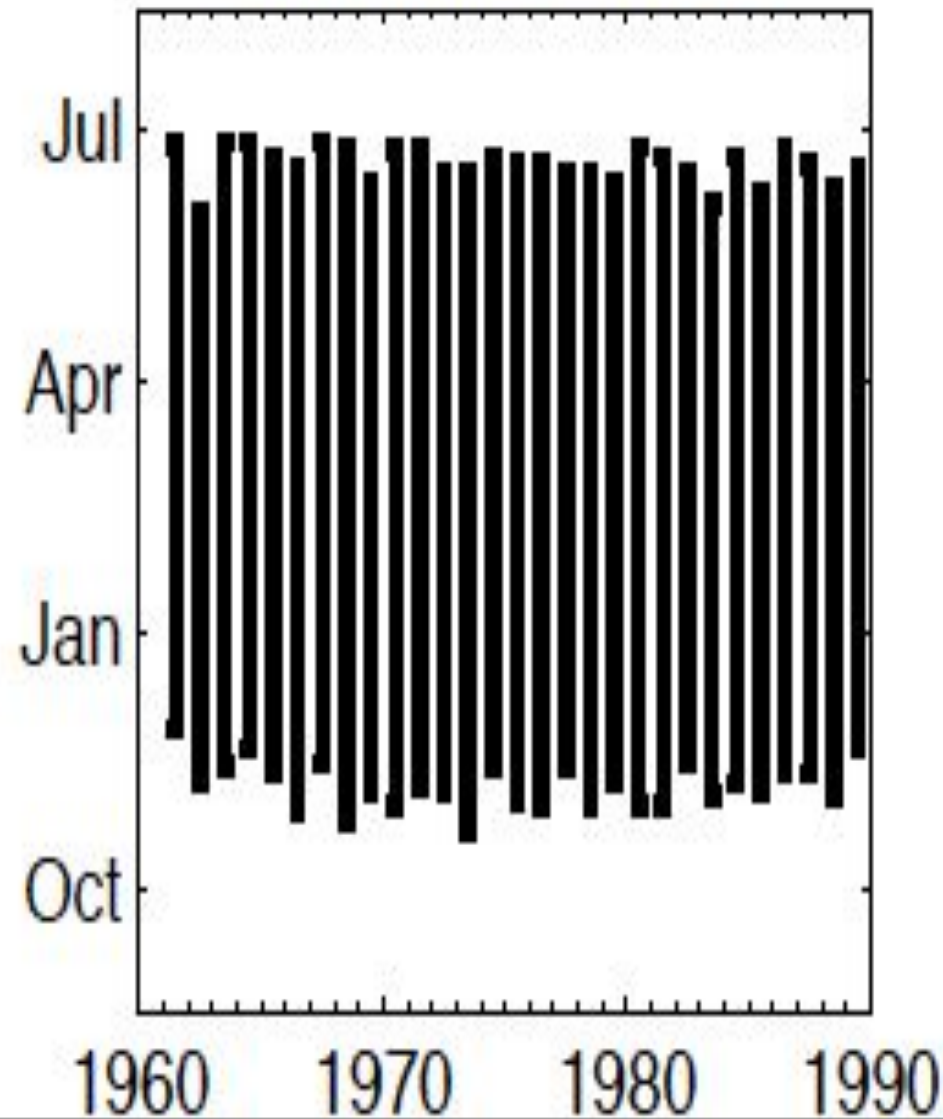
- Trend 10 days/100 years
- Aperiodic
- Variability 80 days
- Extrema far from mean

Colder climate $\square$ less variability Kirillin et al. (2012)

Stechlin 53N 13E

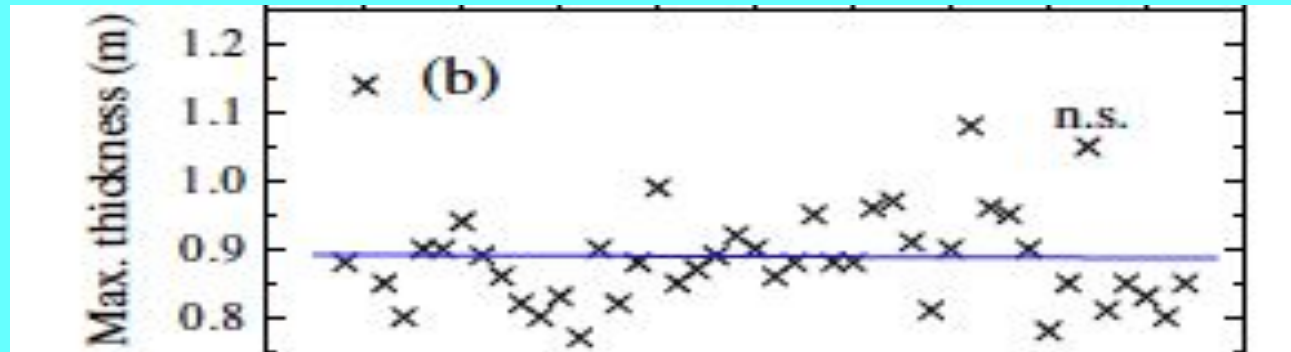
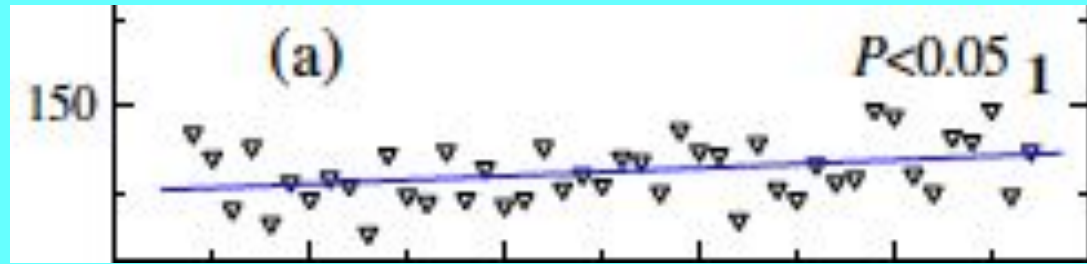


Kilpisjärvi 69N 21E

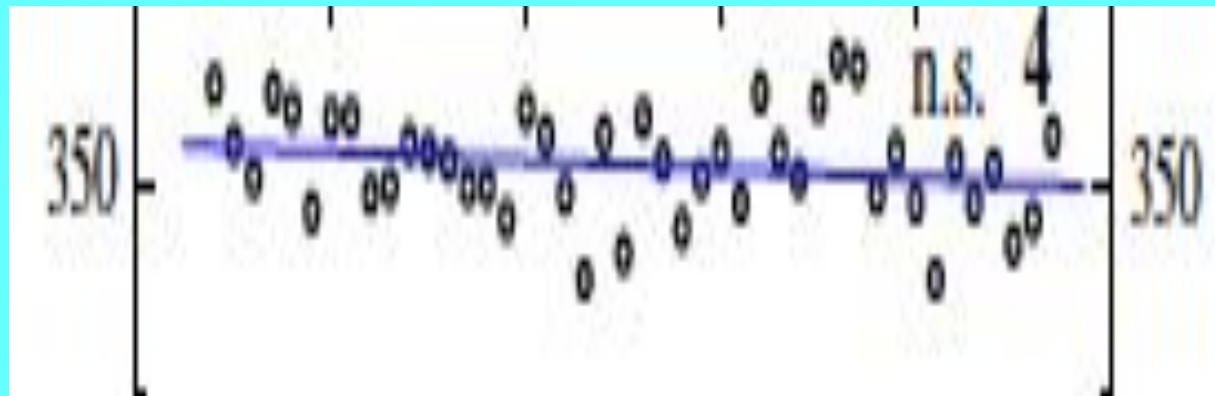


Kilpisjärvi trends 1952 – 2010 (Lei et al., 2012)

*Freezing
date*



*Breakup
date*



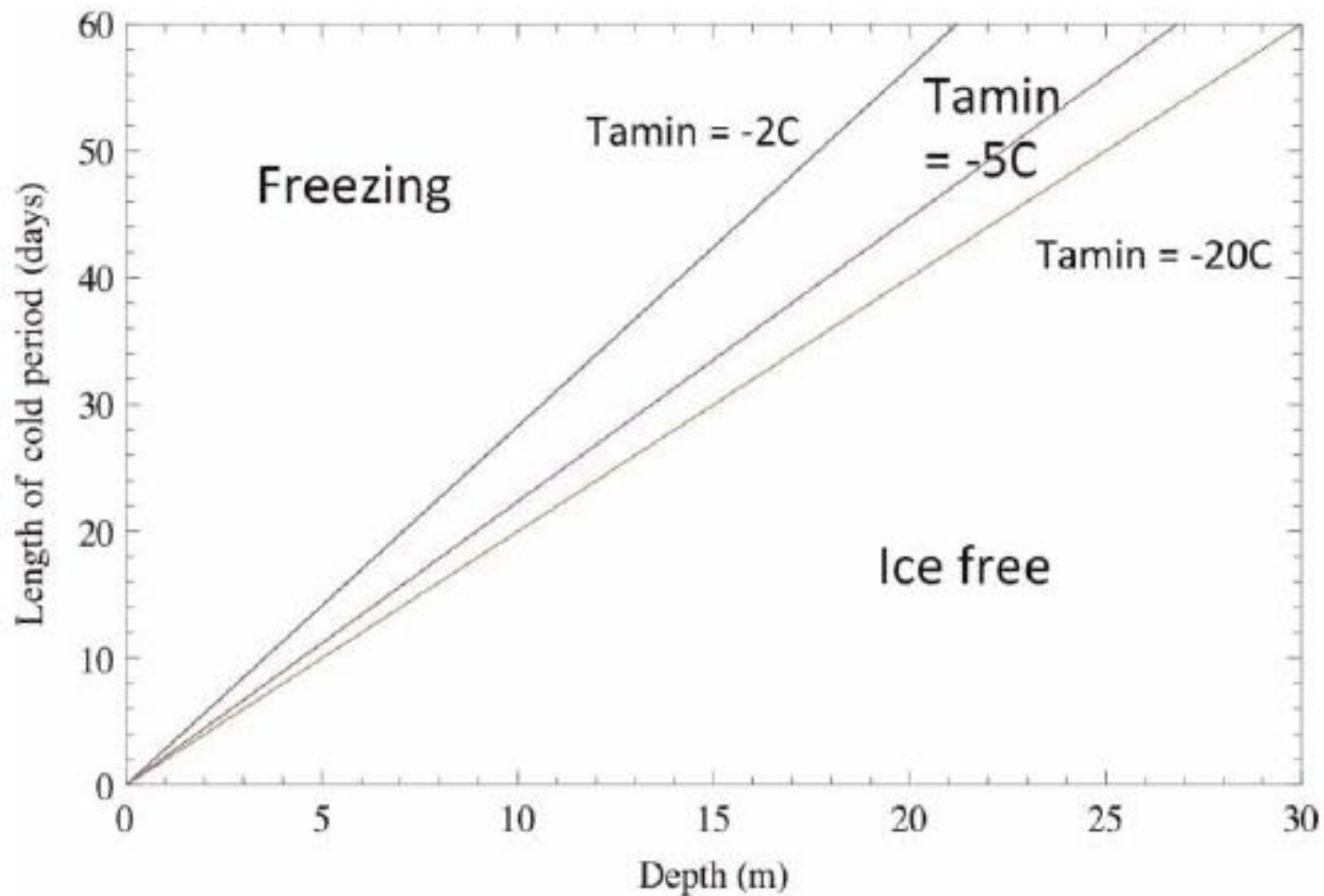


Figure 1 | Freezing conditions for lakes as a function of the lake depth and length of the cold period ($T_a < 0^{\circ}C$).

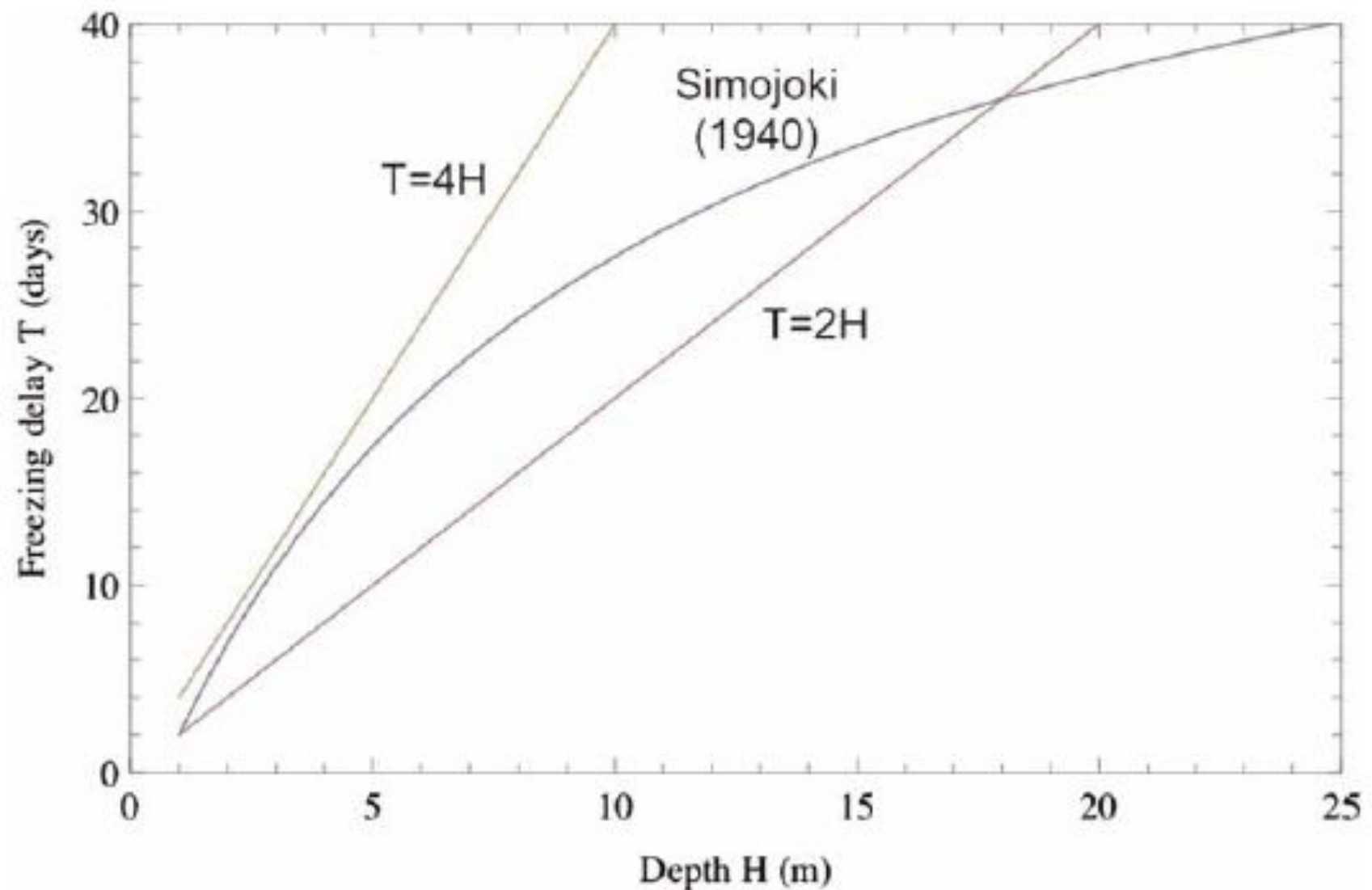
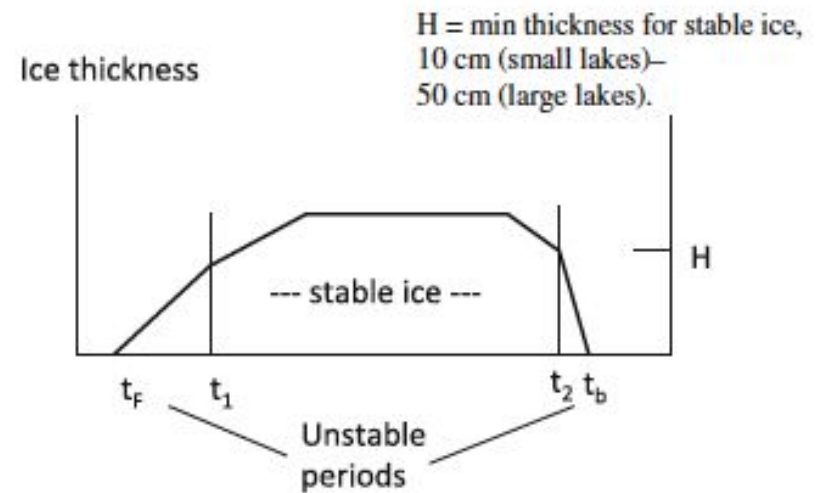


Figure 2 | Delay of the freezing date from the air temperature downcrossing of 0°C as a function of the mixed layer depth (H) of the lake. The empirical curve of Simojoki (1940) is shown together with lines $T[\text{days}] = 2H[\text{m}]$ and $4H[\text{m}]$.

1st order: climate change impact

- **Freezing date**
~ 5 day/°C
- **Ice thickness**
5–10 cm/°C
- **Breakup date**
~ n days after zero upcrossing of heating

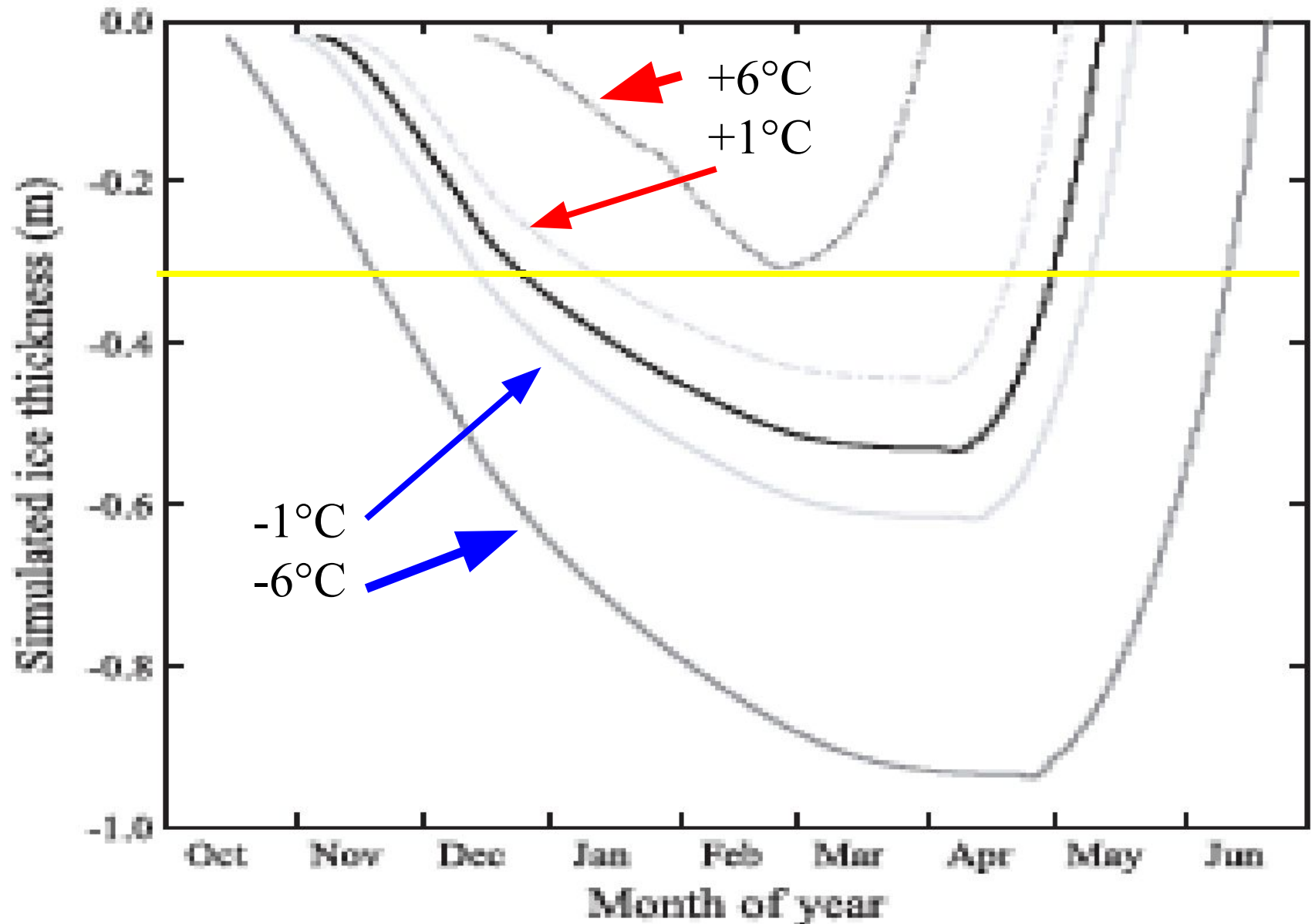


$$\Delta t_F = \frac{\Delta T_a}{\dot{T}_a}$$

$$\frac{h_2}{h_1} = \frac{a_2}{a_1} \cdot \left(1 + \frac{\Delta T_a}{T_{a,\min}}\right)^{\frac{3}{4}}$$

$$t_b - t_m = \left[\frac{3}{\mu c} (\rho L h_0 - k_1 R) \right]^{\frac{1}{3}}$$

Lake Vanajavesi: model for climate change impact



Ice thickness cycle – albedo sensitivity, Prydz Bay

*Yang et al.
(2016)*

$$\alpha = 0.5$$

$$\alpha = 0.7$$

$$\alpha = 0.6$$

$$\alpha = 0.5$$

Polar ice does not melt fully but breaks due to internal deterioration. Light transmissivity of ice also has an important role.

Lake Ladoga: Finnish – Soviet – Russian data



1943 – 1992

Aircraft observations

- Approx. twice a month
- Plots of ice distribution'

1971 ->

- NOAA and MODIS satellite images
- On average 19 images /winter

1913 – 1937

Ice charts and reports

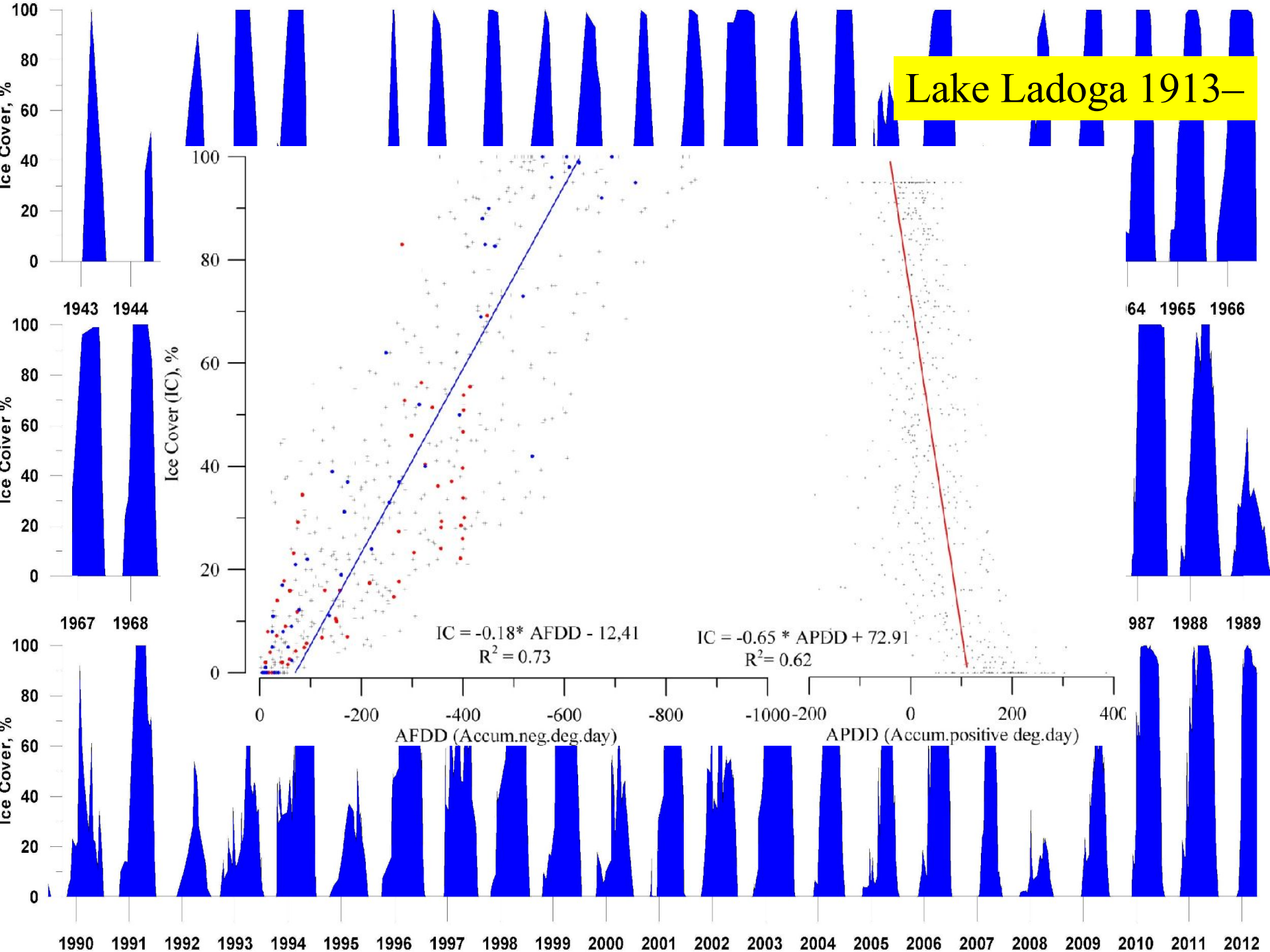
Ice concentration A

- A = relative area of ice in the lake
- Freezing $\square$ depth: $t = F(h)$
- Hypsographic curve = $G(h)$

Formally:

$$A(t) = G[F^{-1}(t)/\max(h)]$$

Thus fall evolution of ice concentration is related on the hypsographic curve. Also decrease of concentration depends on that as melting starts from shallow parts. Wind and lake size add further modifications.



Summary: warming (?) □

- Freezing day delays
- Max annual ice thickness likely decreases
- Ice quality (congelation ice/snow ice) ?
- Period of stable ice cover shortens
- Transient open water periods in smaller lakes than presently
- Ice breakup date likely earlier

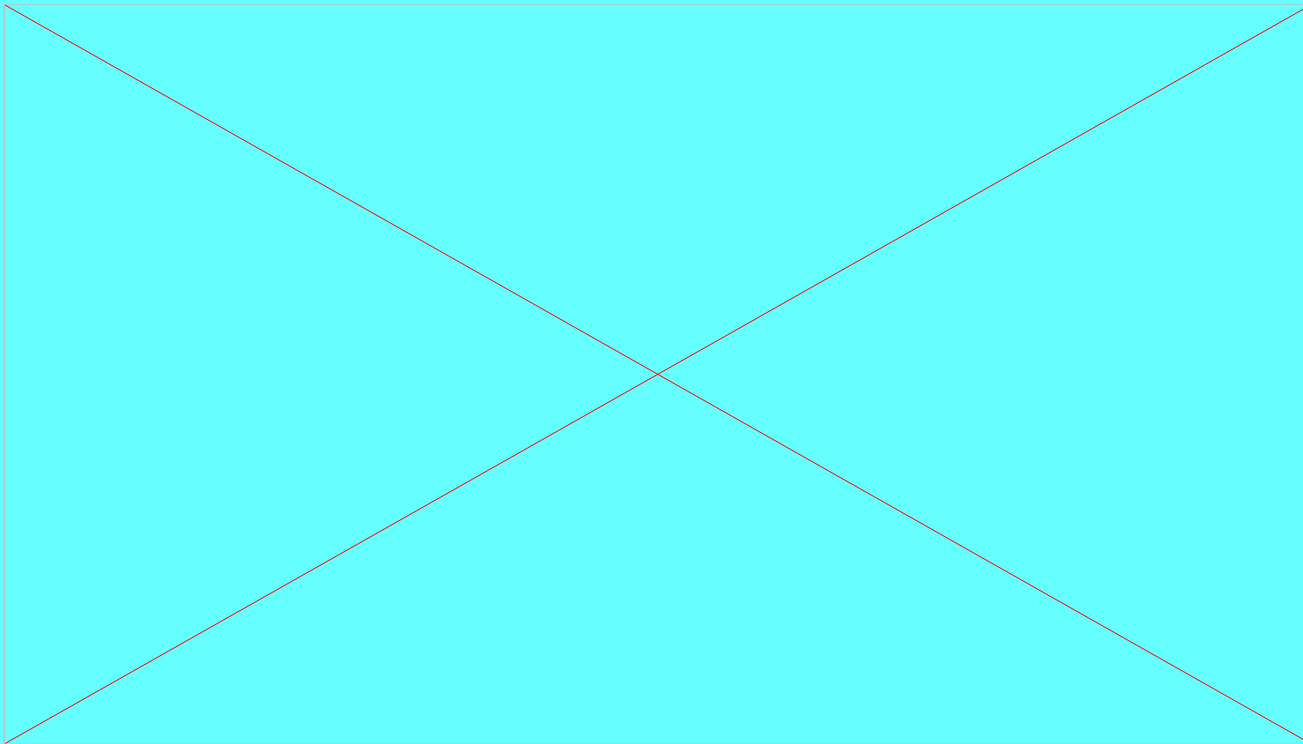
... consequences to water body

- Shorter ice season

AND

- More sunlight
- More transient open water periods
- Improved oxygen level
- How winter ecology will be adapted?

Climate warming □ Lake seasons



Annual cycle:
qualitative changes
-Summer stratification
stronger
-Stable ice period shorter

Lake ice and society: climate change impact

- Lake ecology (+/- ?)
- Traffic on-ice
- Recreation: sport, fishing
ice-water bathing
- Local weather changes
 - warmer surfaces
- Open areas may persist
 - moisture fluxes, frazil ice
- *Snow is main question!*



Jacob Grimmer: Winter (1500s)

If the climate changes, not only the length of ice season and the thickness of ice change, but the quality of physics, ecology and practical life will be different.