Sea Ice Lecture Notes
ESS 431

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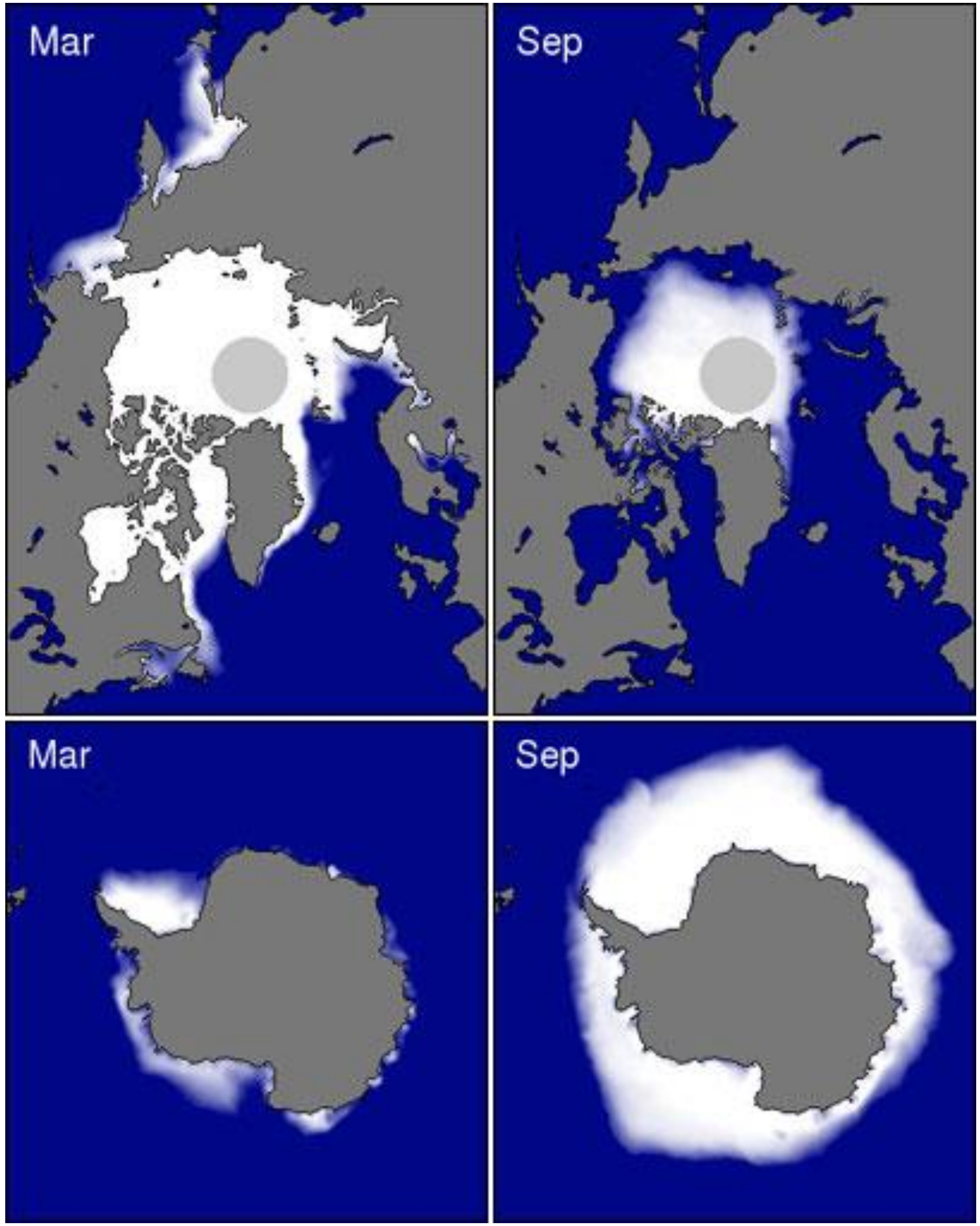
11/26/18, 11/28/18

What is sea ice?

- Frozen ocean water
- Forms, grows, melts in the ocean
- Grows in winter, melts in summer, can melt completely or survive multiple years
- Typical thickness: “first-year” <= 1.8 m, 2-3 year old = 2 – 3 m, 6 year old ~ 5 m

Maximum and minimum climatology 1979-2000



Arctic

<= 5% hemisphere

1.5 – 2.5 m thick

Winter extent = 15×10^6 km^2

Summer extent = 3.4×10^6 km^2

Antarctic

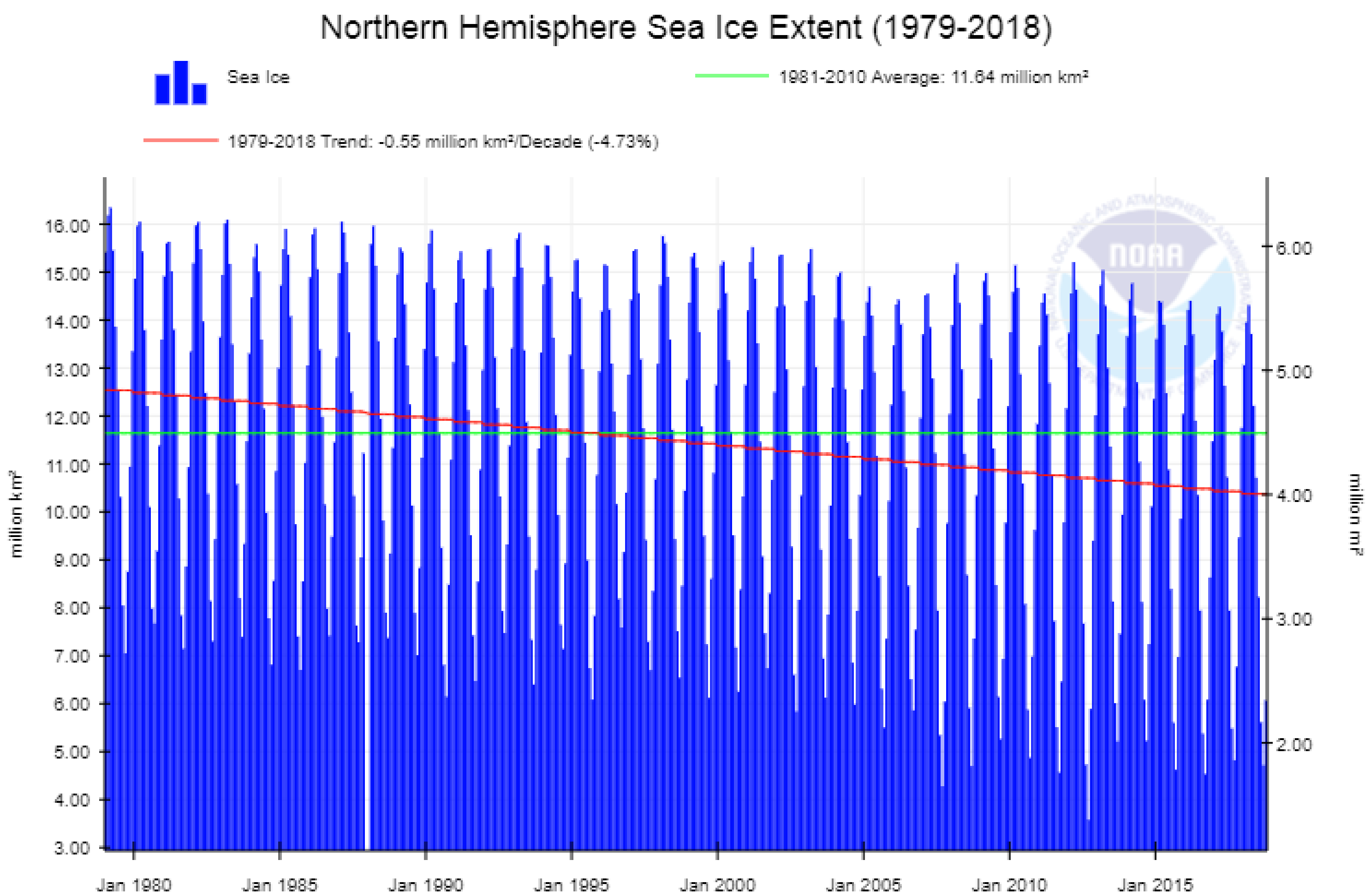
<= 8% hemisphere

0.5 – 1.0 m thick

Winter extent = 20×10^6 km^2

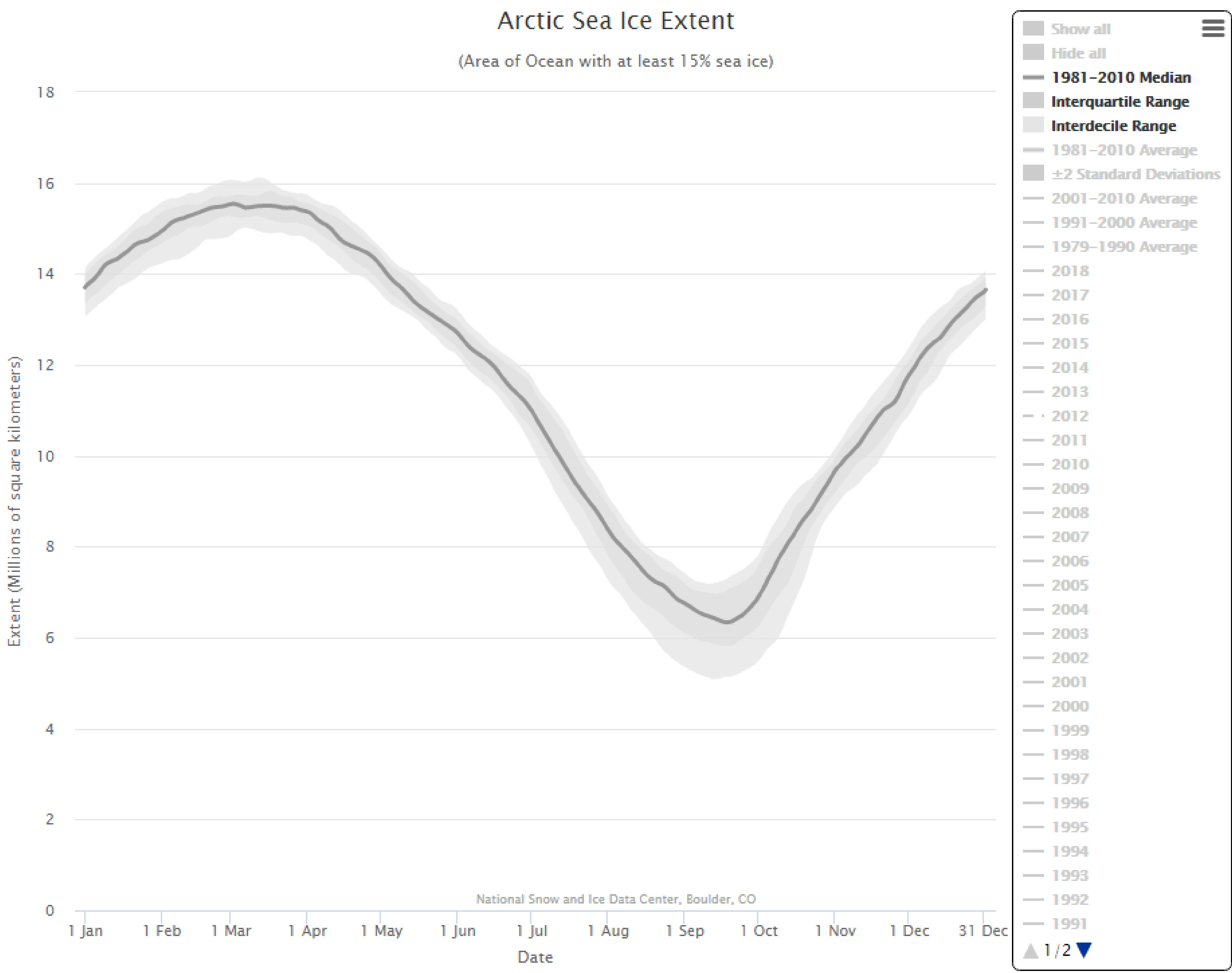
Summer extent = 2.1×10^6 km^2

Image courtesy of the National Snow and Ice Data Center, University of Colorado



Passive microwave-derived (SMMR / SSM/I) sea ice area for the Northern Hemisphere January 1979 – November 2018

Image from https://www.ncdc.noaa.gov/snow-and-ice/extent/sea-ice/N/0


Arctic Sea Ice Extent
(Area of Ocean with at least 15% sea ice)
Extent (Millions of square kilometers)
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1 Jan
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National Snow and Ice Data Center, Boulder, CO
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1981-2010 Median
Interquartile Range
Interdecile Range
1981-2010 Average
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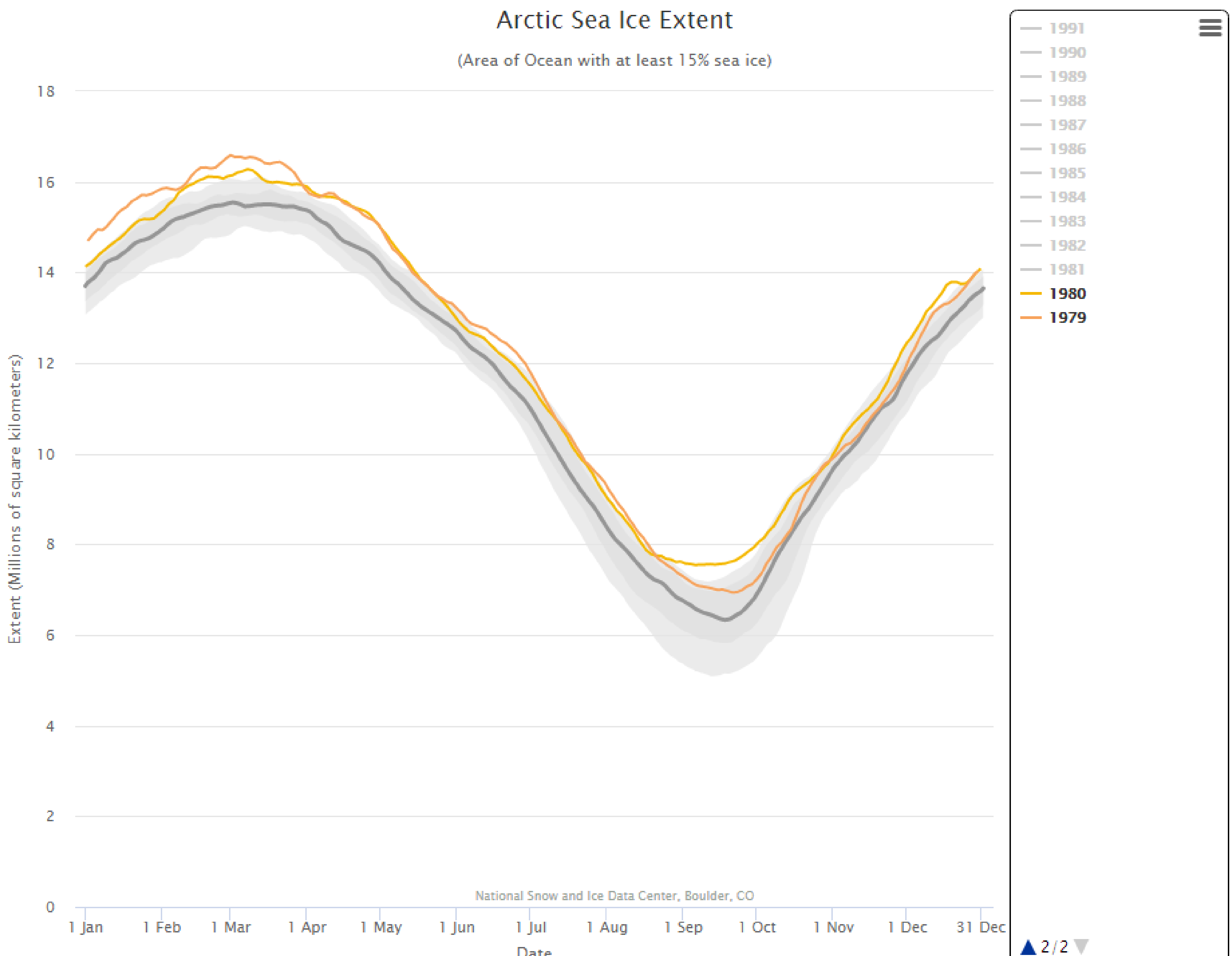
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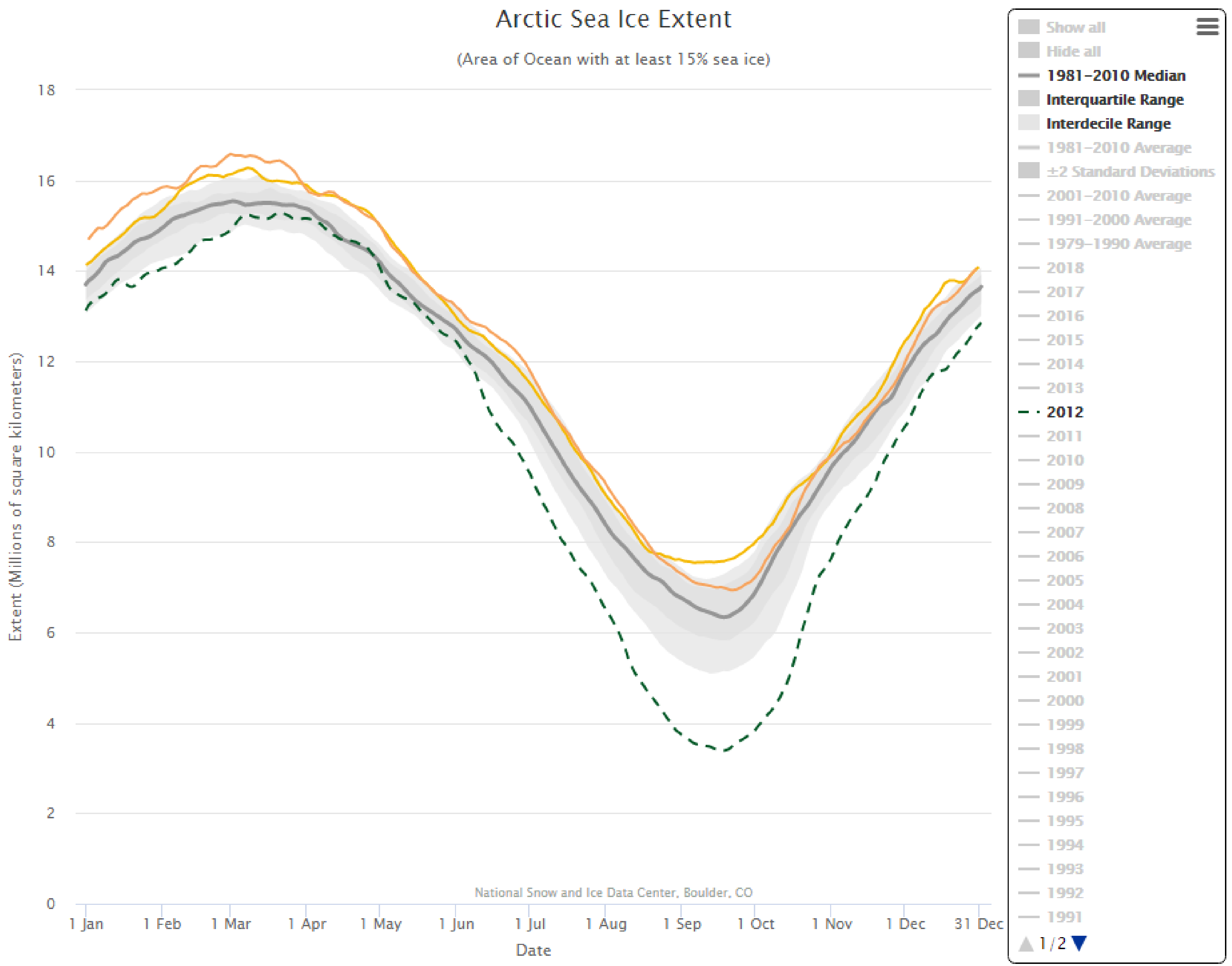

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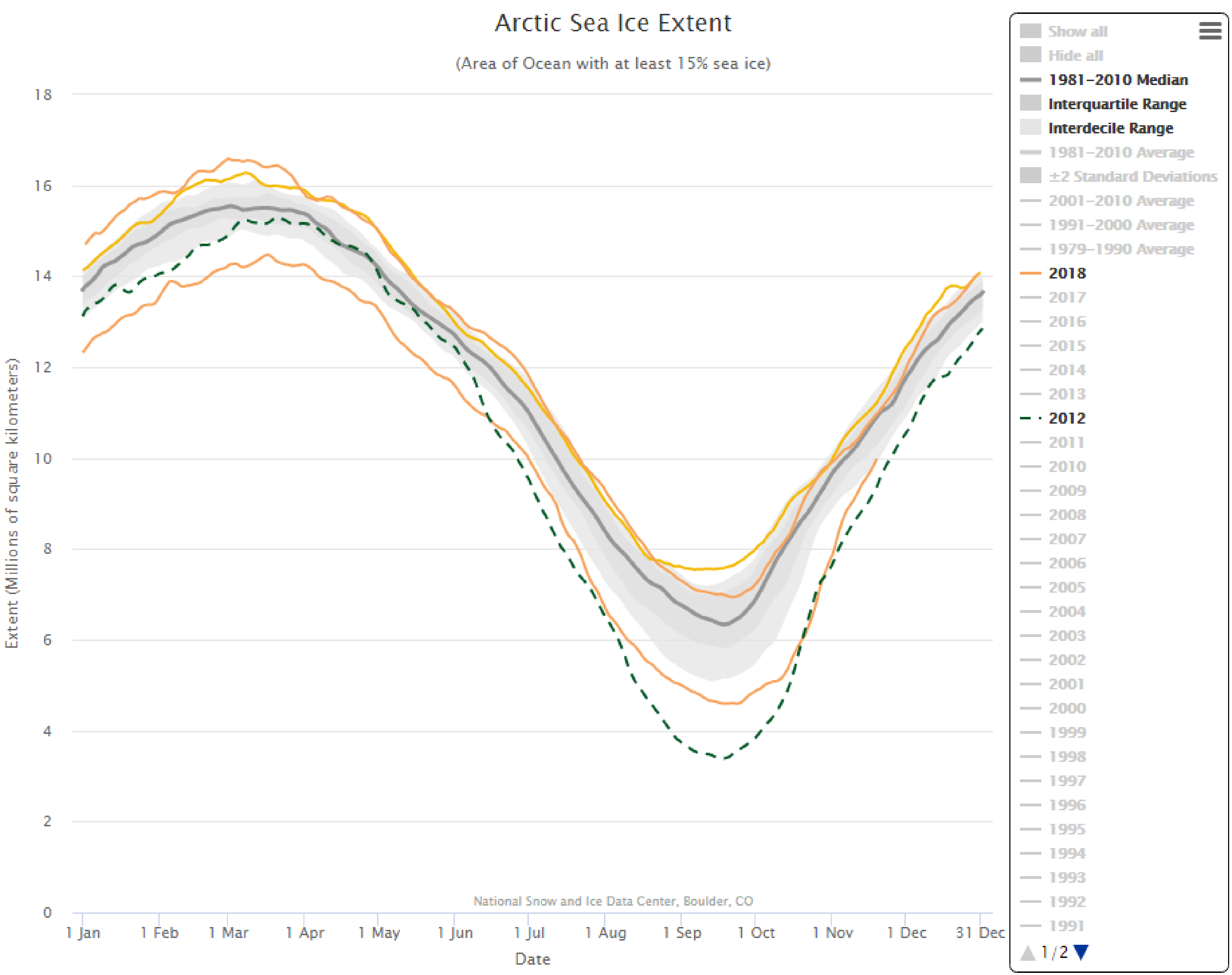

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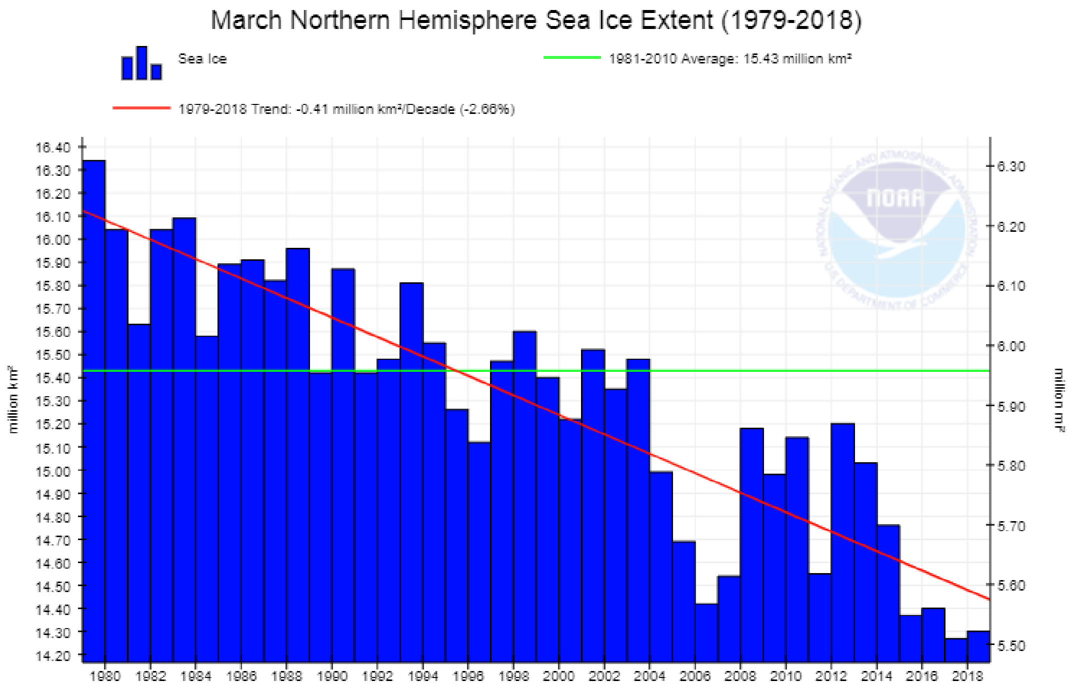
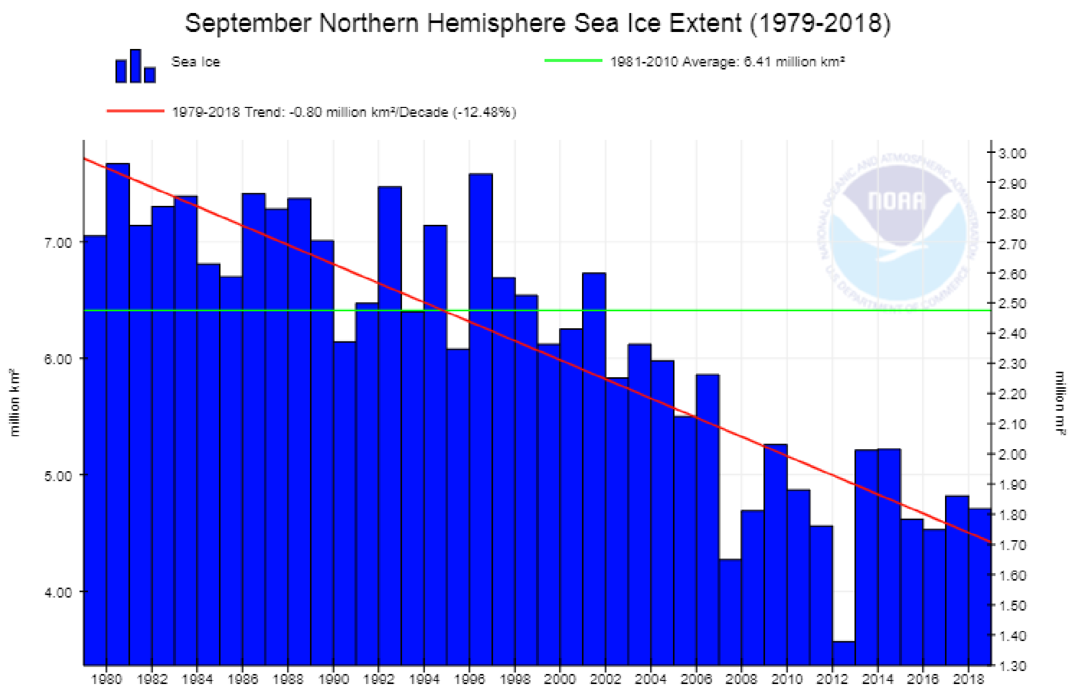


- 0.4 million km^2 / decade
- 2.7 %



- 0.8 million km^2 / decade
- 12.5 %

WHY IS SEA ICE IMPORTANT?

1. **Affects polar ecosystem, wildlife**

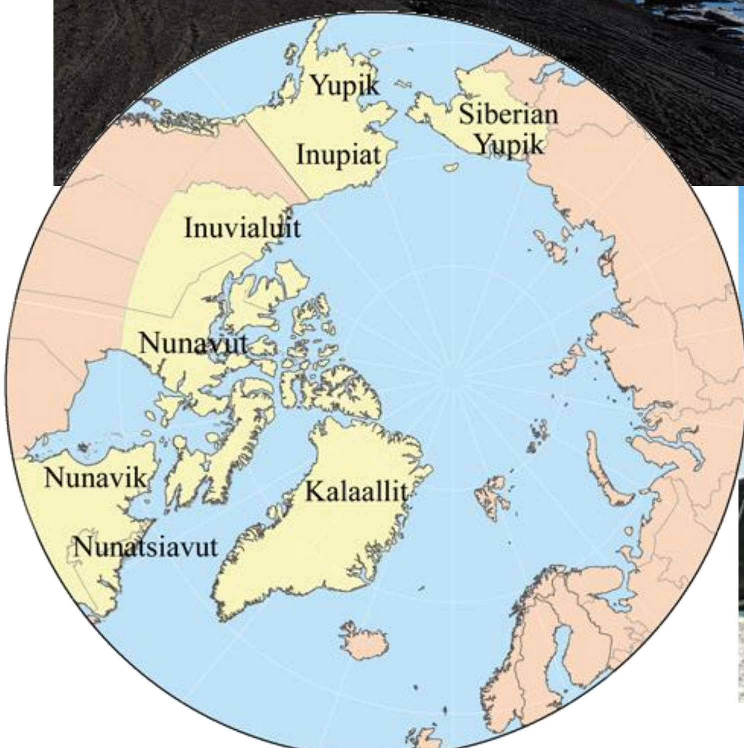
- Important habitat for phytoplankton, zooplankton, Arctic cod, seals/walrus, polar bear

- Ice algae contributes 10 – 20% to Arctic primary production

- Effect of reduced ice cover uncertain

WHY IS SEA ICE IMPORTANT?

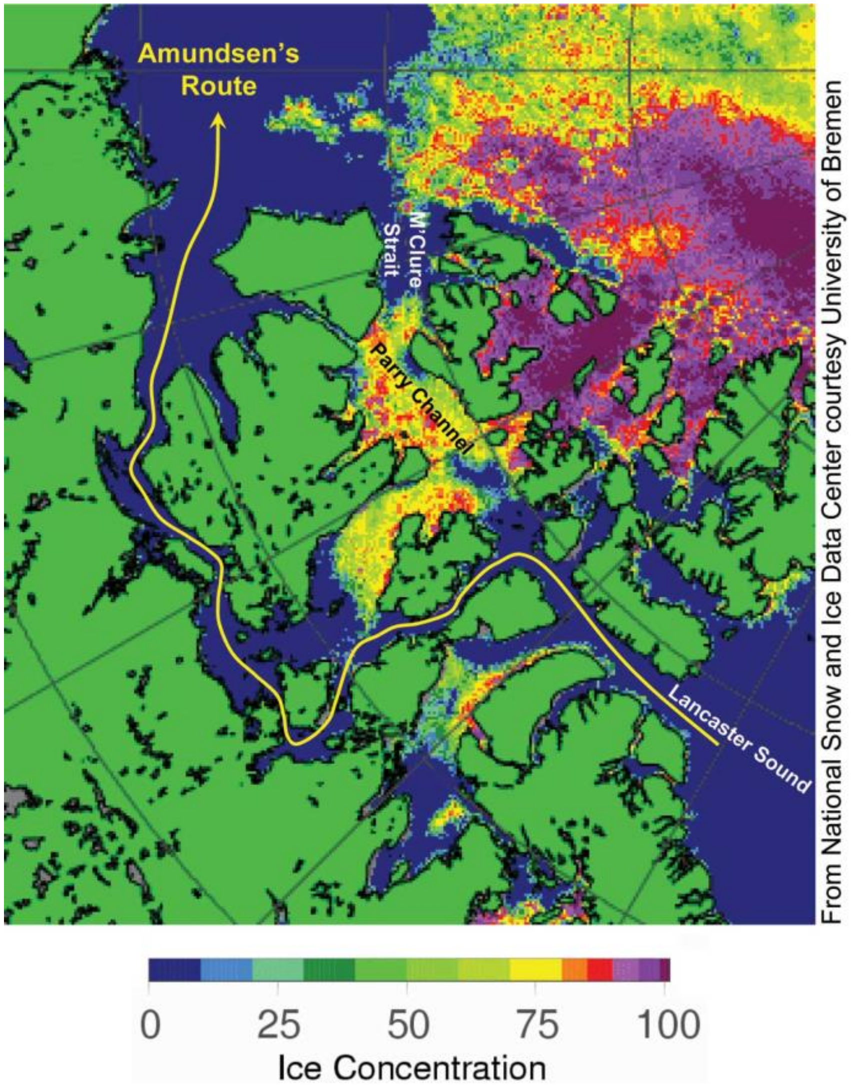
1. Affects polar ecosystem, wildlife
2. **Affects people who live in polar regions (subsistence hunting, travel)**



Alaska Coastal Management Program

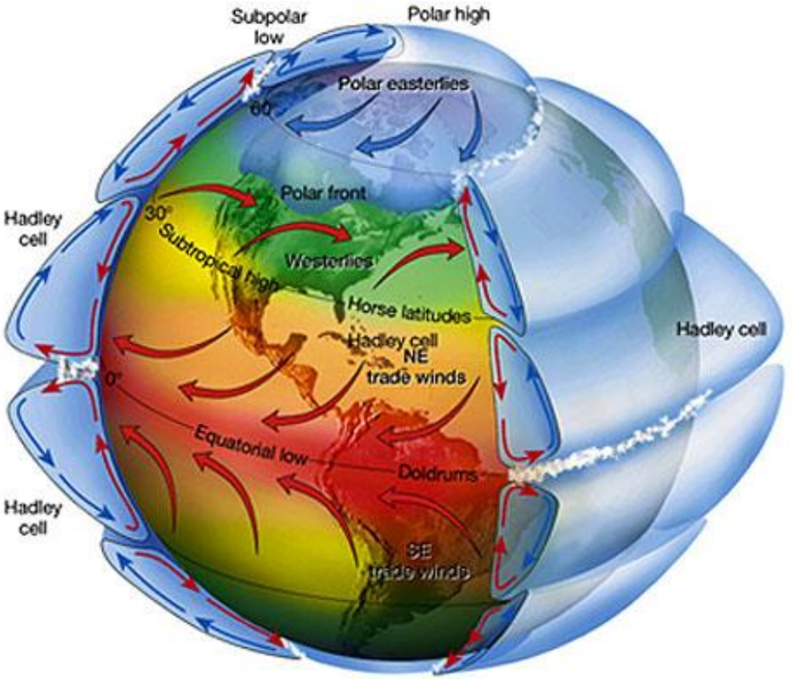
2007: Northwest passage open for first time in human memory

2008: Both Northern Sea Route and Northwest passage open for 1 week



WHY IS SEA ICE IMPORTANT?

1. Affects polar ecosystem, wildlife
2. Affects people who live in polar regions (subsistence hunting, travel)
3. **Role in earth's climate**



- How heat is absorbed / dissipated on earth determines climate
- Poles are earth's "heat sinks"
- Summer sunlight 24/7
- Ice *extent, concentration, thickness* matter
- Sea ice is thin (large area, small volume)
- Annual melt / freeze cycle produces large changes in areal coverage, surface properties
- Climate sensitivity

Change in climate → change in ice
Change in ice → change in climate

SEA ICE AND CLIMATE

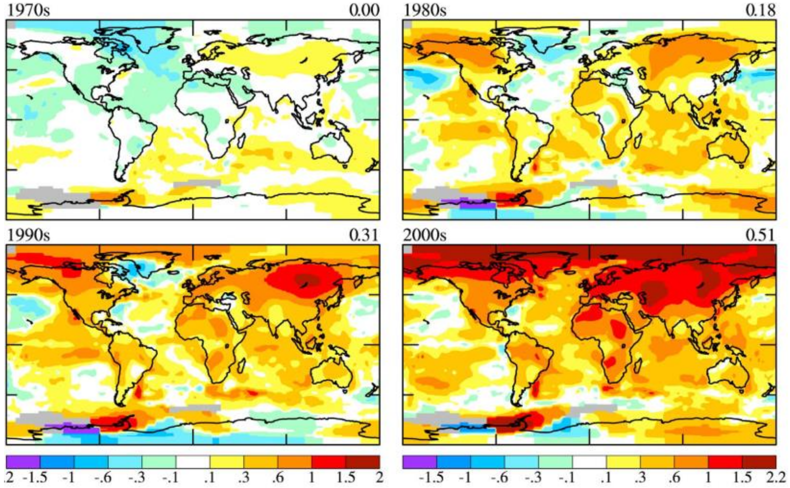
- Paleotemperature data indicate ΔT_a increased with increasing latitude, e.g.,during last ice age:

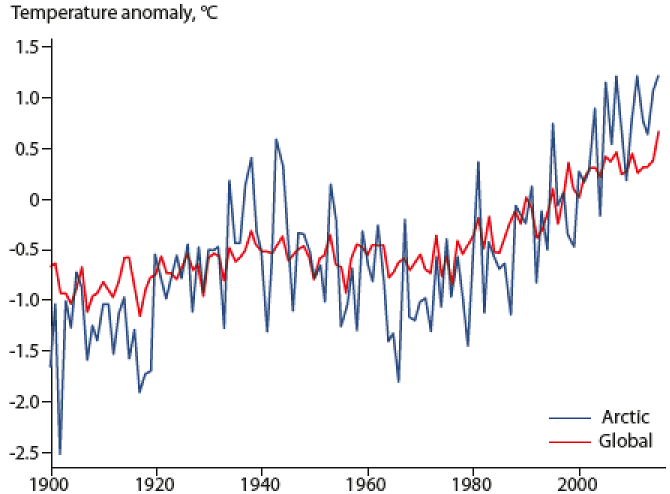
  ΔT_a = 3 - 5 ºC at low, mid-latitudes
  ΔT_a = 8 - 10 º C at high latitudes

- Suggests strongest indications of climate change would be in the polar regions

- Climate models predict similar pattern
- Atmospheric temperatures in the Arctic are warmest in 400 years
- Average temperature has risen at almost twice the rate as the rest of the planet during past few decades (ACIA, November 2004; ww.acia.uaf.edu)

Decadal surface temperature anomalies relative to 1951–1980 base period.



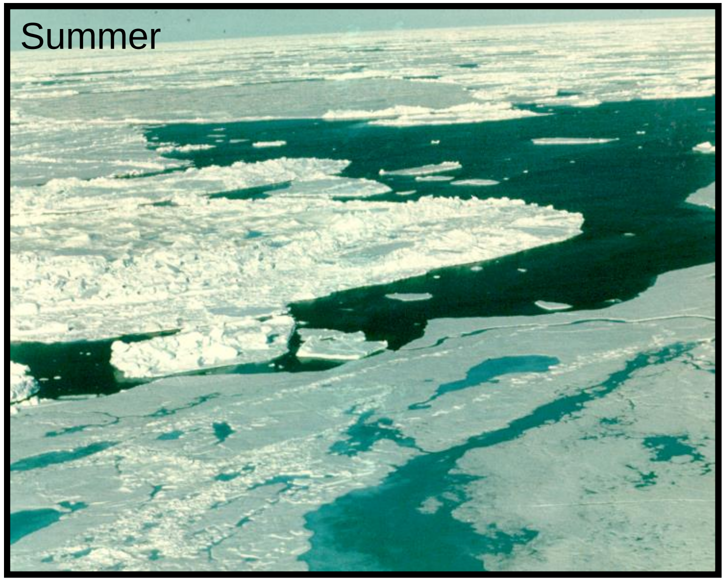


Hansen, J., R. Ruedy, M. Sato, and K. Lo (2010), Global surface temperature change, Rev. Geophys., 48, RG4004, doi:10.1029/2010RG000345.

“Polar amplification”

- heat at high latitude warms atmosphere, heat at low latitude goes to evaporation
- reduced sea ice cover allows for enhanced sea-air heat transfer
- loss of snow, ice increases heating → “ice – albedo feedback"

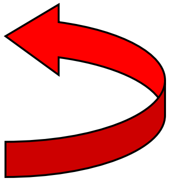
ICE - ALBEDO FEEDBACK



- Ample sunlight

- Sea ice reflects 60-90% of the incoming solar radiation, ocean < 10%

- A slight warming of ocean or atmosphere
  ice extent decreases
  more ocean exposed
  increased solar energy absorbed



- This *__positive feedback process__* has the potential to amplify variations in climate

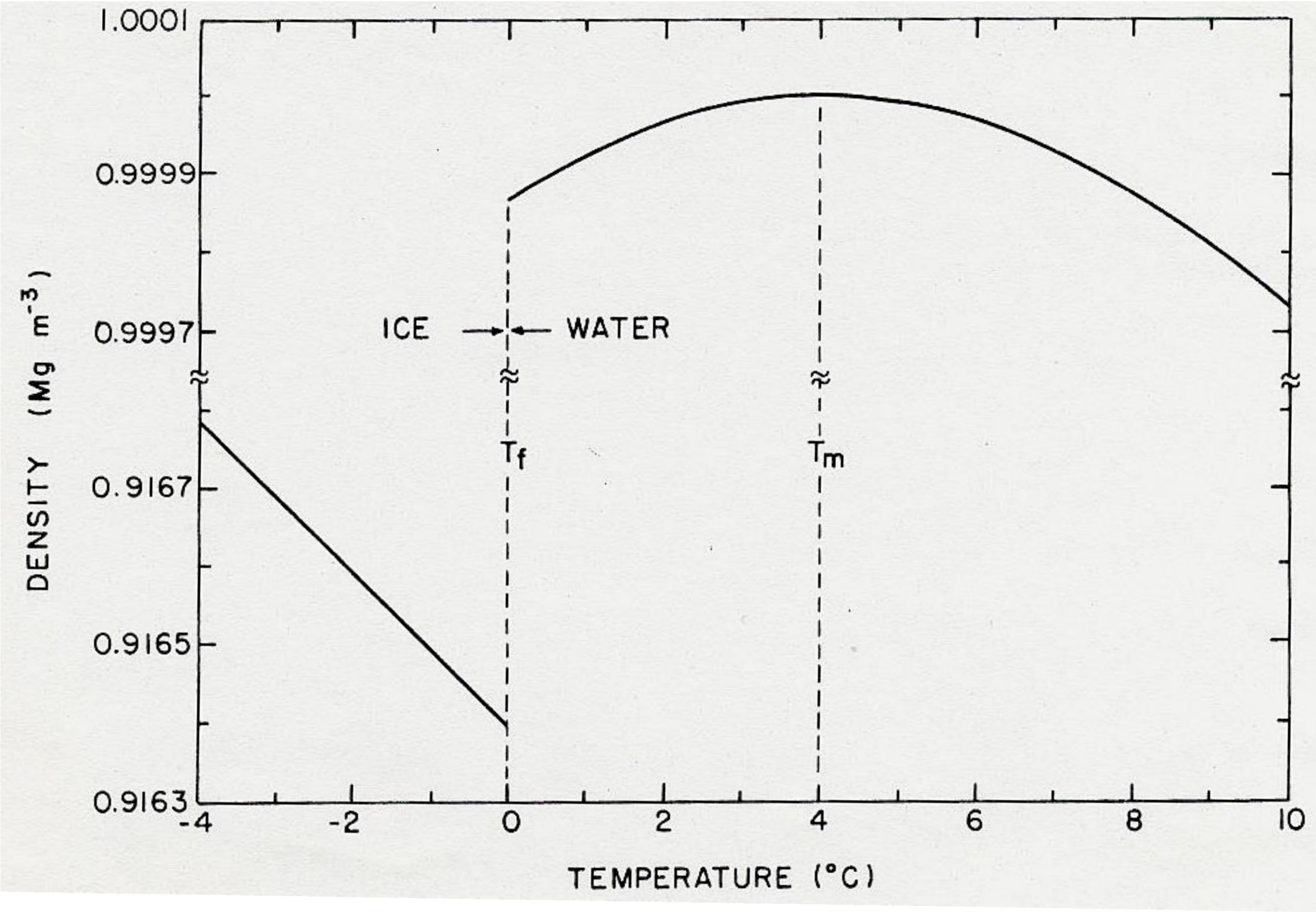
What is the difference between sea ice and lake ice?

- Sea ice forms from salty ocean water

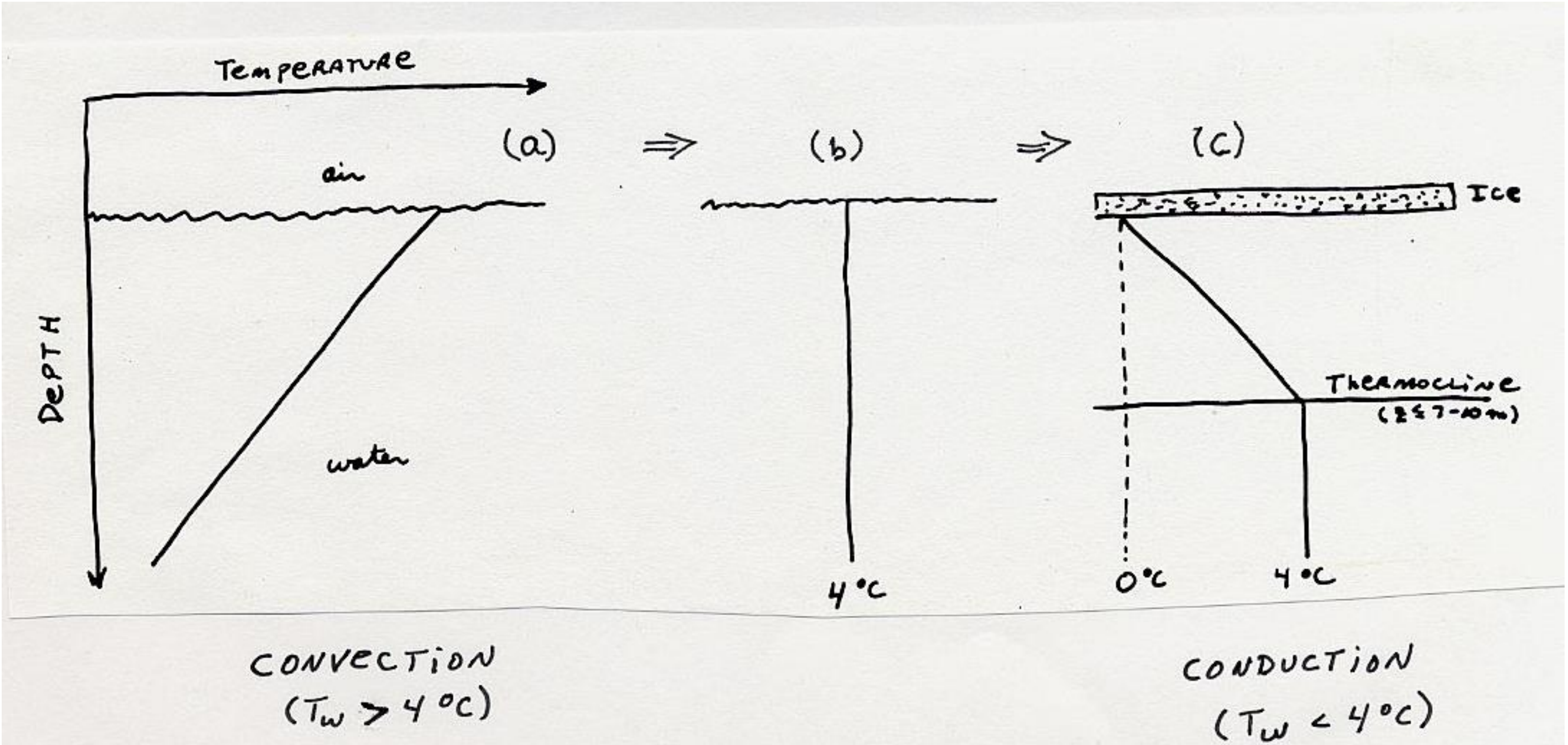
- Lake ice forms from fresh water

⇒ **What happens as warm water cools?**

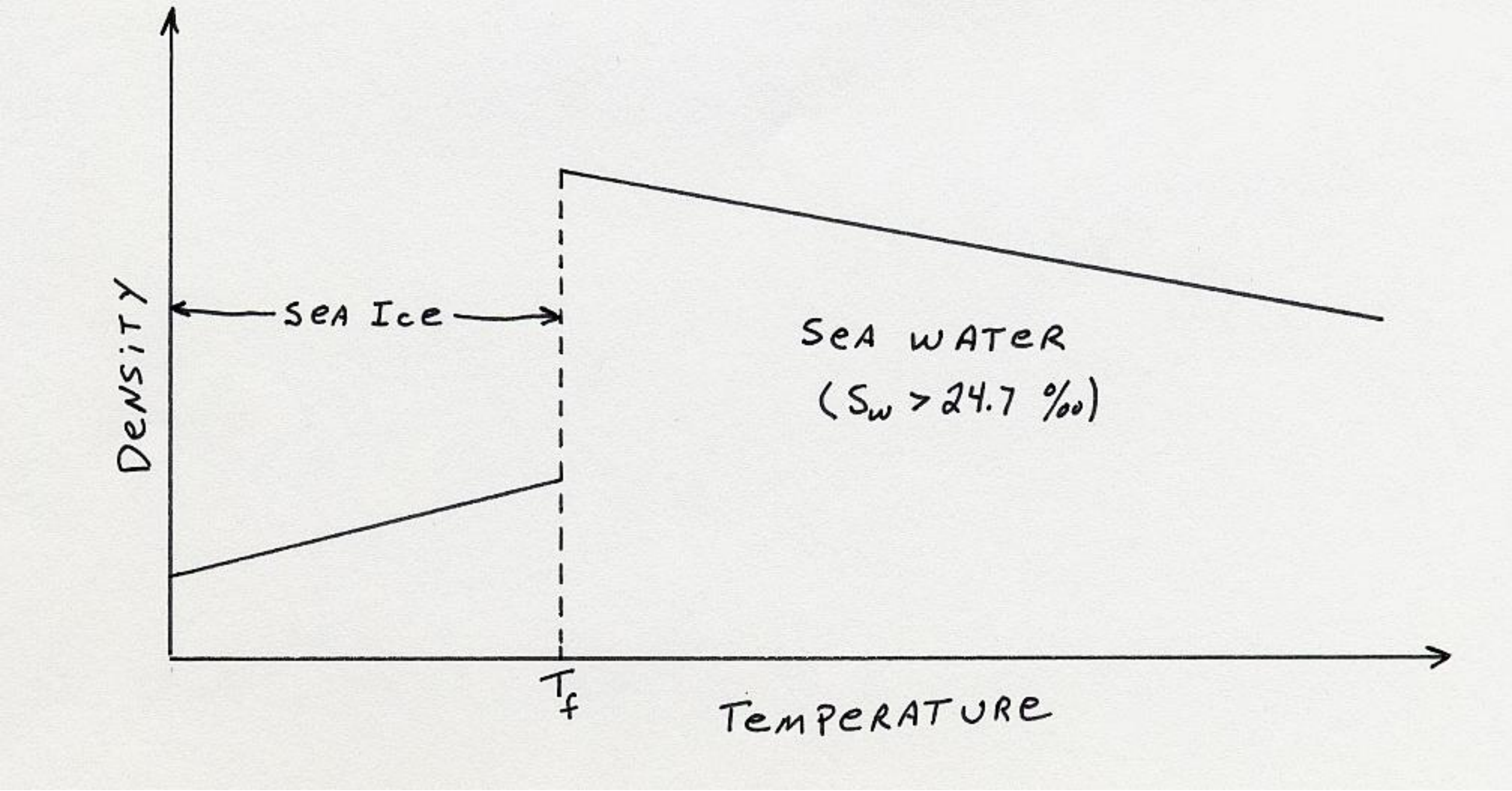
ρ-T DIAGRAM FOR FRESH WATER



LAKE ICE FORMATION



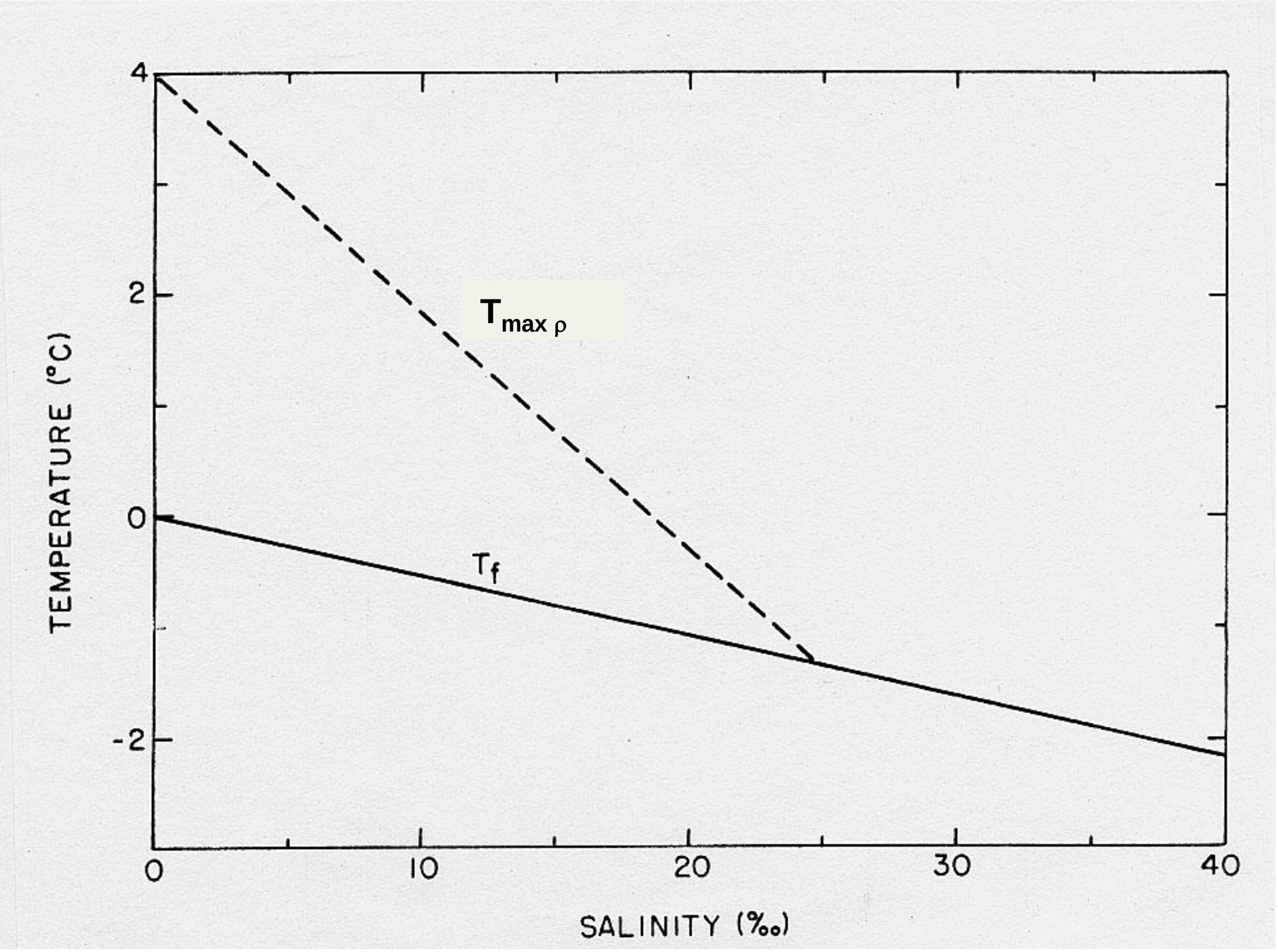
ρ - T DIAGRAM FOR SALT WATER



SEA ICE FORMATION

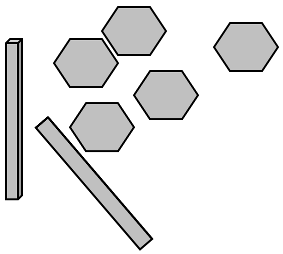
- If $S > 24.7\ ^{o}/_{oo}$ then colder is denser
- Cooling water sinks away from cold surface
- Sea ice forms more slowly than fresh ice
- T_f = -1.8 C for S~ 32 ppt
- Typically, top 100 – 150 m of ocean must be cooled to T_f for ice to form

T-S DIAGRAM FOR SALT WATER



Ice Growth

Frazil



Wind, waves

Calm conditions

Pancakes

Consolidation

Grease ice

Nilas

Rafting

Congelation ice

Young ice

snow

Thickens by growth at bottom

First-year ice

30 – 200 cm thick, typically snow covered

INITIAL ICE FORMATION

- **Frazil Crystals**
  - Initial freezing occurs at many points of nucleation within water column
  - Needles and platelets of ice (3-4 mm diameter) float to surface to form slush

INITIAL ICE FORMATION

- **Frazil Crystals**
  - Initial freezing occurs at many points of nucleation within water column
  - Needles and platelets of ice (3-4 mm diameter) float to surface to form slush

- **Grease Ice**
  - Ocean covered by grey, soupy mixture of frazil crystals which look “greasy”
  - Forms solid ice cover when H is about 1 cm, <u>if</u> no wind or waves

Photo D. Perovich

INITIAL ICE FORMATION (continued)

- **Pancake Ice**
  - In presence of waves, grease ice evolves into flat, circular, rounded masses of semi-consolidated slush called "pancakes"
  - Pancakes typically 0.3 to 3 m in diameter
  - Wave motion can delay formation of solid ice cover until H is 10-50 cm

INITIAL ICE FORMATION (continued)

- **Congelation Growth**
  - Once solid cover forms, ice grows at the bottom due to heat conducted upward toward the colder surface - called *congelation growth*

SEA ICE STRUCTURE

• **Crystal Orientation**

- Initially c-axes oriented randomly

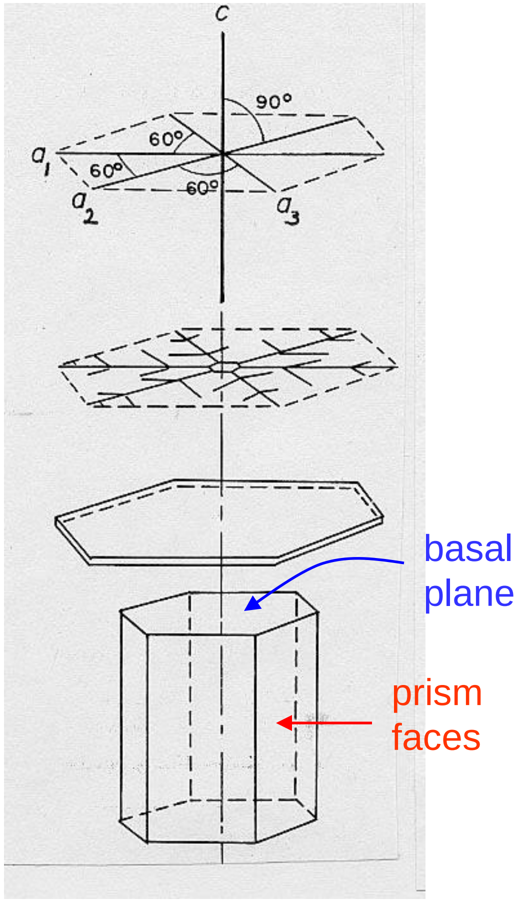
- After 10 -20 cm congelation growth c-axes are horizontally-oriented

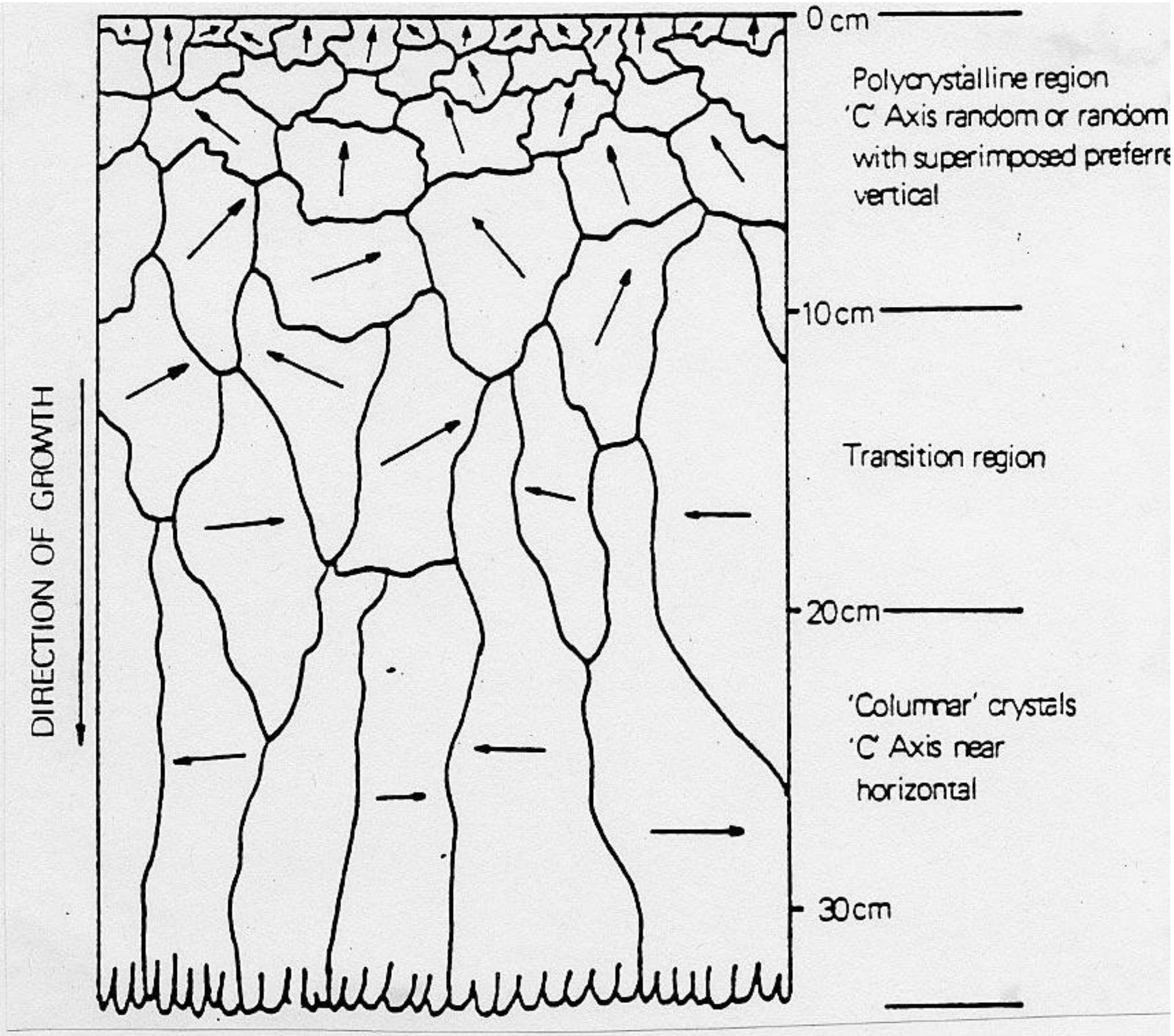
- Preferential growth of crystals with horizontal c-axes

- Crystals with horizontal c-axes grow downward up to 2 orders of magnitude more rapidly than those with more vertical c-axes

- “Geometric selection”

- Horizontal c-axes important to development of characteristic properties of sea ice





0 cm
Polycrystalline region
'C' Axis random or random
with superimposed preferre
vertical
10 cm
Transition region
20 cm
'Columnar' crystals
'C' Axis near
horizontal
30 cm
DIRECTION OF GROWTH

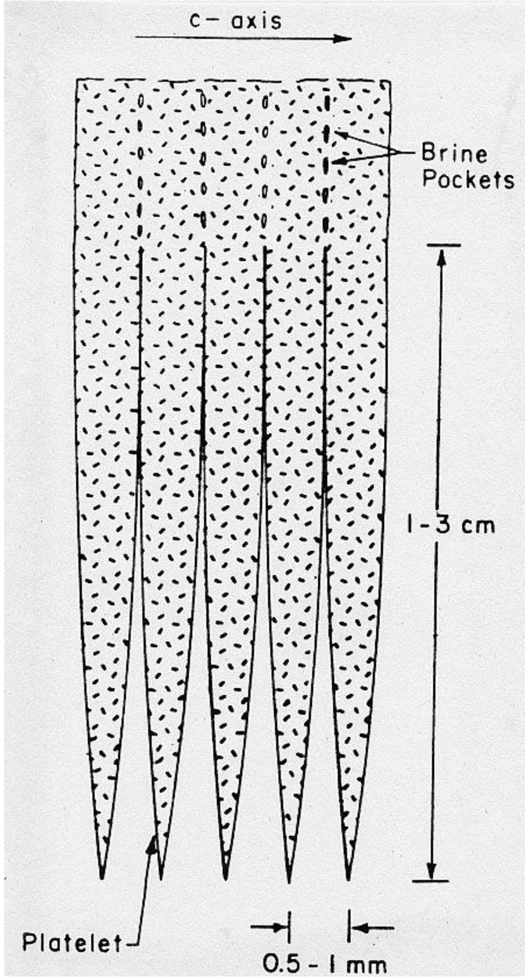
- **Skeletal Layer**
  - In sea water, delicate layer of thin platelets grows on prism faces perpendicular to c-axis

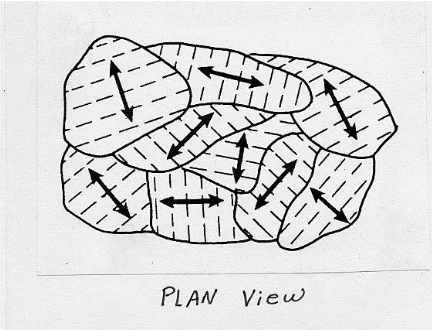
  - Platelets are parallel, form a single crystal. Thickness ~ 0.5 mm and spacing of 1-2 mm.

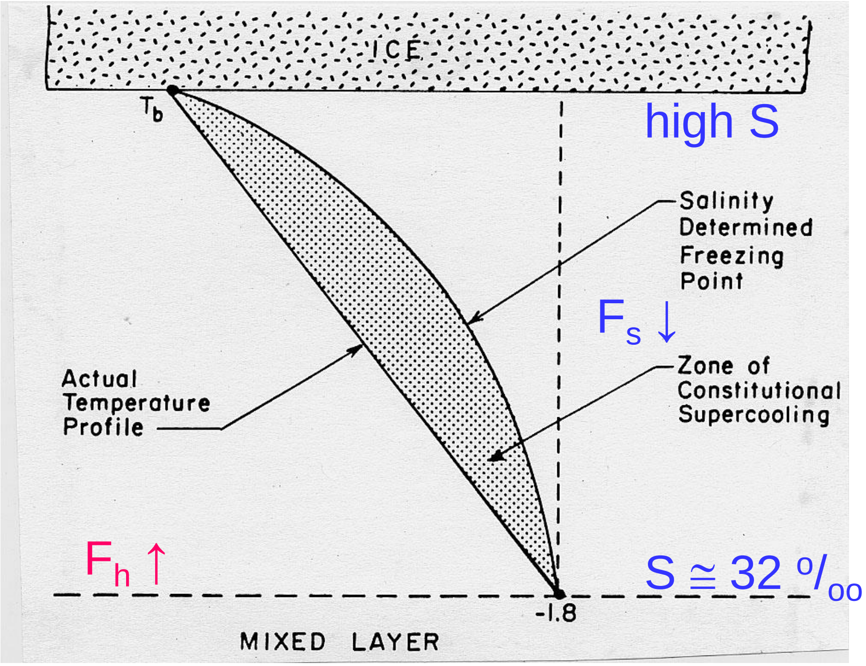
  - No skeletal layer in fresh water ice, so salt must be important

  - Similar phenomena observed when metals solidify ("constitutional supercooling")

http://www.mcs.vuw.ac.nz/Main/ResearchSpotlightOnSeaIceGrowth







- **Constitutional Supercooling**

- Rejection of salt produces steep salinity gradient in the boundary layer

$F_s \downarrow$

- Temperature at ice-water interface must be at freezing (for high S), causing a temperature gradient

$F_h \uparrow$

- Heat diffusion >> salt diffusion ⇒ region of supercooling

- Ice projecting into supercooled region will grow faster than planar interface ⇒ platelet formation

- Length and spacing of platelets act to minimize amount of supercooling ahead of growing interface

- Mathematical theory describes observed platelet patterns

SEA ICE SALINITY

- Amount of salt trapped in the ice described by "ice salinity" (S_i)

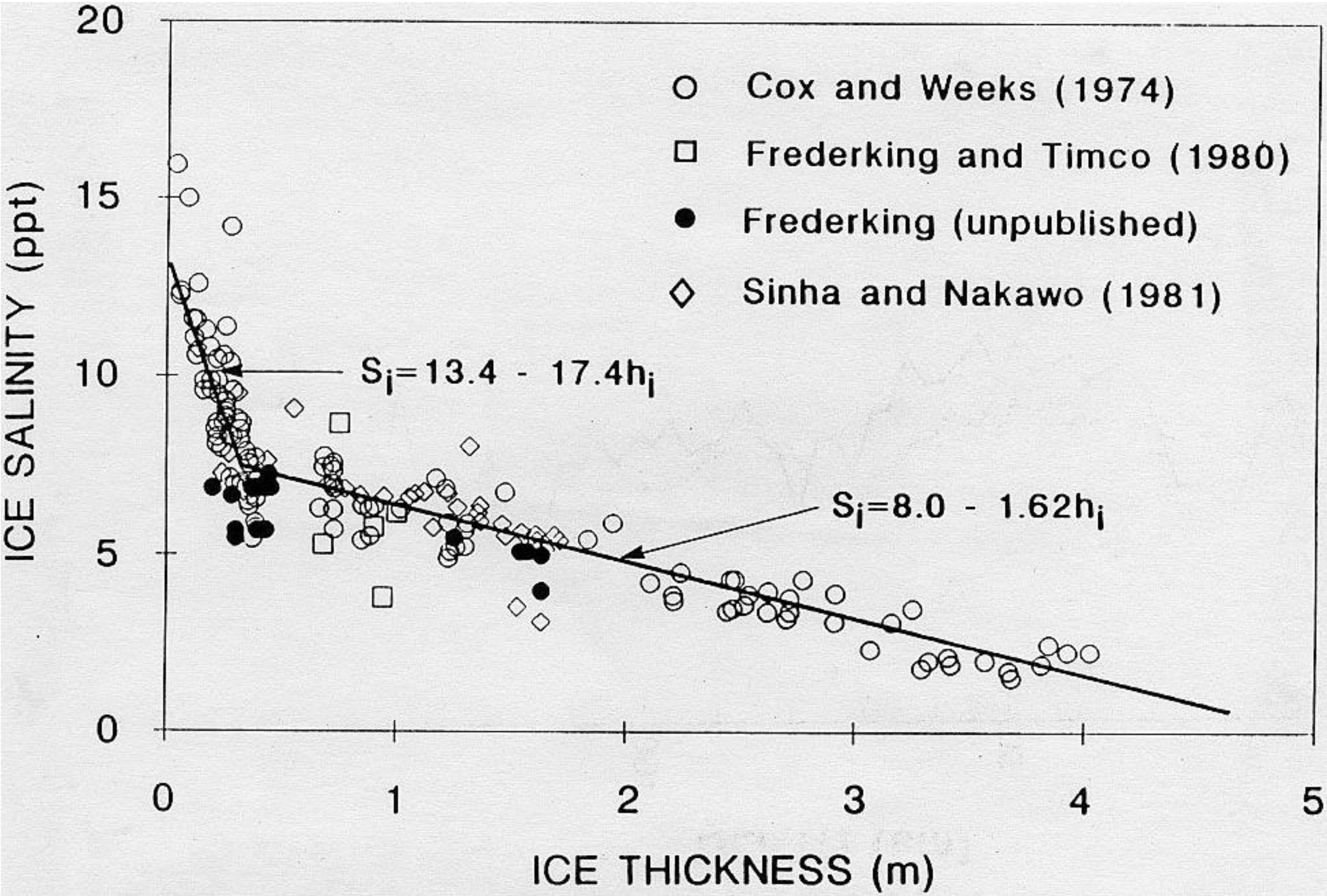
$$S_i = \frac{\text{mass of salt}}{\text{mass of ice} + \text{mass of brine}} \cdot 10^3 \ {}^{o}/_{oo} \qquad \text{(ppt)}$$

- S_i directly related to rate of ice growth

- Faster the growth, the greater the amount of salt trapped

- S_i should be <u>high</u> when ice is thin and decrease as ice becomes thicker

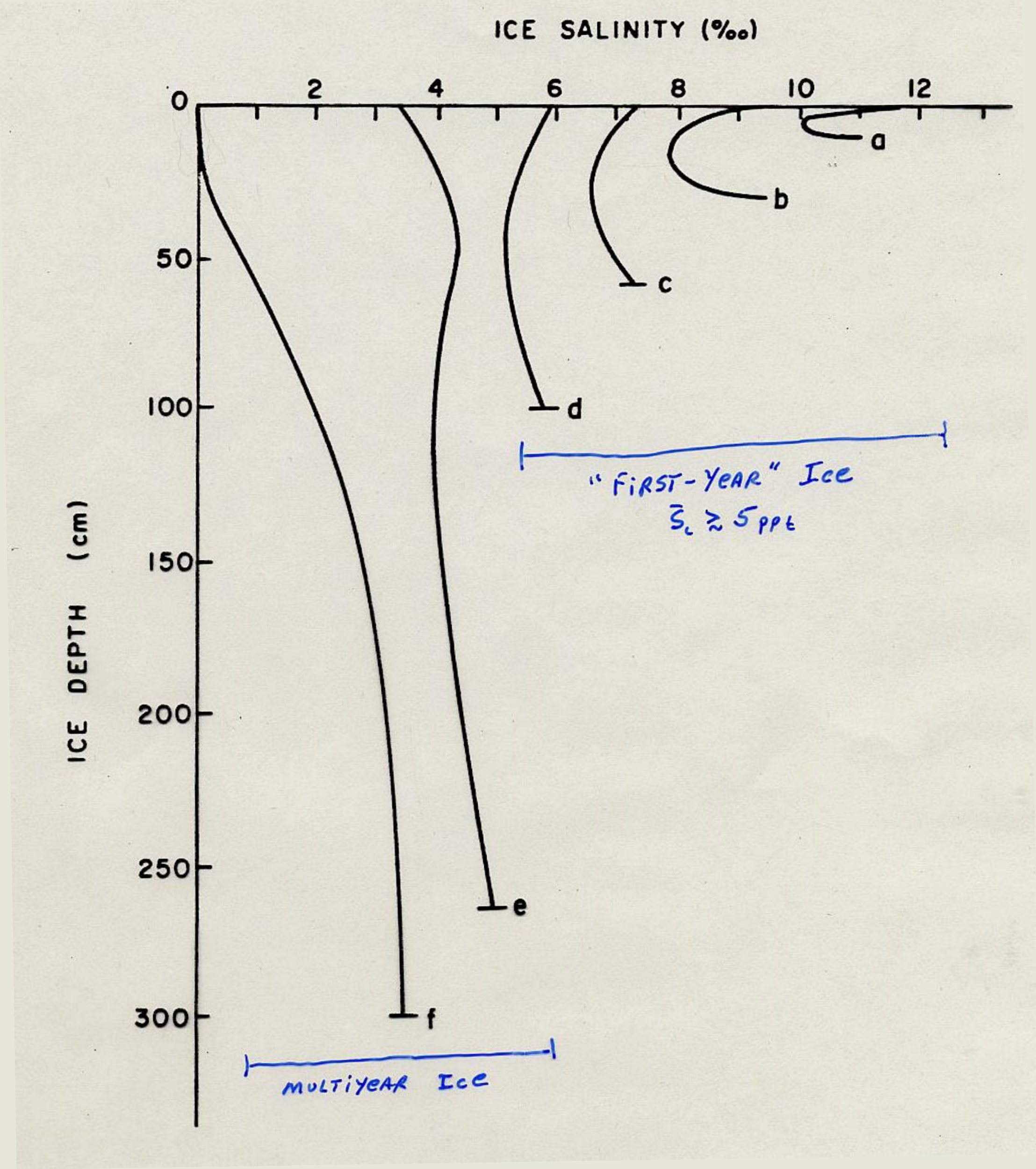
SEA ICE SALINITY



- Profiles in thin ice tend to be “C” shaped, indicating salt enrichment in lower half of slab

- Average salinity decreases as ice ages, indicating loss of salt to ocean

- Dramatic change as ice goes from FY to MY



BRINE INCLUSIONS

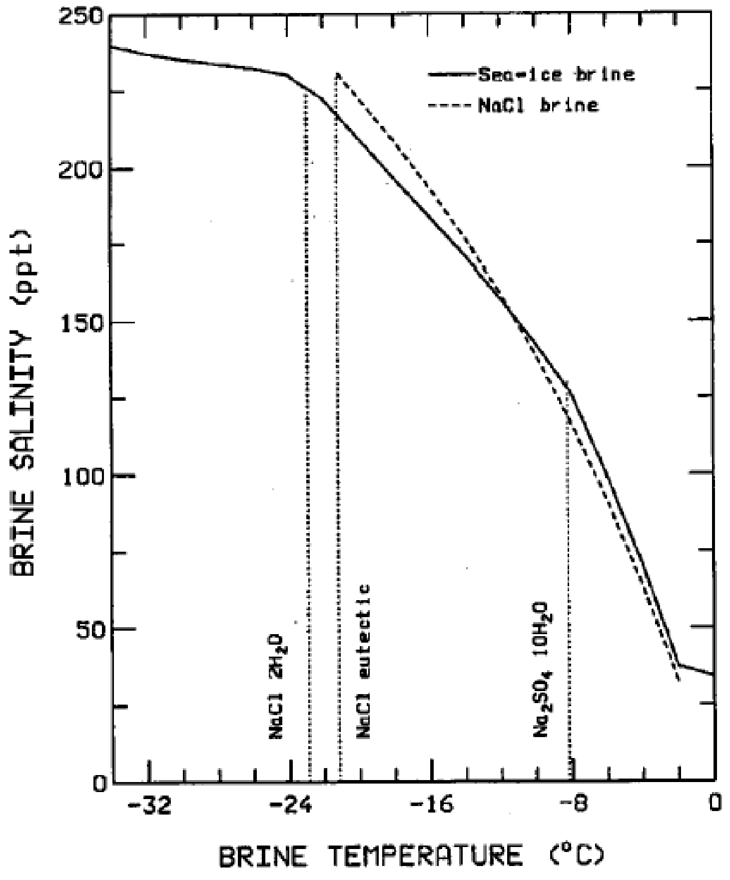
- Bridging between platelets traps pockets of brine (d $\cong$ 0.05 mm)

- Brine pockets form in vertical strings marking boundary between platelets

- Salinity in brine pockets (S_b) independent of original water salinity because brine must be at salinity-determined freezing point

$$S_b = \frac{\text{mass of salt}}{\text{mass of brine}} \cdot 10^3 \ {}^{o}/_{oo}$$

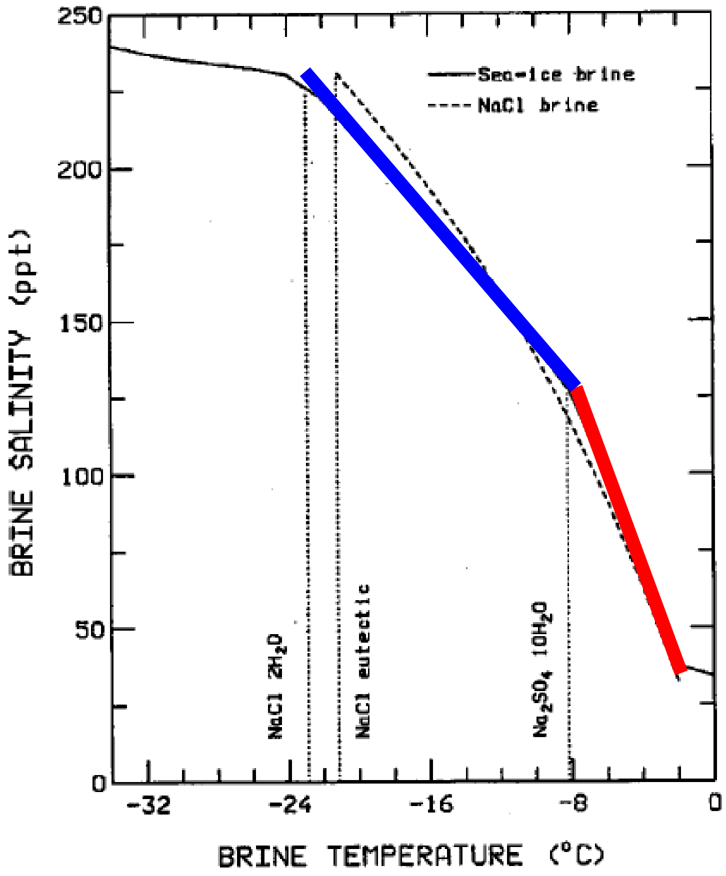
FREEZING EQUILIBRIUM



- Changes in T_i cause melting or freezing in brine pockets, causing S_b to change until the brine is in freezing equilibrium with surrounding ice

- These changes are independent of S_i

FREEZING EQUILIBRIUM

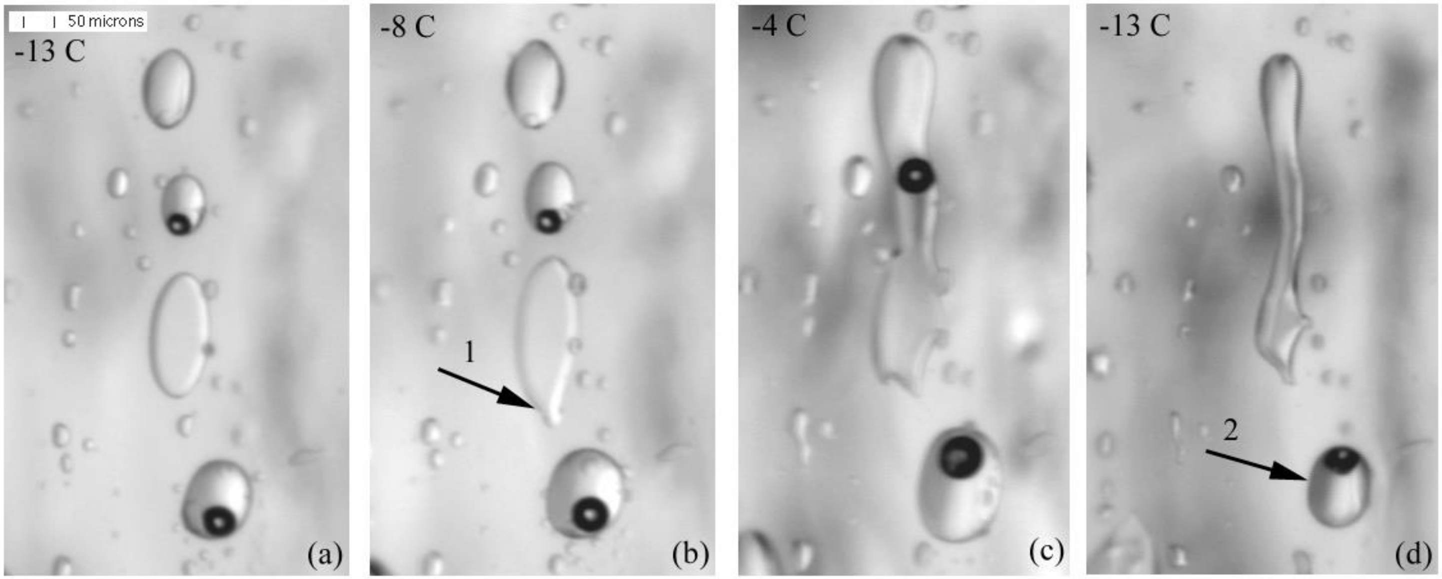


$$S_b \approx -\frac{T_i}{m}$$

- Changes in T_i cause melting or freezing in brine pockets, causing S_b to change until the brine is in freezing equilibrium with surrounding ice

- These changes are independent of S_i

FREEZING EQUILIBRIUM

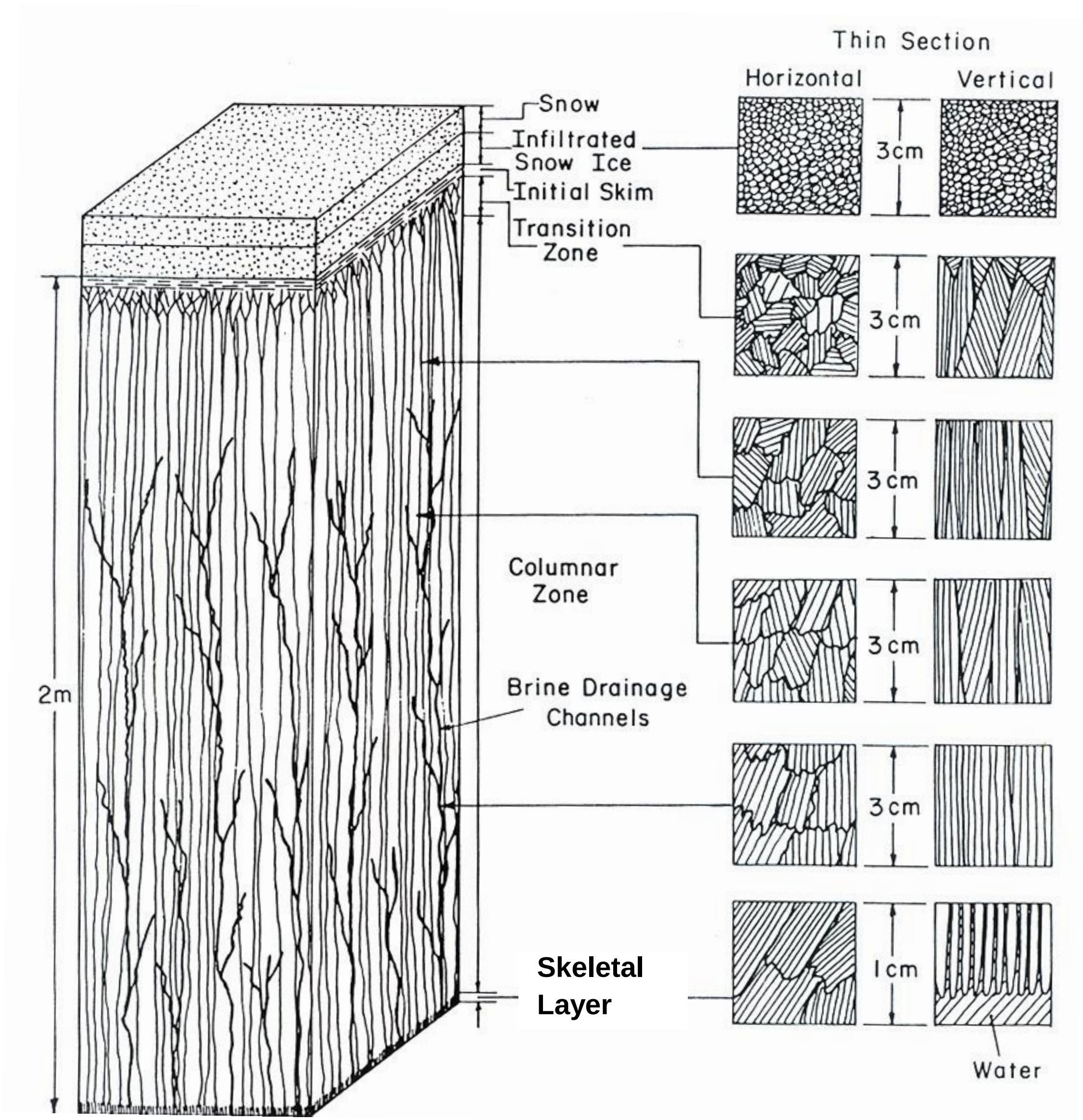


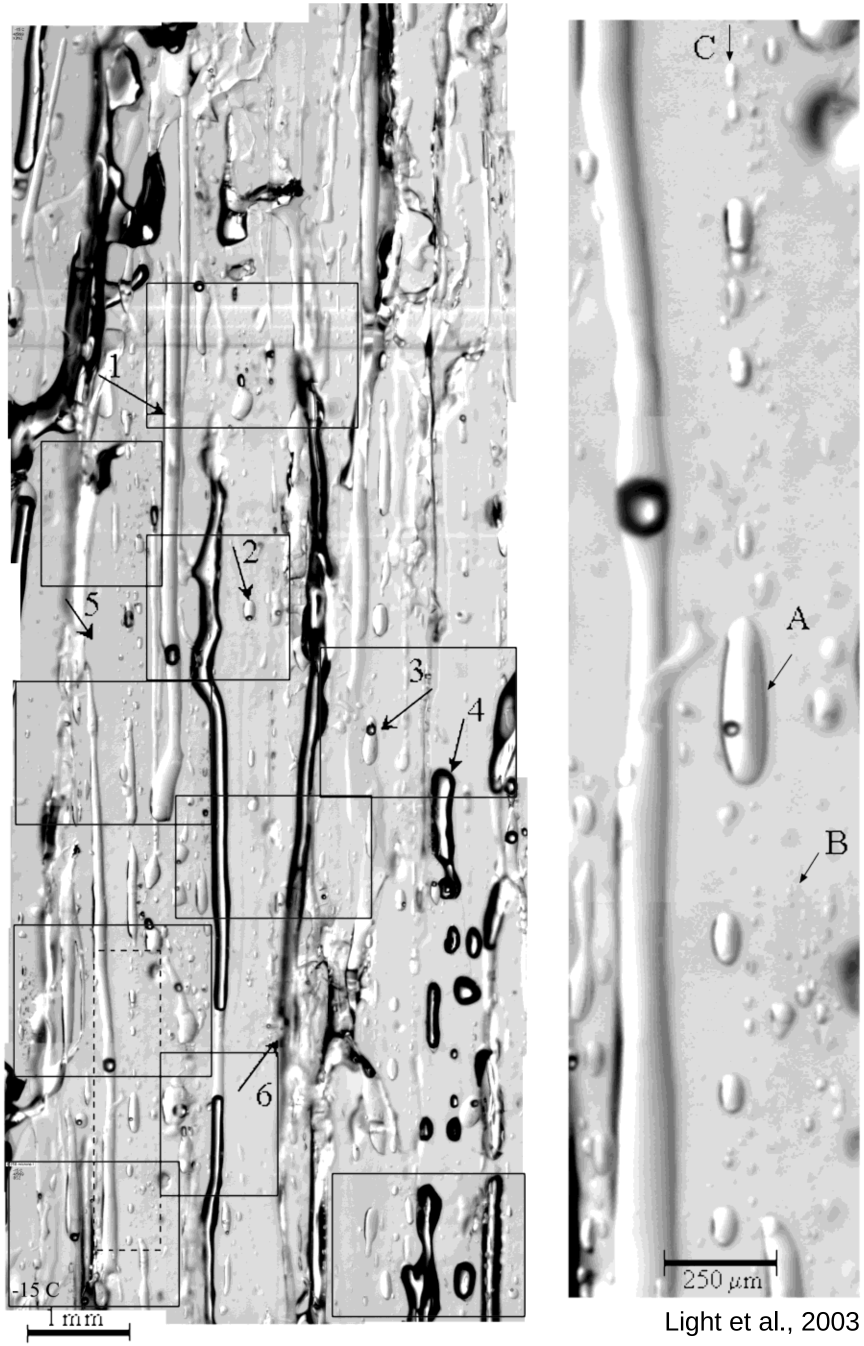
DESALINATION MECHANISMS

- Gravity Drainage
  - thermal and mechanical stresses form vertical cracks along brine pocket strings
  - result in vertical channels once $H > 40$ cm
  - brine in the interior is colder and denser than brine near the bottom, causing downward drainage

- Flushing
  - sea ice becomes very porous during summer
  - surface meltwater produces hydrostatic pressure forcing low salinity meltwater into upper part of ice and a loss of higher salinity brine through the bottom of the ice

SEA ICE STRUCTURE





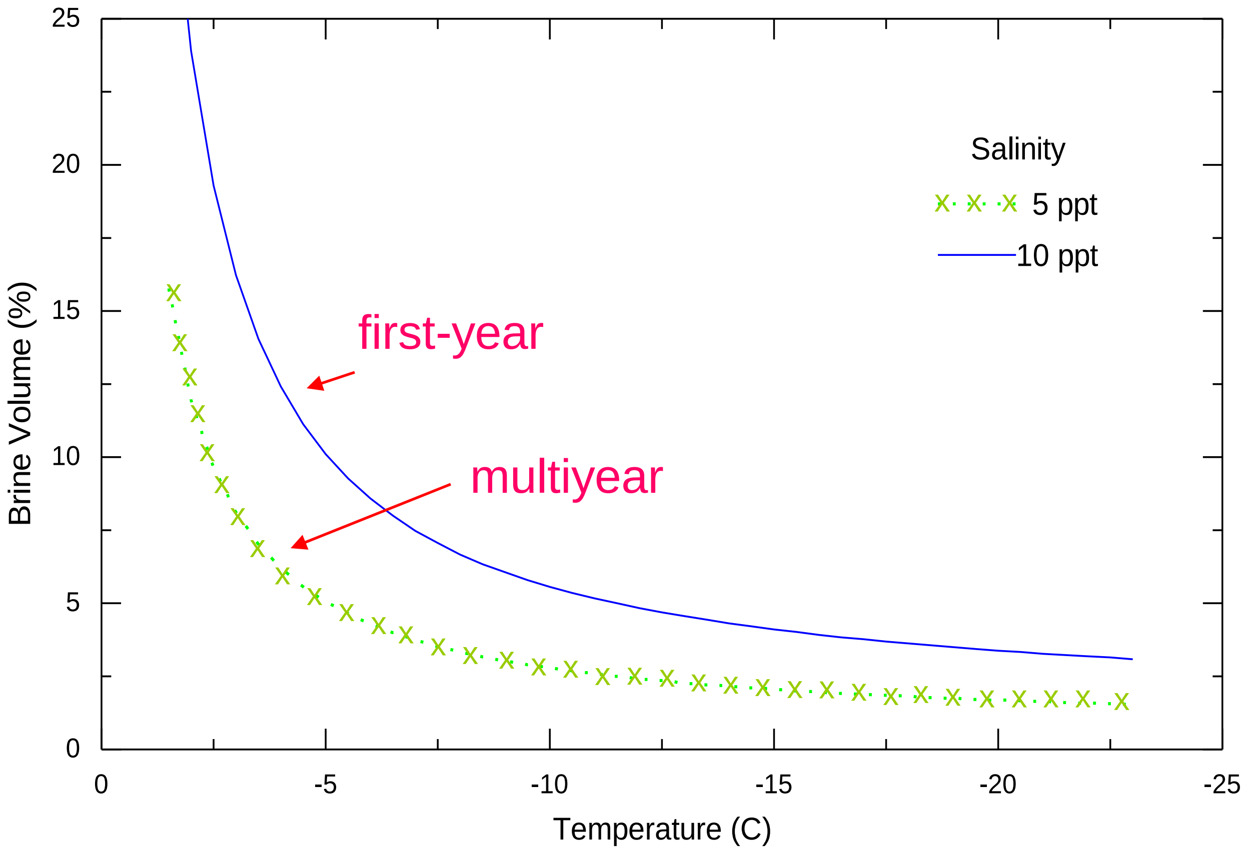
Light et al., 2003

FRACTIONAL BRINE VOLUME

Presence of brine in sea ice alters essentially all its physical properties, making them very sensitive to temperature especially when ice becomes warm

Brine Volume

Define fractional brine volume (ν_b) as: $$\nu_b = \frac{V_b}{V_i} \cong \frac{\rho_i S_i}{\rho_b S_b}$$



PHYSICAL PROPERTIES OF SEA ICE

1. Thermal

2. Mechanical

3. Electromagnetic
    a. Optical
    b. Infrared
    c. Microwave

4. Thermodynamic growth

5. Dynamic

• **Thermal Properties**

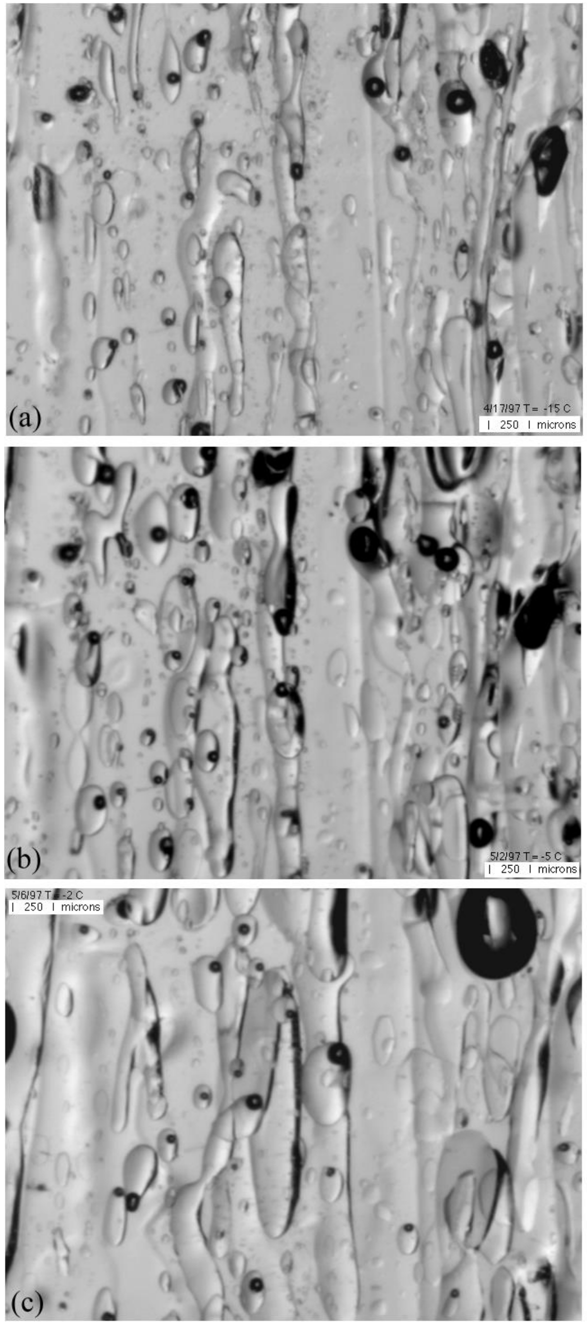
Melting/Freezing Point

No single melting or freezing point because any change in T_i produces internal melting or freezing in the brine pockets

-15 °C

-5 °C

-2 °C



Latent Heat of Fusion : Heat required to melt a unit volume of sea ice

$$L_i = L_o(1-\nu_b)$$

- L_o is the latent heat of fusion of pure ice (333.55 J/g)

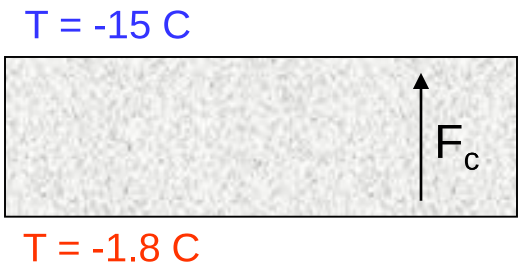
- For new ice, L_i typically 0.6 L_o

- For thick multiyear ice, L_i typically 0.9 L_o

Thermal Conductivity

Determines rate of heat conduction through the ice

$$F_c = k\frac{\partial T}{\partial z}$$

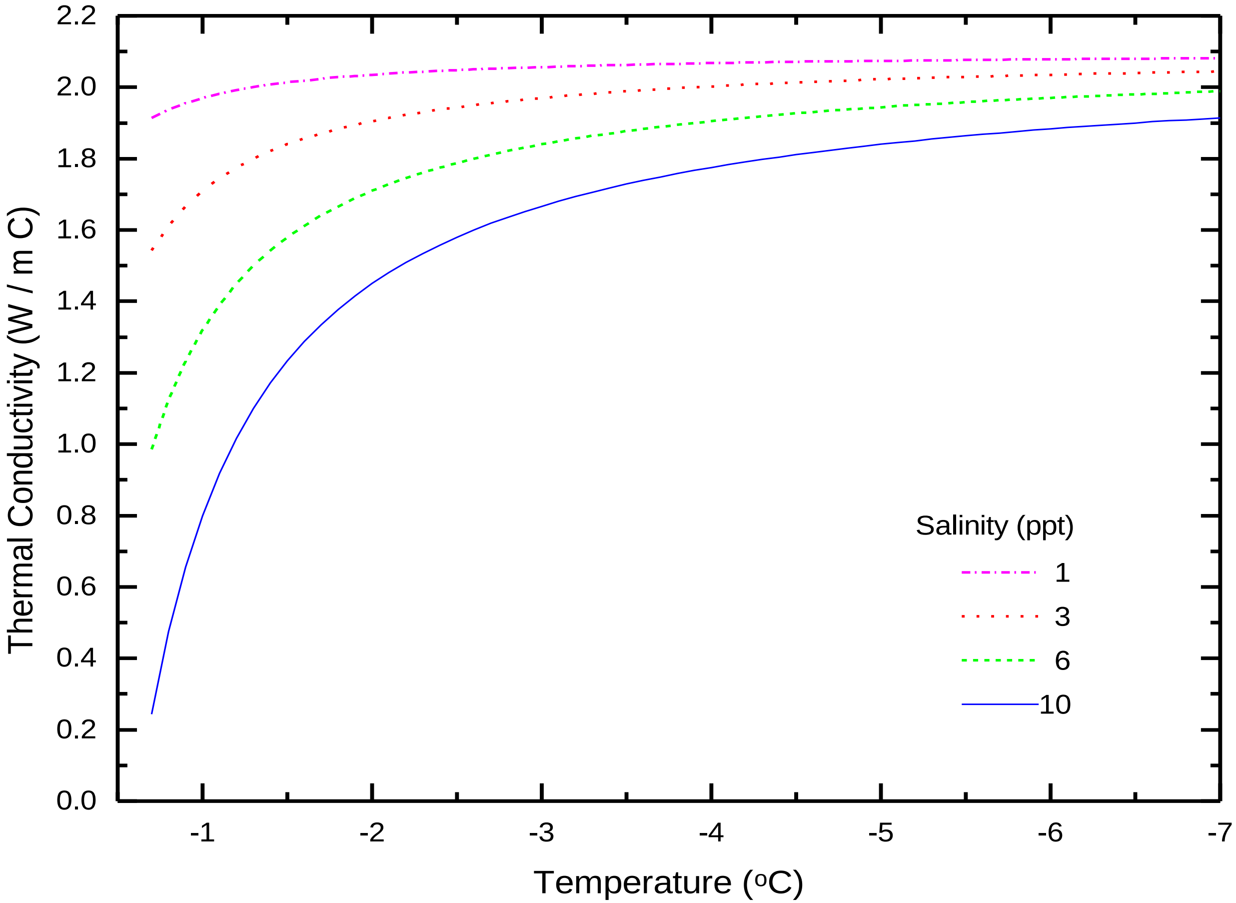


Brine pockets act as thermal buffers to retard the conduction of heat and the warming or cooling of the ice

k_{ice} = 2.4 W/mC
k_{brine} = 0.6 W/mC

} factor of 4

What happens to k_{ice} with increasing brine volume?



- k_{ice} varies by 10-20% in multiyear ice

- k_{ice} varies by 50% in warm first-year ice

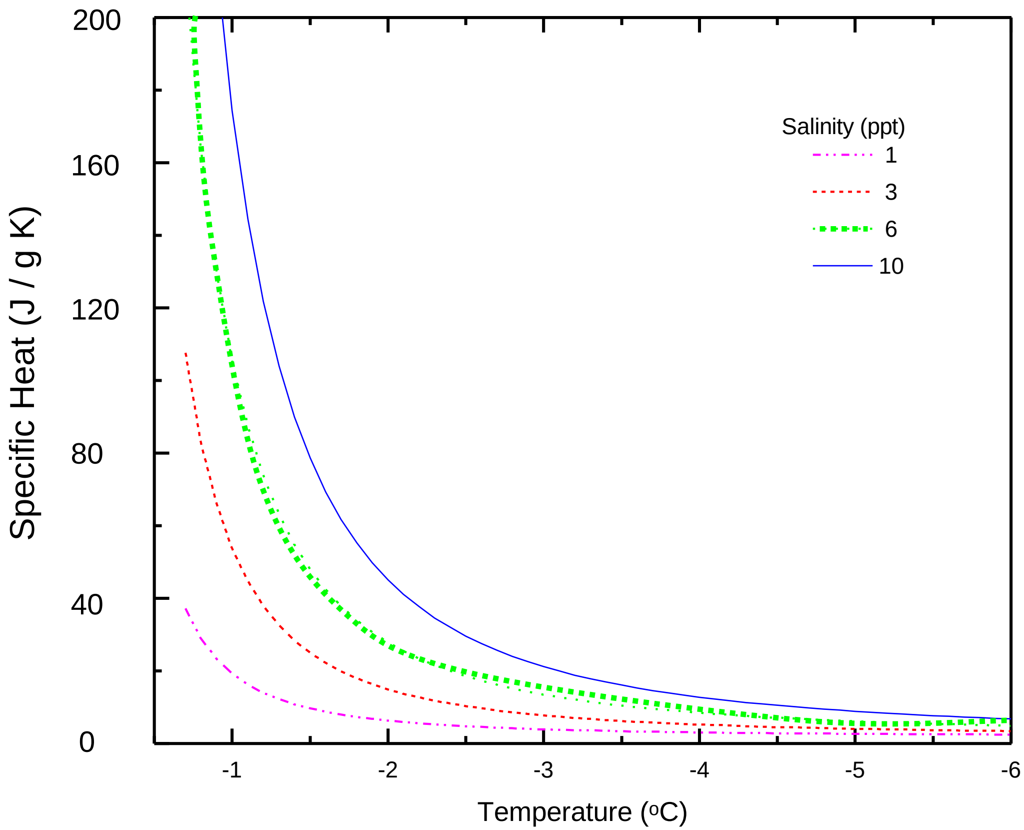
Specific Heat : Heat required to raise 1 g of sea ice 1 °C

$$c_i = c_o + aT_i + \frac{bS_i}{T_i^2}$$

c_o is the specific heat of pure ice

a and **b** are constants

c_i can vary by nearly two orders of magnitude



• Mechanical Properties

- As T_i increases, the ice becomes more porous due to increased ν_b
- This causes the ice to become weaker
- *All* mechanical properties are thus sensitive to ν_b, i.e. to T_i and S_i

- Empirical data show that <u>compressive strength</u> (σ_i) can be related to ν_b by

$$\sigma_i = \sigma_o (1 - A\nu_b^{0.5})$$

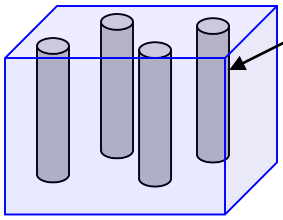
where σ_o is the compressive strength of pure ice and A is a constant

- For engineering purposes, $\sigma_i \rightarrow 0$ as $\nu_b \rightarrow 30\%$

- In nature, ice can still retain integrity until $\nu_b \cong 60\%$, even though it may have negligible compressive strength

- Mechanical properties are directional
  - stronger under vertical stress
  - important for offshore structures or load-bearing capacity of the ice

Idealized picture of sea ice structure



ELECTROMAGNETIC PROPERTIES (OPTICAL)

- Interaction with solar (shortwave) radiation
- Shortwave (SW) radiation is one of largest components of surface heat balance
    - 300 nm (UV) – 4000 nm (IR)
    - roughly half of the energy is visible, near UV (300 – 700 nm)
    - important for calculating mass changes
    - heat storage in the ice and upper ocean

• **Albedo**

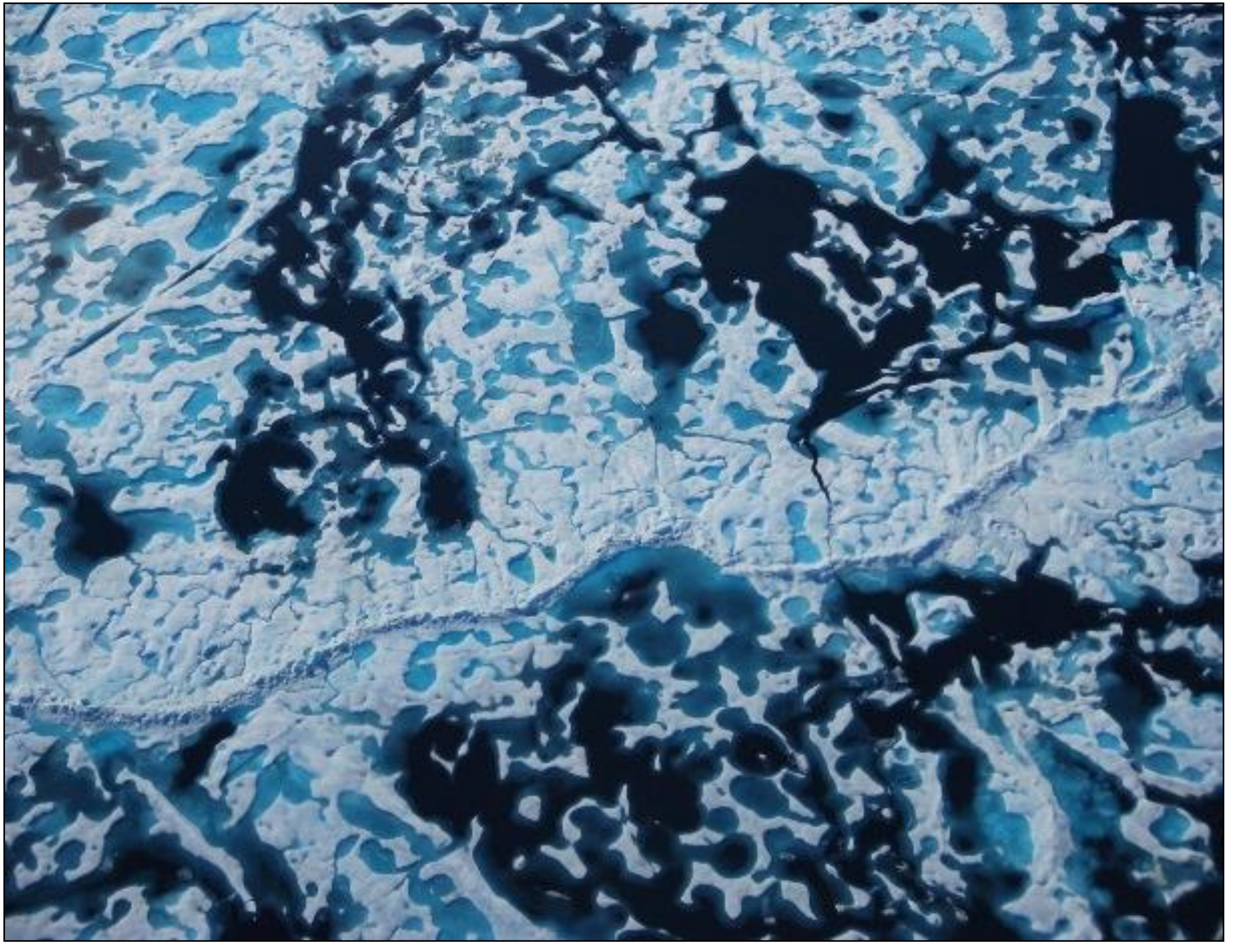
$$\alpha = \frac{\text{reflected SW}}{\text{incident SW}}$$

α depends on

- ice thickness and type
- snow cover
- presence of liquid water near the surface
- examples:

.80 - .90	cold, snow-covered ice
.65 - .75	melting, snow-covered ice
.55 - .65	clean, melting multiyear ice
.35 - .60	cold, thin ($20<H<100$ cm) first-year ice
.45 - .55	melting first-year ice
.15 - .45	melt ponds
.10 - .35	new ($H<20$ cm) ice
.07 - .10	open water

Photo: B. Elder



Spatially-averaged (i.e. measured by aircraft or satellite) albedos typically reduced to 0.45-0.50 during summer due to presence of melt ponds

Spectral Albedos

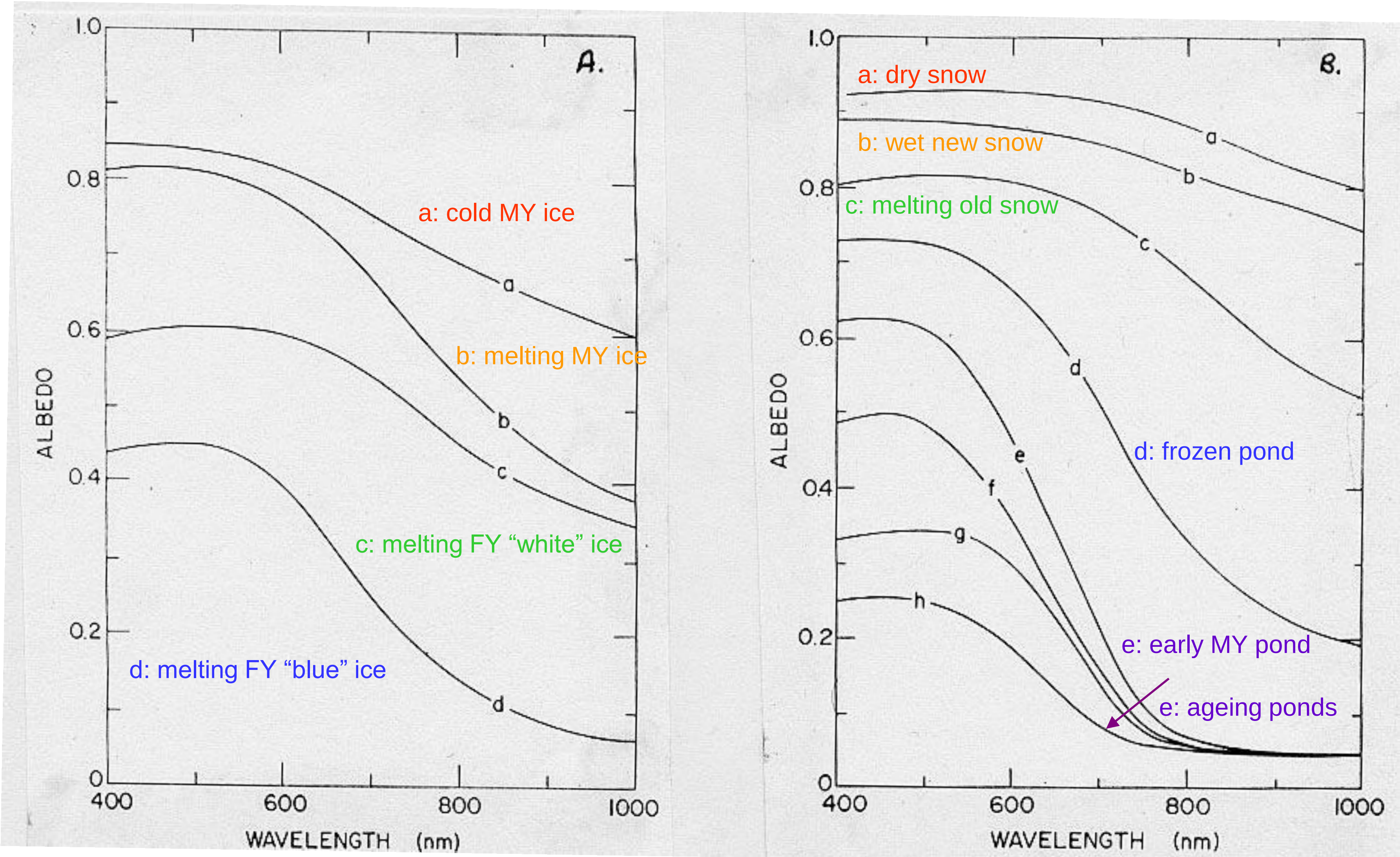
- $\alpha(\lambda)$; where λ = wavelength

- Important for interpreting satellite measurements and for calculating SW energy absorption and transmission within the ice

- Relatively constant between 400-600 nm
  reason why snow and drained ice appear white

- Decreases steadily at near infrared wavelengths

Spectral Albedos



Extinction Coefficient (K_λ)

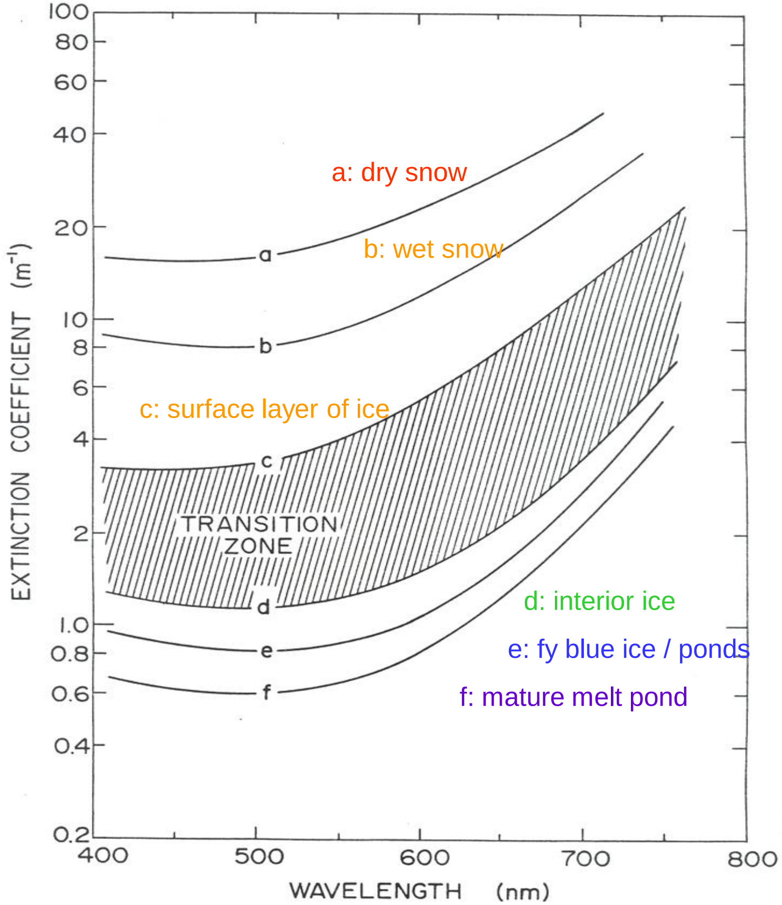
- Needed to calculate:
    - SW energy absorbed by ice
    - SW energy transmitted through ice (mixed layer heating, photosynthesis)

- Beer's Law: $F_z(\lambda) = F_0(\lambda)\, e^{-\kappa_\lambda z}$

    where $F_o(\lambda)$ is the net SW flux at the surface

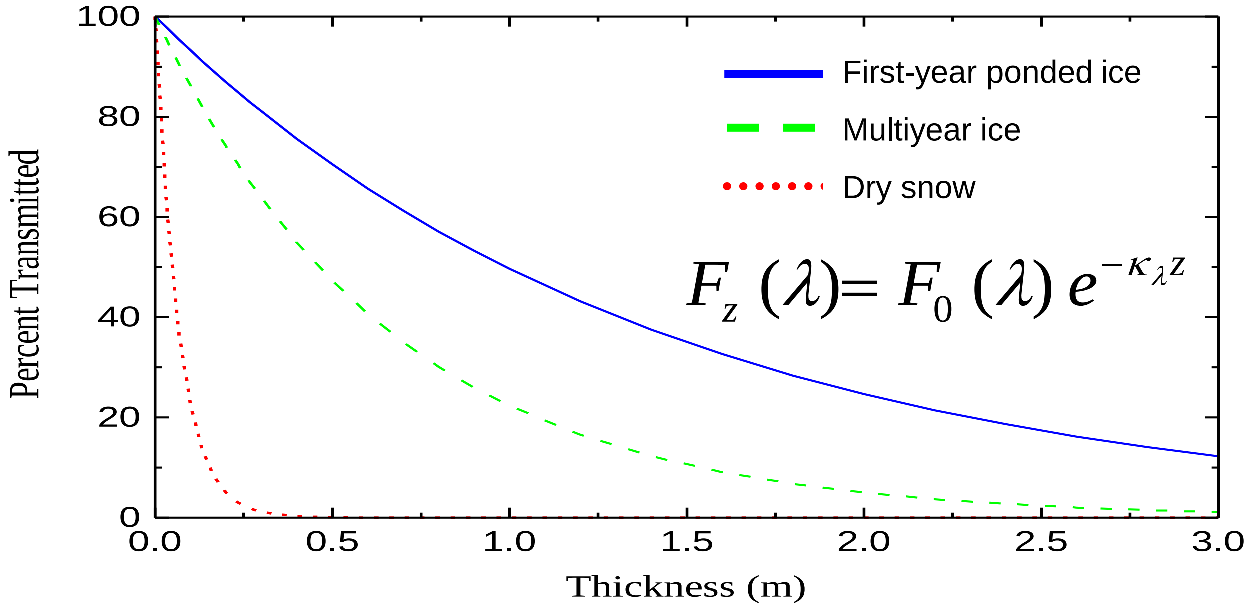
- The larger the K_λ, the less light penetration

- Averaged over λ:
    - $K = 0.5 - 1.5\ m^{-1}$ for sea ice
    - $K = 15\ m^{-1}$ for dry snow



- Relatively constant between 400-600 nm
- Increases roughly an *order of magnitude* between 600-800 nm
- Visible light (particularly blue) penetrates deep into ice
- Most near-infrared energy is absorbed close to surface

Beer's Law equation predicts:



- Field data from 1940-70s showed very little bottom melting during summer
- Data from late 1990s: total bottom melting ≅ total surface melting
- Data from 2000s indicates bottom melt in some areas > surface melt
- Average summer ice thickness **H** decreased from 2.5 to 1.5 m between these two earlier periods, allowing more SW radiation to be transmitted to ocean through ice
- Figure above points to a strong positive feedback between decreasing **H** and increasing bottom melting
- **This "ice-transmittance" feedback is likely contributing to Arctic sea ice loss**