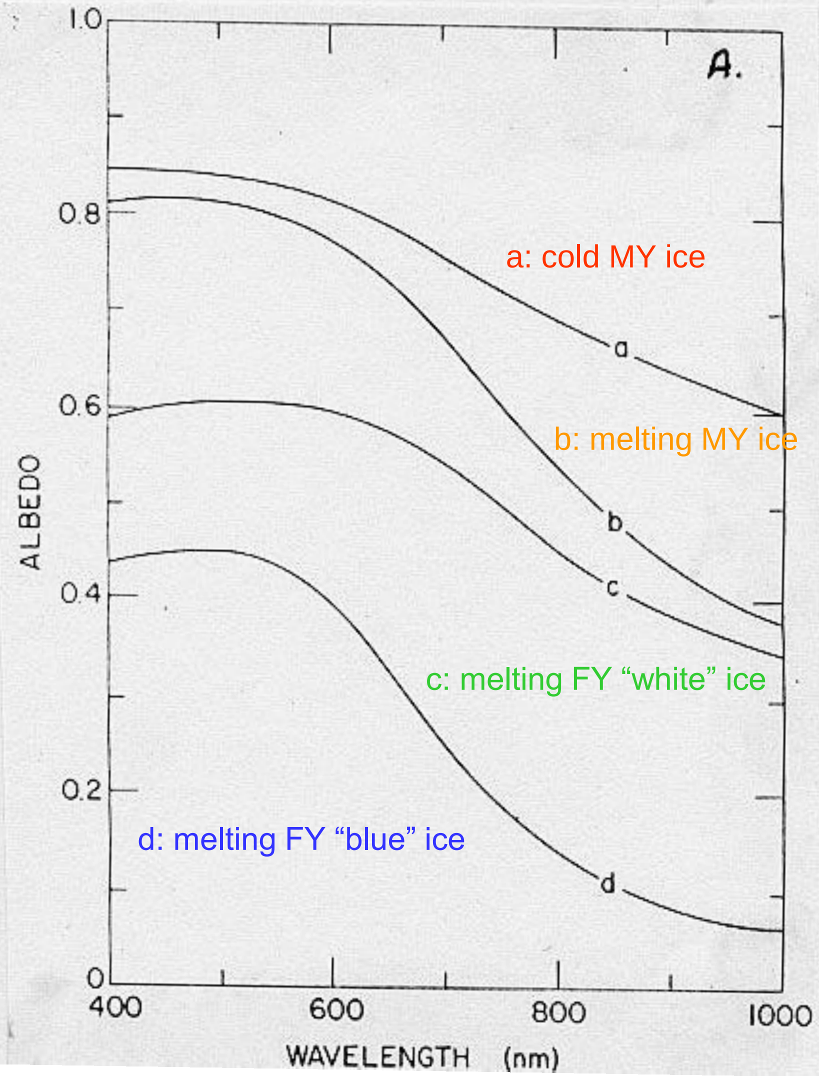
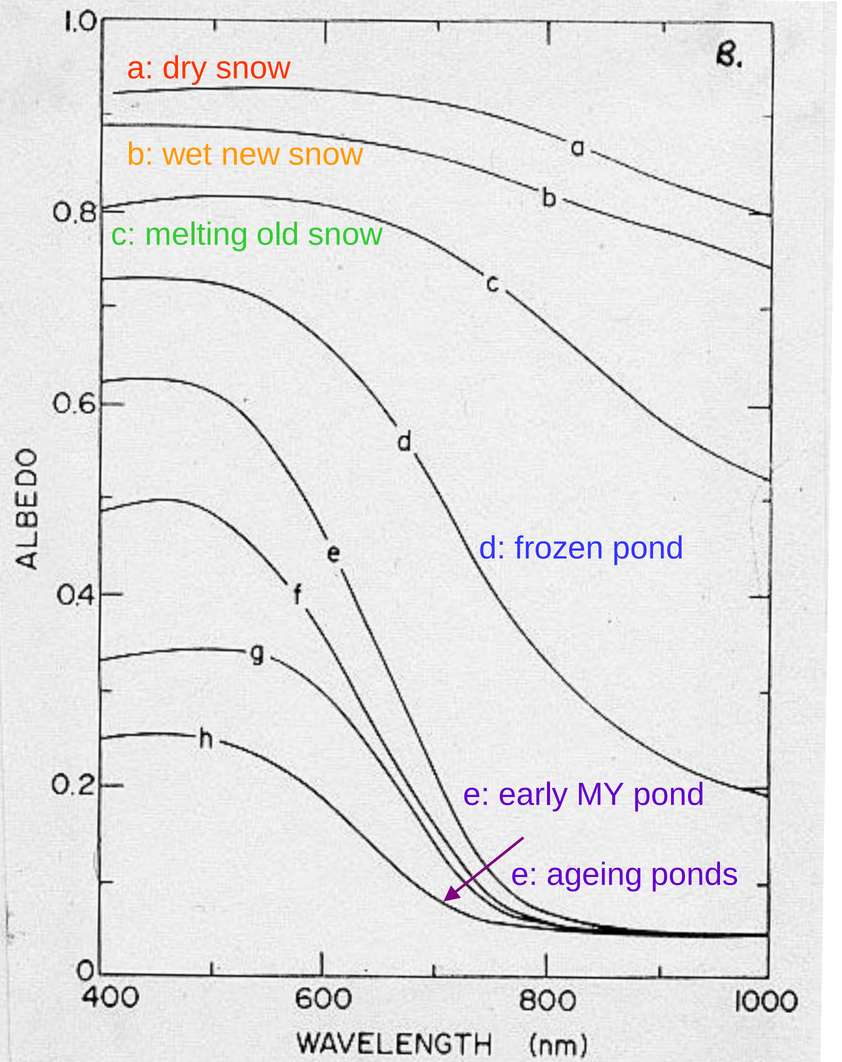
Spectral Albedos





Extinction Coefficient (K_λ)

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

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

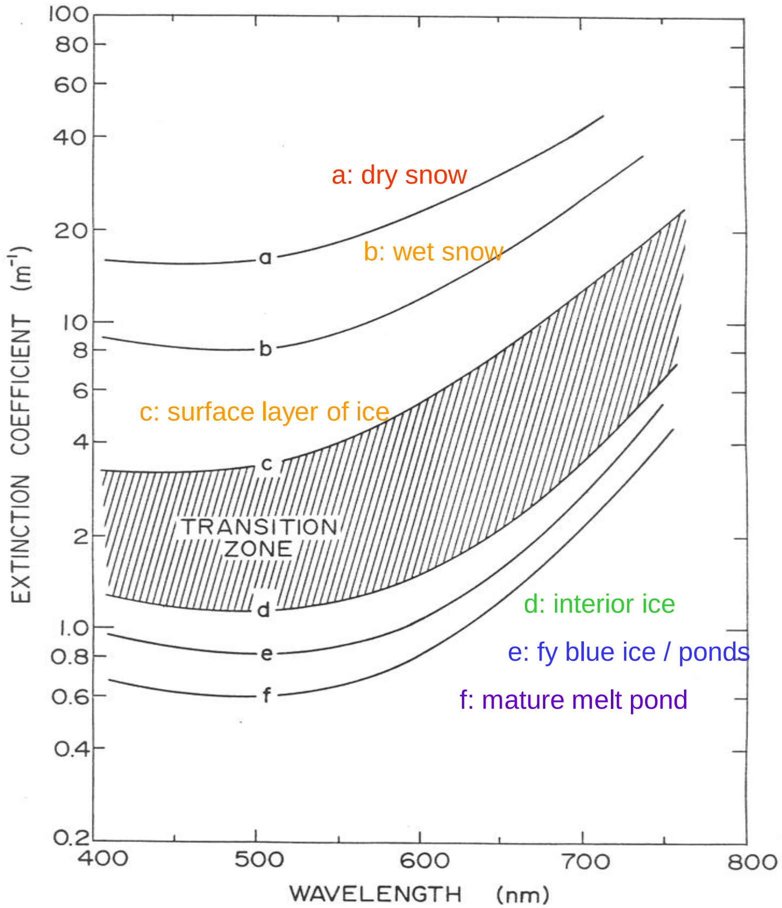
  where $F_o(\lambda)$ is the net SW flux at the surface

- The larger the K_λ, the less light penetration

- Averaged over λ:

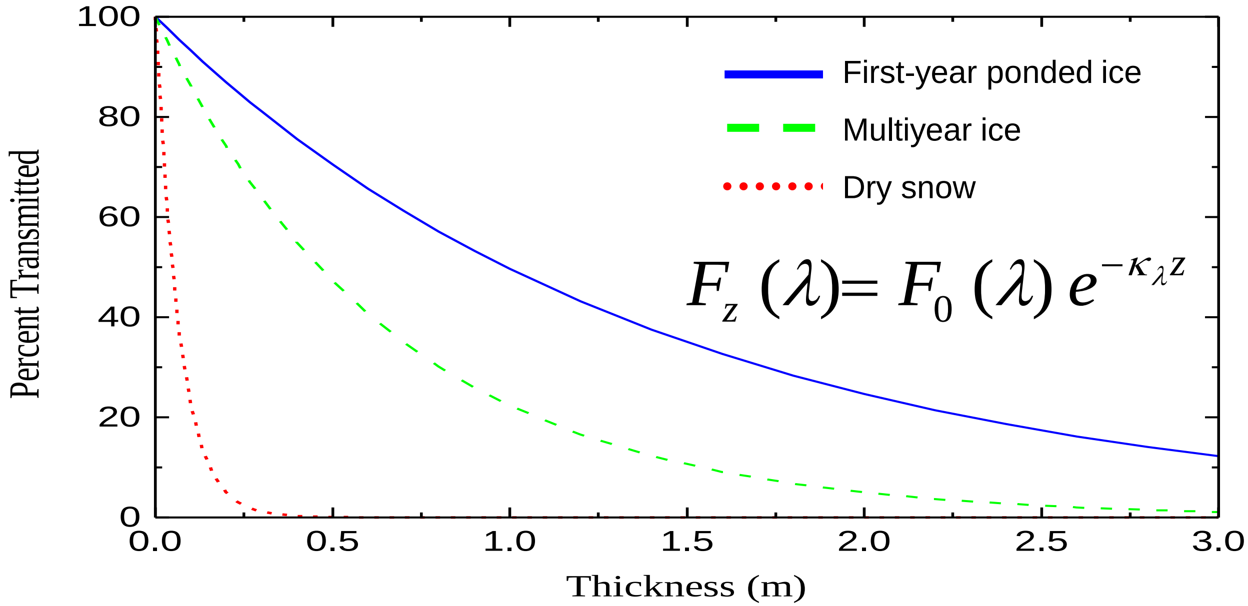
  $K = 0.5 - 1.5\ m^{-1}$ for sea ice

  $K = 15\ m^{-1}$ 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:

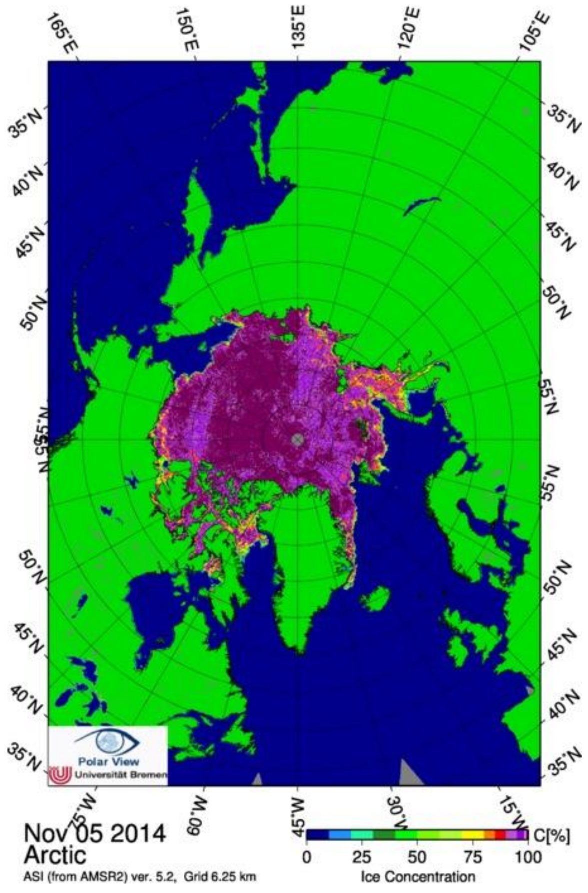


- Field data from 1940-70s showed very little bottom melting during summer
- Data from late 1990s: total bottom melting ≅ total surface melting
- Data from 2000s indicates bottom melt in some areas > surface melt
- Average summer ice thickness **H** decreased from 2.5 to 1.5 m between these two earlier 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**

ELECTROMAGNETIC PROPERTIES (MICROWAVE)

- Remote sensing at visible and infrared wavelengths limited by dark, clouds

- Ice cover emits energy in *microwave* region [1 to 100 GHz or 0.3 - 30 cm wavelength]
    - unaffected by clouds or darkness
    - current technology for following temporal changes in the ice pack



ELECTROMAGNETIC PROPERTIES (MICROWAVE)

- Methods depend on resolving differences in microwave emissivity (ε_λ)

$$\varepsilon_\lambda = \frac{I_\lambda}{B_\lambda(T)}$$

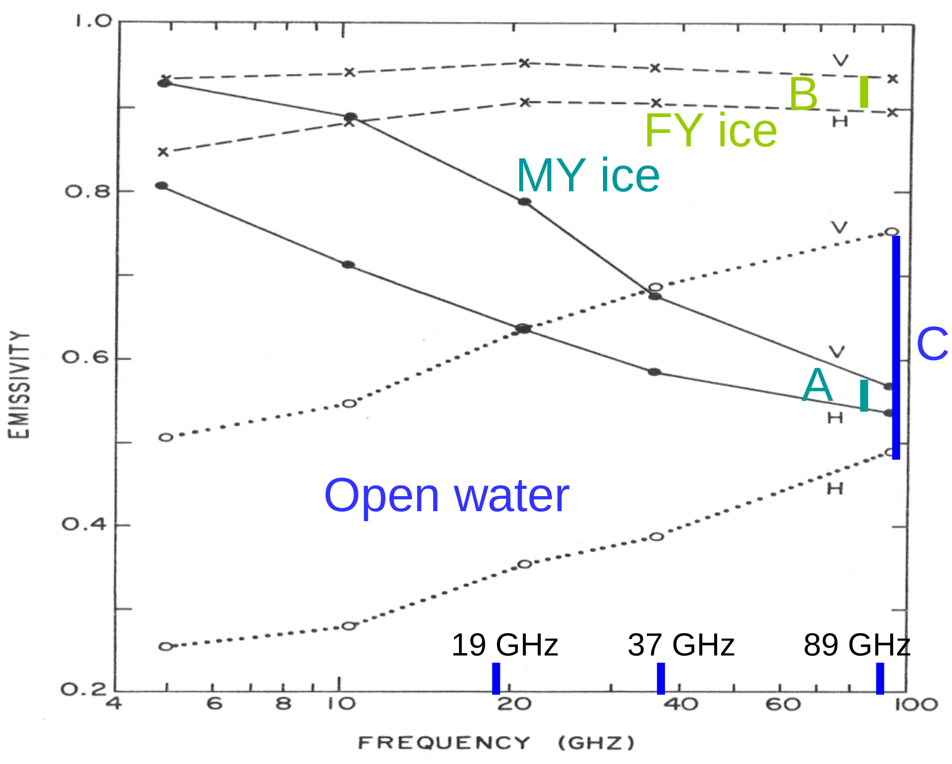
  - I_λ is intensity emitted by the surface (what sensor measures)

  - B_λ is intensity emitted by a blackbody at the same thermodynamic temperature, Planck's law:

$$B_\lambda(T) = \frac{2h\upsilon^3}{c^2}\frac{1}{e^{\frac{h\upsilon}{kT}}-1}$$

ELECTROMAGNETIC PROPERTIES (MICROWAVE)

The dependence of ε_λ is distinct for open water, FY ice and MY ice



- Open water: large difference vert. polarization – horiz. pol. **C**

- Sea ice at 89 GHz: small difference, similar for different ice types **A** ≅ **B**

- Multi-year ice: decreasing emissivity with increasing frequency

- Vanishing radiometric difference between FY ice and MY ice during summer

ELECTROMAGNETIC PROPERTIES (MICROWAVE)

- Intensities are small, so instrument sensitivity is a problem

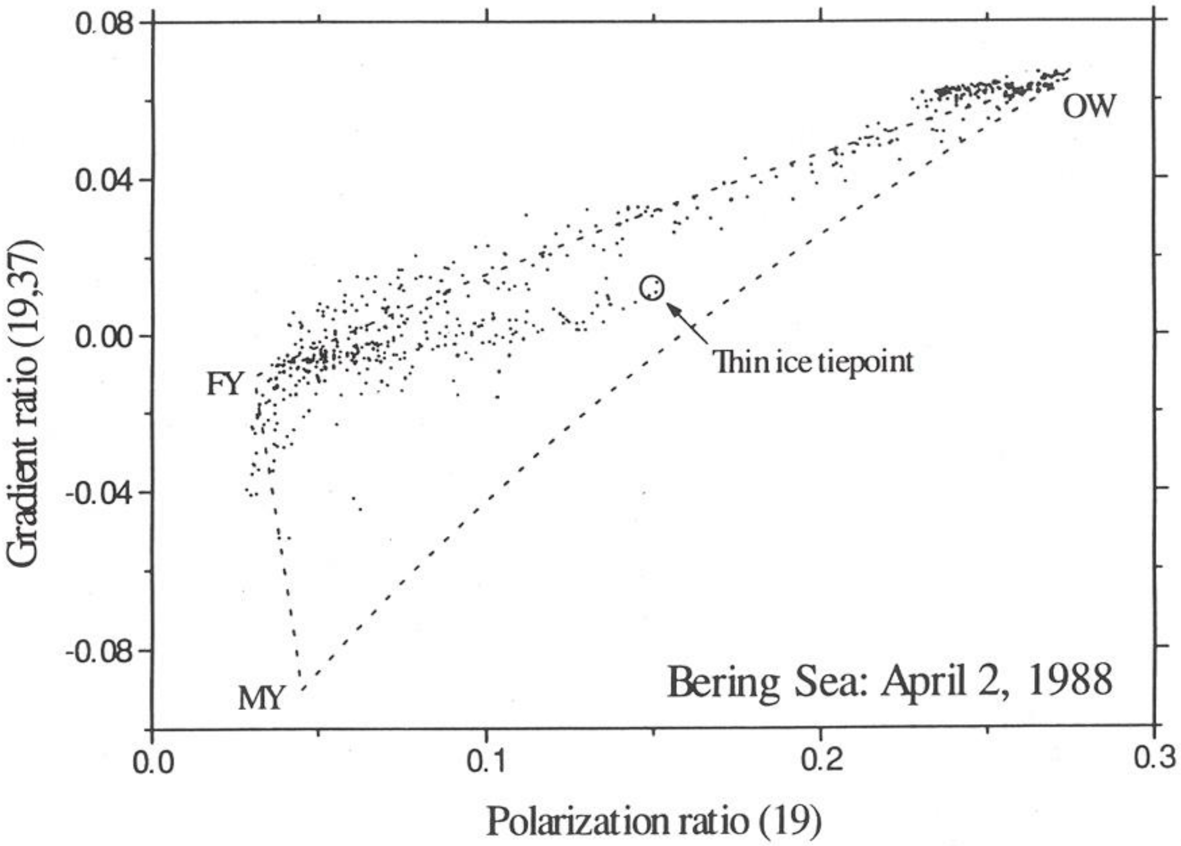
- To get enough signal, must look over large footprint (20-50 km)

- Typical area may contain all 3 surface types

- What is fractional area covered by each type within the footprint?

- NASA has developed algorithms that combine information on both the spectral gradient and polarization differences. This involves plotting the Spectral Gradient Ratio (GR) vs the Polarization Ratio (PR), which are strictly functions of intensities measured by the satellite

ELECTROMAGNETIC PROPERTIES (MICROWAVE)



Problems

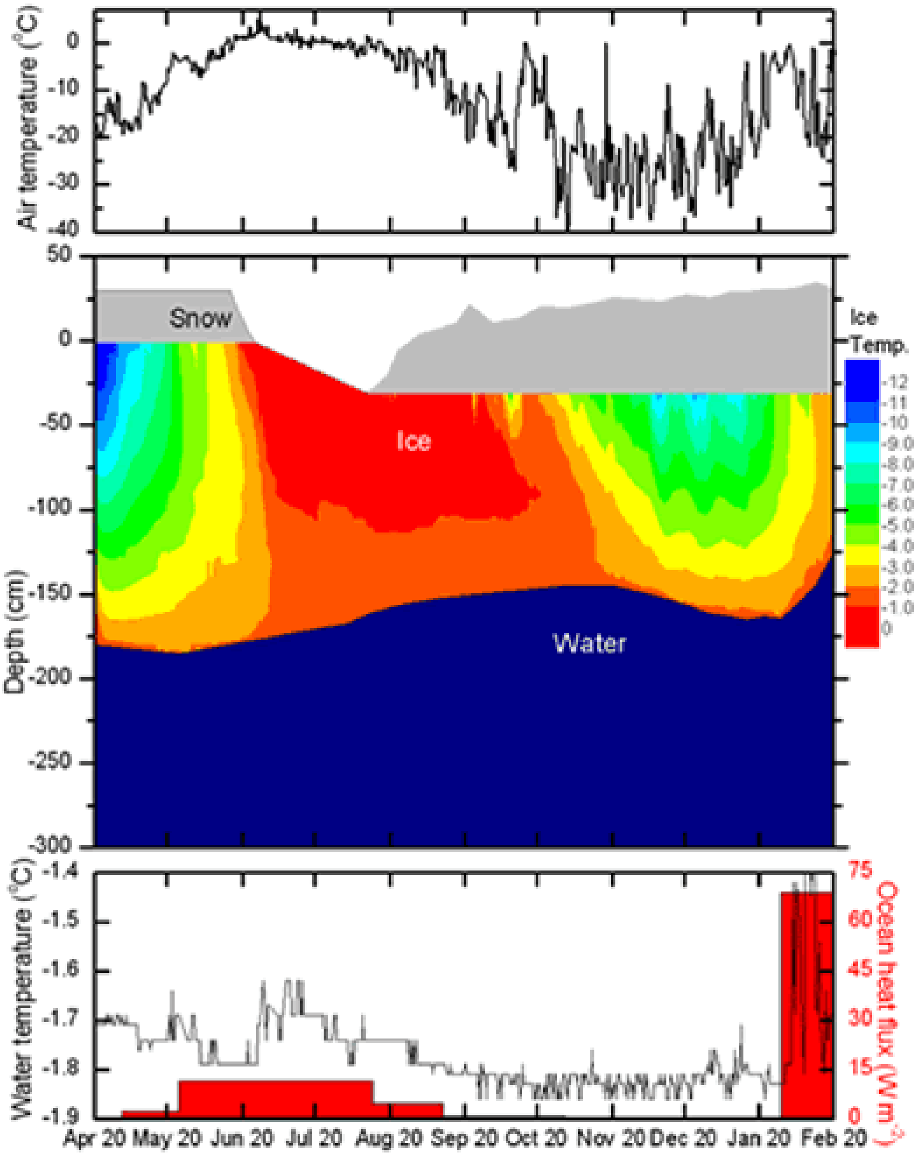
- Snow layering
- Surface melt water
- Refrozen surface melt water

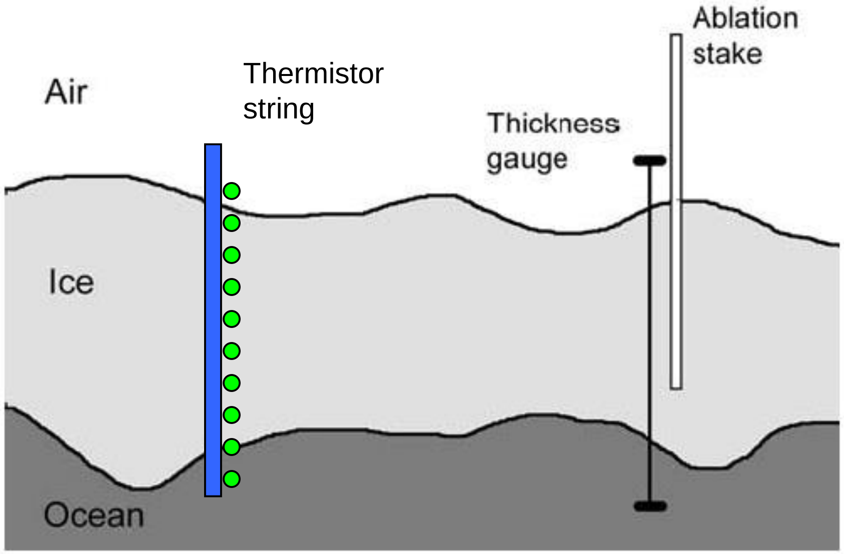
T_B is “brightness temperature”

$$GR(19,37) = \frac{T_B(37,V) - T_B(19,V)}{T_B(37,V) + T_B(19,V)}$$

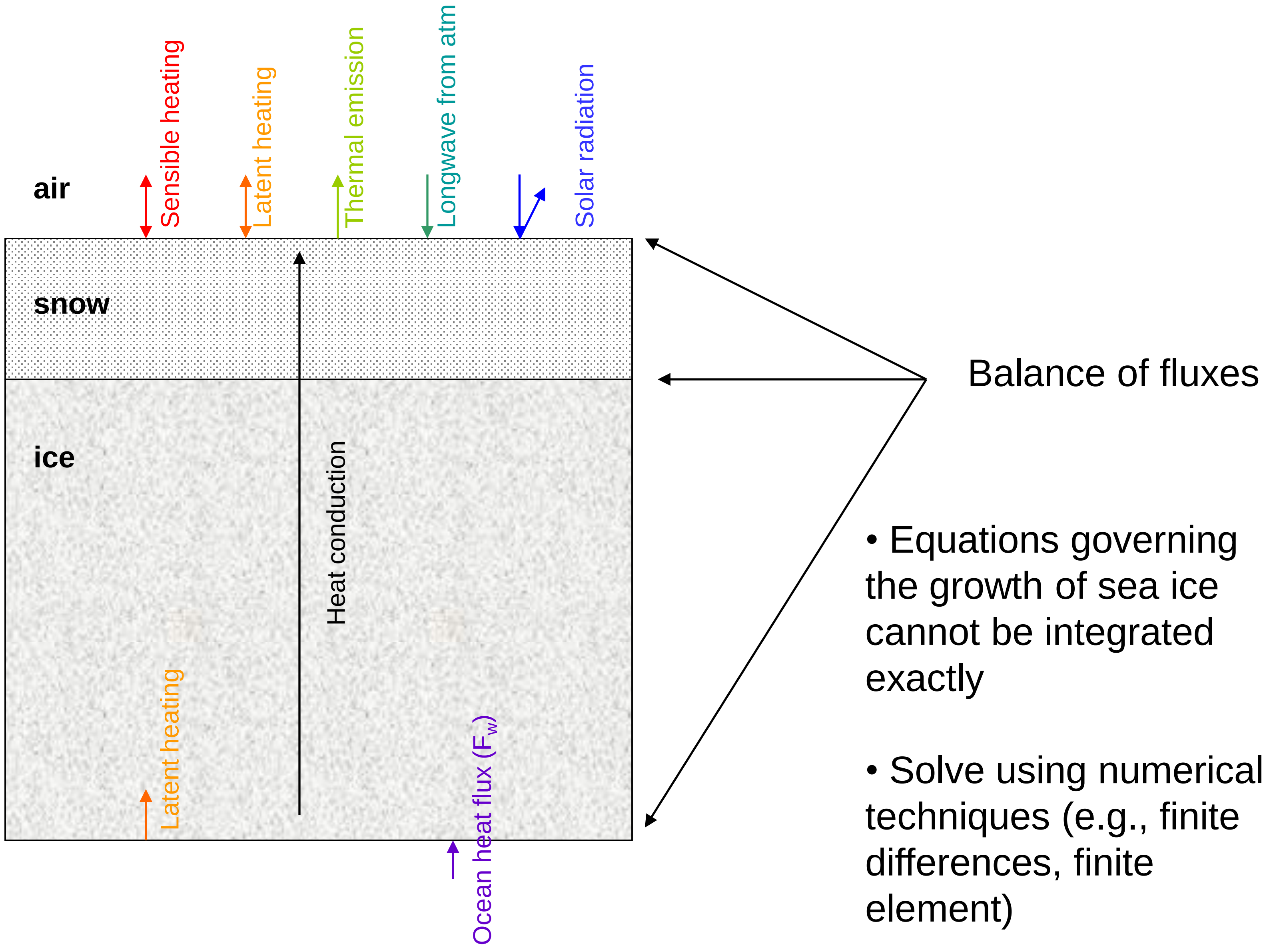
$$PR(19) = \frac{T_B(19,V) - T_B(19,H)}{T_B(19,V) + T_B(19,H)}$$

THERMODYNAMIC PROPERTIES OF SEA ICE





1-D Thermodynamic Equations: heat conduction and heat balance



- Equations governing the growth of sea ice cannot be integrated exactly

- Solve using numerical techniques (e.g., finite differences, finite element)

1-D Thermodynamic Equations

Annual cycle:
- growth during fall, winter
- melt during summer

- Ice thickness does not increase indefinitely!

- *Equilibrium thickness* (H_e)

  - net growth exactly balances net melt over an annual cycle

  - thickness on any given date does not change from one year to the next, as long as climate does not change from year to year

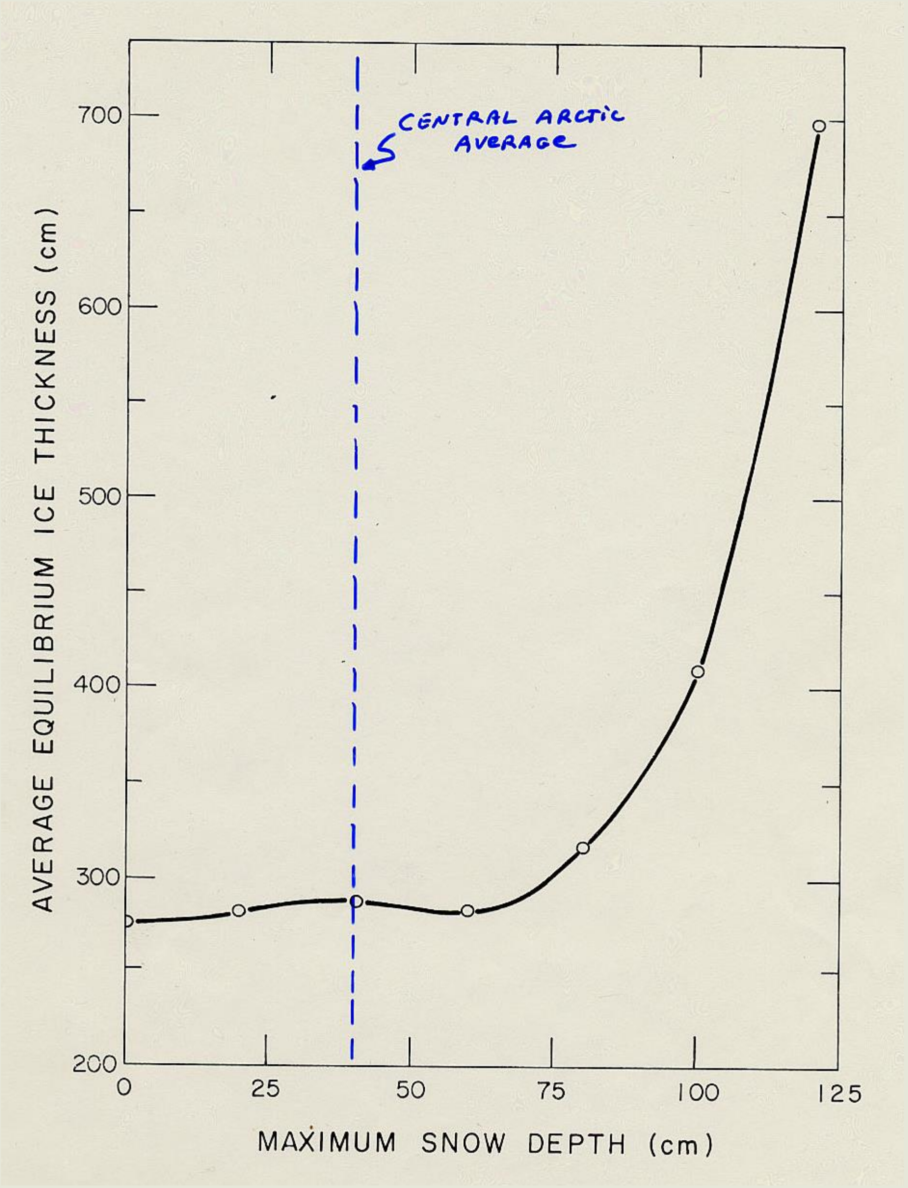
- Thermodynamic ice models often used to investigate how changes in thermal forcing or ice properties affect the equilibrium state of the pack

SENSITIVITY OF H_e IN 1-D MODEL

- **Oceanic Heat Flux**
  - Annually averaged F_w is typically a few W m^{-2}
  - $F_w = 0 \Rightarrow H_e = 5\text{-}6$ m
  - F_w increased by 400% $\Rightarrow H_e = 0$ m (ice vanishes)

- **Snow Depth** (h_s)
  - Little change in H_e when $0 < h_s < 80$ cm because large winter growth balanced by large summer ablation
  - Rapid increase in H_e when $h_s > 80$ cm as less and less surface melting possible
  - h_s large enough and ice pack becomes a “sea-glacier” growing from above and ablating only from below

H_e as a function of maximum annual snow depth



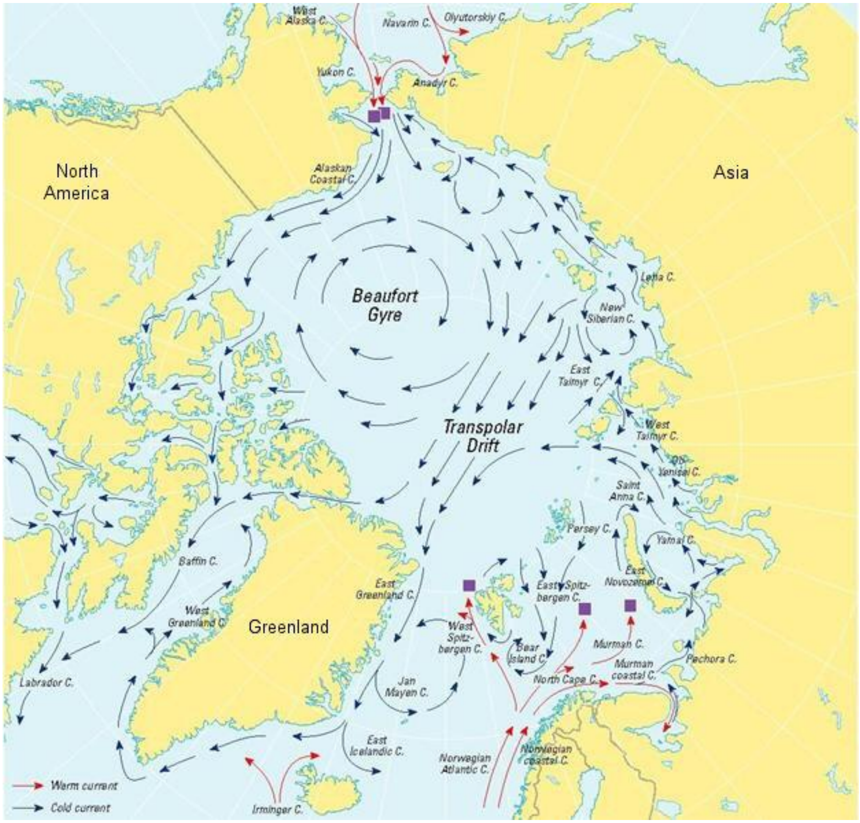
SENSITIVITY OF H_e

- **Air Temperature**
  - In 1D model, ice pack vanishes if T_a increased by 2-3 ^oC
- **Limitations**
  - Simple 1-D calculations do not take into account
    -- response of atmosphere and ocean to changes in state of the ice cover
    -- spatial variations in ice thickness

  - For this we need to understand how the ice moves, redistributes, and interacts with the atmosphere and the ocean (ice dynamics)

ICE DYNAMICS

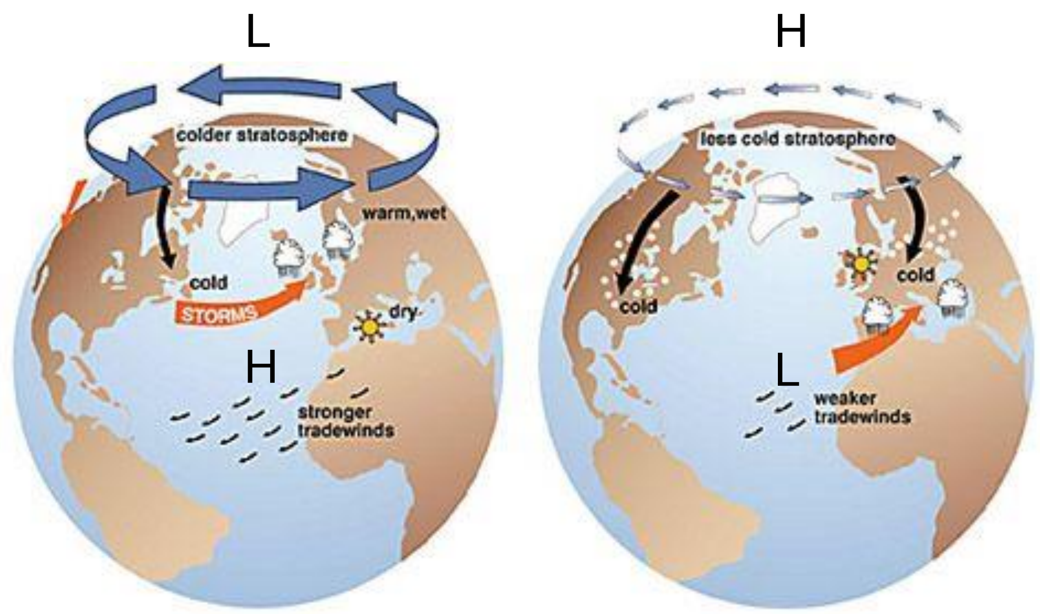
- Ice in continual motion
- Moves 7-8 km/day in Central Arctic; 15 km/day or more in Greenland Sea
- On annual average, clockwise ice circulation north of Alaska (the "Beaufort Gyre"), and cross-basin transport on the Eurasian side (the "Transpolar Drift Stream") out through Fram Strait
- Each year roughly 10% of ice in Arctic Basin is exported through Fram Strait into the Greenland Sea where it melts



Arctic Ocean circulation. Image courtesy of Arctic Monitoring and Assessment Programme (AMAP), Figure 3.29, AMAP (1998).

ARCTIC OSCILLATION

- Relative (non-seasonal) surface pressure changes between Arctic Basin and lower latitudes vary with time
- See changes in advection of heat into Arctic Ocean via Atlantic Ocean, also atmospheric heat transport
- Also changes in amount of ice exported through Fram Strait



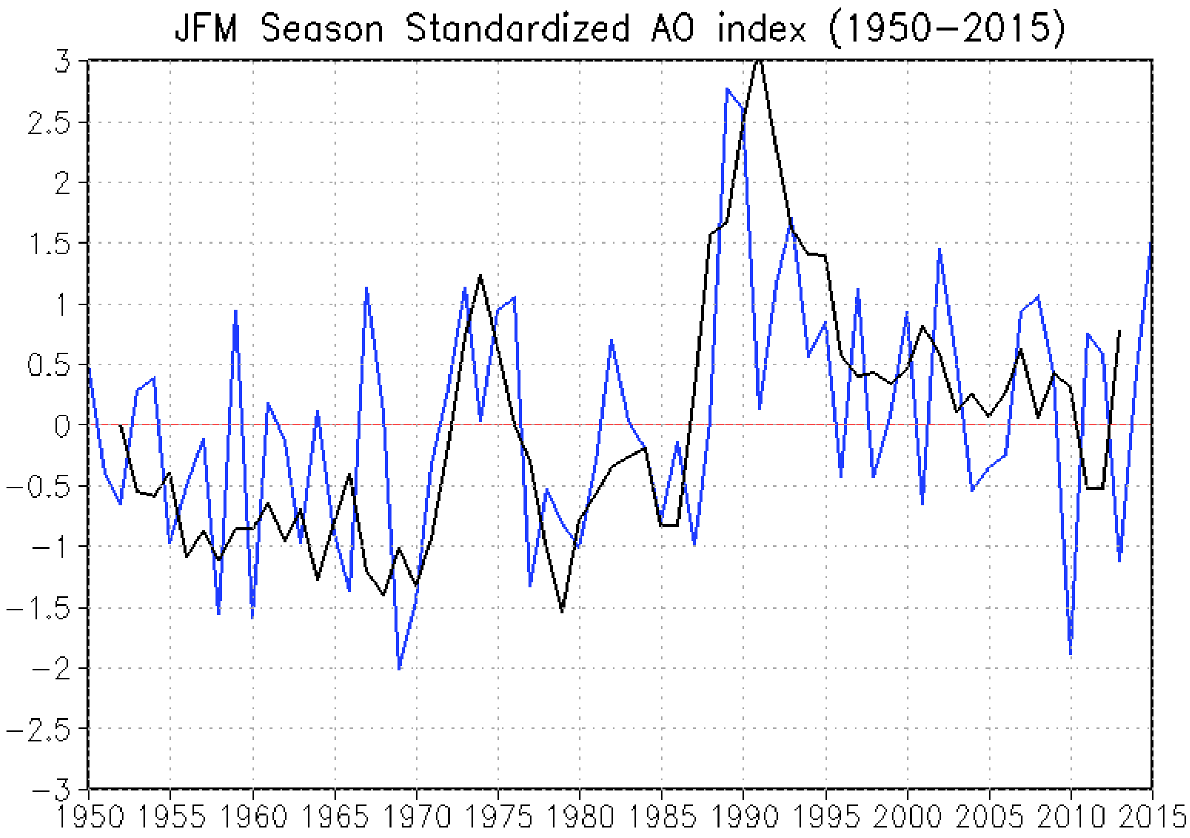
Positive (warm) phase

Negative (cool) phase

(Figure courtesy of J. M. Wallace, University of Washington)

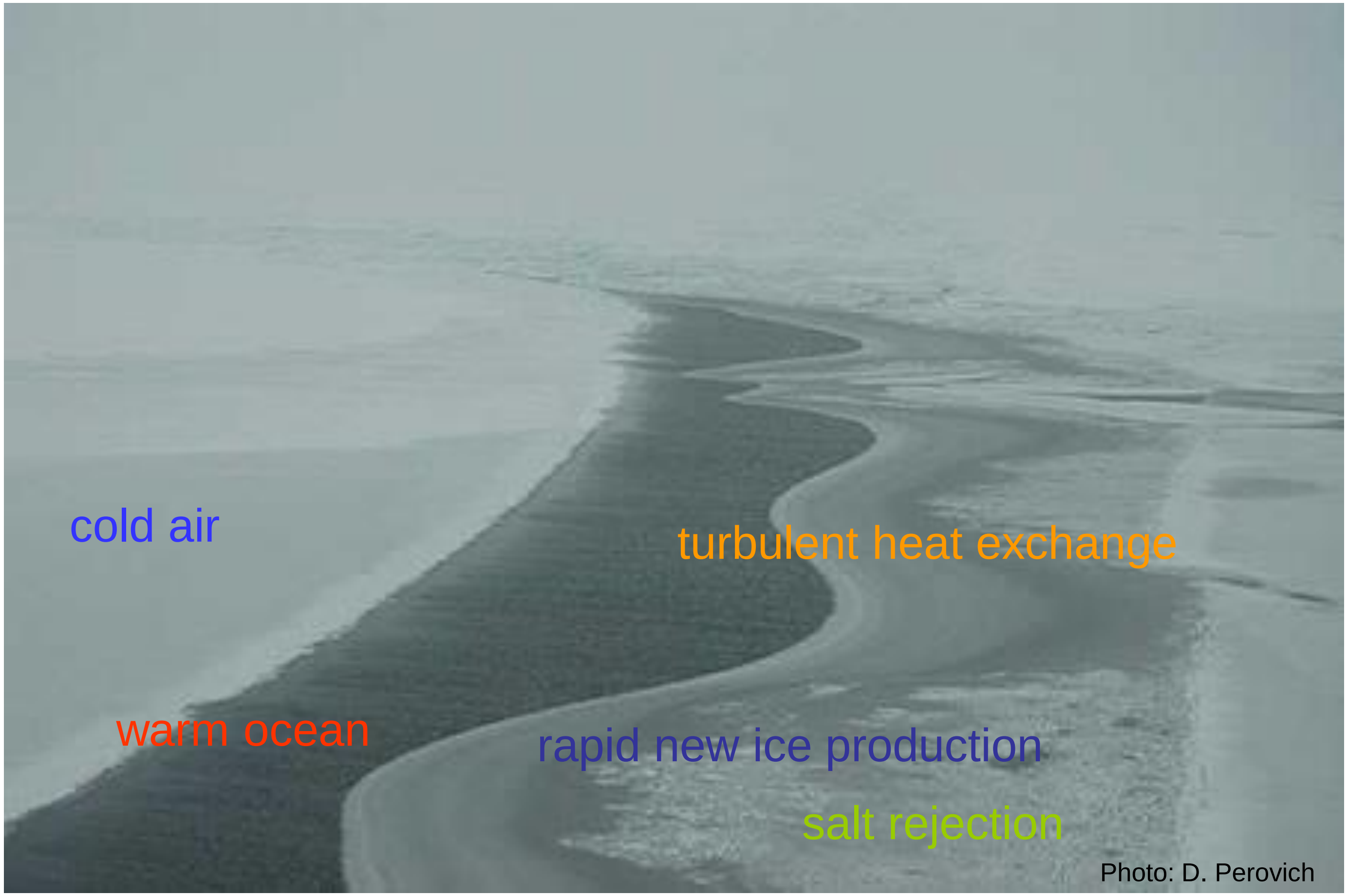
ARCTIC OSCILLATION

- Negative (cool) phase thought to be “normal” -- until 1990s
- Response of sea ice is complex, delayed
- Domination of the positive (warm) phase beginning 1989 is thought to be a driver for export of multiyear ice from the Arctic basin



SMALL SCALE DYNAMICS: LEADS

- "Leads" are fractures in sea ice (generally large enough for a small ship to pass)
- Warm ocean becomes directly exposed to cold air



LEADS (continued)

• Produced by diverging motion in the ice (wind, water stresses)

• Typically 10's to 100's of meters in width; leads on the order of 1 km wide and larger are called *polynyas*

• In the Arctic, leads cover ~0.5% in winter, 10 – 20% in summer

• Rapid ice formation in winter leads

• Areas of open water are much more common in the Antarctic because of greater divergence in the ice pack (as much as 20% during the winter)

• Ice production, turbulent heat exchange and salt fluxes can be as much as 100 times larger over a refreezing lead as compared to fluxes over the surrounding ice

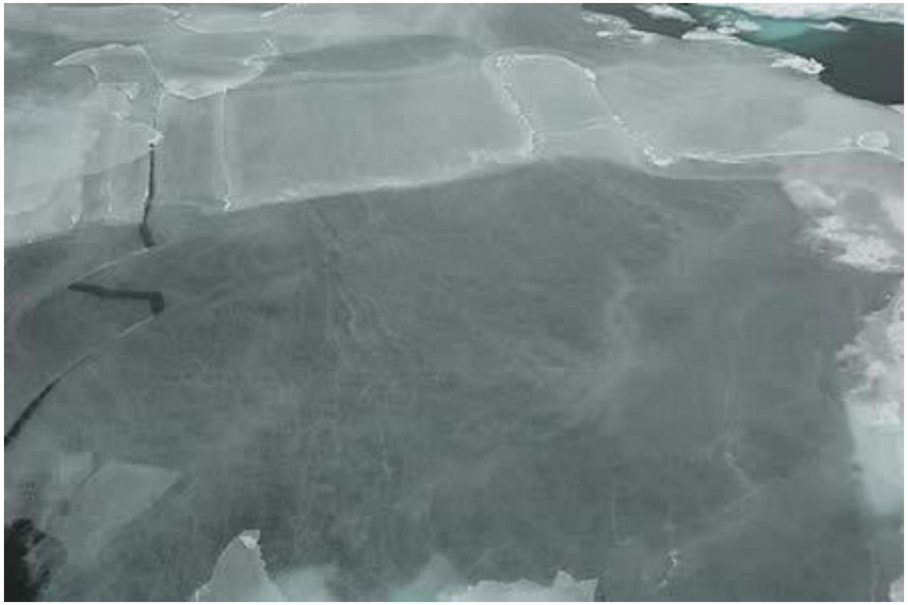
• Thus, relatively small areas of open water can have a large impact on area-integrated flux totals within a region

PRESSURE RIDGES

(1) Simple Rafting – Commonly occurs in leads and areas of very thin (1-30 cm) ice

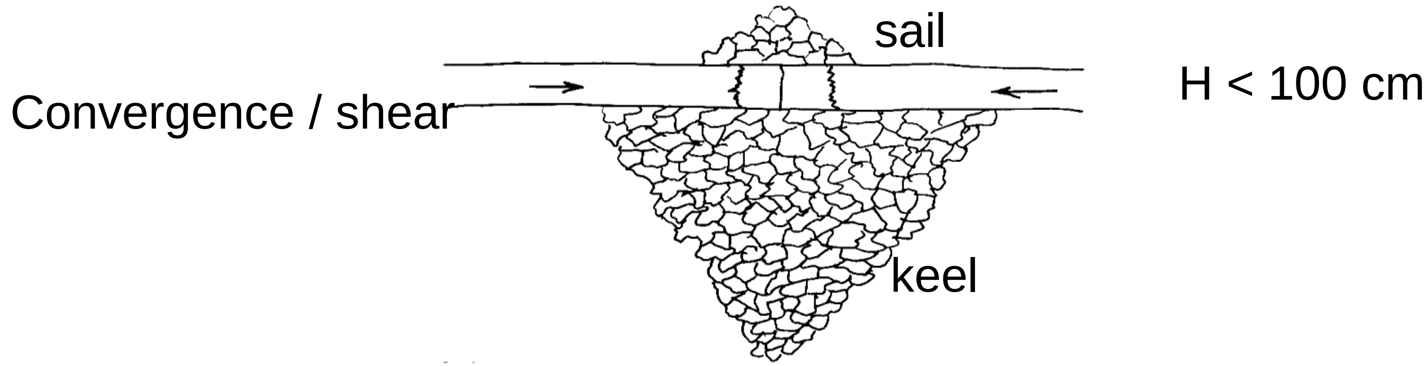
convergence

H = 1 – 30 cm

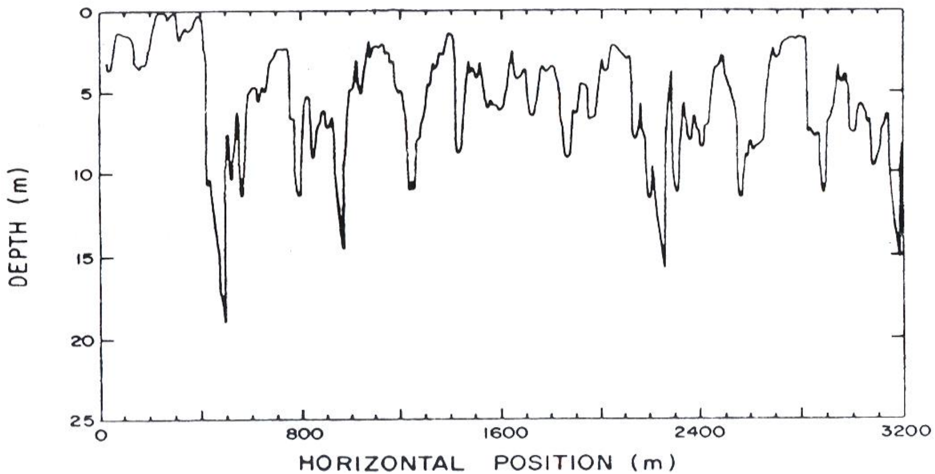


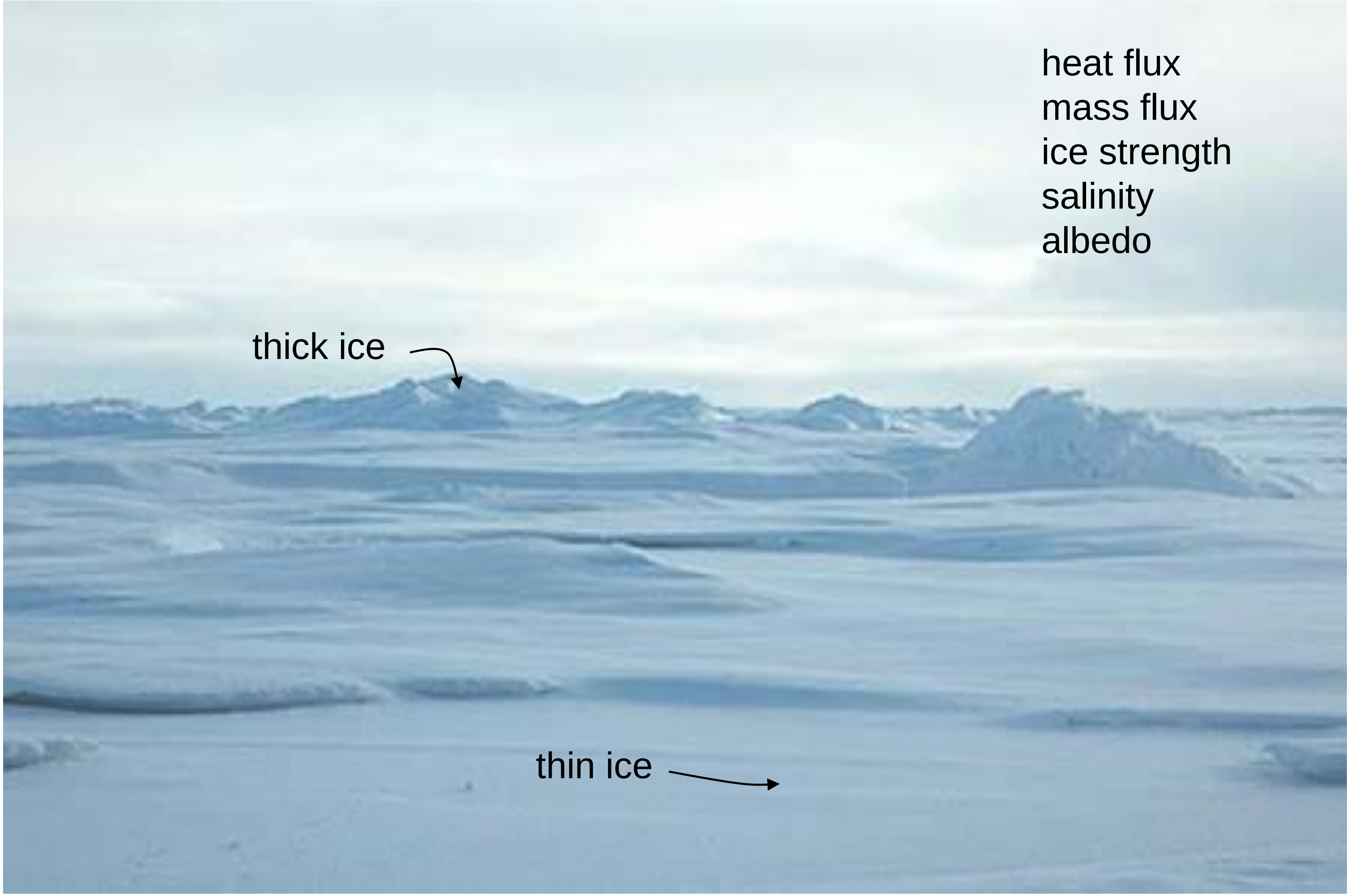
PRESSURE RIDGES

(2) Fracture Ridges - Convergence of floes too thick to bend often causes ice to fracture and blocks to pile up above and below the ice



- Keel depths usually about 5X the sail height. In Arctic, keels can reach 25-30 m, but sail heights are normally < 5m. There are as many as 3-8 ridges per km in some regions, e.g. submarine sonar profile taken beneath ice N of Greenland.




heat flux
mass flux
ice strength
salinity
albedo
thick ice
thin ice

SPATIAL VARIATIONS IN ICE THICKNESS

- Variations in thickness important for determining air-sea-ice interactions

- No deformation ⇒ thickness determined by thermal forcing
  - thermodynamics alone strives to produce a single thickness
  - net growth for thin ice
  - net ablation from thick ice

- Mechanical processes produce leads / ridges
  - leads open and young ice forms
  - some compacted into pressure ridges
  - some grows undisturbed

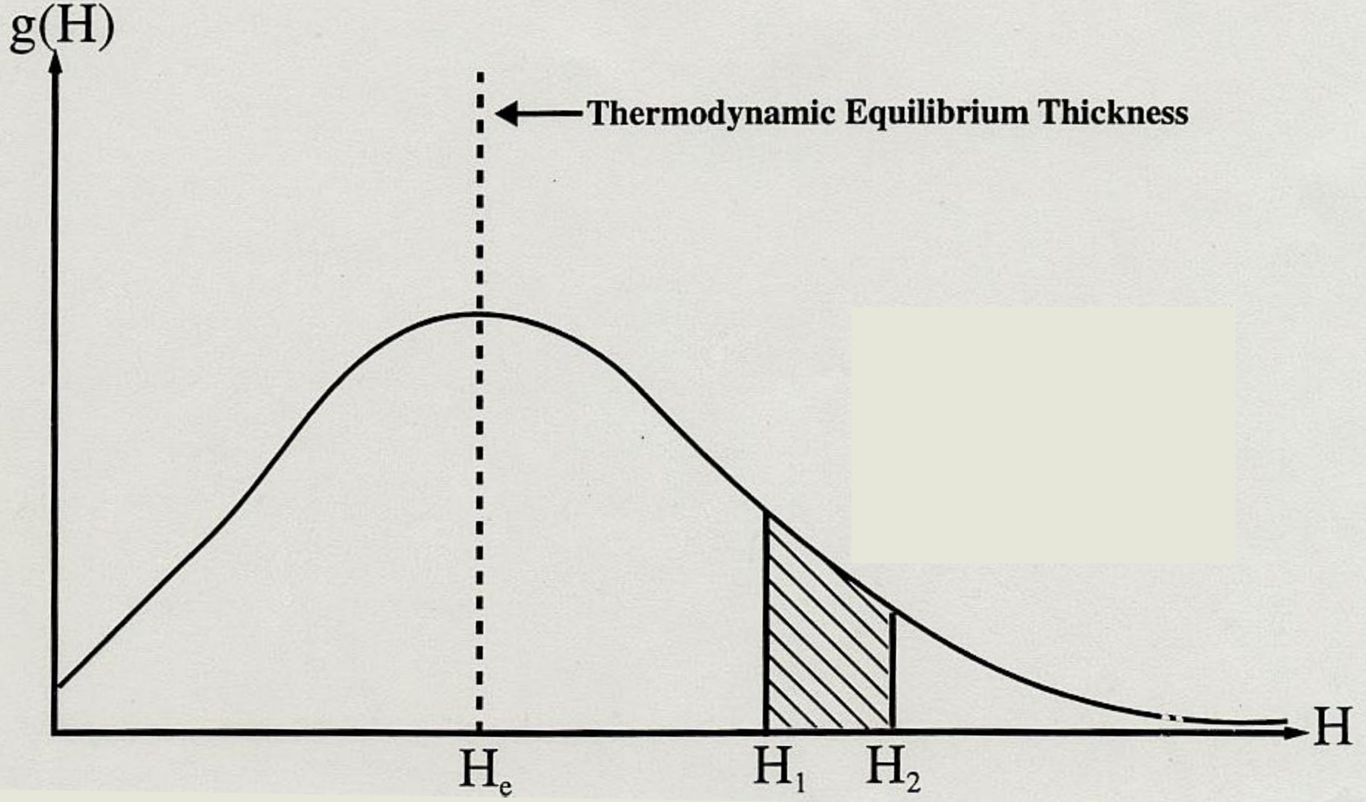
- Result is a distribution of thicknesses (0 – 10s m)

- To understand sea ice in climate system, need to know what happens regionally
  - GCM grid cell
  - magnitude of heat and mass fluxes averaged over large / spatially complex area instead of just at a particular point or thickness

- These fluxes very sensitive to H, so need to quantify spatial variations in ice thickness ⇒ *ice thickness distribution function* g(H)

ICE THICKNESS DISTRIBUTION

An idealized picture of g(H) for the Central Arctic is



Ice thickness distribution models

Change in thickness distribution =

ice growth + divergence + advection + mechanical redistribution

Challenges:

- heat and mass balance measurements have typically been made at manned camps established on multiyear ice (3-4 m thick!)

- these data may accurately describe conditions over thick ice, but they may not represent an entire region

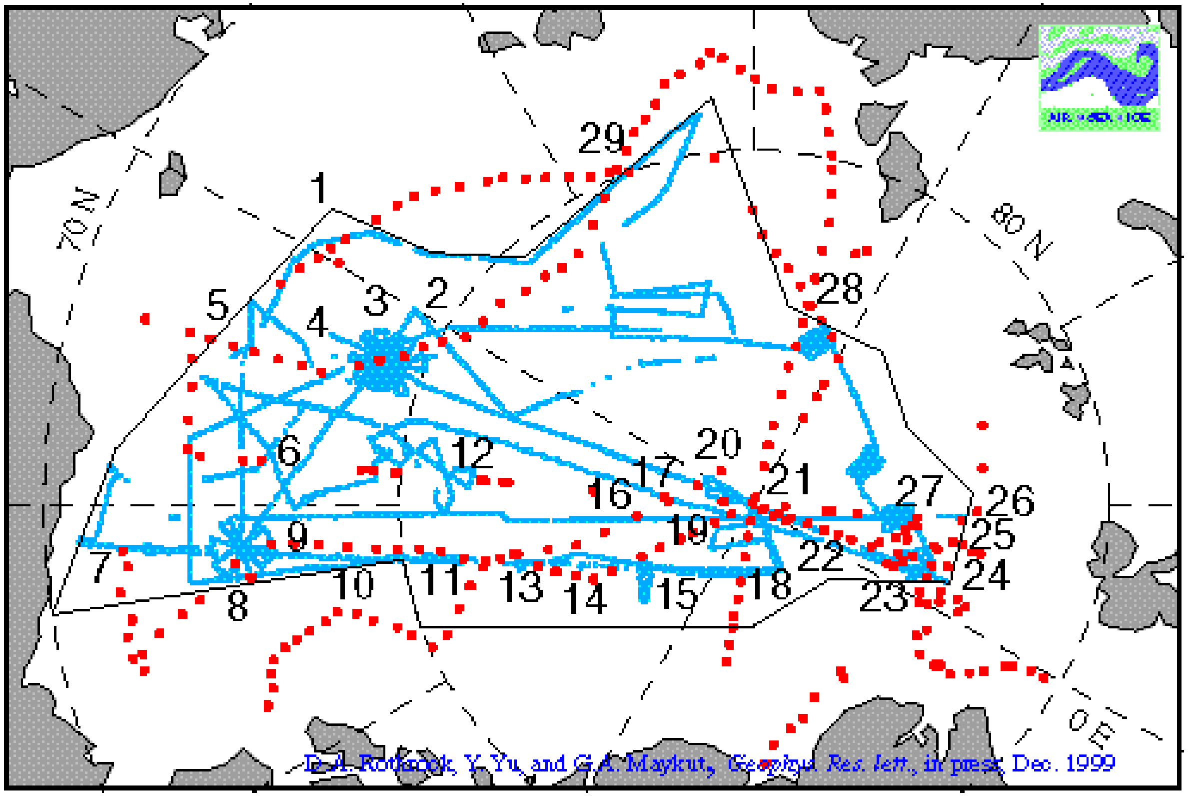
Sometimes just knowing the **average ice thickness** is useful…

AVERAGE ICE THICKNESS

- Traveling to a particular location and measuring ice thickness at a few sites is unlikely to produce accurate estimate of mean ice thickness (H_b)

- One practical method to obtain H_b is to utilize submarine sonar data averaged over tens to hundreds of km

- Rothrock et al. (1999) used this method to compare average ice thicknesses measured during scientific submarine cruises in the mid-1990s (SCICEX Program) with similar data collected in the 1960s and early 1970s

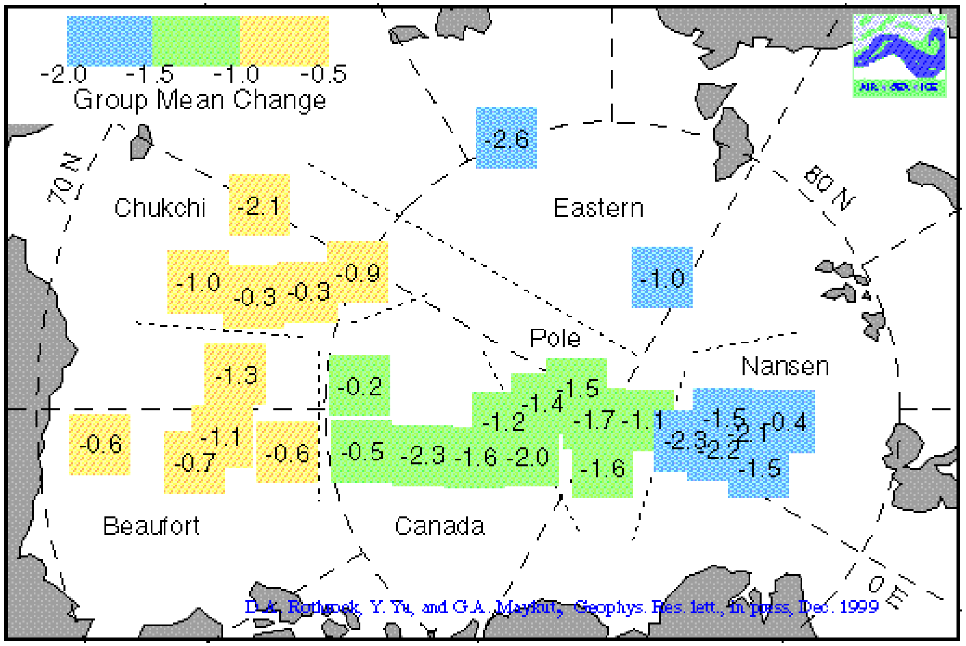


AVERAGE ICE THICKNESS (con't)

- Calculate H_b values along 100 km track segments in regions where data was available from autumn, both periods

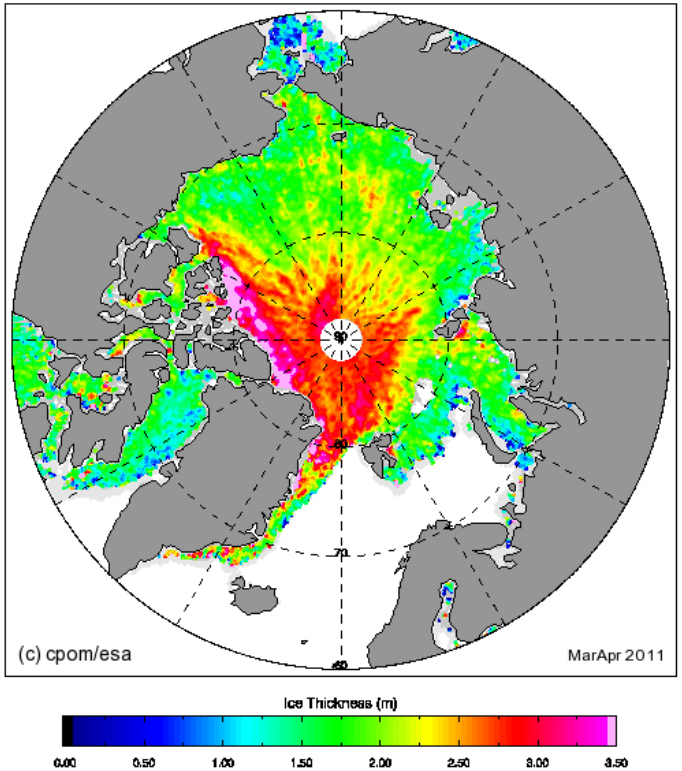
- Results show decreased ice thickness in every part of the Central Arctic Basin over the 30+ year period

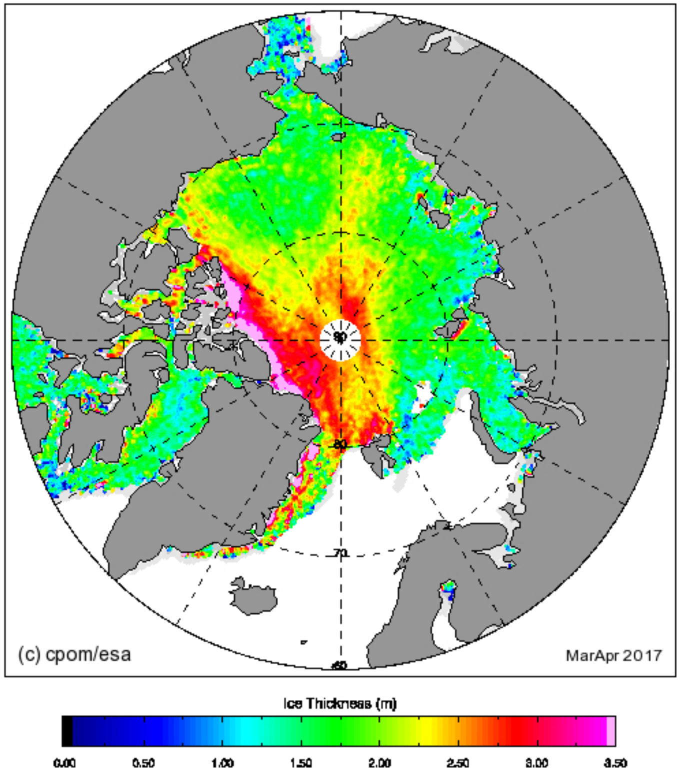
- Average thickness decreased about 1.3 m, ~40%, with losses exceeding 2 m in some parts of the Central and Eastern Arctic

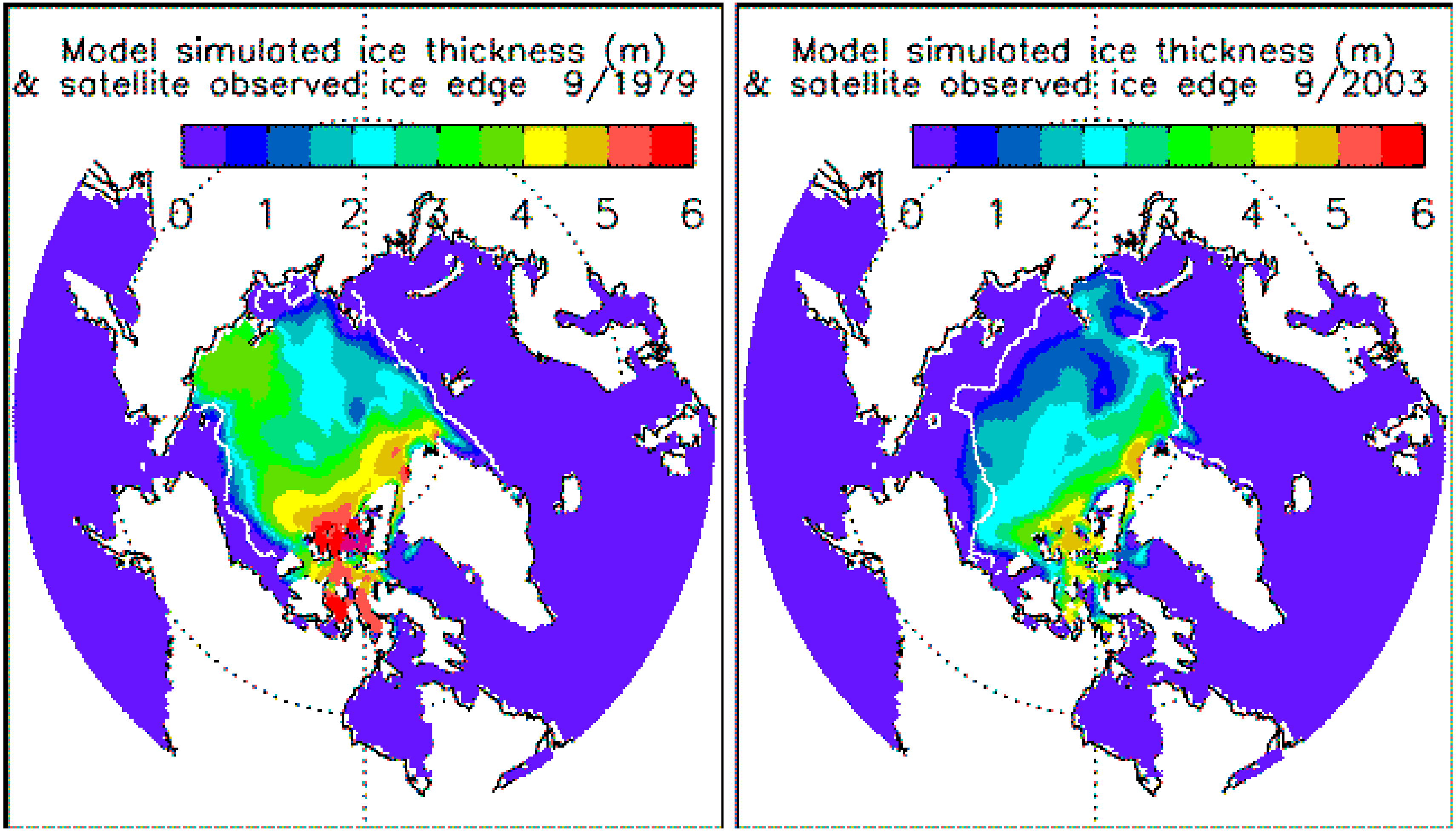


LASER / RADAR Altimetry

- Round-trip travel time of pulses recorded
- Sensor altitude above the surface
- Maps of ice thickness
- ICESat (Ice, Cloud, land Elevation Satellite) 2003 – 2009; CryoSat (2010 – present)
- ICESat2: launched September 2018

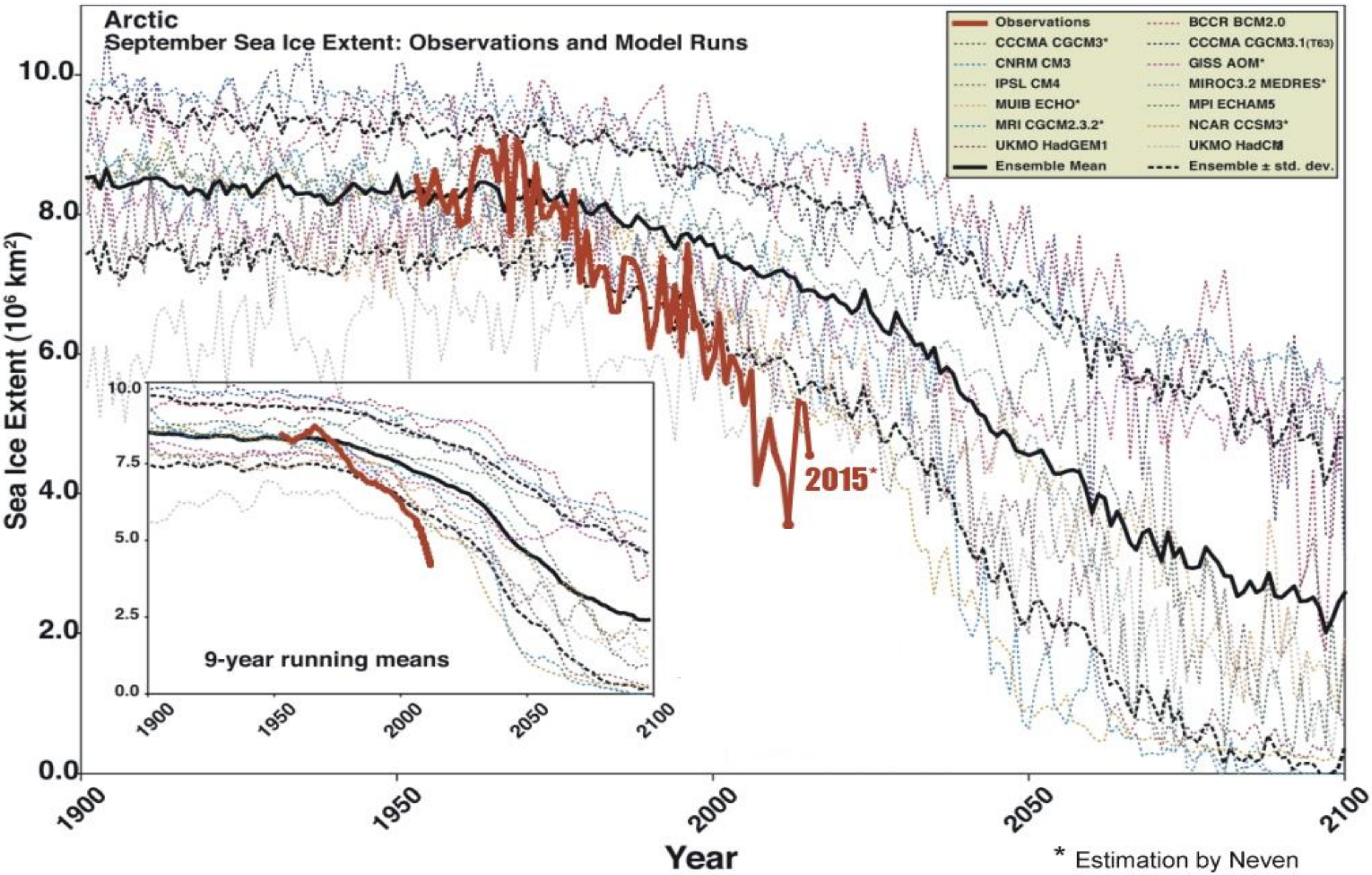






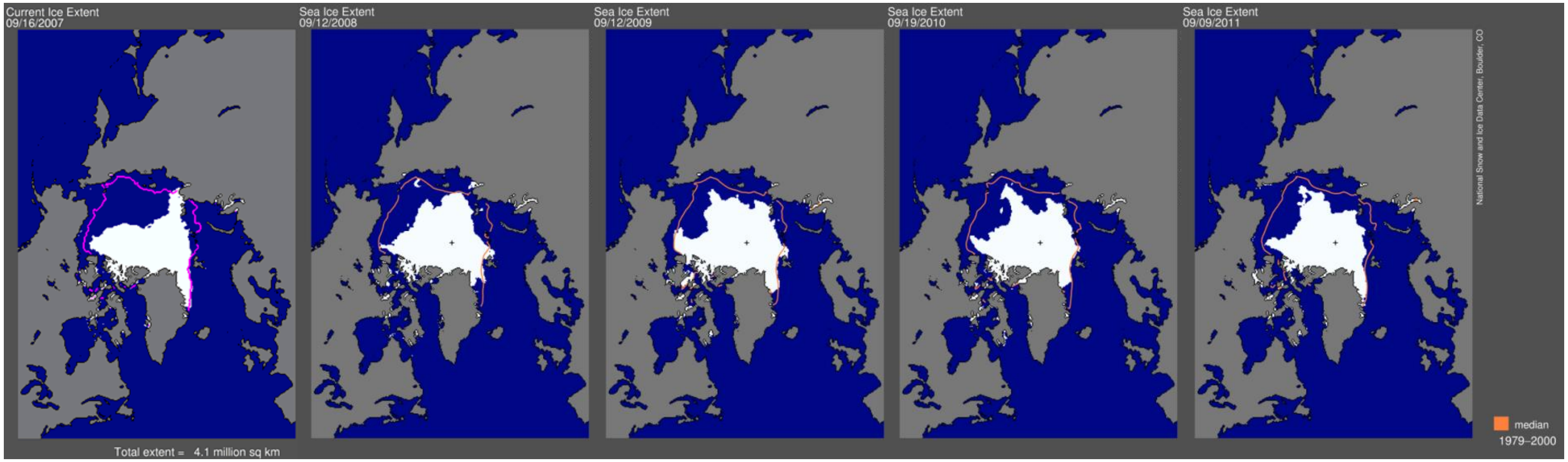
J. Zhang PSC/APL/UW

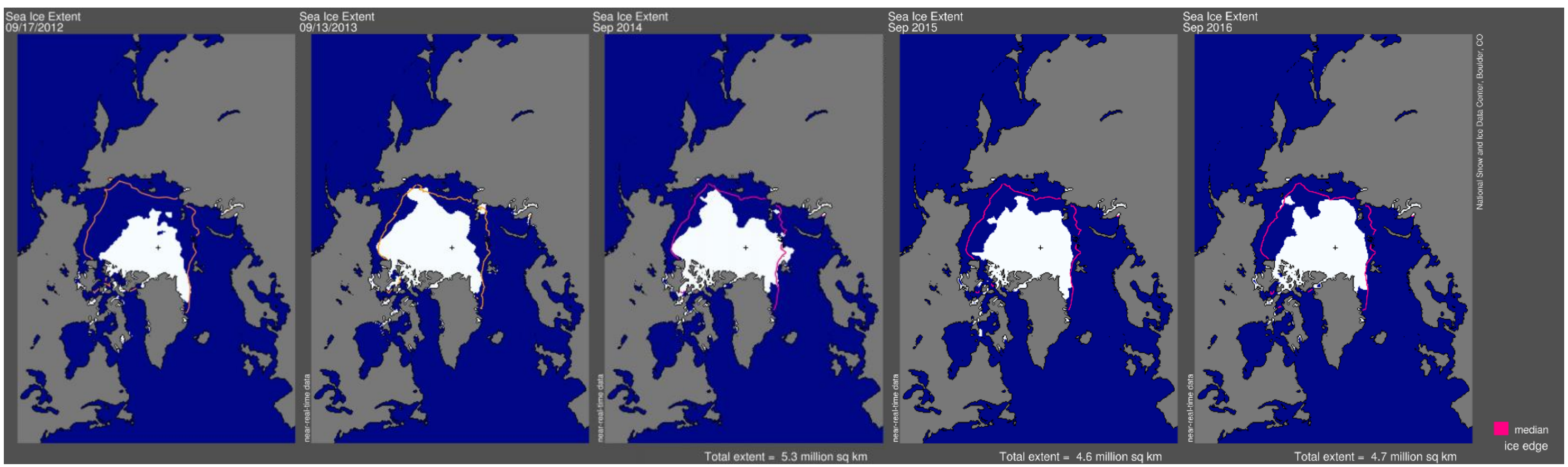
Observations and model predictions of Arctic sea ice extent



* Estimation by Neven

Recent minimum sea ice extents





- https://www.youtube.com/watch?v=ZSWigRpqY64&feature=youtu.be

Some obvious questions to ask

Has the atmosphere been unusually warm?

Has the ocean been unusually warm?

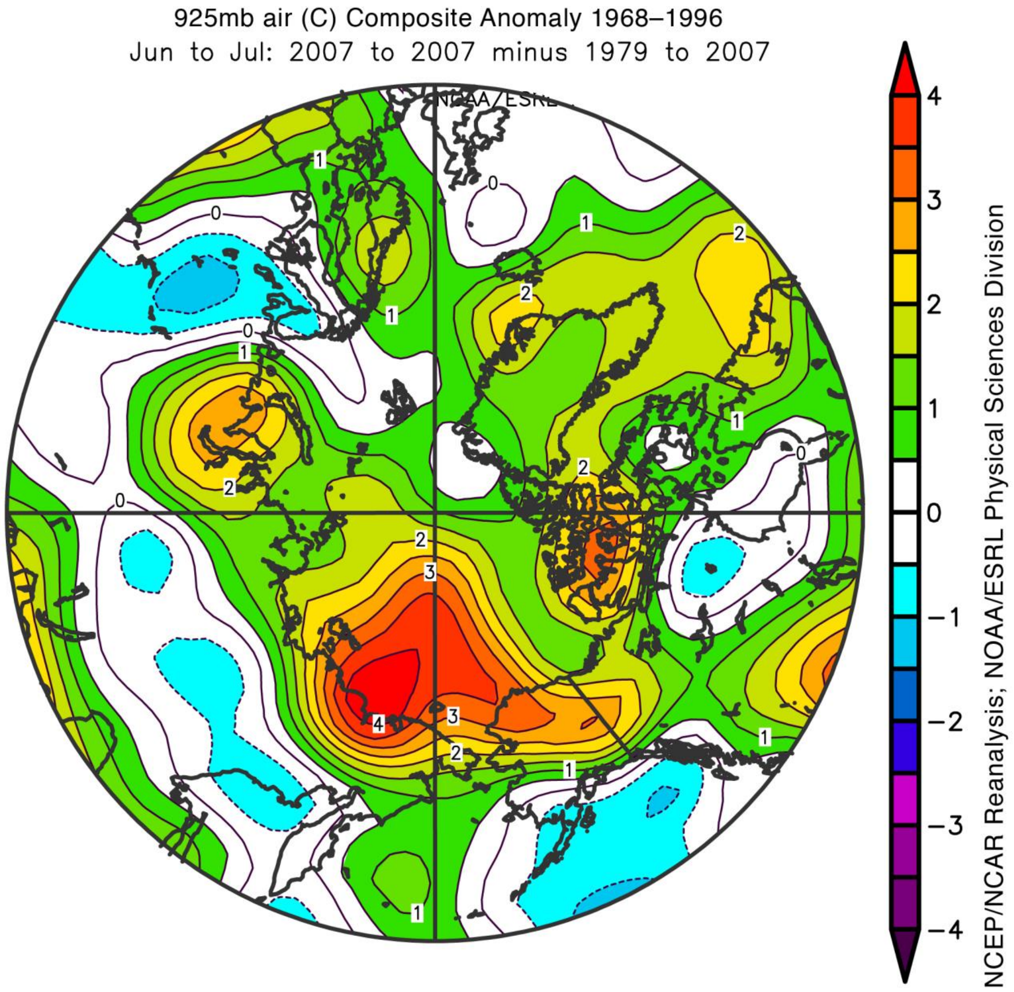
Unusually windy or stormy?

Is the ice somehow “preconditioned”?

Has the ice / ocean been absorbing unusual amounts of sunlight?

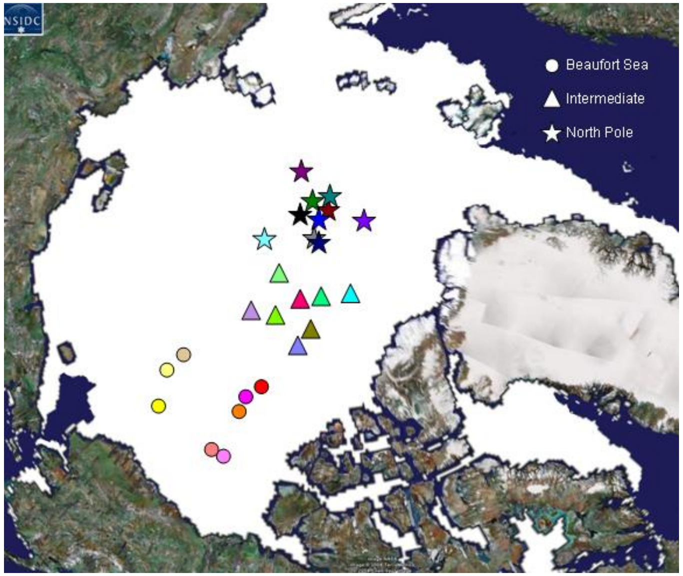
Some obvious questions to ask

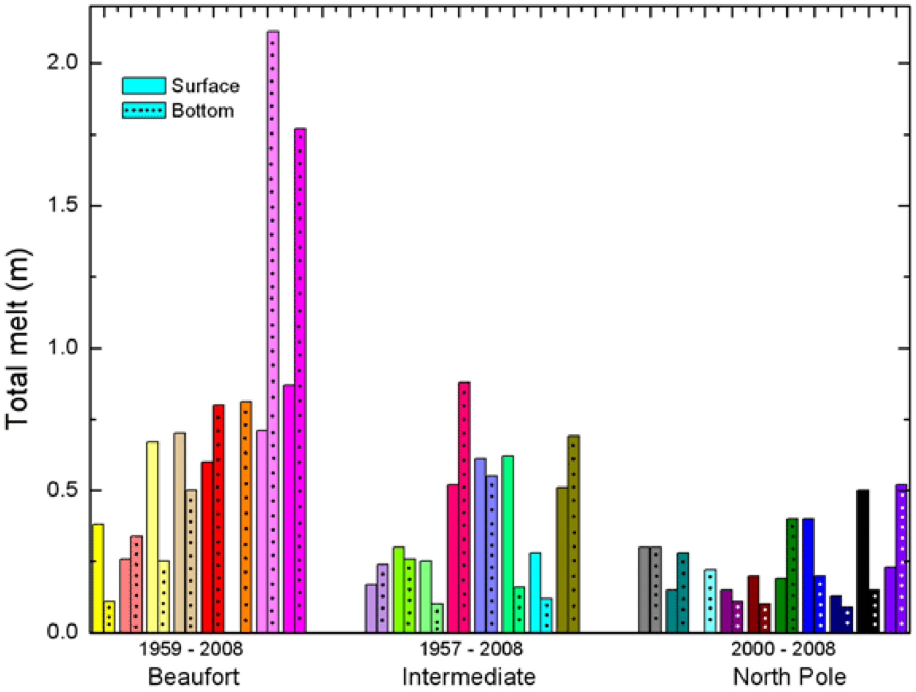
Has the atmosphere been unusually warm?



Some obvious questions to ask

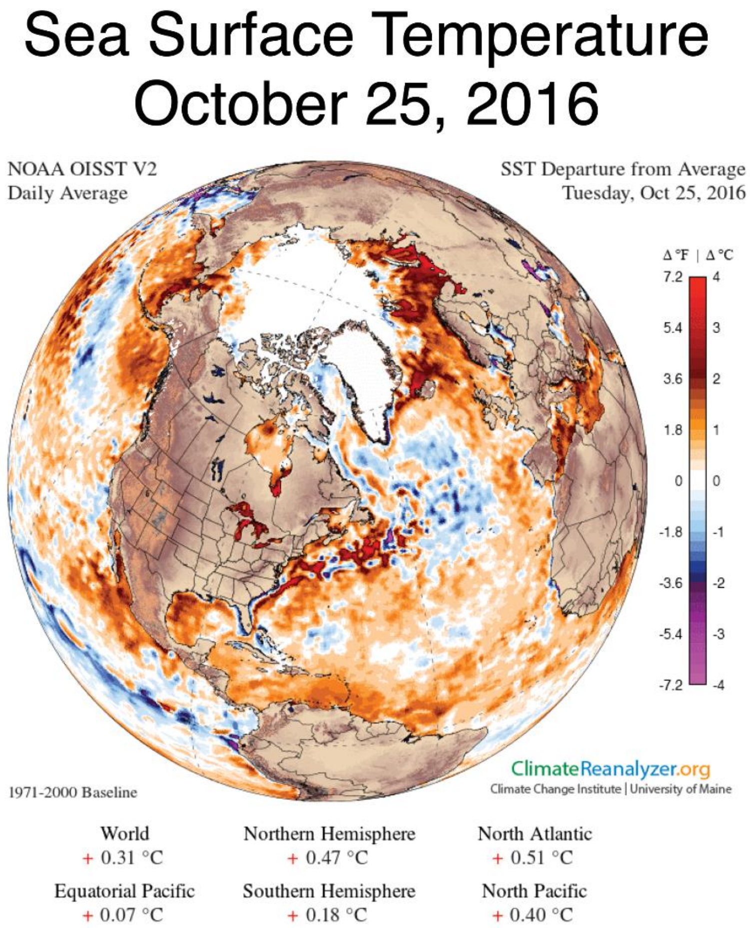
Has the atmosphere been unusually warm?





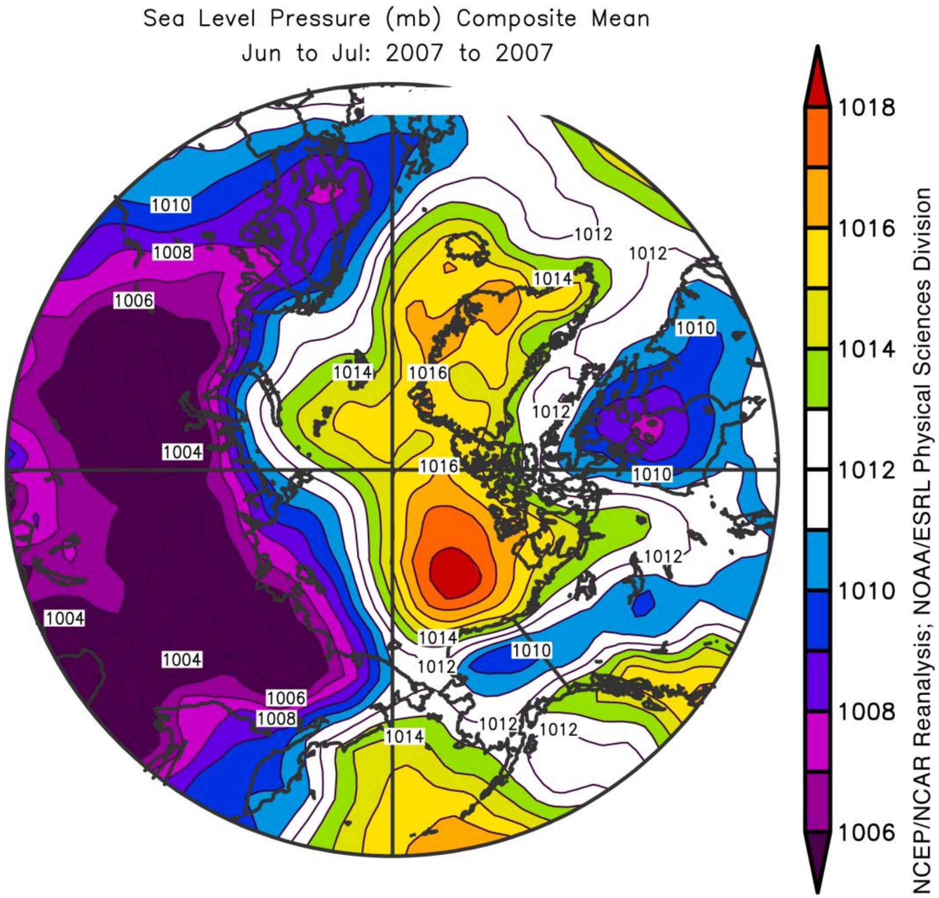
Some obvious questions to ask

Has the ocean been unusually warm?



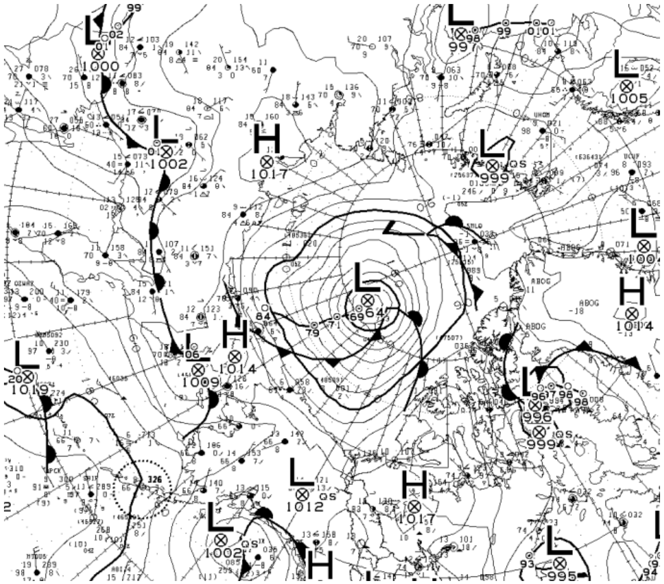
Some obvious questions to ask

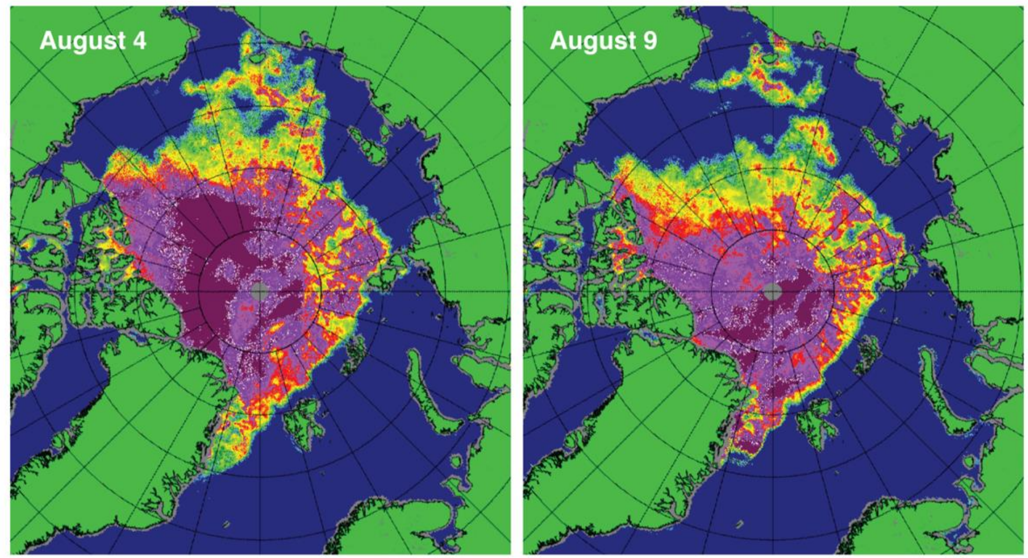
Unusually windy?



Some obvious questions to ask

Unusually stormy? The “great’ Arctic cyclone Aug 2012

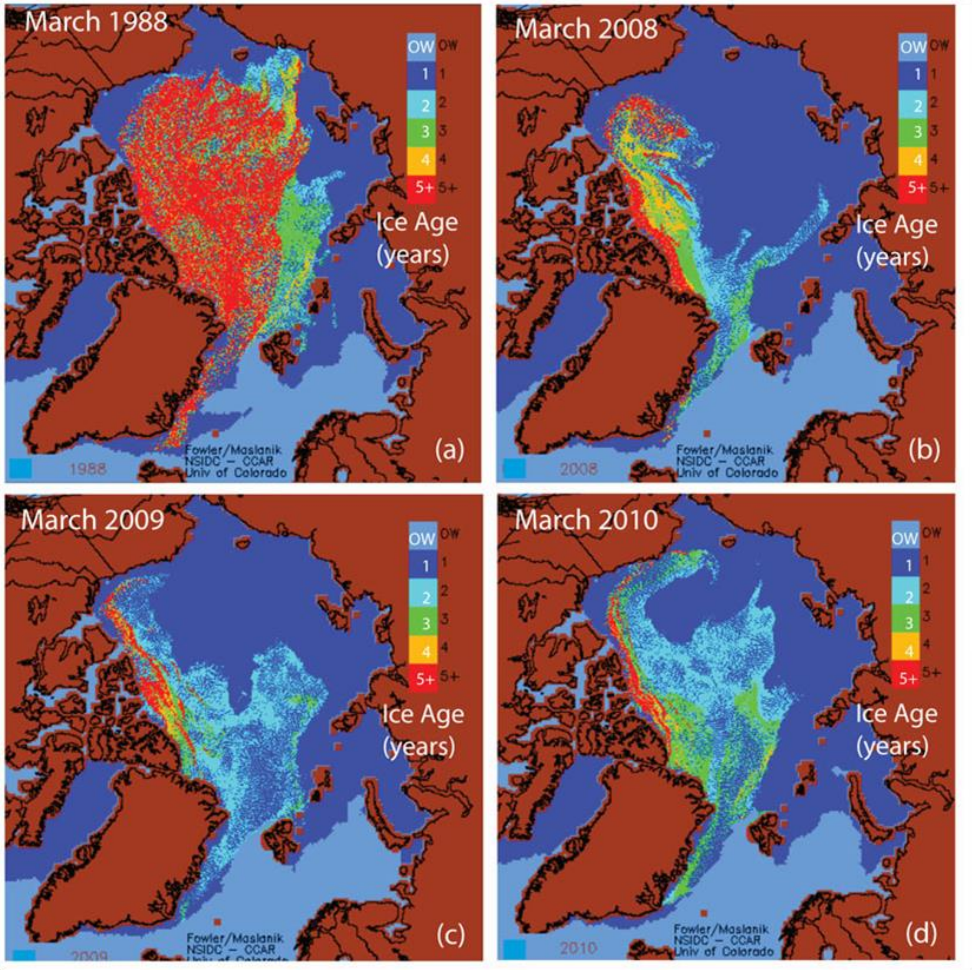


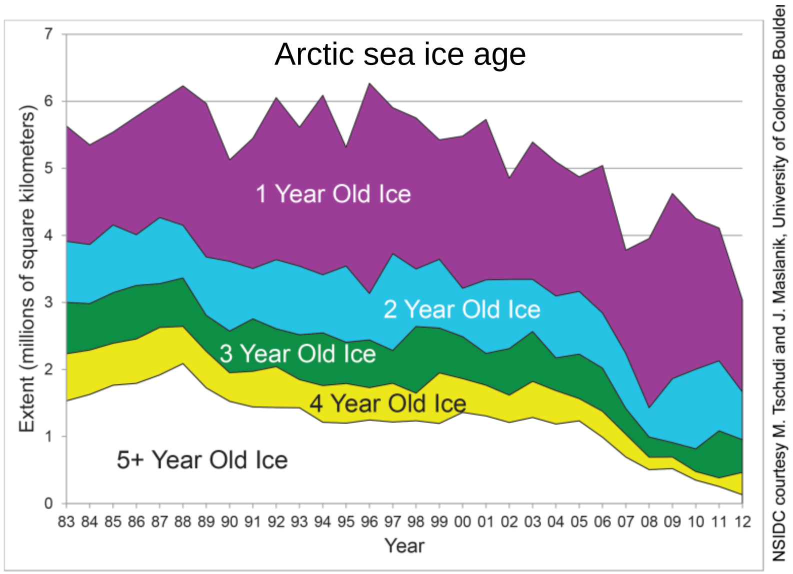


Some obvious questions to ask

Is the ice somehow "preconditioned"?

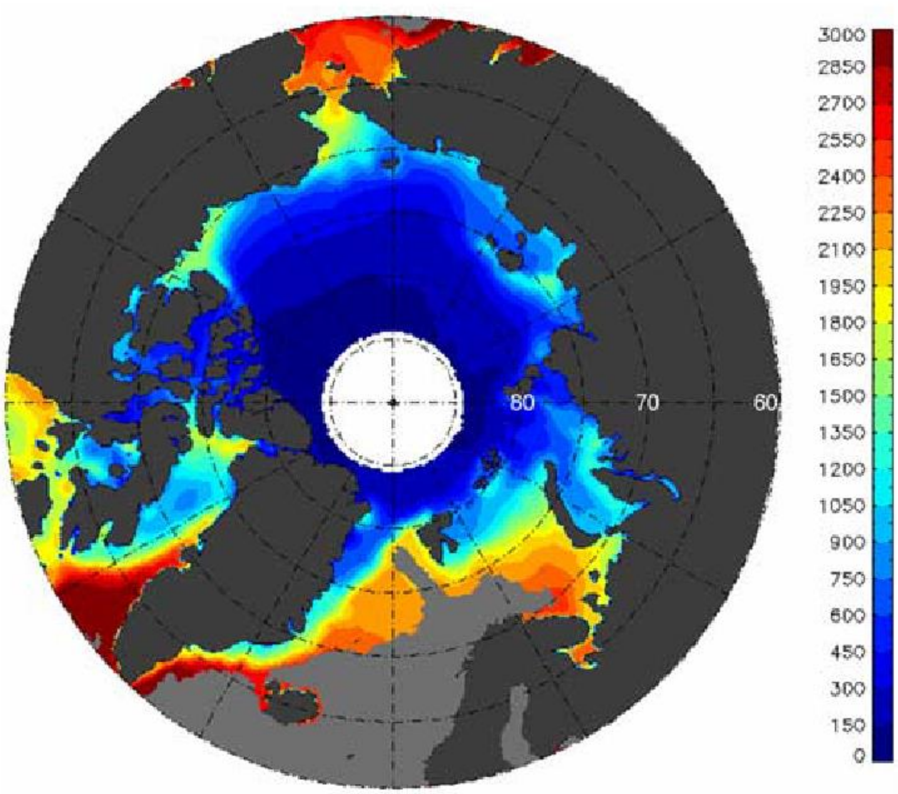
Sea ice age derived from drift tracking



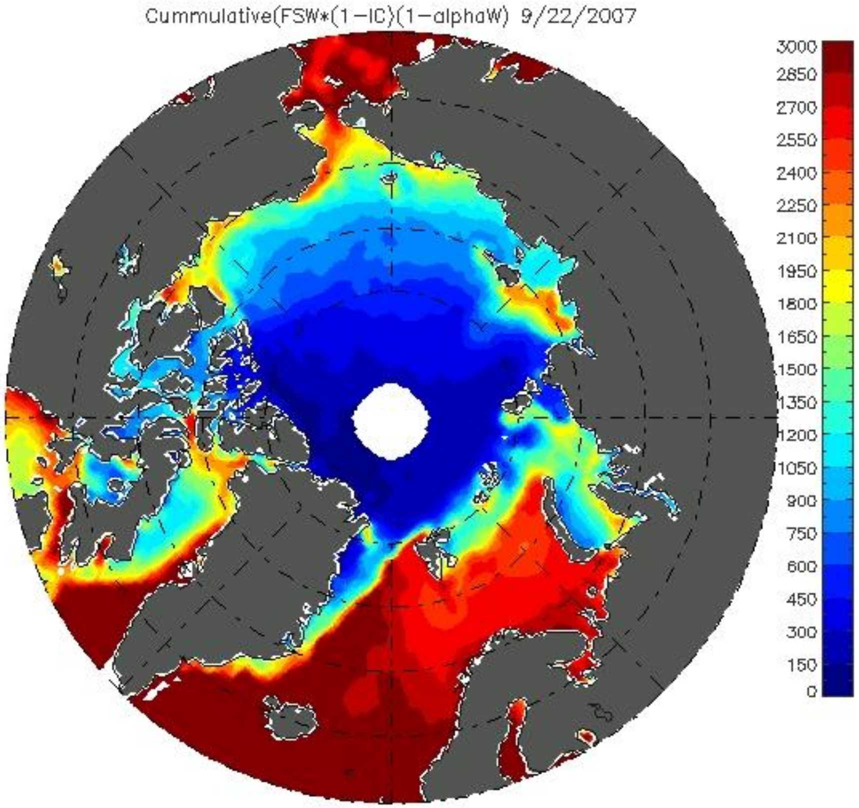


https://www.youtube.com/watch?v=QKoru4Hnm7Q

Cumulative solar heat absorbed by the ocean

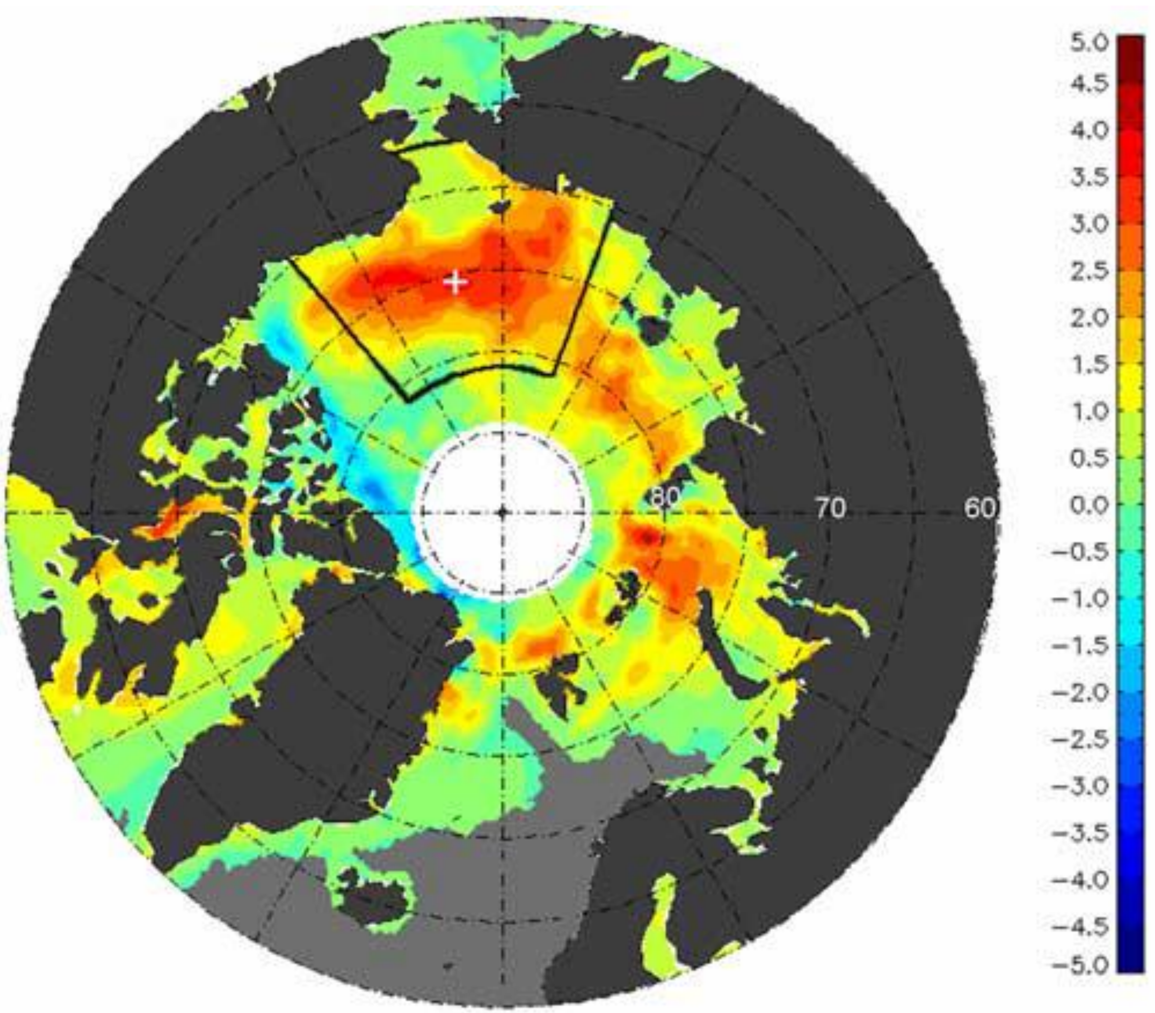


1979 – 2005 mean

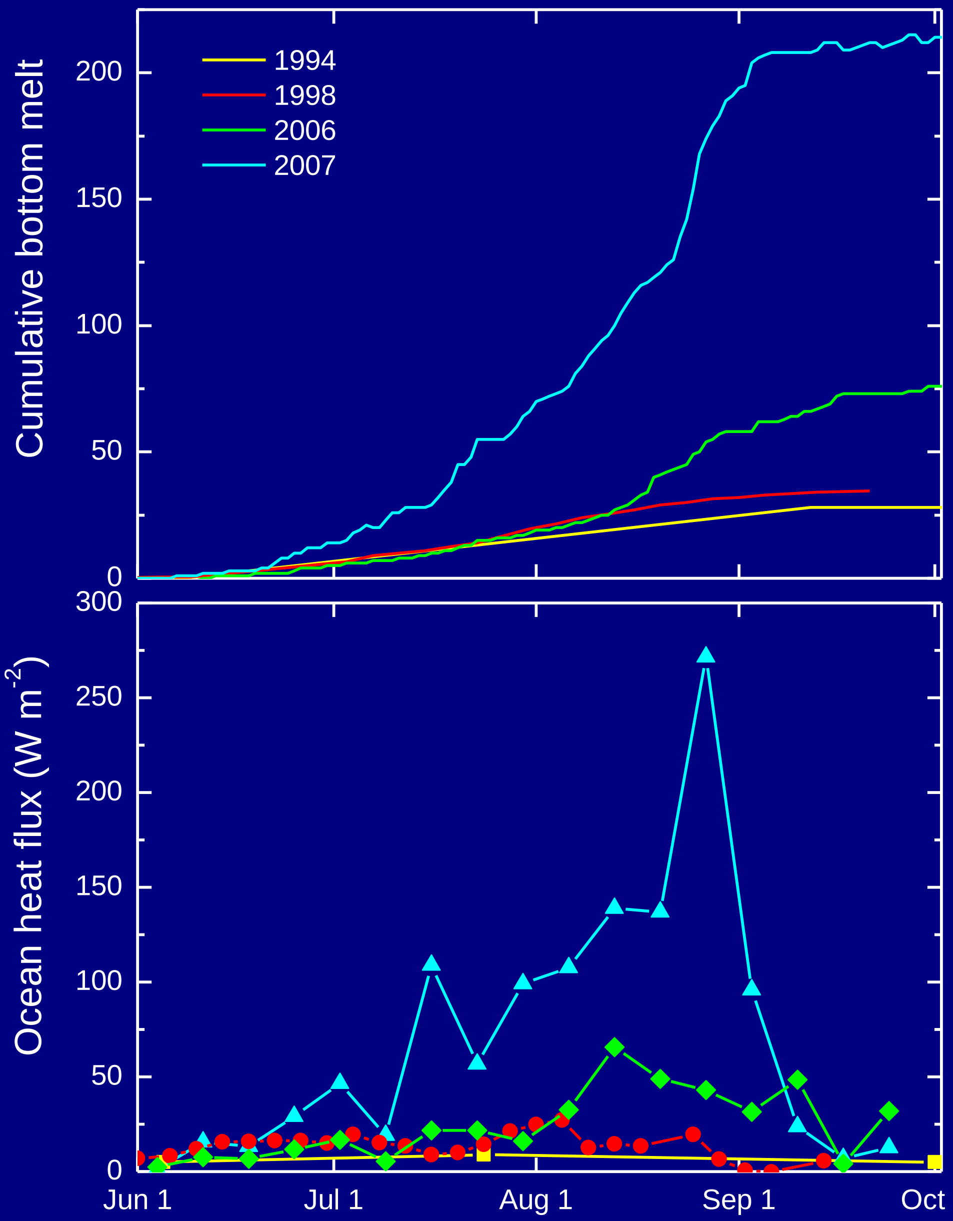


2007

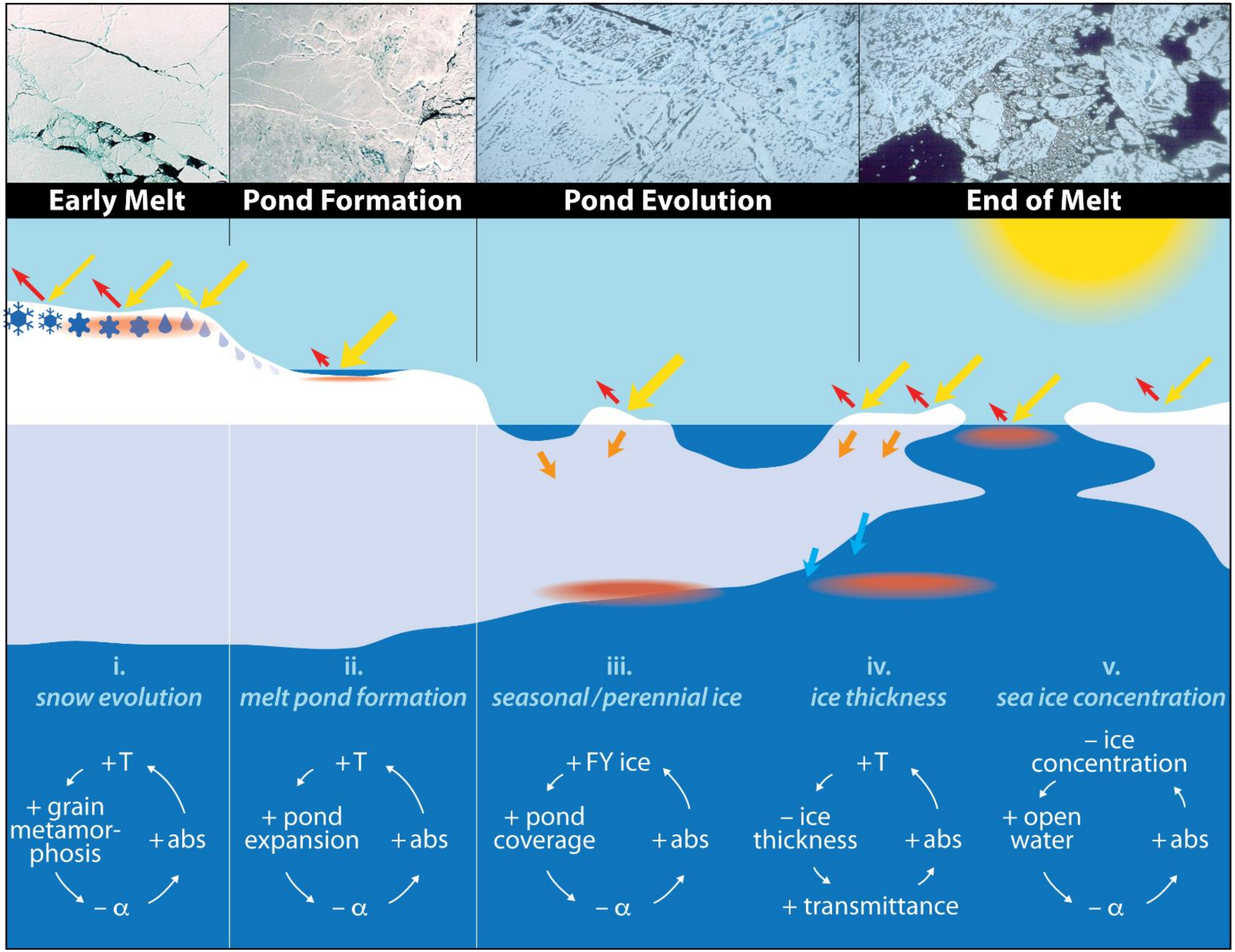
Linear trend of annual solar heat input to the ocean (% $year^{-1}$)

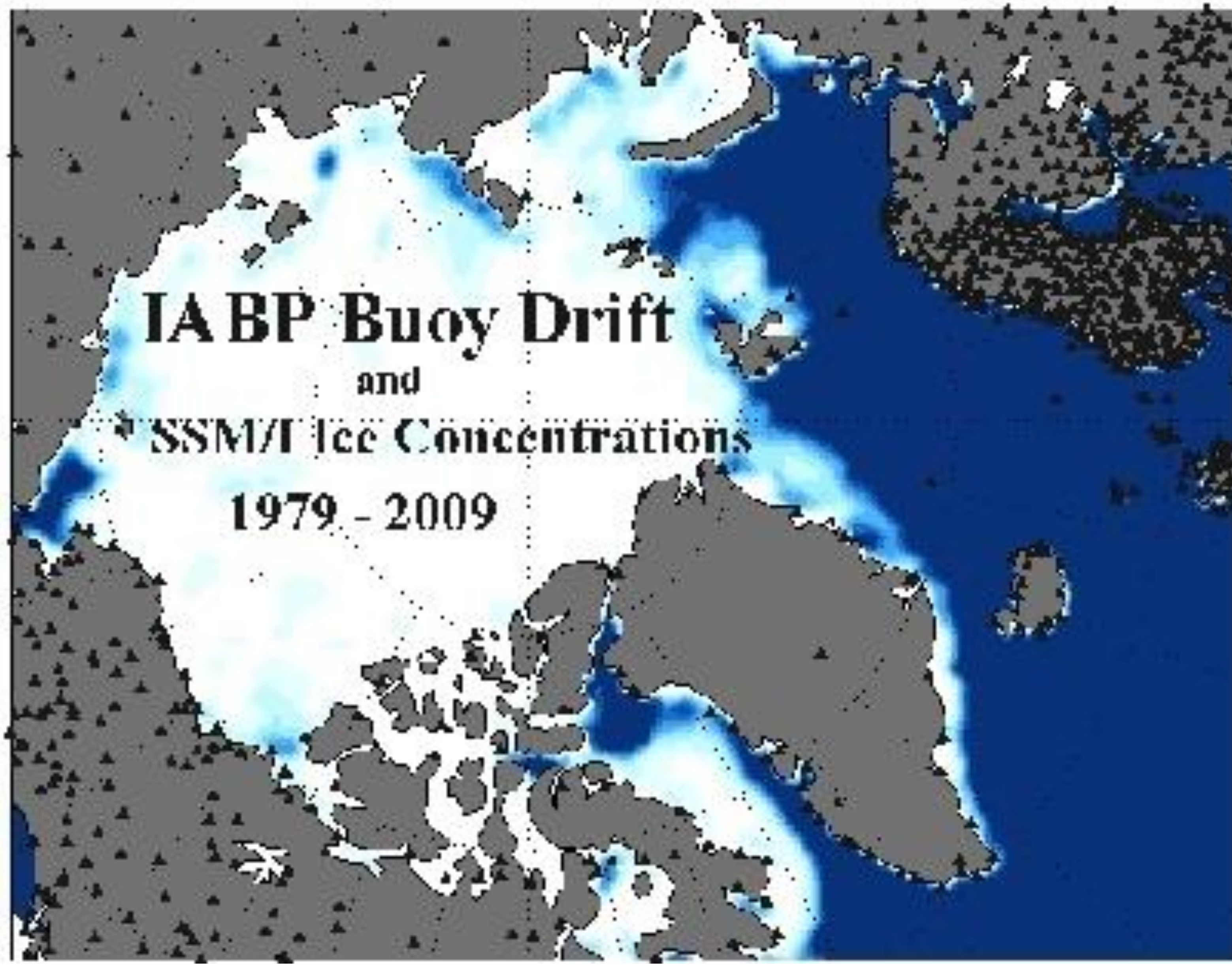


Data from Ice Mass Balance Buoys



Ice-albedo feedback




IABP Buoy Drift
and
SSM/I Ice Concentrations
1979 - 2009