Sea Ice Modeling for Climate Applications

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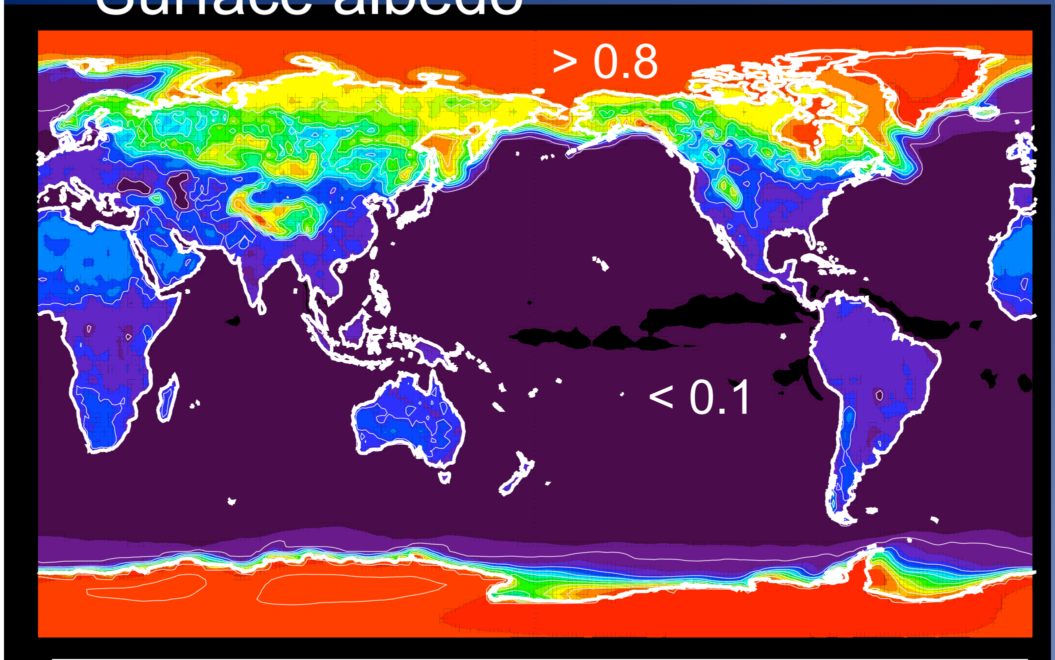
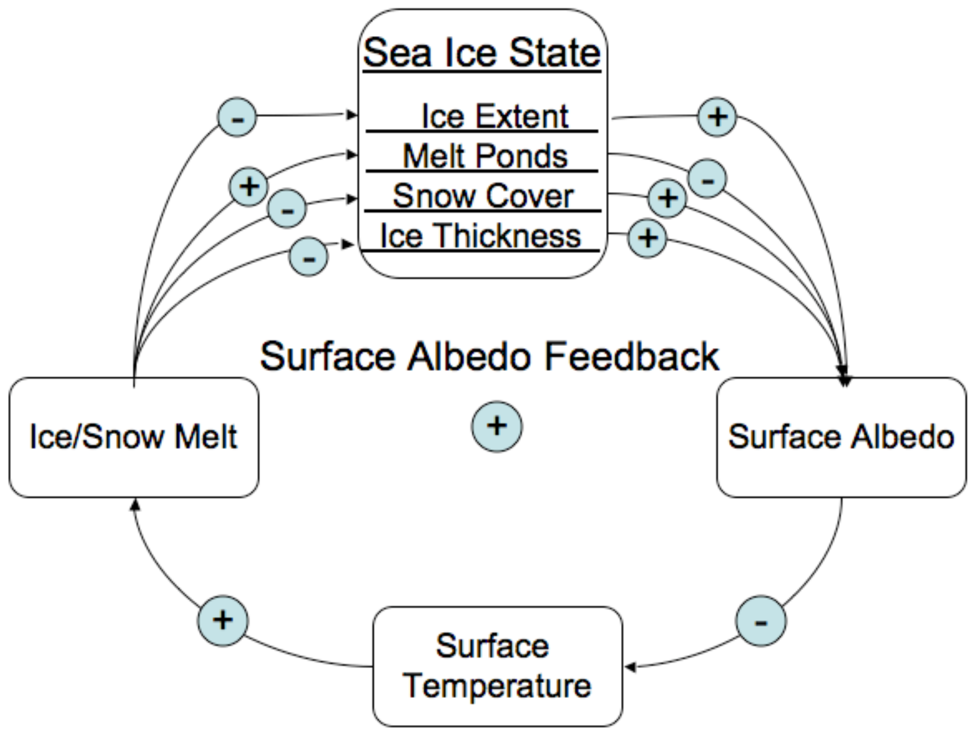
Outline

- Background
  - Role of sea ice in the climate system
  - Changes in observed sea ice
- Sea ice models used for climate simulations
  - Relevant equations
  - Parameterizations
- Using climate models to assess influence of sea ice on climate
  - Feedback analysis, Tipping points
  - Using lower order systems to elucidate sea ice response

Why do we care about sea ice? Surface energy (heat) budget

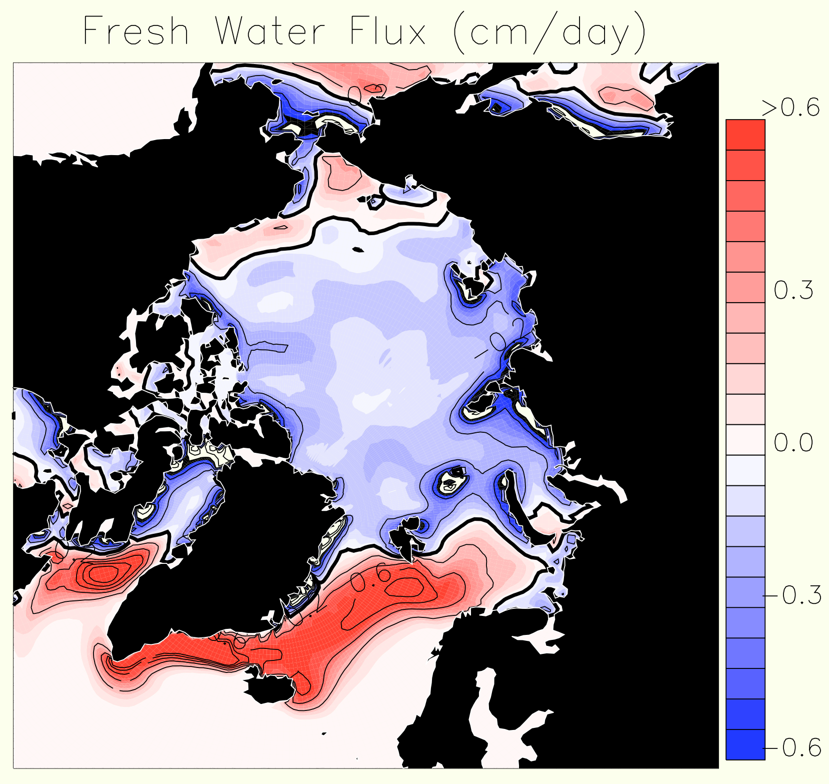
Surface albedo





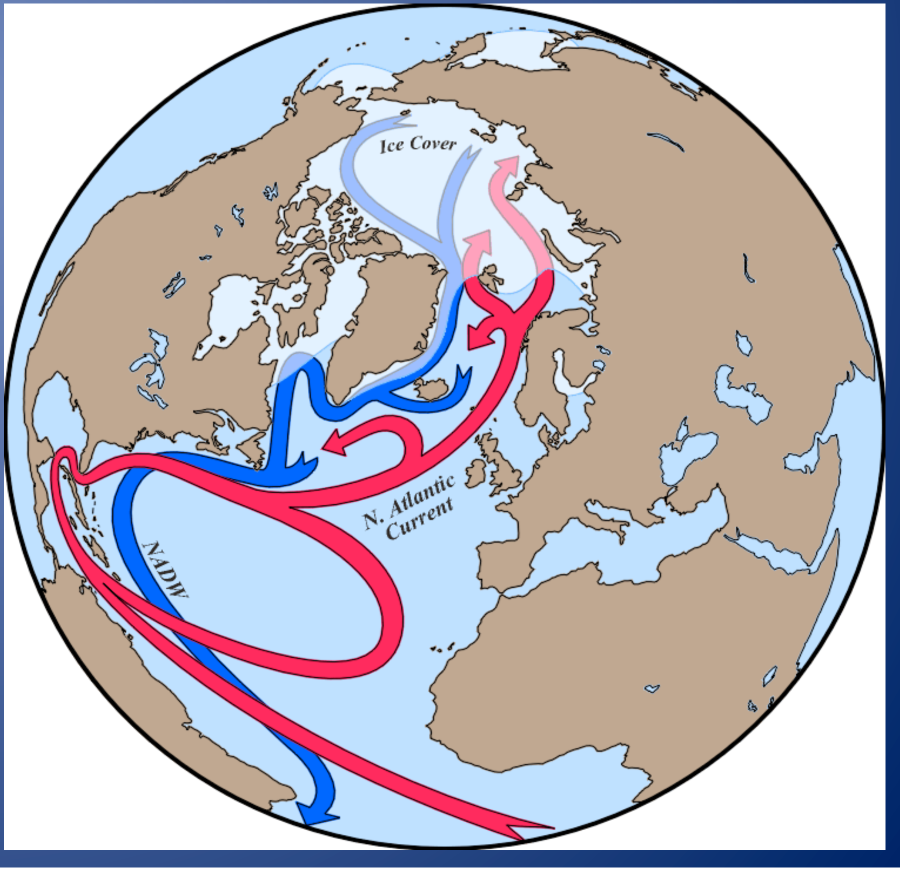
- High albedo of sea ice modifies radiative fluxes
- Sea ice insulates ocean from atmosphere influencing turbulent heat & momentum exchange

Why do we care about sea ice? Hydrological Cycle

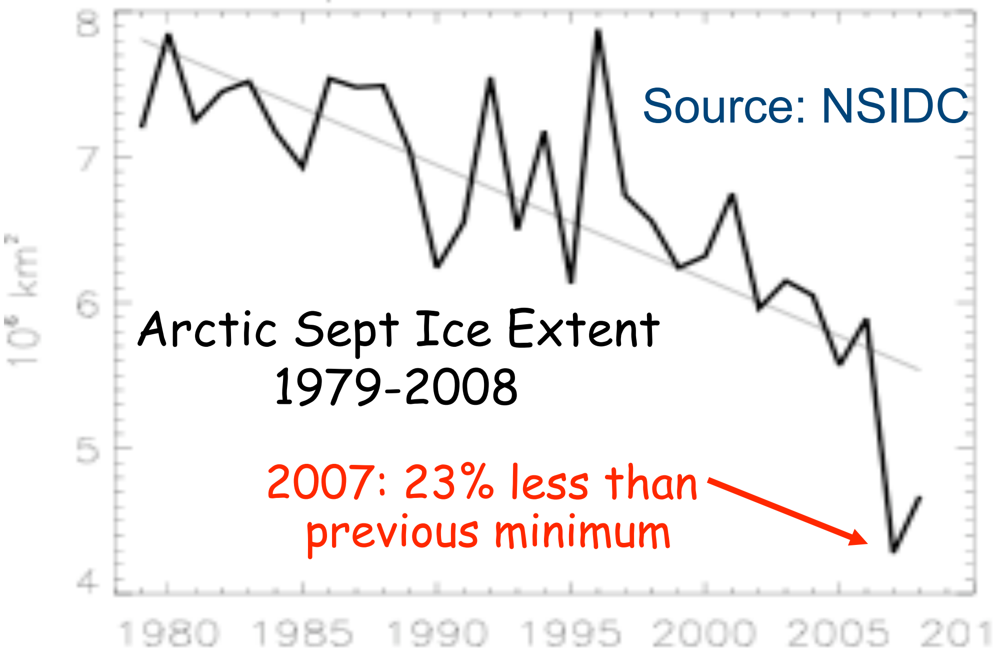


Ice-Ocean Freshwater Exchange

- Salt rejection during ice formation leaves sea ice relatively fresh (salt flux to ocean)
- Ice melt releases freshwater back to the ocean
- Can modify ocean circulation



Arctic September sea ice



Source: NSIDC

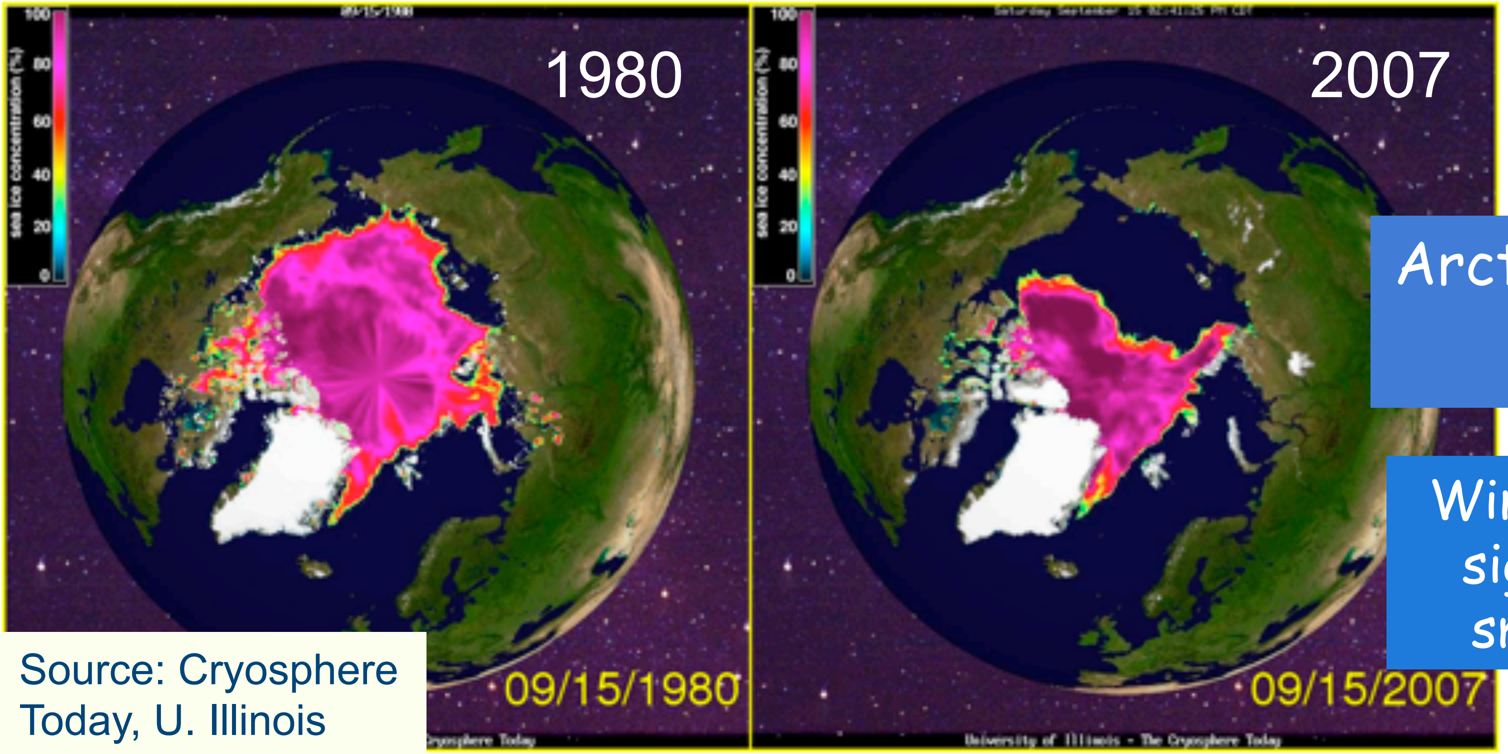
Arctic Sept Ice Extent
1979-2008

2007: 23% less than previous minimum

The New York Times

Arctic Melt Unnerves the Experts

l Oceanic and Atmospheric Administration



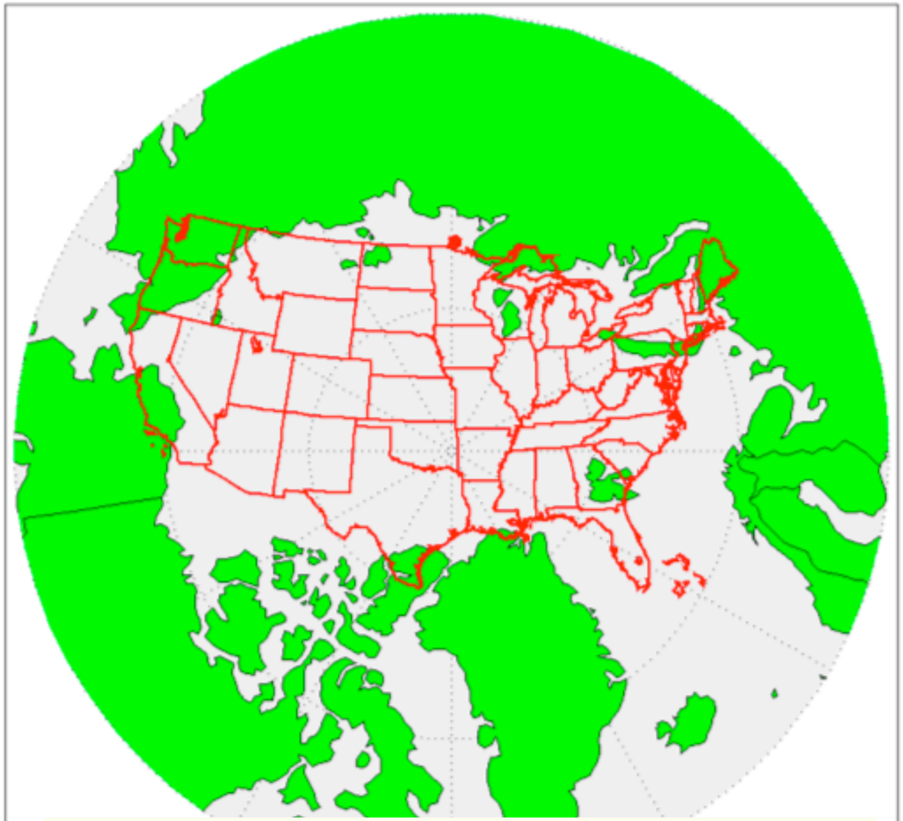
Source: Cryosphere Today, U. Illinois

Winter ice shows significant but smaller trends

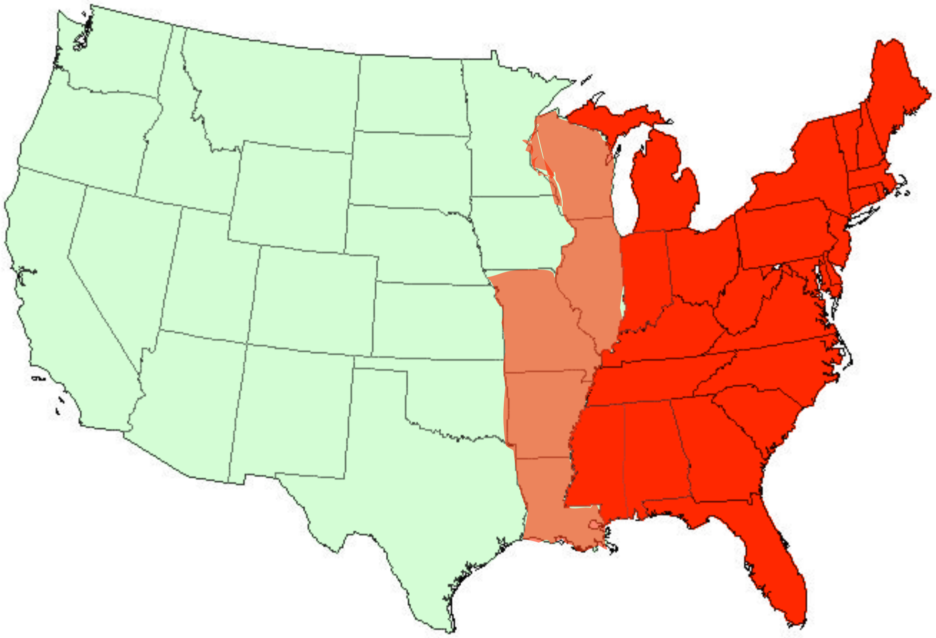
Loss of the summer ice cover in context

From 1980 to 2005: ice loss equal to 24 states; most of the US east of the Mississippi

To 2007: 5 additional states

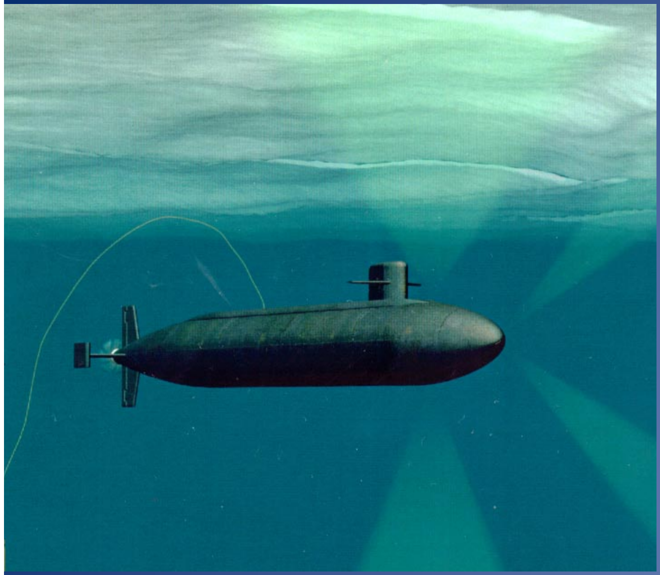


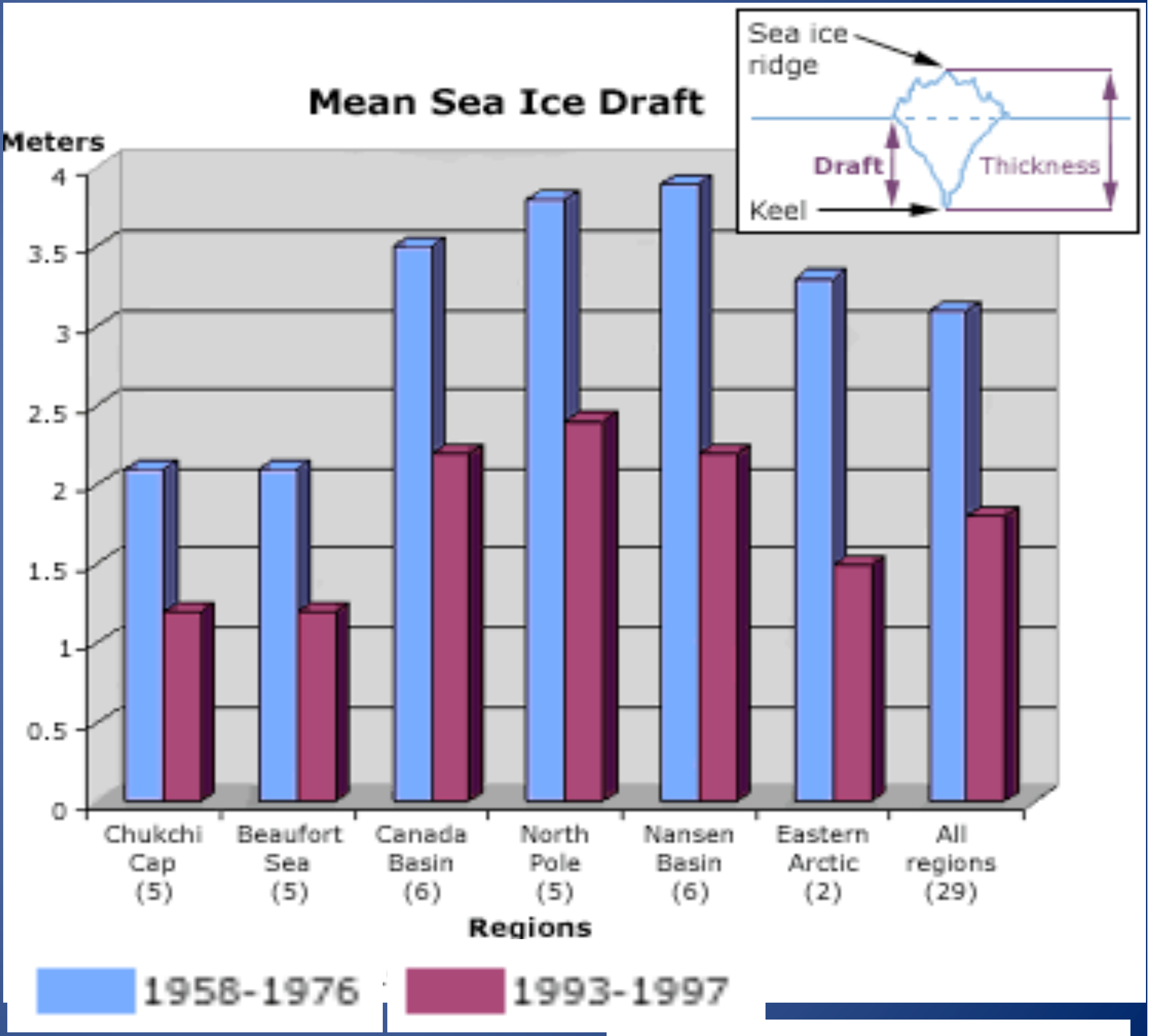
(courtesy of Harry Stern, U. Washington)



(courtesy of Dr. Don Perovich, CRREL)

Change in Arctic Ice Thickness



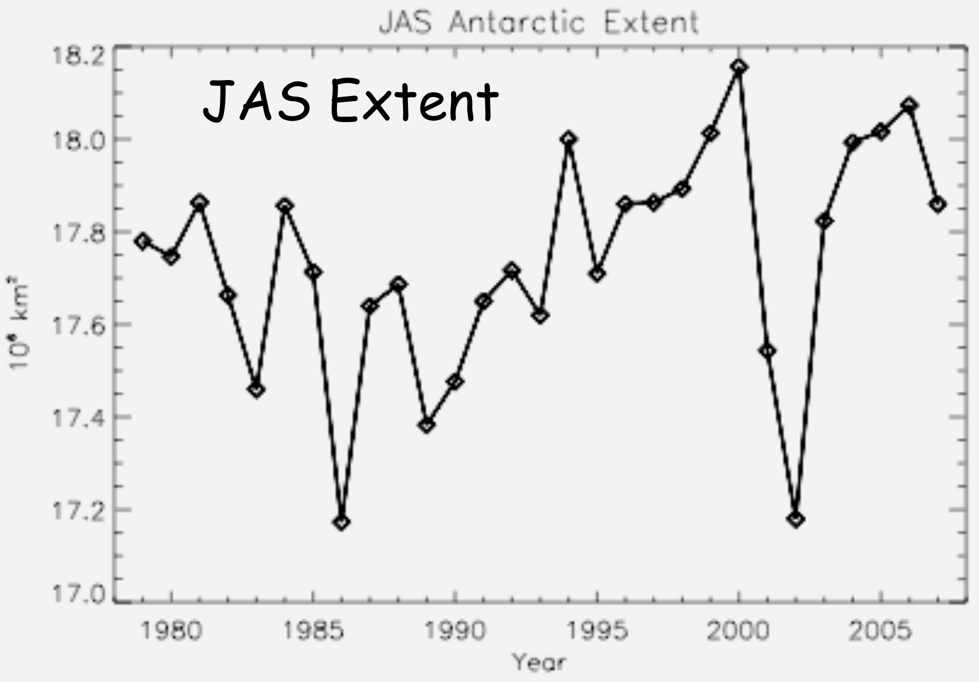


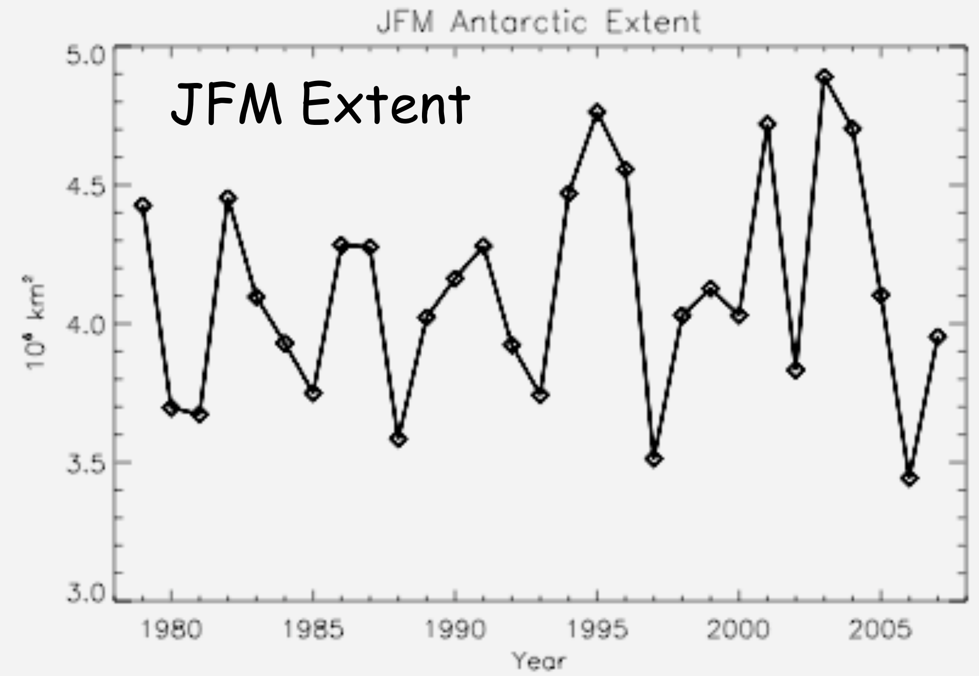
Rothrock et al., 1999

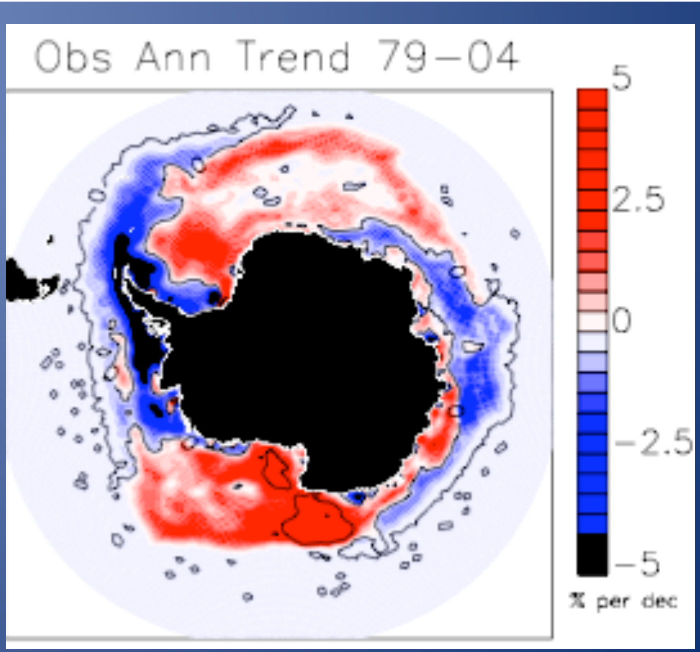
In stark contrast!

Antarctic sea ice

Both winter and annual average have small increasing trend in both area and extent

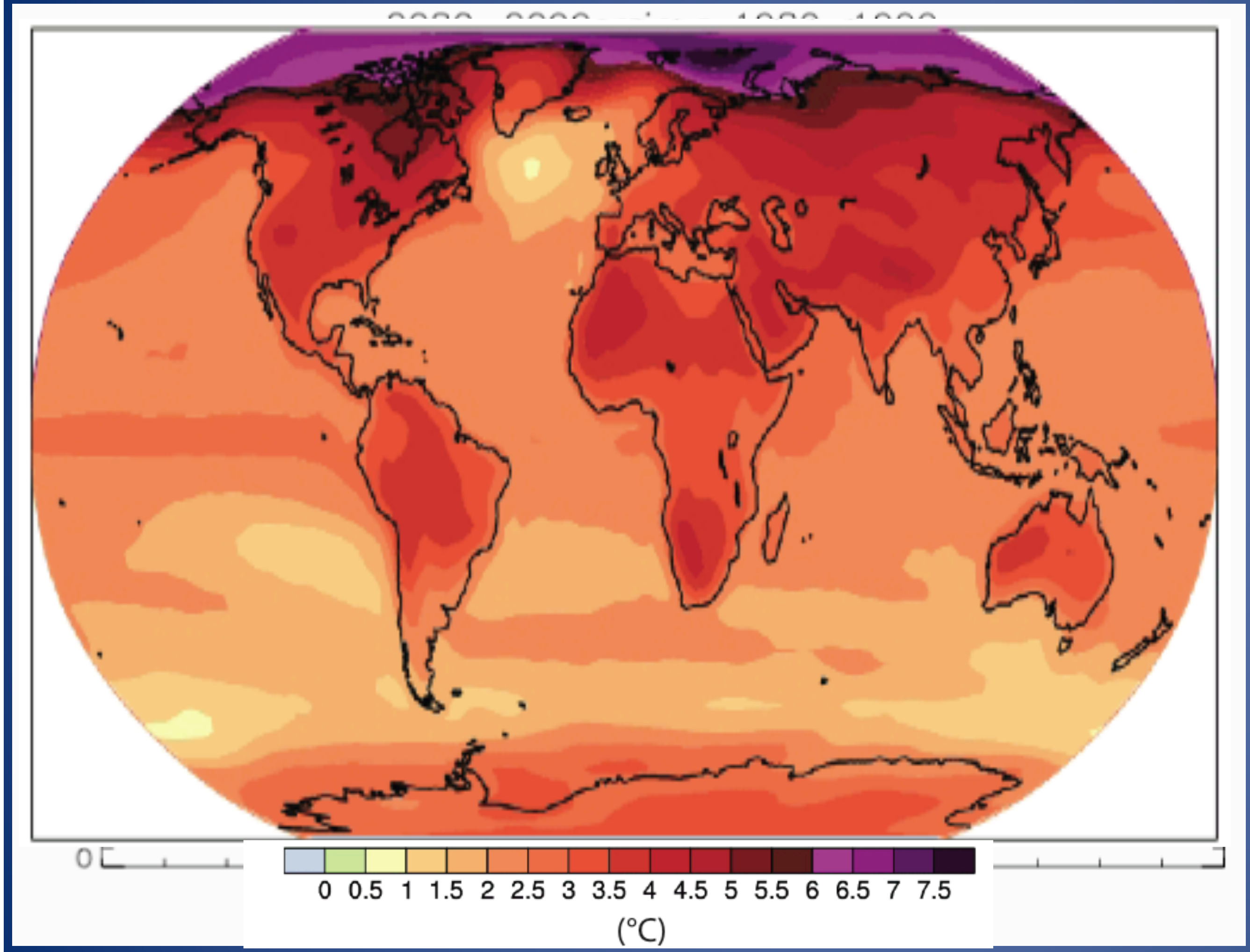






Ann Avg Ice Concentration Trend from 1979-2004

Projected Surface Temperature Change



Models show reduced warming ~40-60S

Little SH polar amplification

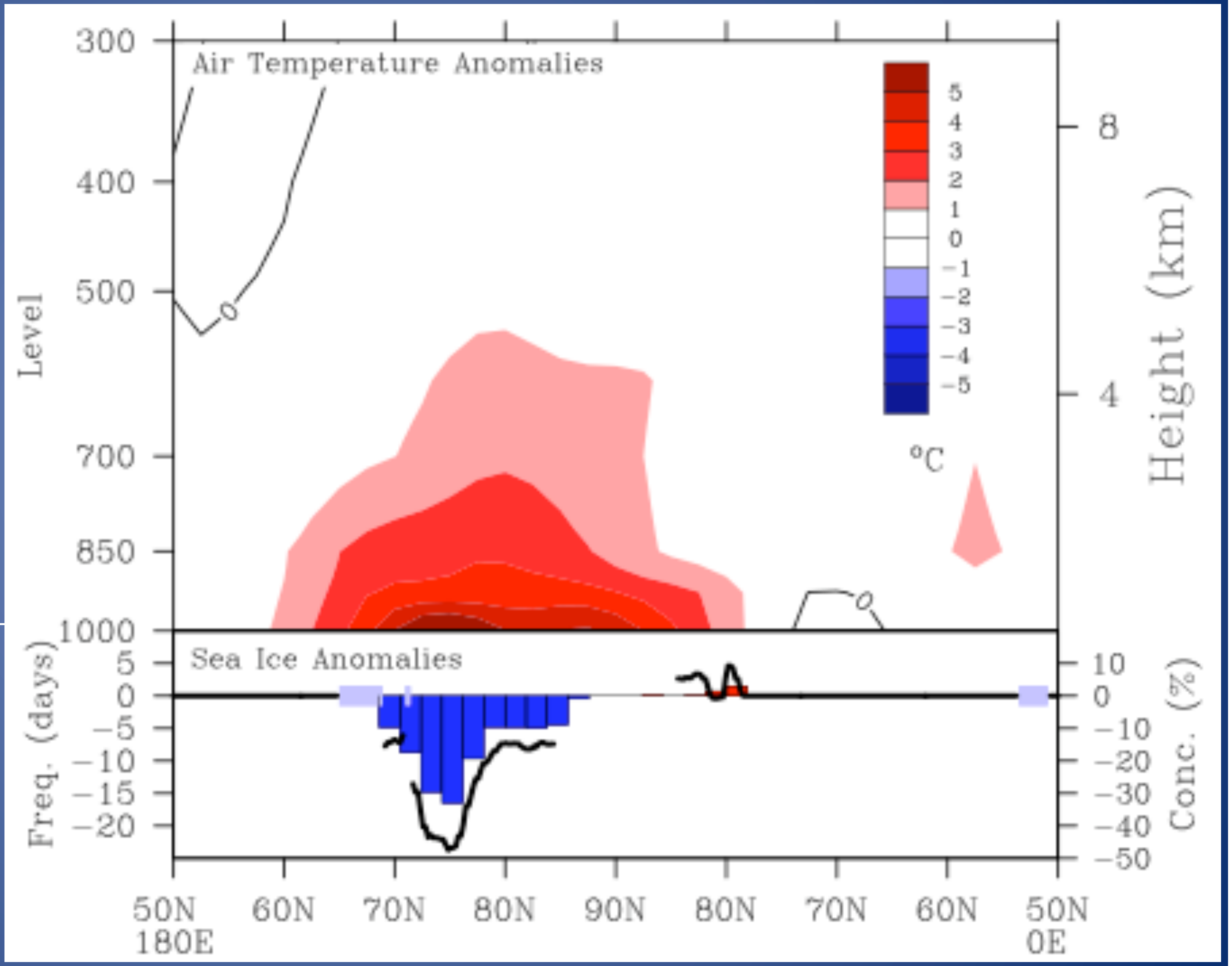
Ocn heat uptake the culprit

Reduced Antarctic surface change is broadly consistent with model results

Zonally Avg Surface Temperature (2080-2099 minus 1980-1999)
Normalized by Global Mean Change

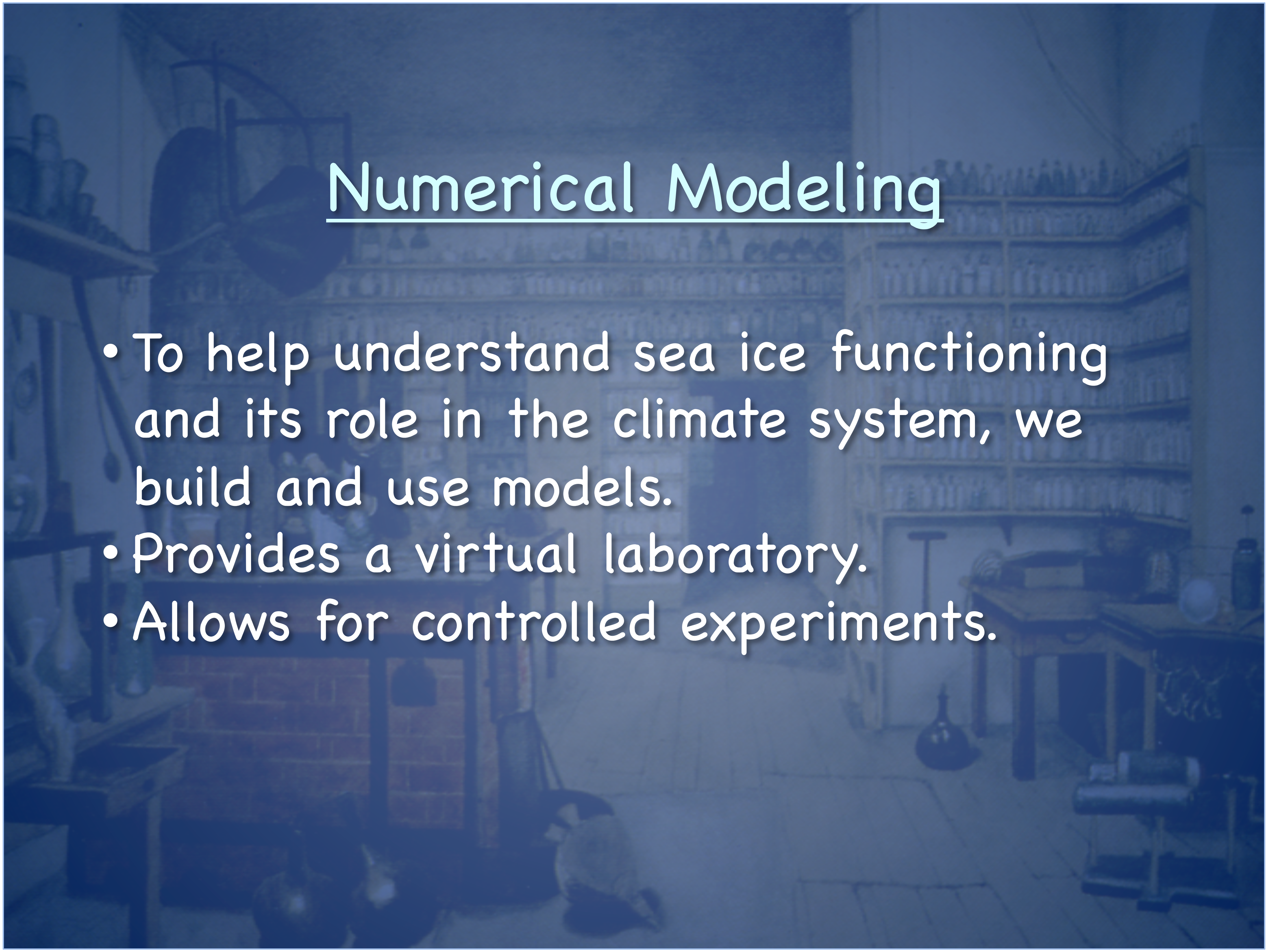
Observations show indications that Arctic Amplification is emerging

Sept-Nov 2003-2007 Air Temperature Anomalies Relative to 1979-2007



Sept Sea Ice Anomalies

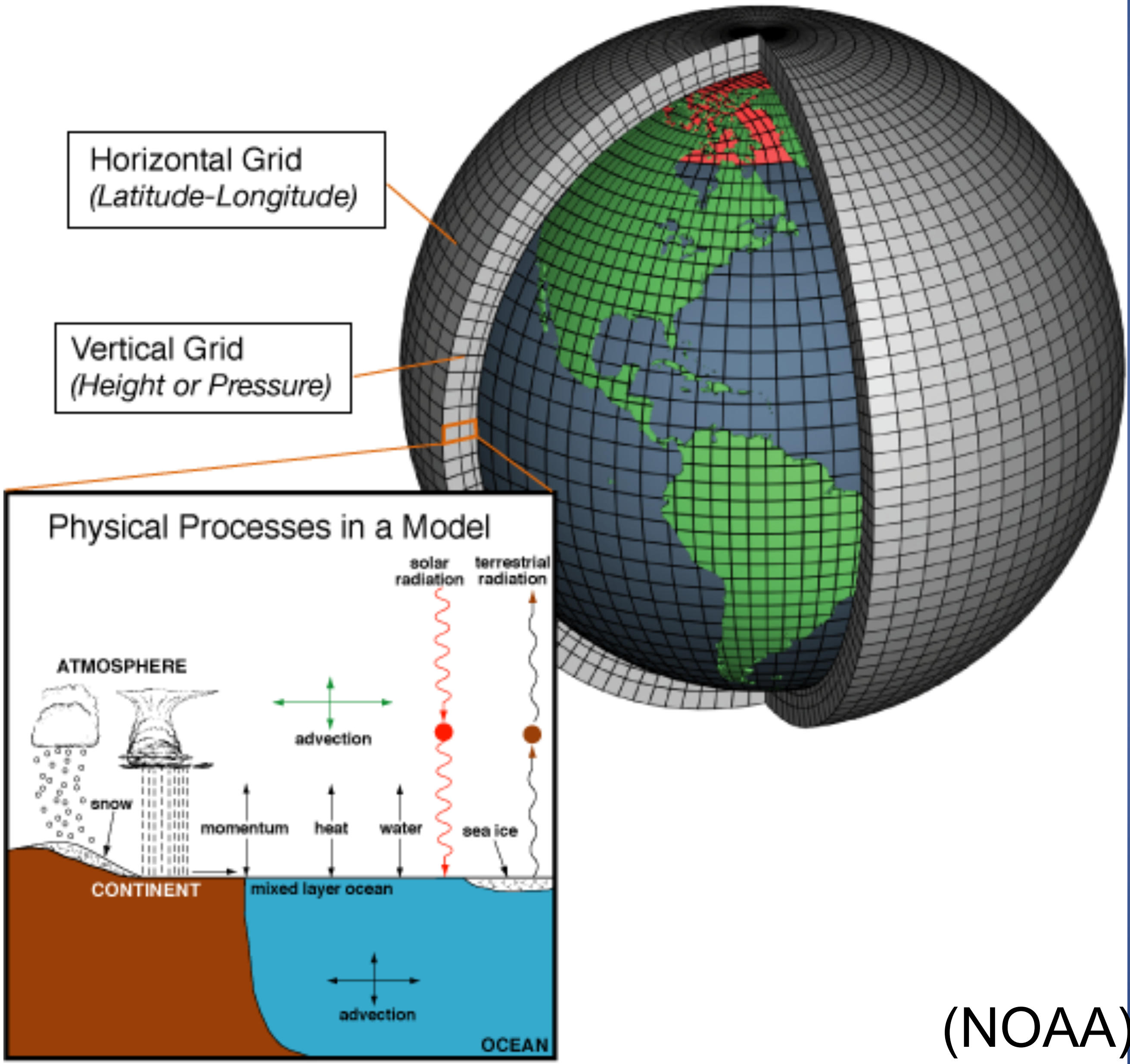
(Serreze et al., 2008)



Numerical Modeling

- To help understand sea ice functioning and its role in the climate system, we build and use models.
- Provides a virtual laboratory.
- Allows for controlled experiments.

Coupled climate model

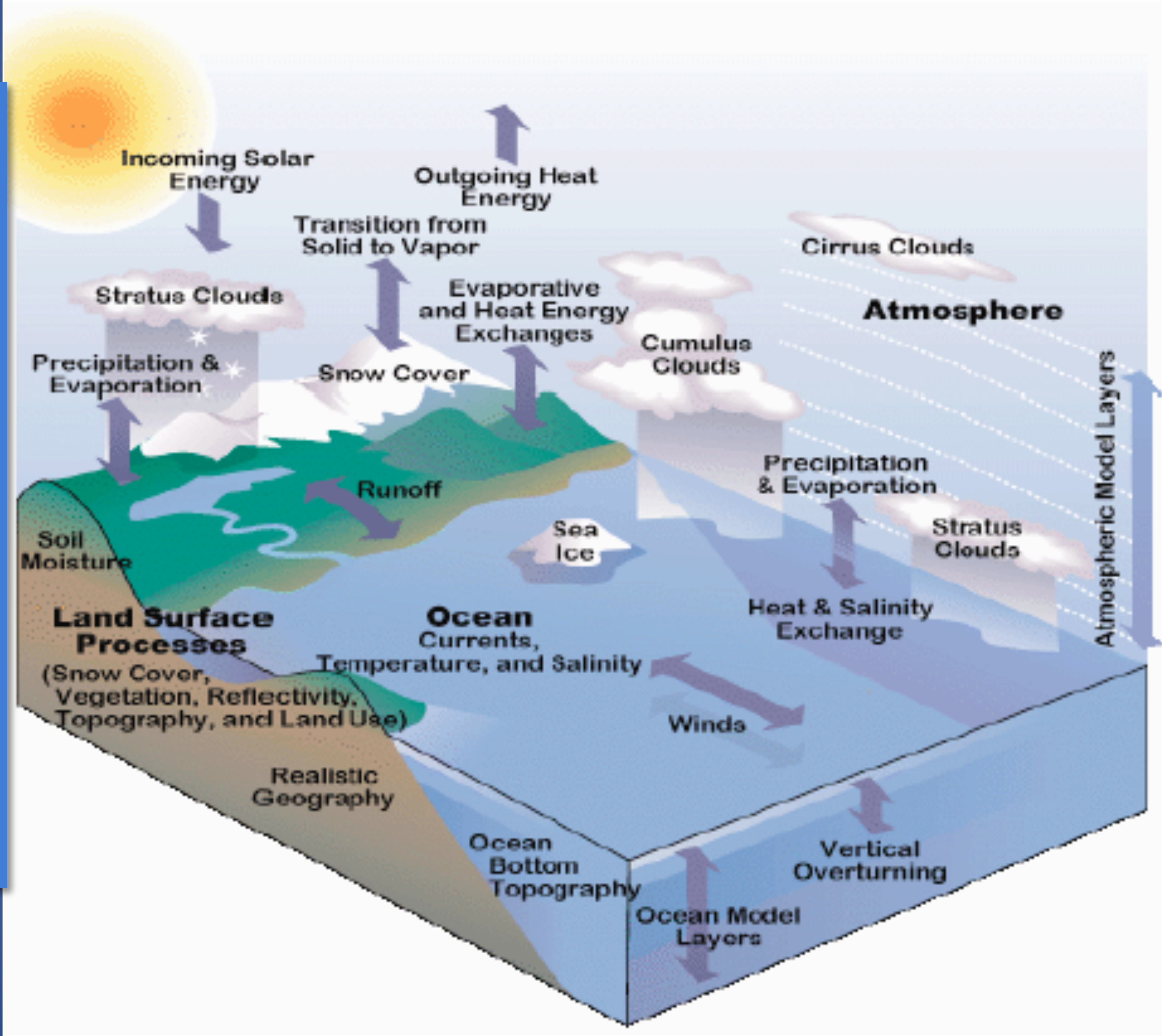


(NOAA)

- Systems of differential equations that describe fluid motion, radiative transfer, etc.
- Planet divided into 3-dimensional grid and equations solved on that grid
- Sub-gridscale, unresolved processes are parameterized

Coupled Climate Models

- Includes atmosphere, ocean, land, sea ice components
- Conservative exchange of heat, water, momentum across components
- Can apply changes in external forcing – solar input, GHG concentrations, volcanic eruptions



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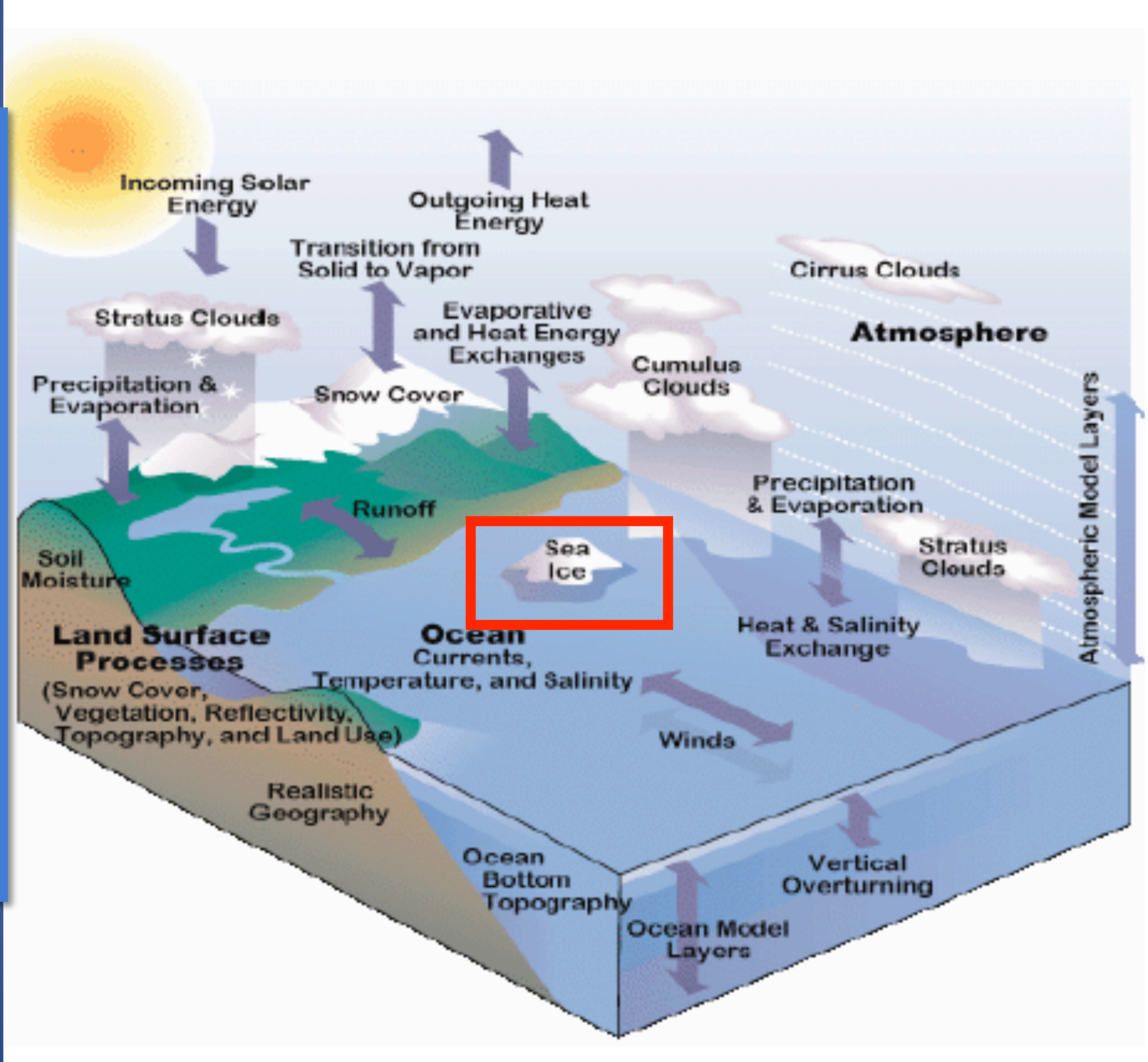


Sea Ice Model

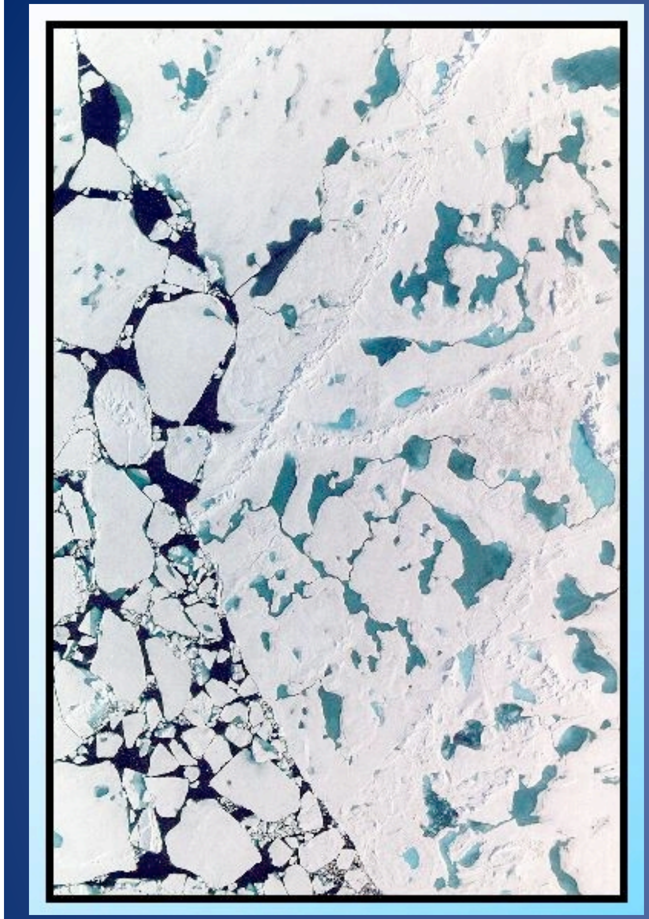
- Three primary components
  - Dynamics
    - Ice motion
  - Ice Thickness Distribution
    - Subgridscale parameterization
    - Accounts for high spatial heterogeneity
    - Redistribution resulting from ridging/rafting
  - Thermodynamics
    - Solves for vertical ice temperature profile,
    - Vertical/lateral melt and growth rates

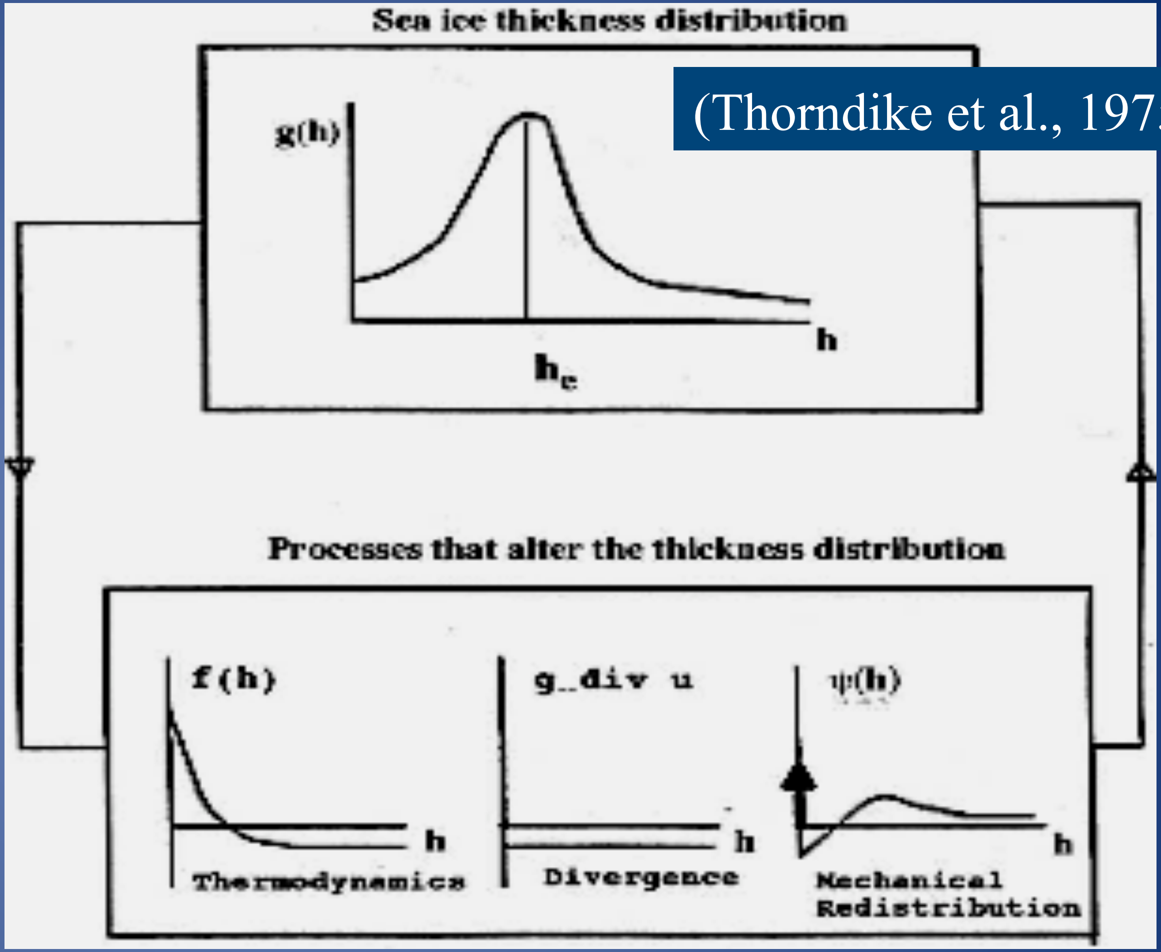
Sea Ice Model – Dynamics

- Ice treated as a continuum with an effective large-scale rheology describing the relationship between stress and flow
- Force balance between wind stress, water stress, internal ice stress, coriolis and stress associated with sea surface slope
- Ice freely diverges (no tensile strength)
- Ice resists convergence and shear
- Multiple ice categories advected with same velocity field

$$m\frac{\partial u}{\partial t} = -mfk \underset{\substack{\uparrow \\ \text{Coriolis}}}{\times} u + \underset{\substack{\uparrow \\ \text{Air} \\ \text{stress}}}{\tau_a} + \underset{\substack{\uparrow \\ \text{Ocean} \\ \text{stress}}}{\tau_o} - m\underset{\substack{\uparrow \\ \text{Sea} \\ \text{Slope}}}{g}\nabla H + \nabla \underset{\substack{\uparrow \\ \text{Internal} \\ \text{Ice Stress}}}{\bullet} \sigma$$

Ice Thickness Distribution





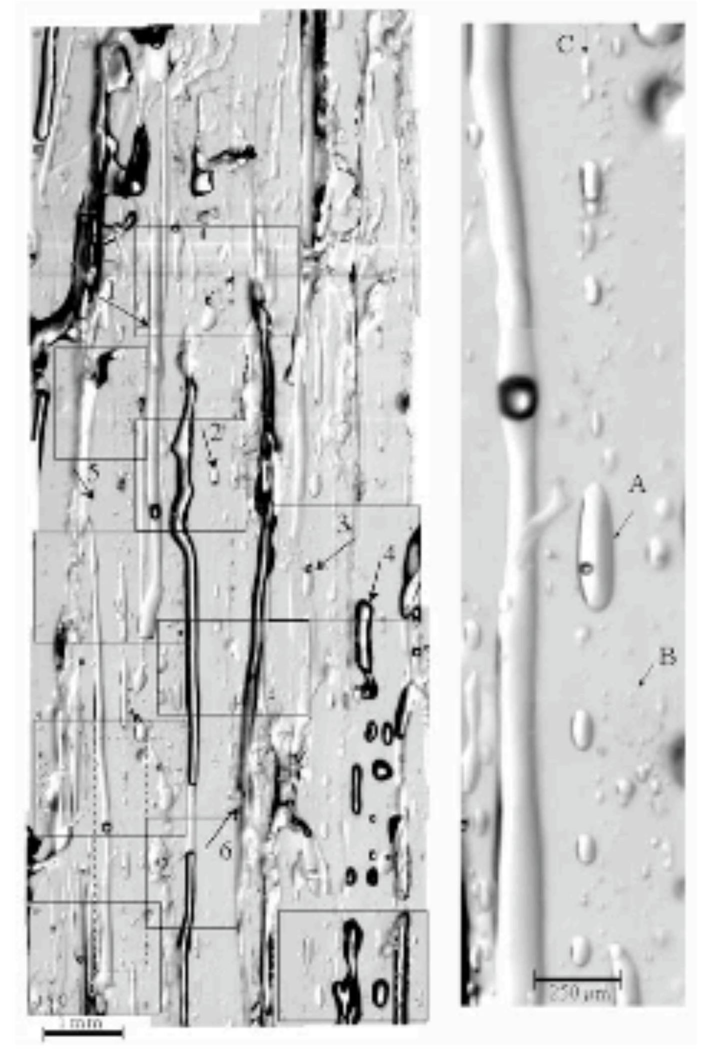
(Thorndike et al., 1975)

$$\frac{\partial g}{\partial t} = -\frac{\partial}{\partial h}(fg) + L(g) - \nabla \bullet (\vec{v}g) + \Psi(h,g,\vec{v})$$

Evolution depends on: Ice growth, lateral melt, ice divergence, and mechanical redistribution (riding/rafting)

Thermodynamics
Vertical heat transfer

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} k \frac{\partial T}{\partial z} + Q_{SW}$$

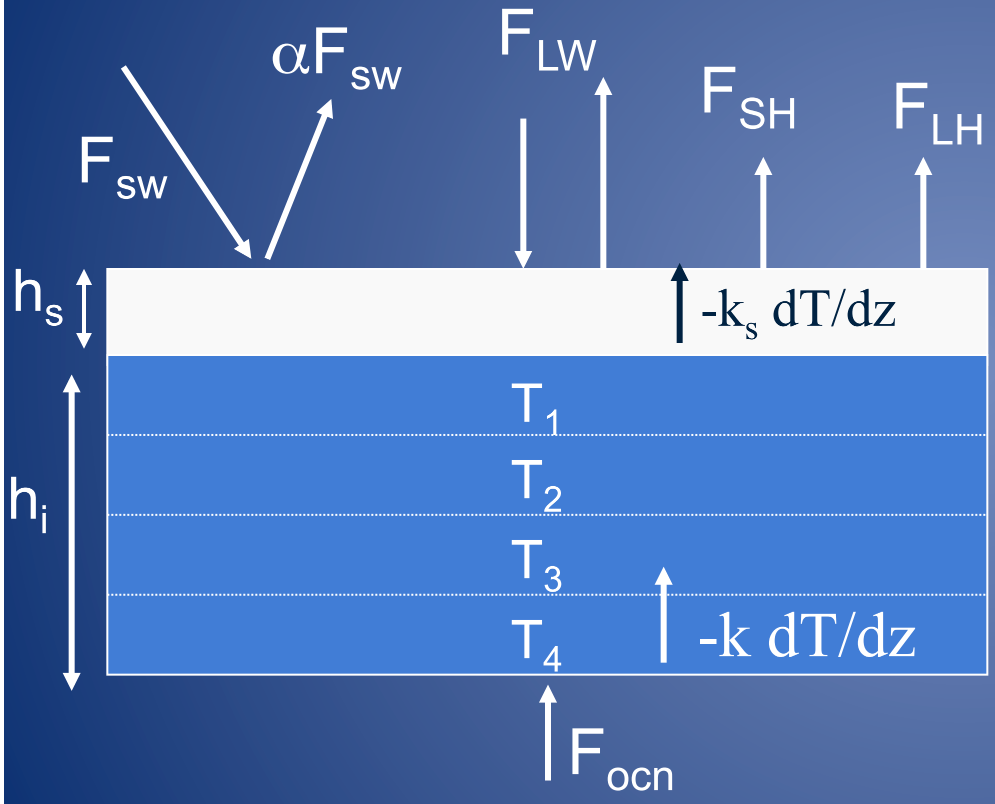


(from Light, Maykut, Grenfell, 2003)

- Assume brine pockets are in thermal equilibrium with ice
- Heat capacity and conductivity are functions of T/S of ice
- Assume constant salinity profile
- Assume non-varying density
- Assume pockets/channels are brine filled
- $Q_{SW} = -\frac{d}{dz} I_{SW} e^{-\kappa z}$ where $I_{SW} = i_0(1-\alpha)F_{SW}$

(Maykut and Untersteiner, 1971; Bitz and Lipscomb, 1999; others)

Sea ice thermodynamics



Balance of fluxes at surface

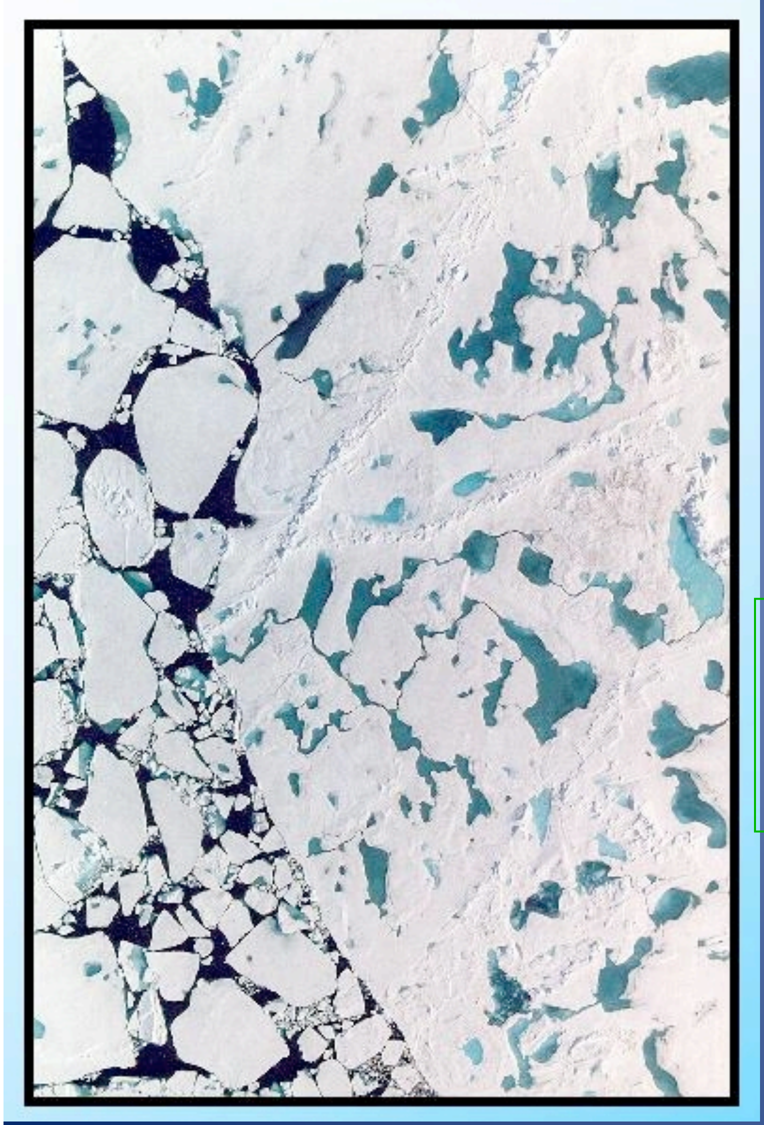
$$(1-\alpha)F_{SW} + F_{LW} - \sigma T^4 + F_{SH} + F_{LH} + k\frac{\partial T}{\partial z} = -q\frac{dh}{dt}$$

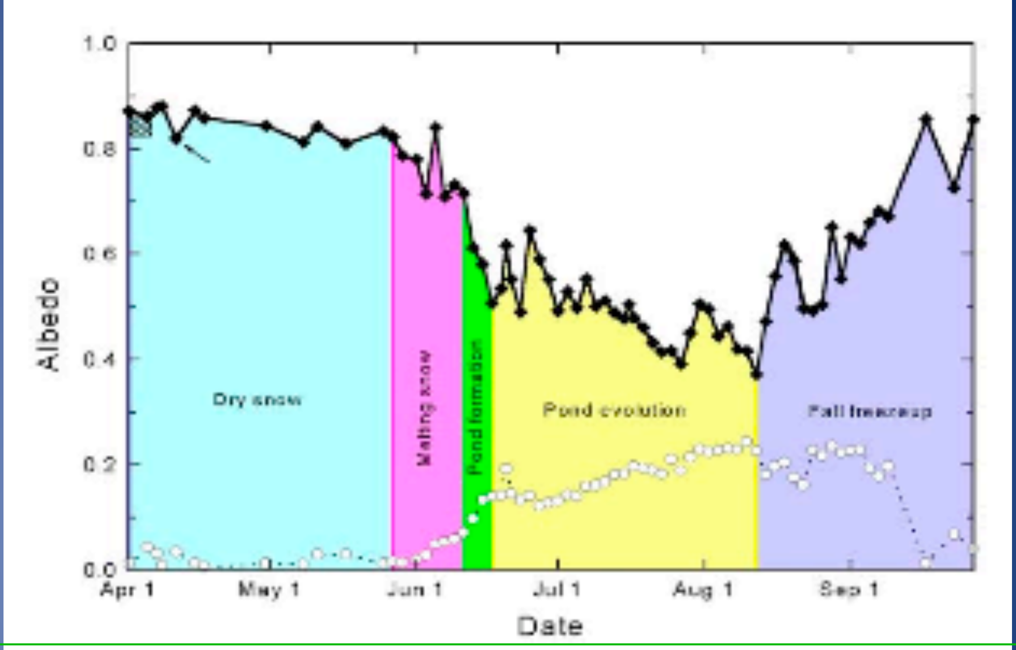
Vertical heat transfer
(conduction, SW absorption)

Balance of fluxes at ice base

$$F_{ocn} - k\frac{\partial T}{\partial z} = -q\frac{dh}{dt}$$

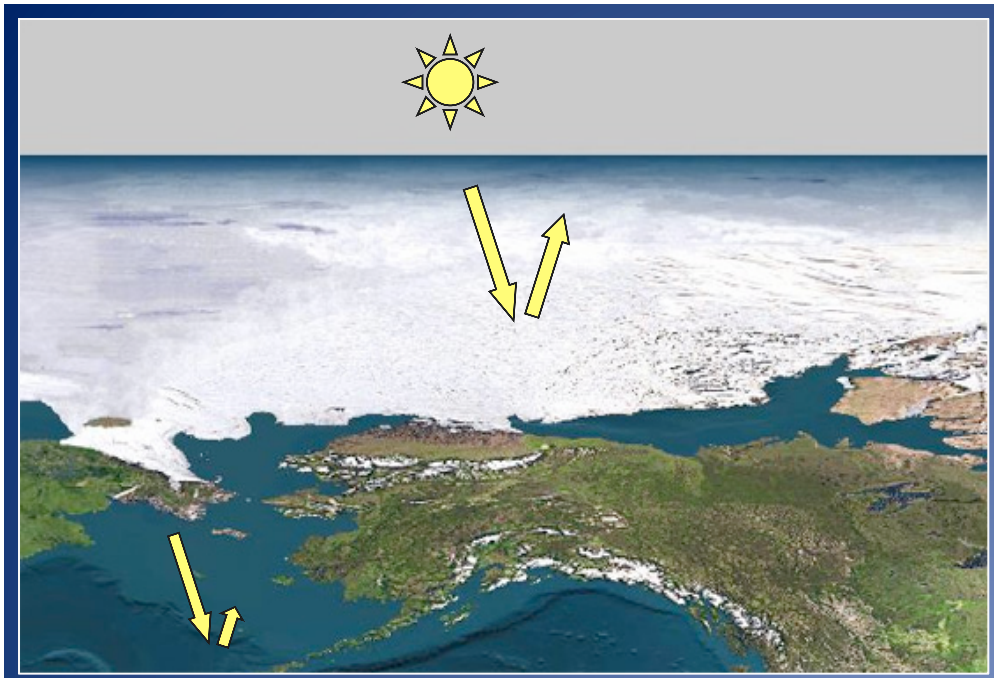
Albedo

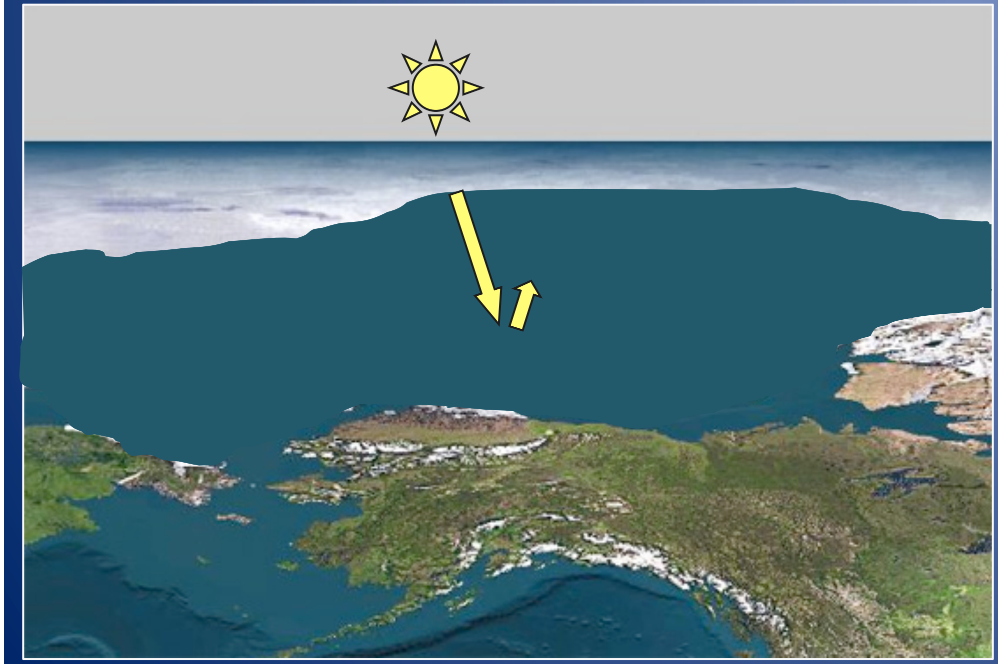




Parameterized sea ice albedo depends on characteristics of surface state (snow, temp, ponding, h_i).

Surface albedo accounts for fraction of gridcell covered by ice vs open ocean

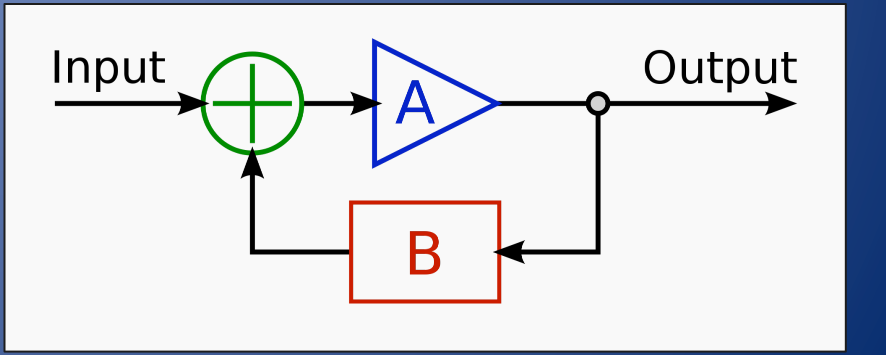




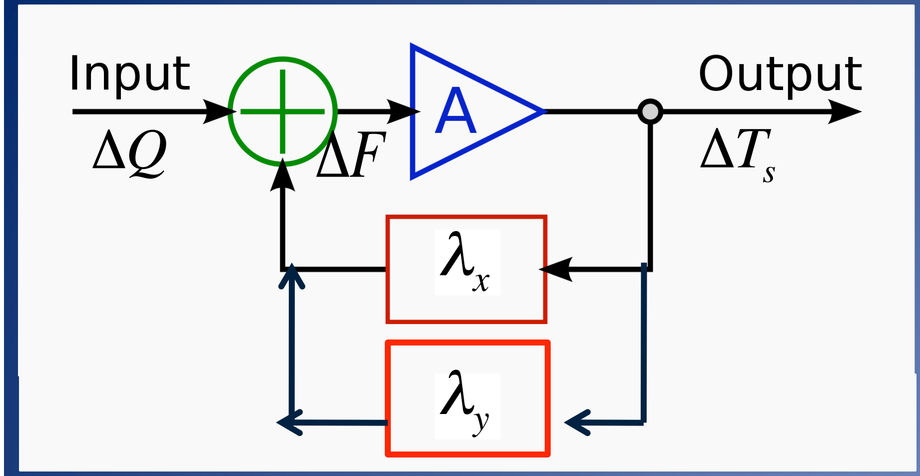
Sea ice change modifies the climate response to perturbed forcing

Direct response

Feedbacks that accelerate or damp the direct response



Assessing climate feedbacks



$$\Delta F = \Delta Q + \lambda \Delta T_S$$

T_s is surface temperature, Q is external forcing, F is TOA balance, λ_x *is the feedback parameter.*

$$\lambda = \frac{\partial F}{\partial T_s} = \sum_x \frac{\partial F}{\partial x}\frac{\partial x}{\partial T_s} + \sum_x \sum_y \frac{\partial^2 F}{\partial x \partial y}\frac{\partial x \partial y}{\partial T_s^2} + \ldots$$

Individual feedbacks Interaction among feedbacks

x = water vapor, clouds, surface albedo, etc.

Studies generally ignore the feedback-interaction term

Dominant feedback negative due to outgoing LW-T_s relationship

Surface Albedo Feedback Analysis

Starting with the classic definition of climate sensitivity:

$$\Delta T_S = \Delta F / \lambda$$

We can quantify the radiative forcing feedbacks:

$$\lambda = \frac{dF_{LW}}{dT} - \frac{dF_{SW}}{dT}$$

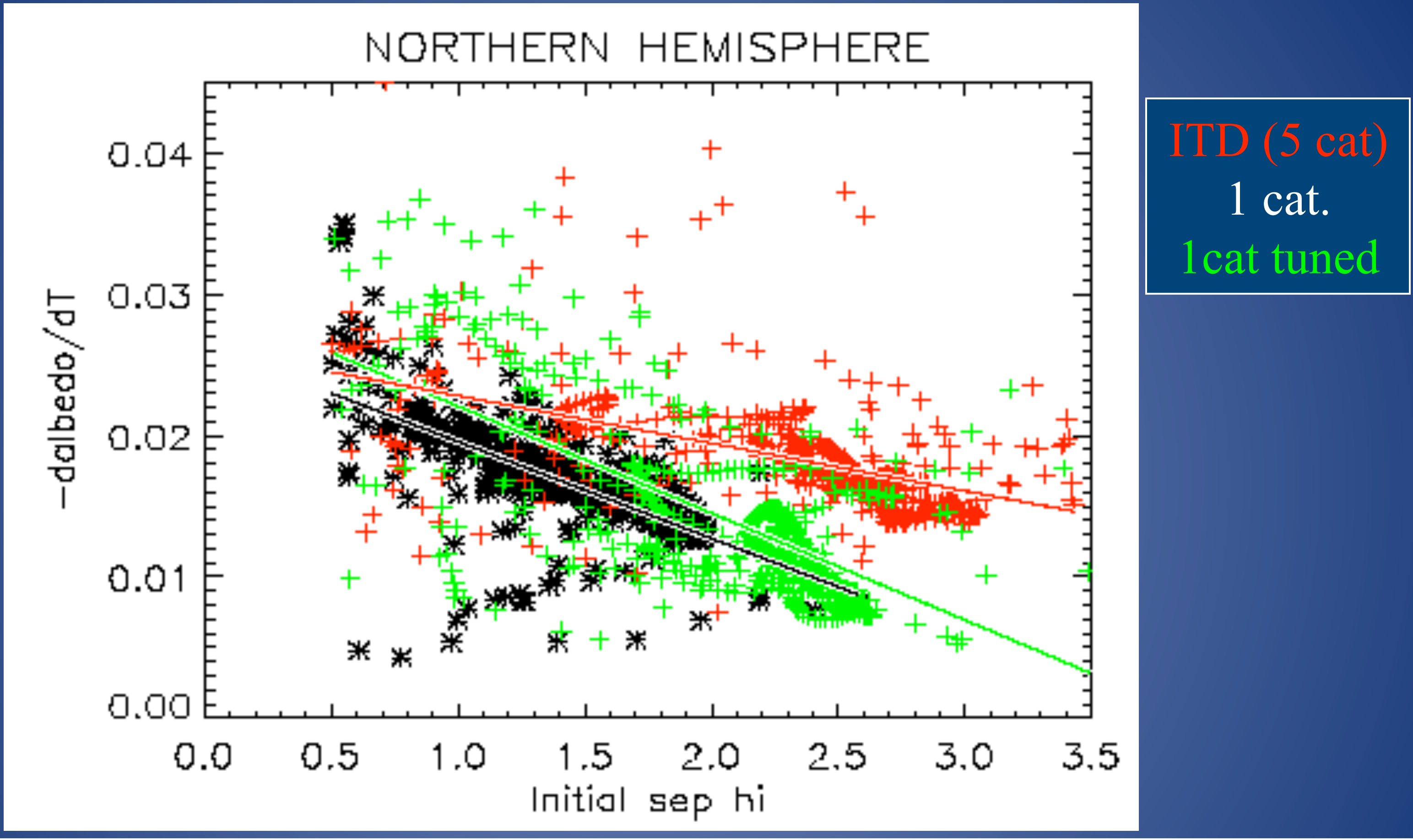
We isolate the albedo feedback component:

$$\left(\frac{\partial F_{SW}}{\partial T}\right)_{SAF} = \frac{\partial F_{SW}}{\partial \alpha}\frac{d\alpha}{dT}$$

And focus on changes in surface albedo per temperature change:

(the $\frac{d\alpha}{dT}$ term) where $\alpha = (1 - a_{ice})\alpha_{ocn} + a_{ice}\alpha_{ice}$

Model parameterizations influence feedback strength
Enhanced albedo feedback in ITD run



Larger albedo change for thinner initial ice

With ITD have larger a change for ice with same initial thickness

Suggests surface albedo feedback enhanced in ITD run

Holland et al., 2006

Ice Growth Rate - Ice Thickness Relationship

Analogous to climate sensitivity, we can define an ice thickness sensitivity:

$$\Delta h_{eq} = \Delta F / \lambda_h$$

We quantify the ice thickness feedbacks (neglecting ice dynamics):

$$\lambda_h = \frac{\partial F}{\partial G}\frac{\partial G}{\partial h} + \frac{\partial F}{\partial M}\frac{\partial M}{\partial h}$$

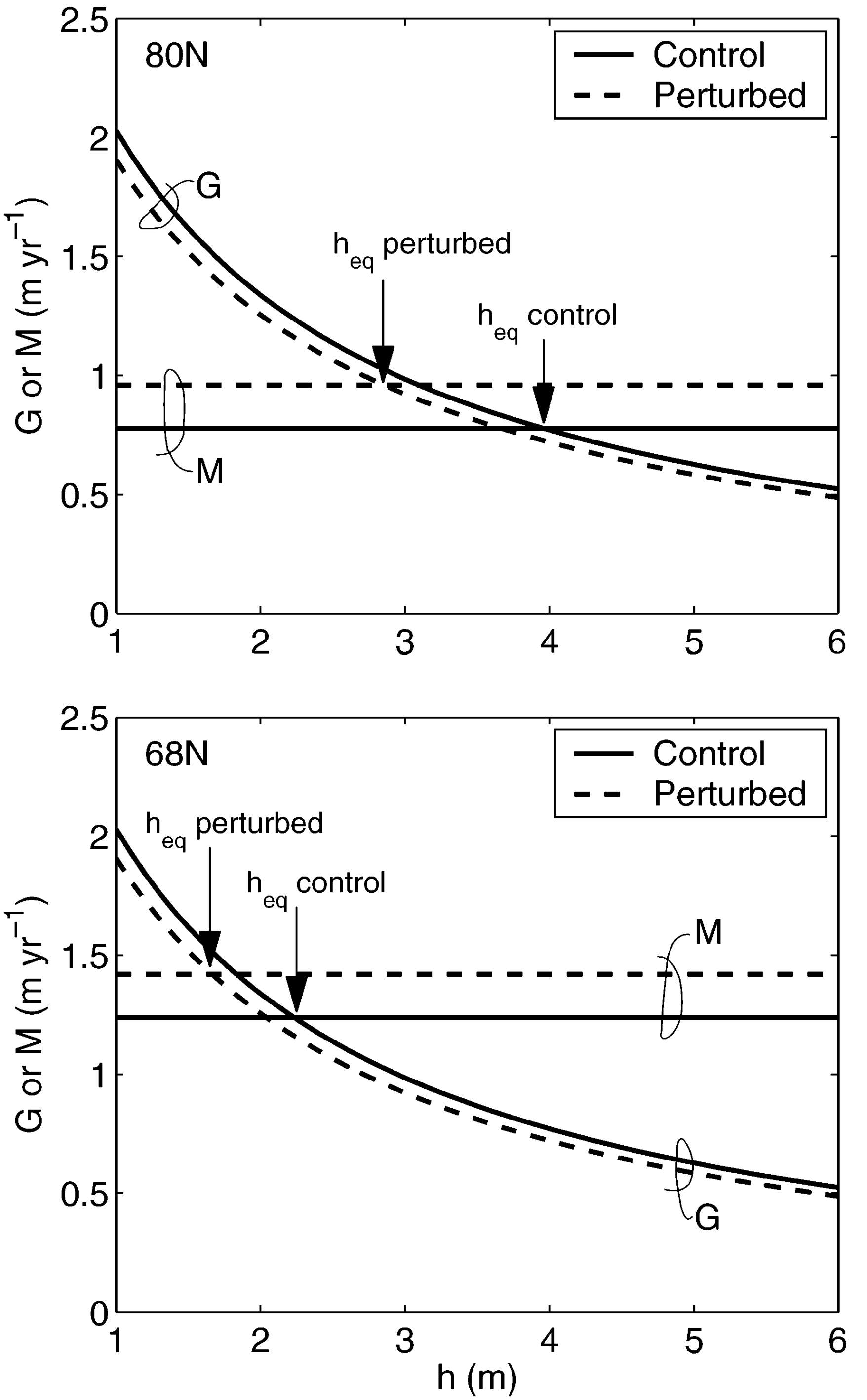
G=Growth
M=Melt

And isolate the ice growth rate-ice thickness feedback by focusing on the change in growth rate per change in thickness:

(the $\frac{\partial G}{\partial h}$ term)

Bitz and Roe, 2004

Ice Growth Rate -Ice Thickness Relationship



Fundamental sea ice thermodynamics causes the ice growth rate (G) to vary as 1/h

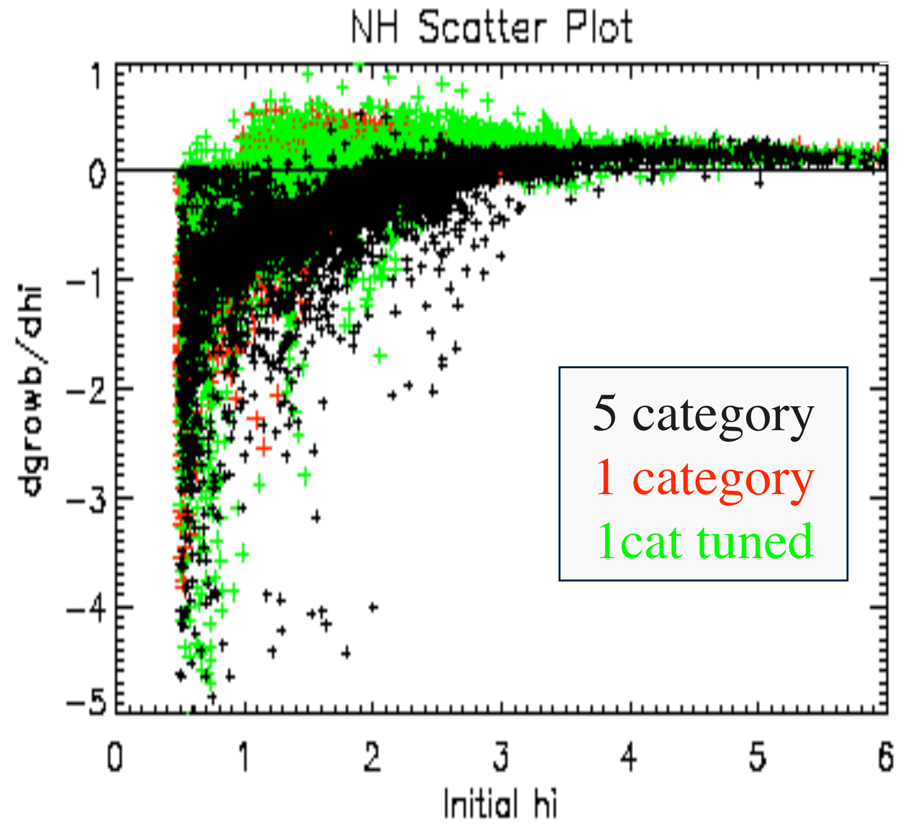
$$G \propto k \frac{\Delta T}{h_i}$$

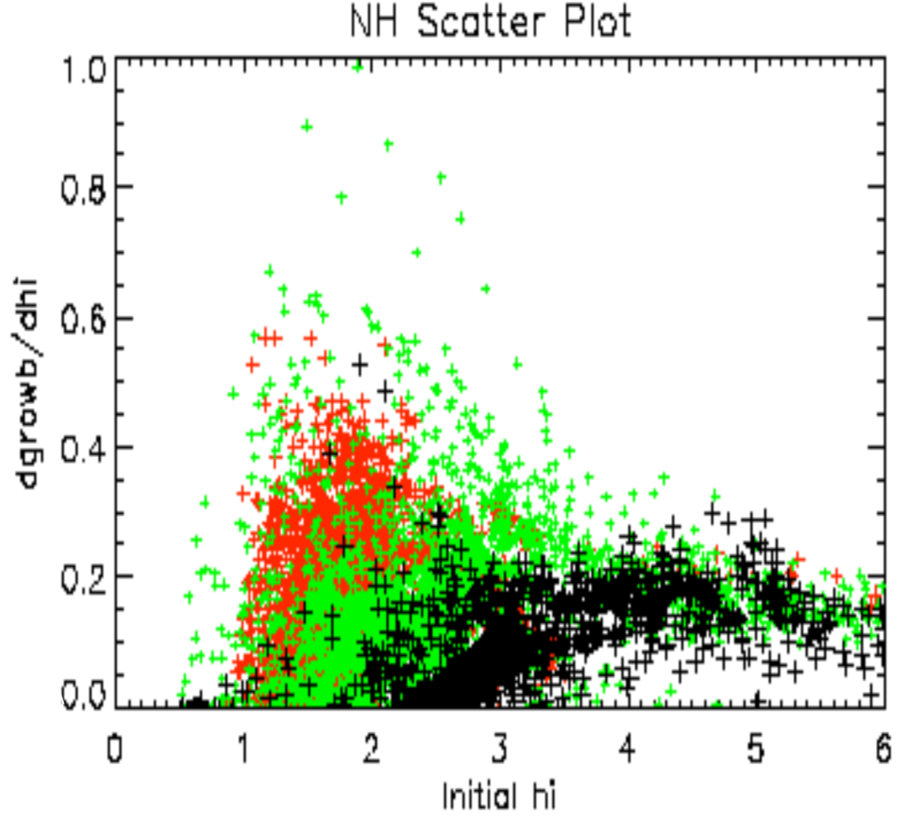
This acts as a negative feedback on ice thickness change

$$\Delta h_{eq} \propto h^2$$

Bitz and Roe, 2004

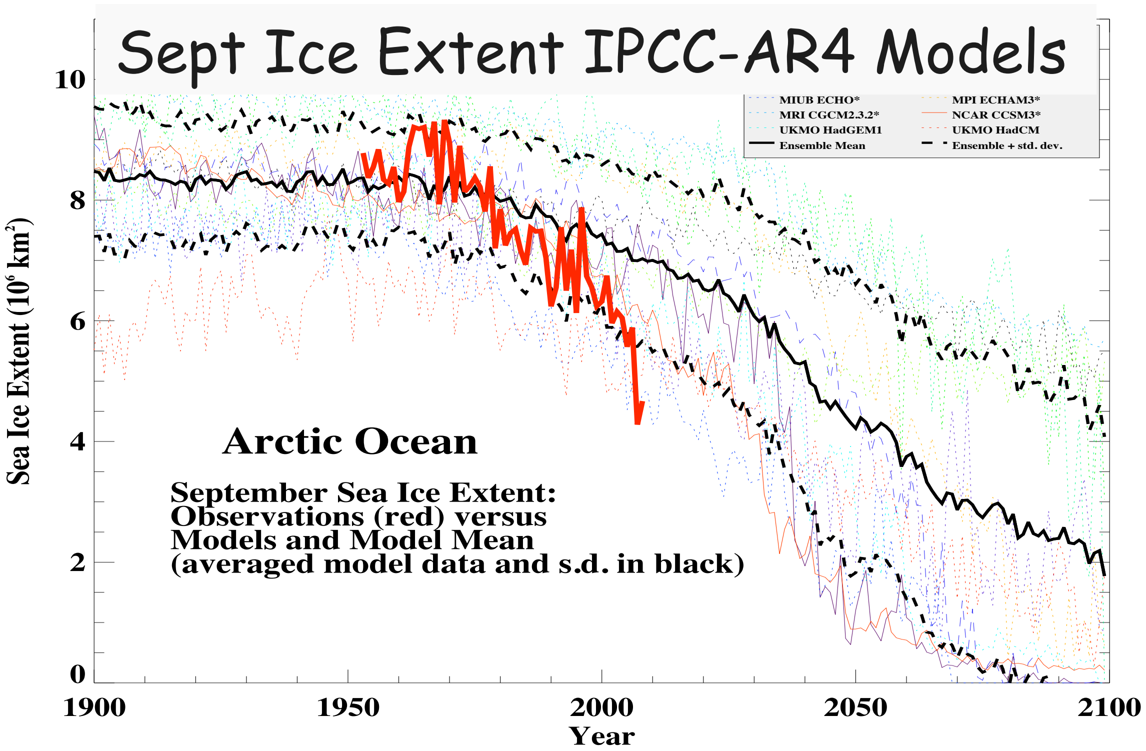
Model parameterizations modify ice growth rate feedback

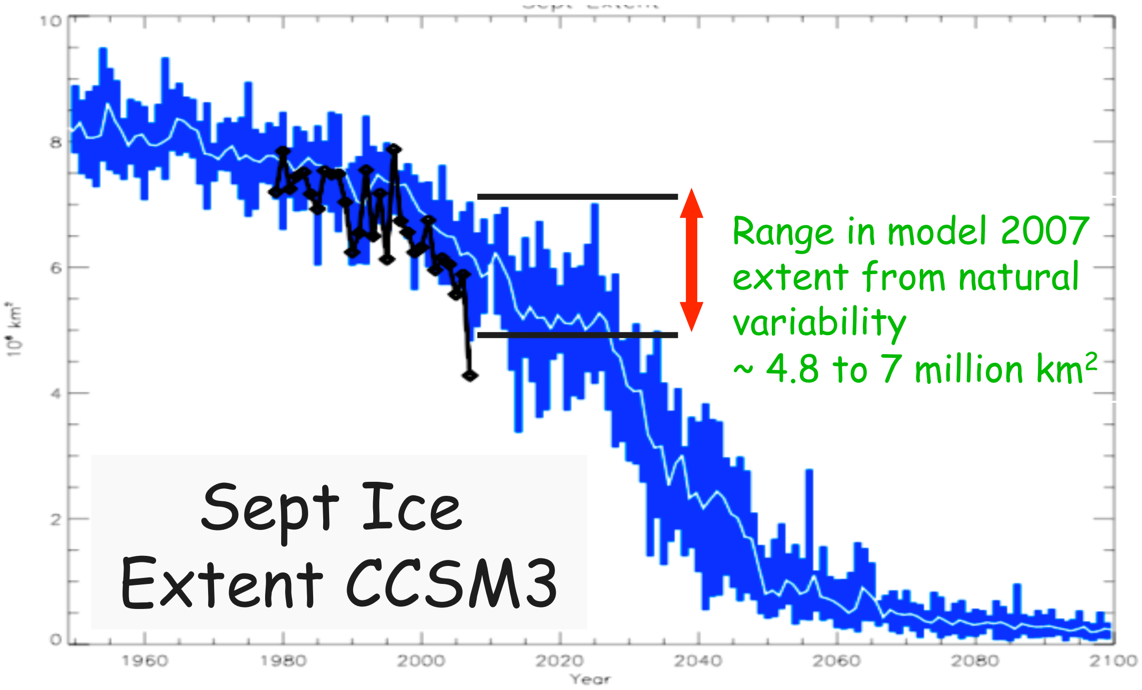




For ice of the same mean thickness,

- The ITD has fewer locations with increased ice growth.
- This suggests a reduced negative feedback on ice thickness

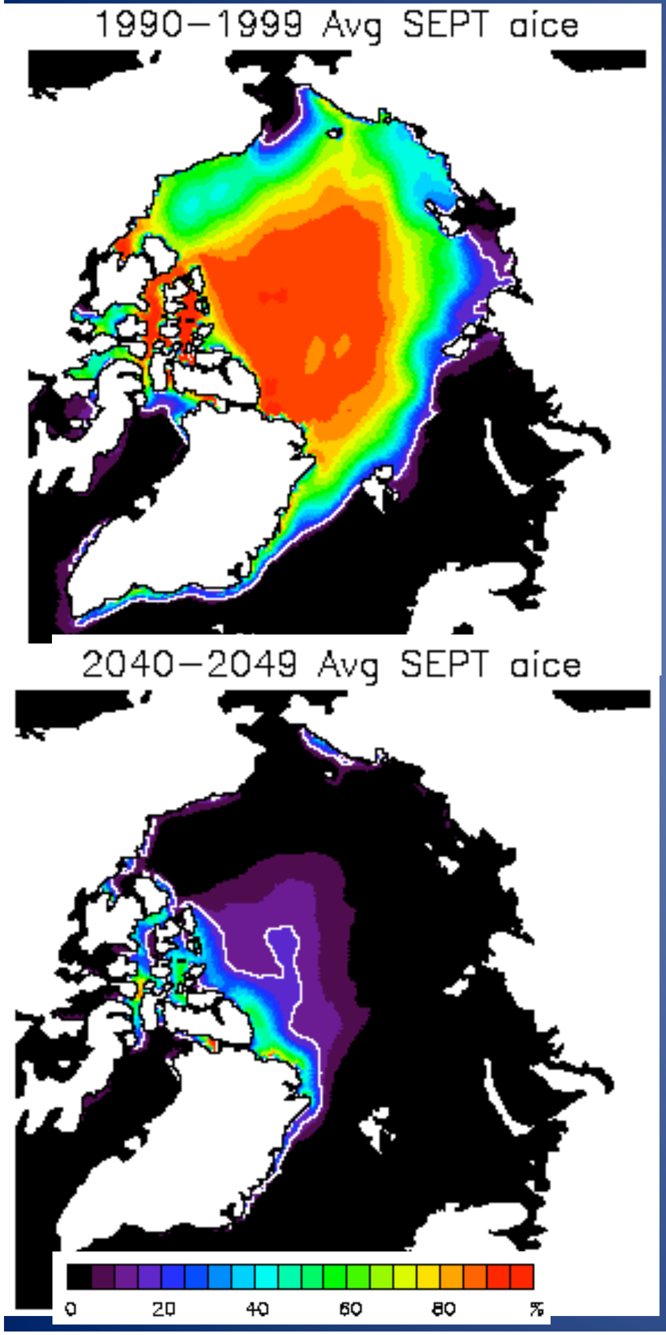

Sept Ice Extent IPCC-AR4 Models

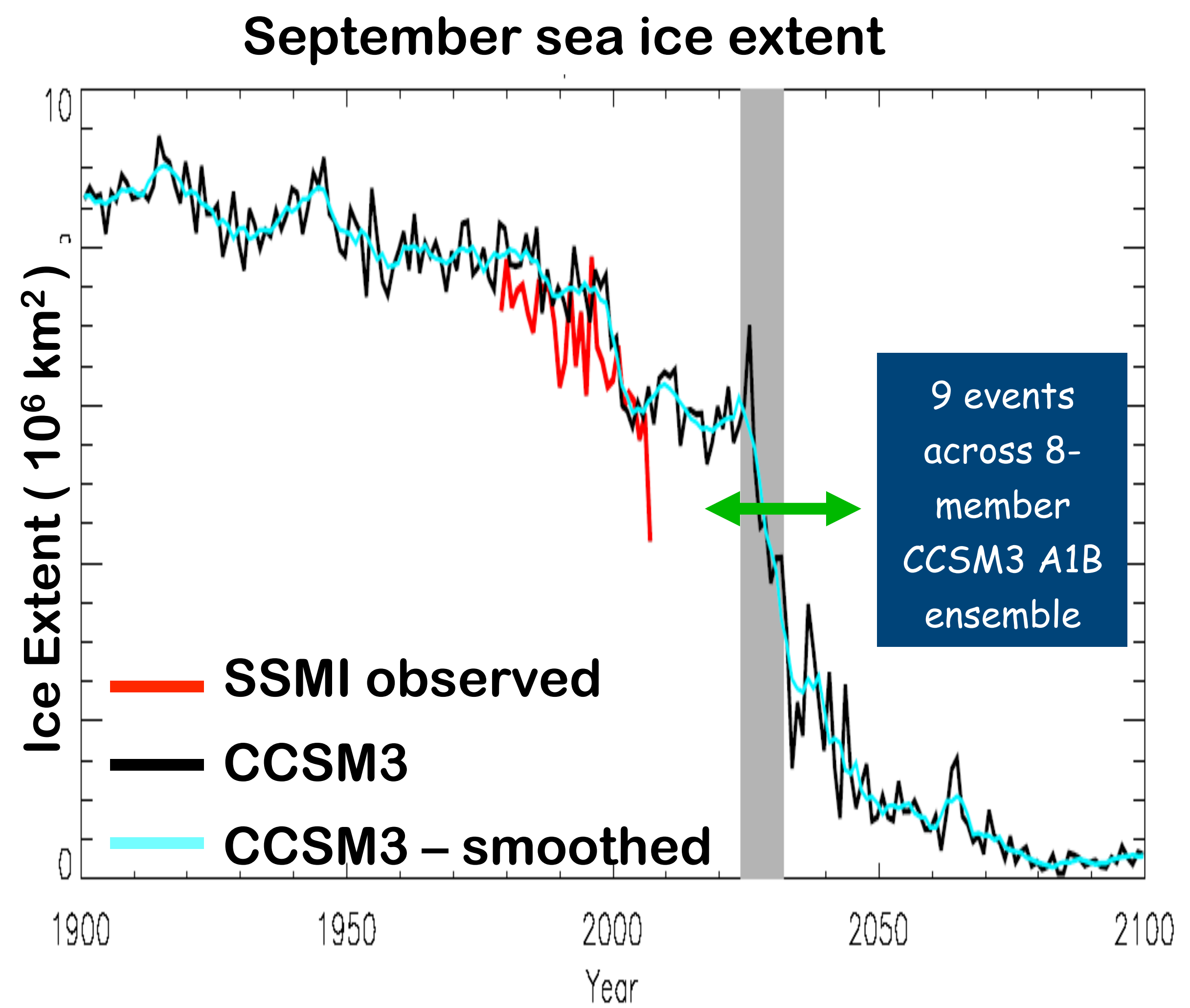

Sept Ice Extent CCSM3

Range in model 2007 extent from natural variability ~ 4.8 to 7 million km^2

Climate models explicitly include these (and other) feedbacks and can be used to explore climate system response

Rapid loss of the September sea ice cover



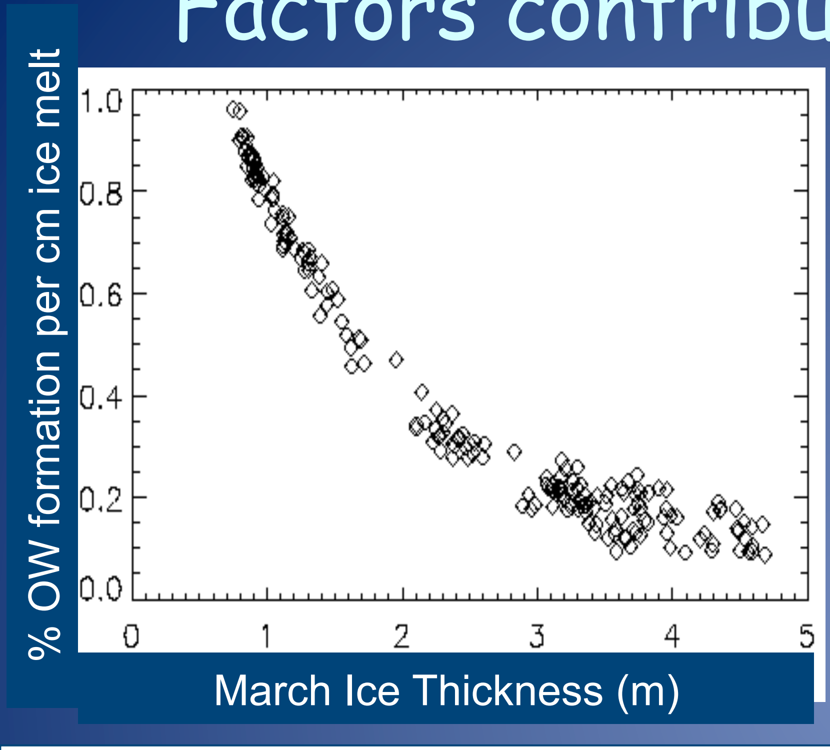


9 events across 8-member CCSM3 A1B ensemble

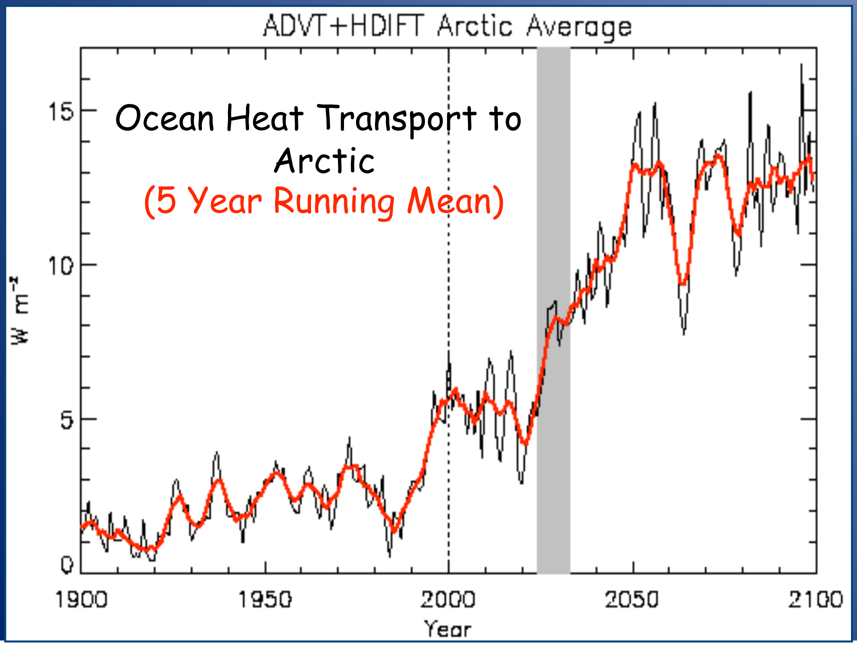
Gradual forcing results in rapid loss of September Arctic ice cover

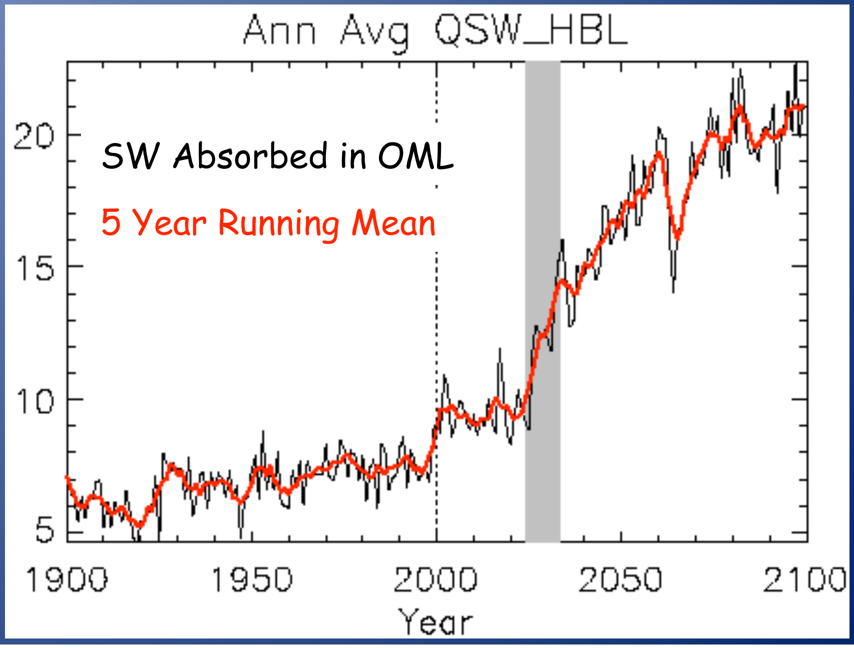
Holland et al., 2006

Factors contributing to rapid ice loss



- Increased efficiency of OW production for a given ice melt with a thinning ice pack
- Increased ocean heat transport preceding and over the event (trigger?)
- Albedo feedback leading to increased solar absorption and enhanced ice melt





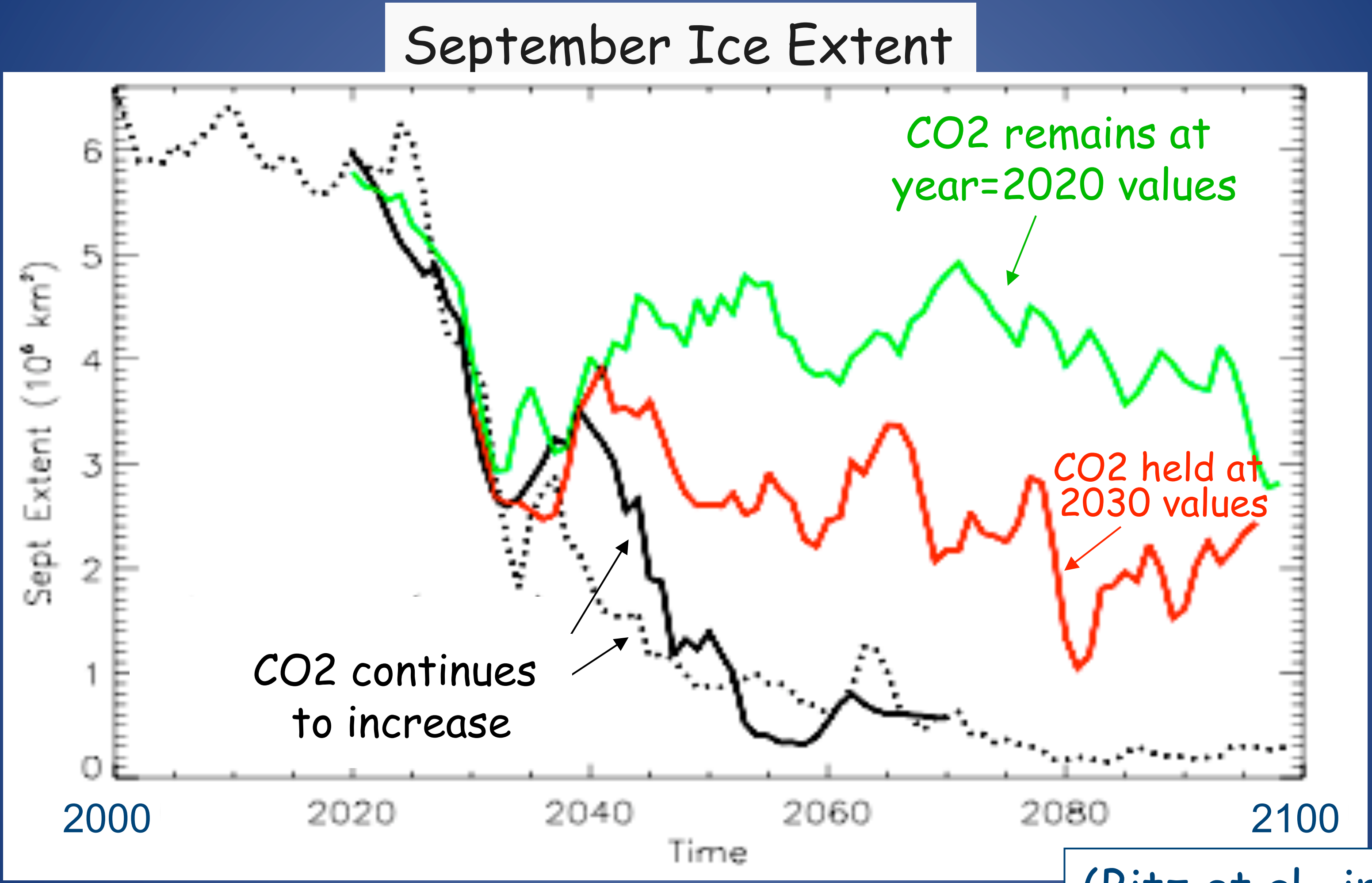
Is this rapid loss indicative of a "tipping point"

Using coupled models to explore possible bifurcation

Where, Tipping Point = an intrinsic threshold such that sea ice decline will become rapid and irreversible once the threshold is crossed

Does a bifurcation exist?

If forcing (GHGs) remains fixed, does ice continue to retreat?



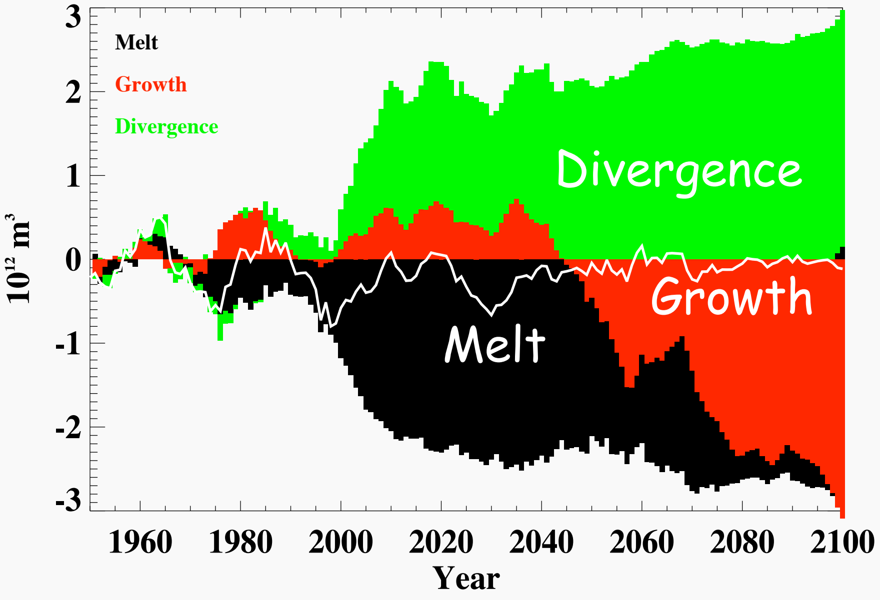
(Bitz et al., in prep)

With no continued increase in forcing, sea ice stabilizes with a reduced but still perennial ice cover. No "tipping point".

What stabilizes the ice cover?

Run with increasing GHG

Mass Budget Change b30.030-040



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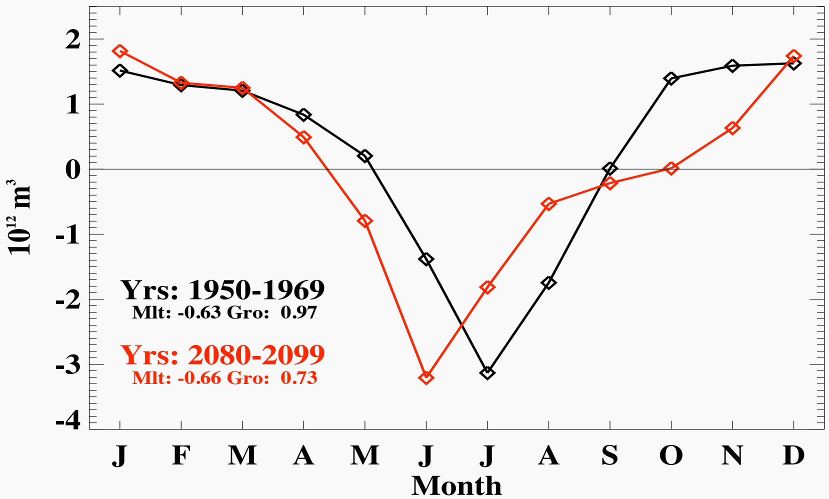
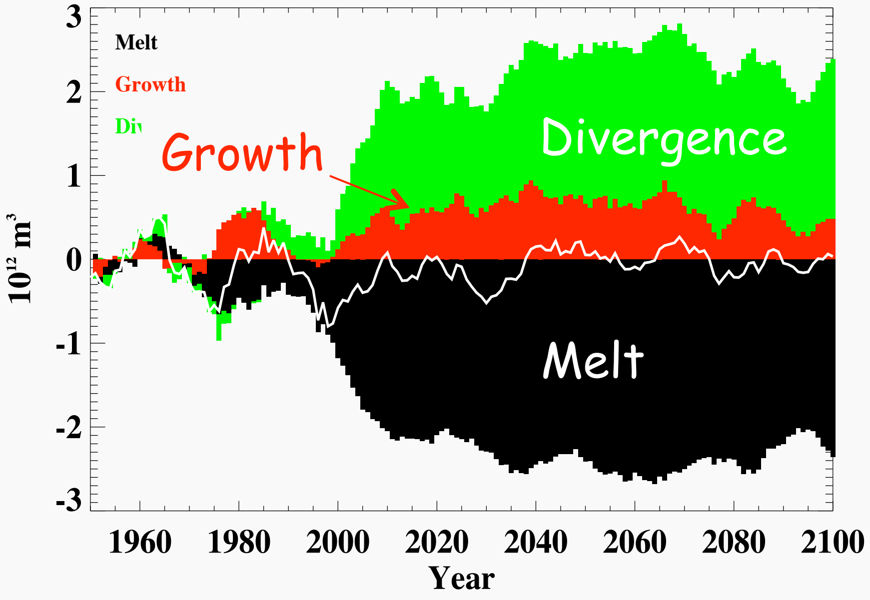


Run with GHG stabilized after 2020

Mass Budget Change b30.040b.ES01bcom



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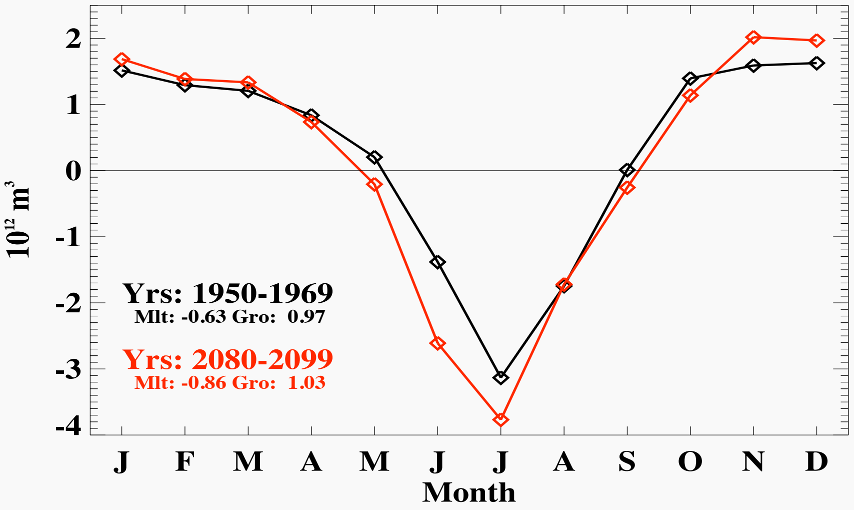
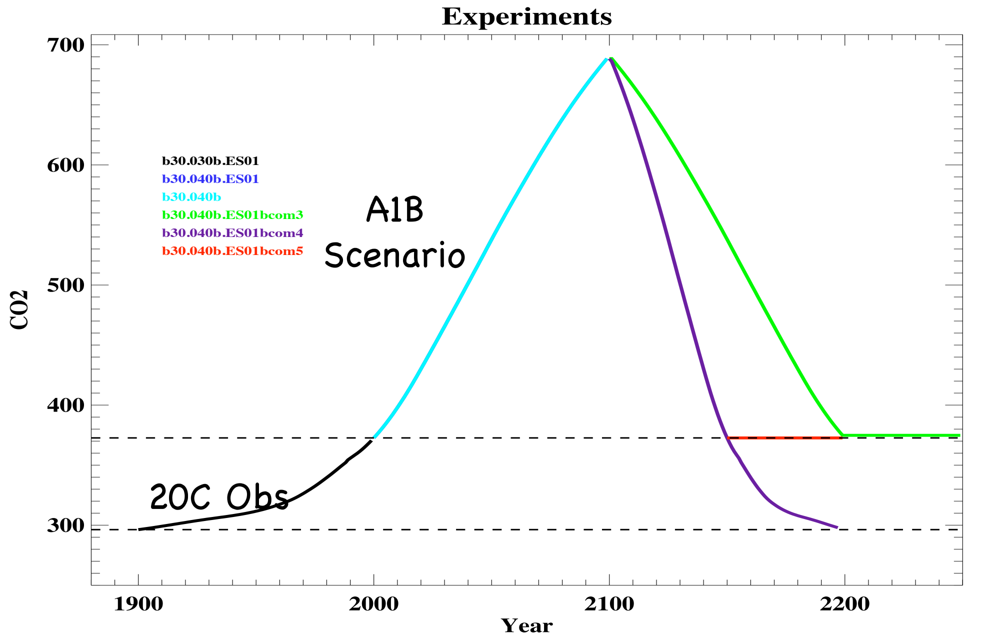


Is ice loss irreversible?

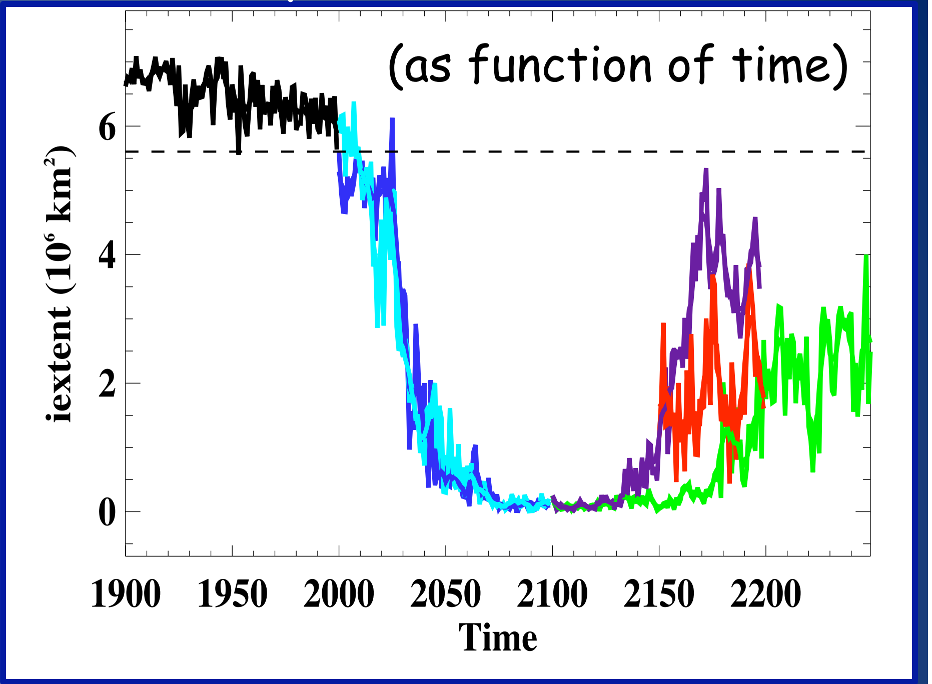
Performed highly idealized experiments with reductions in GHG concentrations

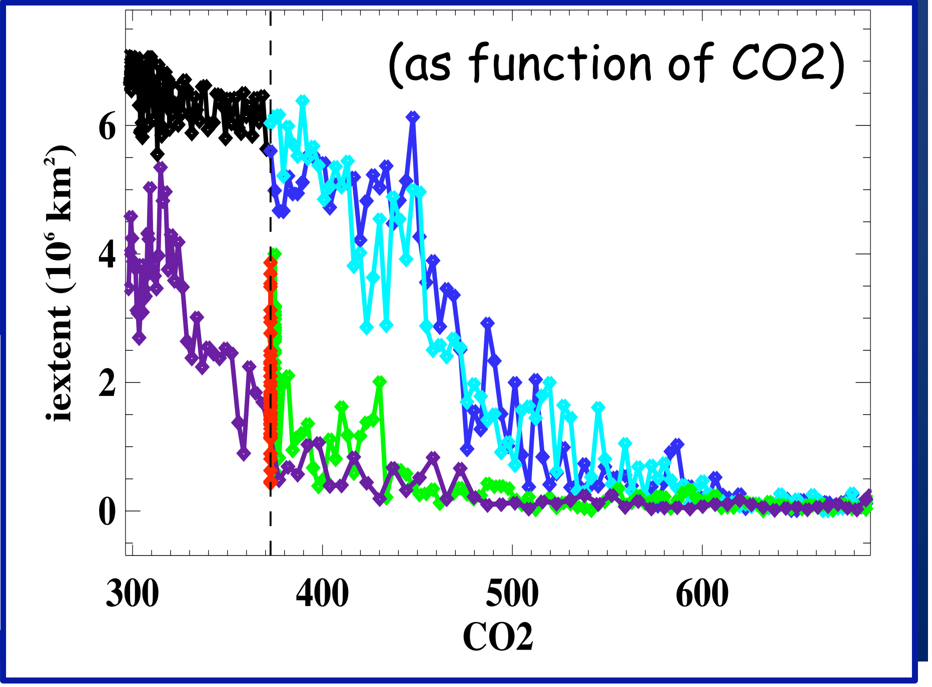


CO_2 Timeseries

- Lagged recovery due to thermal inertia of the system
- Little indication of hysteresis from (approaching) equilibrium values

September Extent





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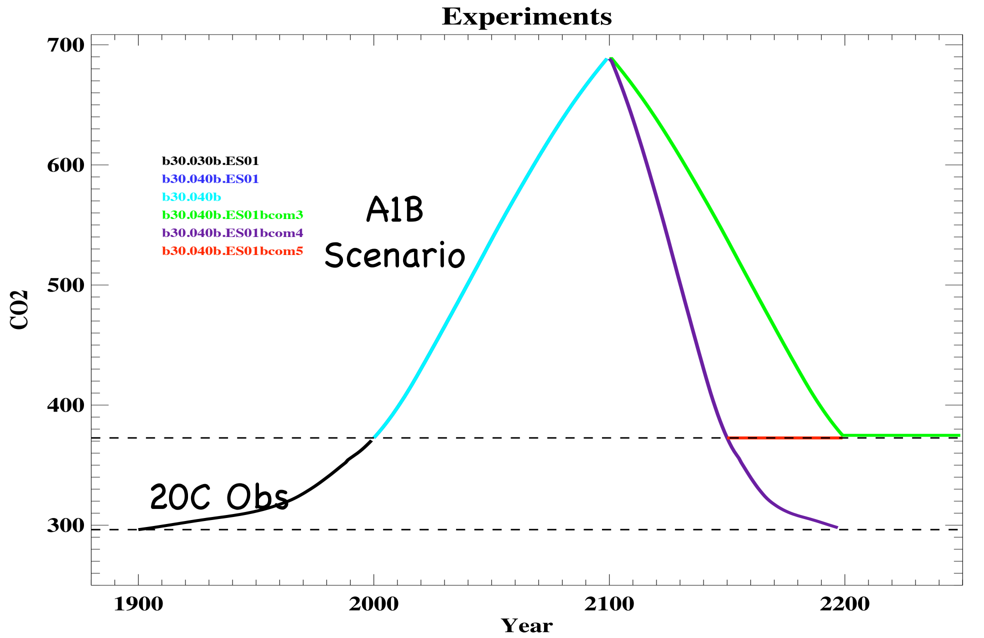

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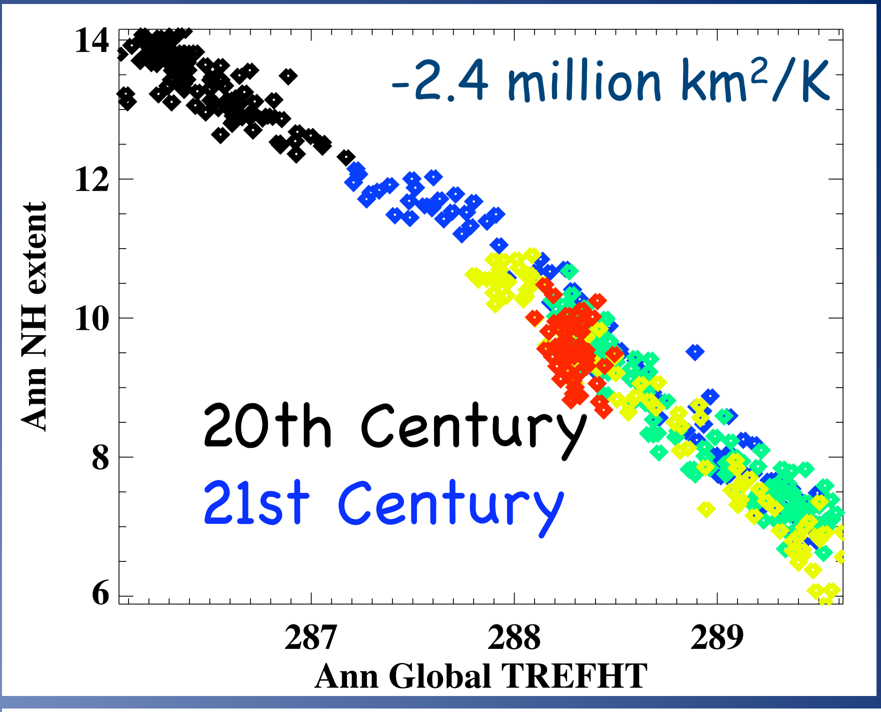
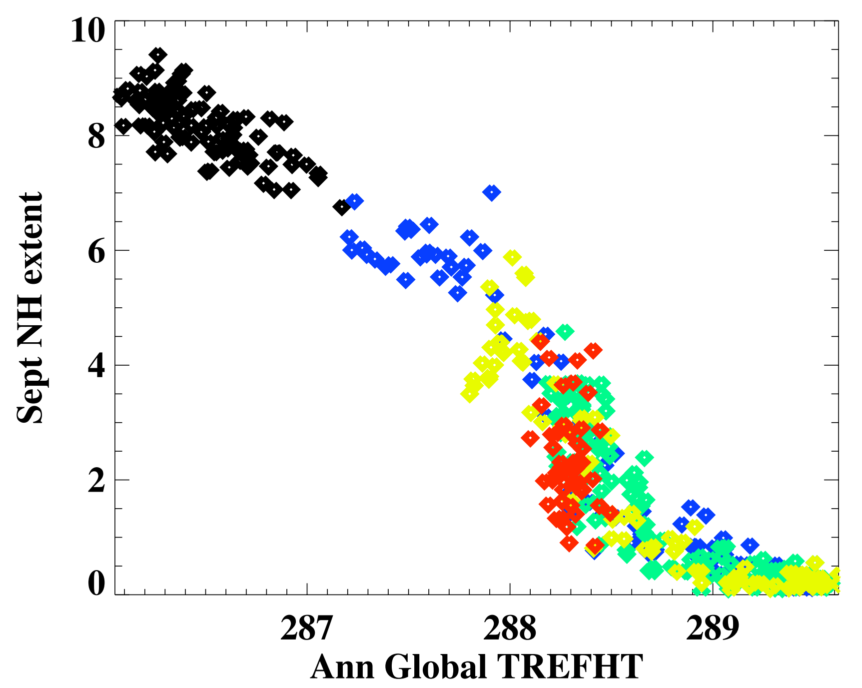




- Assessing ice extent as a function of global temperature shows little difference between ice loss and ice recovery simulations

Using "toy models" to investigate sea ice stability

"The objective is to illuminate the essential processes and not to embellish them or mix them up with others which are less important." Thorndike, 1992

$$T_{n+1} = \max[F - wH_n - wb(A_{\max} - A_n),0]$$

Winter ice thickness depends on heat transport (H_n), SW absorption

$$A_n = A_{\max}[1 - \frac{T^*}{T_n} M_n]$$

Sept ice area related to OW formation efficiency (T^*/T_n) and net summer melt (M_n)

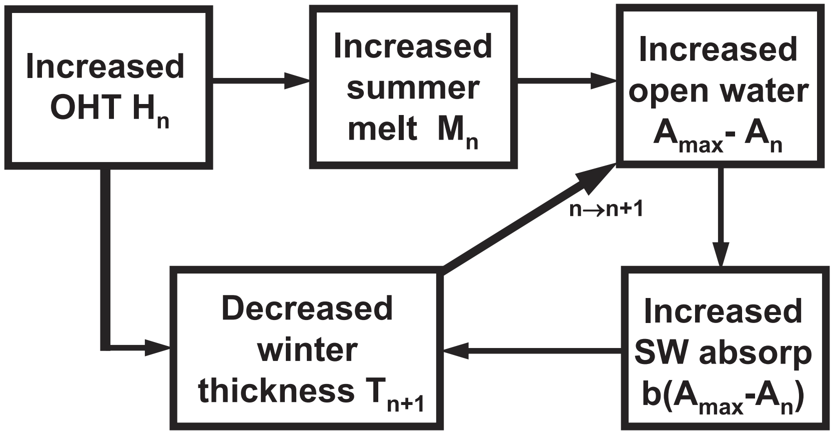
$$M_n = \min[M_0^s + M_0^b + wH_n(1 + A_n / A_{\max})/2, T_n / T^*]$$

Summer melting related to ocean heat transport (H_n)

Equations/processes based on CCSM3 results

Merryfield et al., 2008

Toy model to investigate sea ice stability



Increased OHT H_n

Increased summer melt M_n

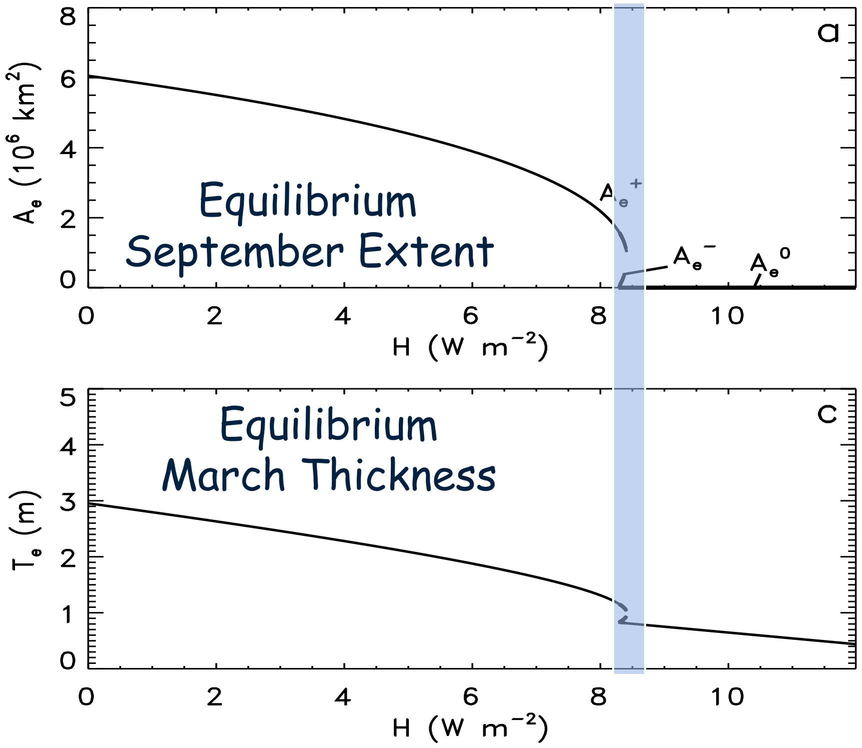
Increased open water A_{max}- A_n

Increased SW absorp $b(A_{max}$-$A_n)$

Decreased winter thickness T_{n+1}

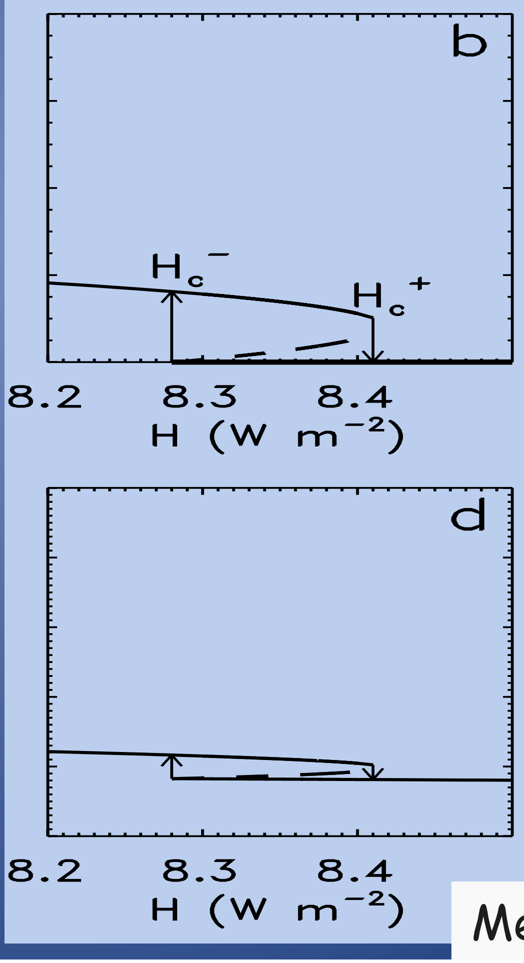
n→n+1

Using these equations, multiple equilibria are found for a narrow range of OHT



Equilibrium September Extent

Equilibrium March Thickness



A saddle-node bifurcation occurs at H_c^+ causing abrupt transition to a seasonal ice cover

However, ice loss in coupled model more likely due to large H fluctuations

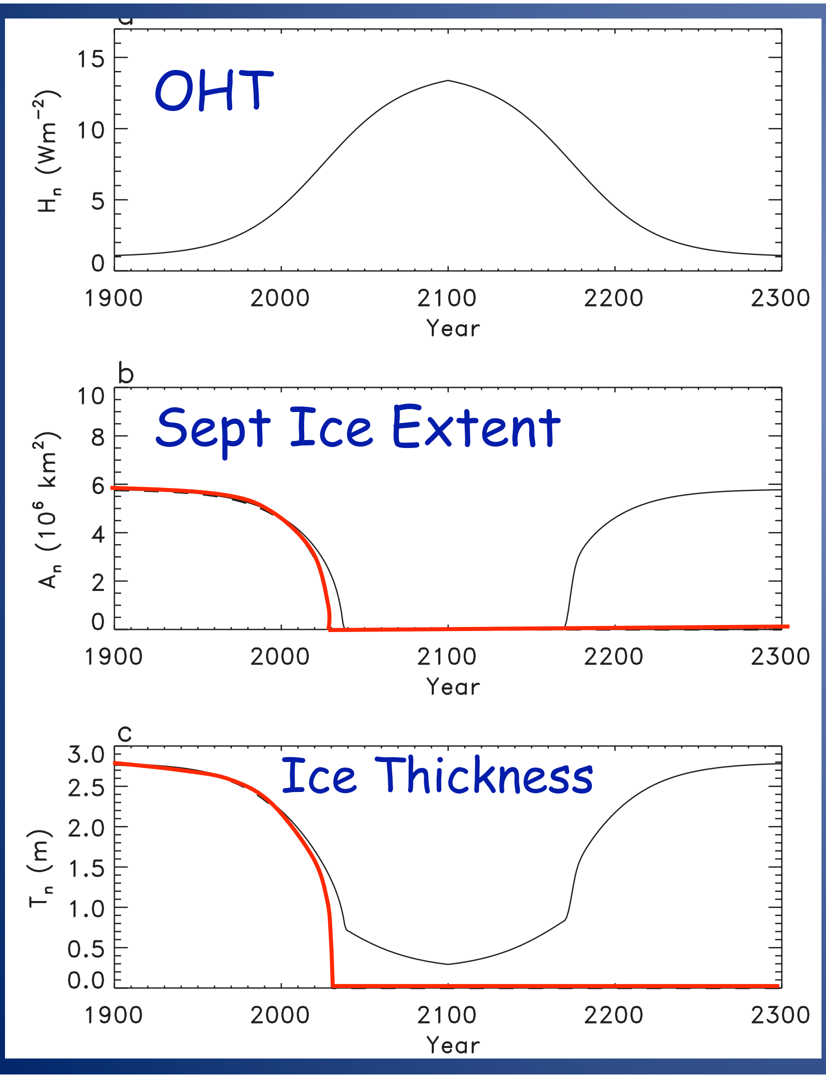
Merryfield et al., 2008

Cautions with "toy model" approach
Simplifications affect model behavior

Winter ice thickness

$$T_{n+1} = \max[F - wH_n - wb(A_{\max} - A_n), 0]$$

Assumes that albedo feedback saturates with ice-free Sept



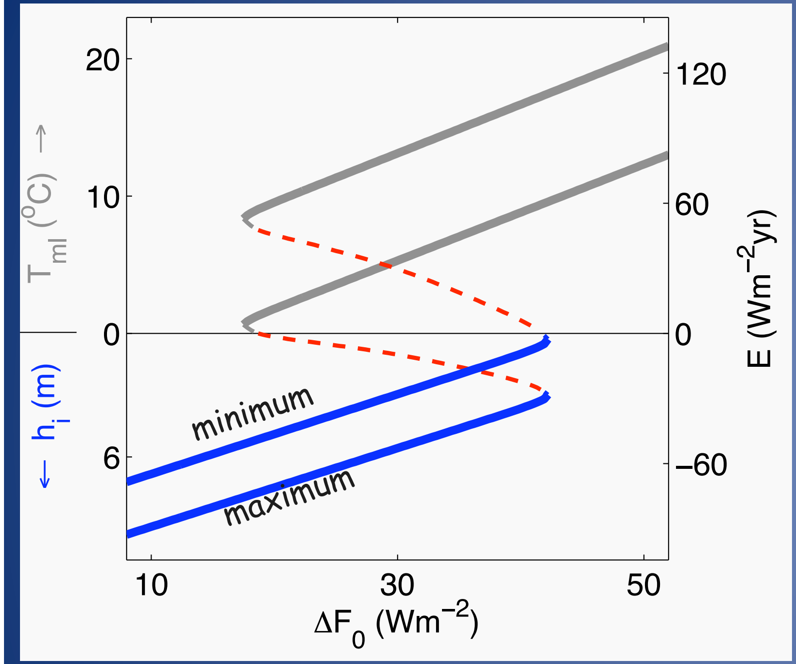
If albedo feedback is instead proportional to annual mean open water fraction then:

- Analytical solution not possible
- Numerical solution suggests
  - a perennial loss of ice
  - extreme hysteresis with no recovery of ice cover
  - similar to small-ice-cap instability found in other studies

Merryfield et al., 2008

Results from other simplified systems

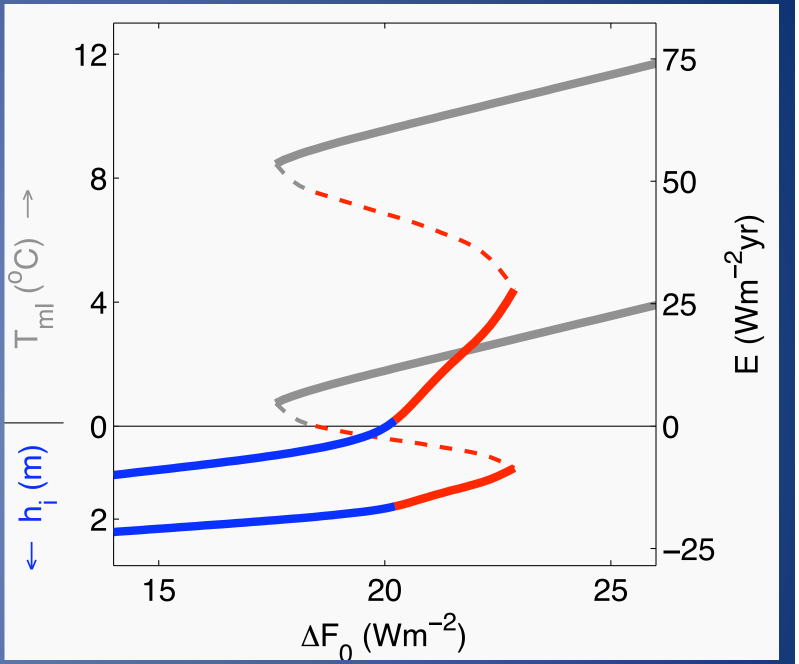
Albedo feedback but no ice-growth feedback



Perennial Ice
Seasonal ice
Ice-free

Dashed lines are unstable solutions

Albedo feedback and ice-growth feedback



- Seasonally ice-free solutions are unstable
- No tipping point in transition to a seasonal ice-pack

- Some stable seasonally ice-free solutions exist
- If system warms enough, abrupt transition to ice-free conditions results

Eisenman and Wettlaufer, 2009

Some final thoughts

Challenges in modeling sea ice

Many aspects of sea ice modeling are well established, based on fundamental physical principals and validated against laboratory and field observations.

However, numerous challenges remain:
A number of processes are only crudely represented: snow-ice formation, snow cover properties, fluid flow through porous brine microstructure, etc.

Some capabilities are not present:
Role in biogeochemical cycles, etc.

Additionally, as fully coupled climate models move to increasingly higher resolutions, questions arise on the appropriateness of some current approximations

Challenges in understanding sea ice response in coupled systems

Other climate model biases (e.g. cloud simulations) strongly influence sea ice response

Models are often so complex, that cause-and-effect are difficult to disentangle.

Simpler systems can aid in this, but caution must be used in the generalizing of results