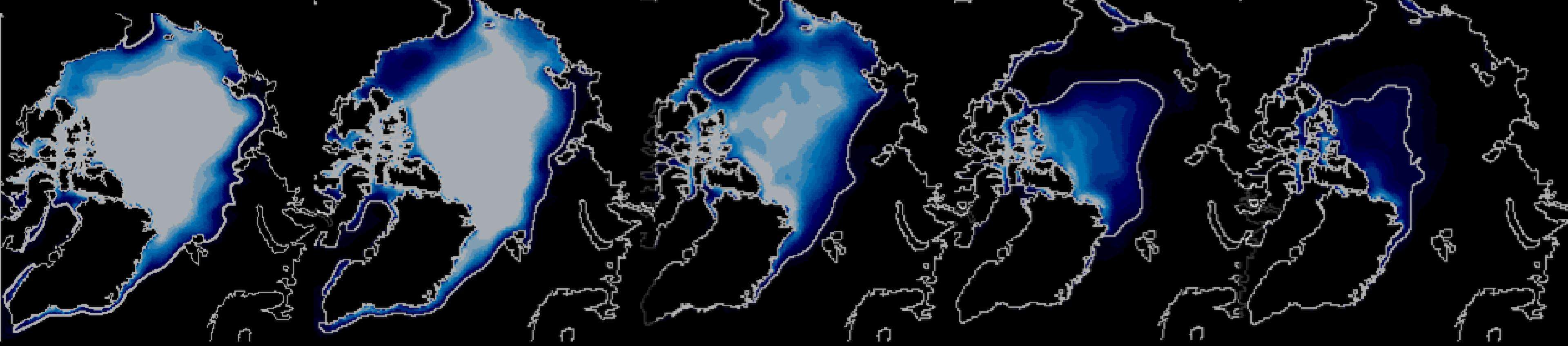

Improving Predictions of Arctic Sea Ice

Marika Holland
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National Center for Atmospheric Research

Acknowledgements

- Polar Climate Working Group Members:
  - Dave Bailey, Cecilia Bitz, Bruce Briegleb, Elizabeth Hunke, Alexandra Jahn, Jennifer Kay, Bill Lipscomb, Julie Schramm, Steve Vavrus
- External collaborators:
  - Mark Serreze, Julienne Stroeve, Bonnie Light
- The CESM Project:
  - CSEG, Working Group co-chairs, SSC, CAB, NSF and DOE, CESM Scientists

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Improving Sea Ice Predictions
Outline

- Motivation
- Importance of sea ice model developments
  - Sea ice spatial heterogeneity
  - Inclusion of prognostic “absorbers” within the ice
- Improved understanding of sources of uncertainty in future projections
  - New appreciation for the role of natural variability in the presence of anthropogenic change
- Summary

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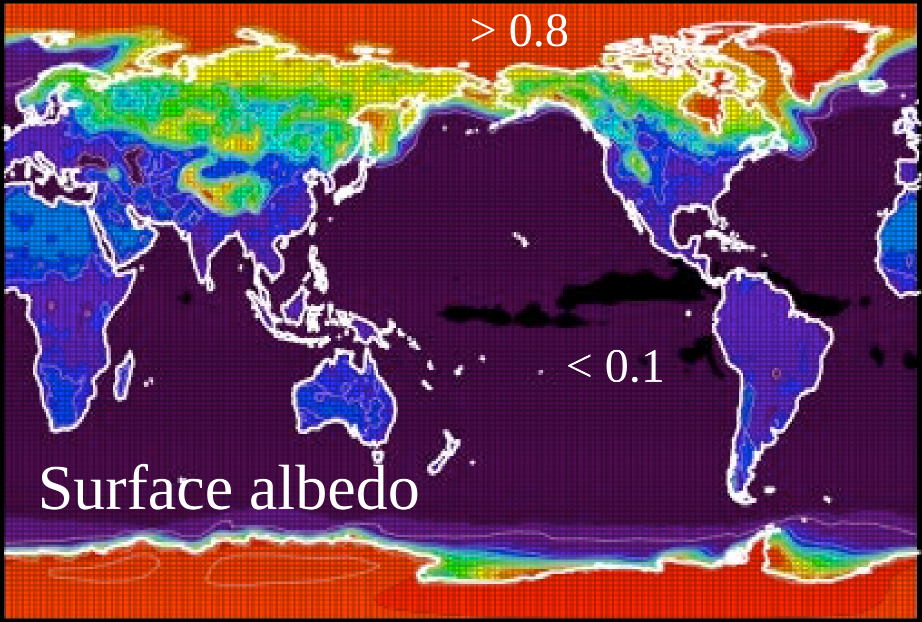
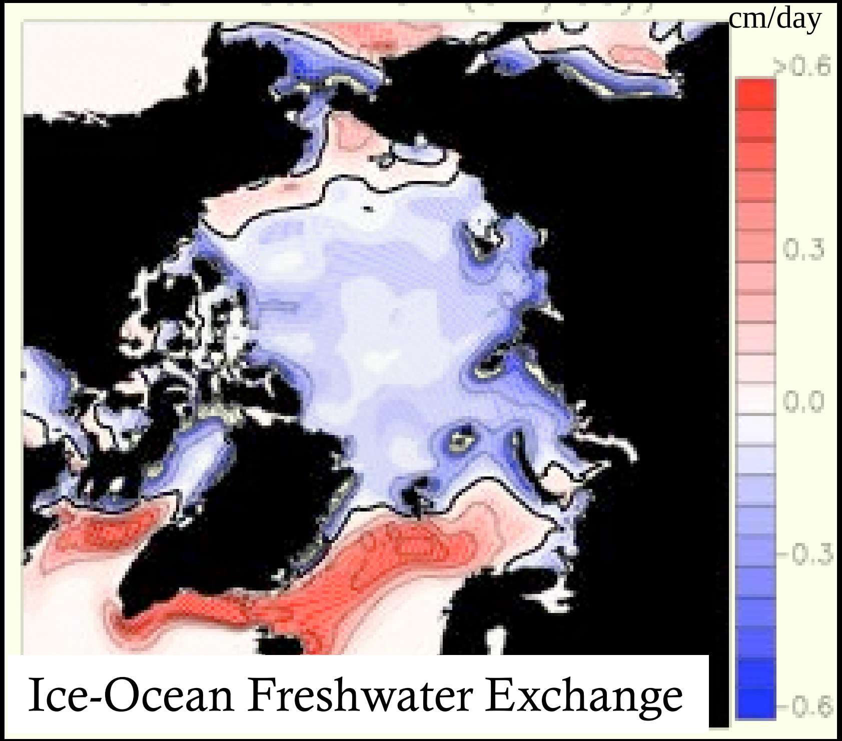
Climate Impacts of Sea Ice

Surface Heat Budget



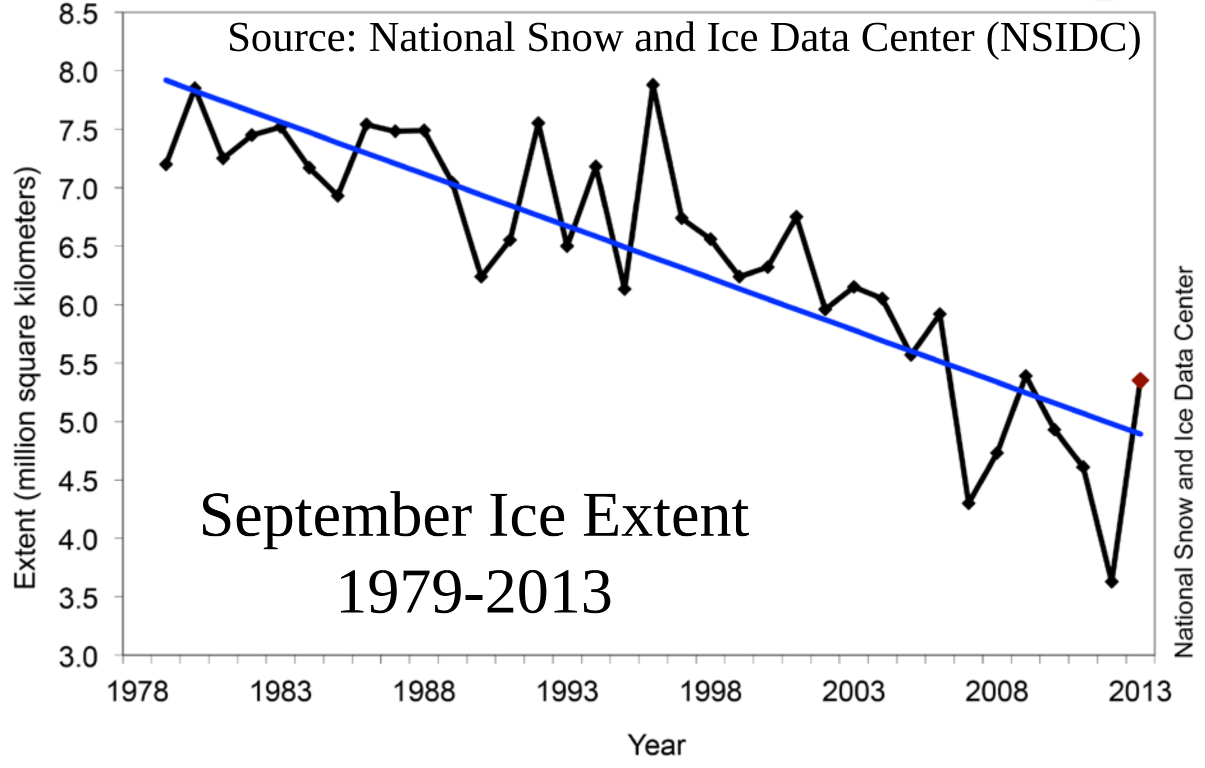
- High albedo affects net SW
- Insulates ocean from atmosphere influencing turbulent heat exchange

Hydrological Cycle



- Ice formation rejects salt
- Ice melt releases freshwater
- Modifies ocean buoyancy flux

Observed Sea Ice Change



Source: National Snow and Ice Data Center (NSIDC)

September Ice Extent
1979-2013

Sept 1979

7.2 million km^2

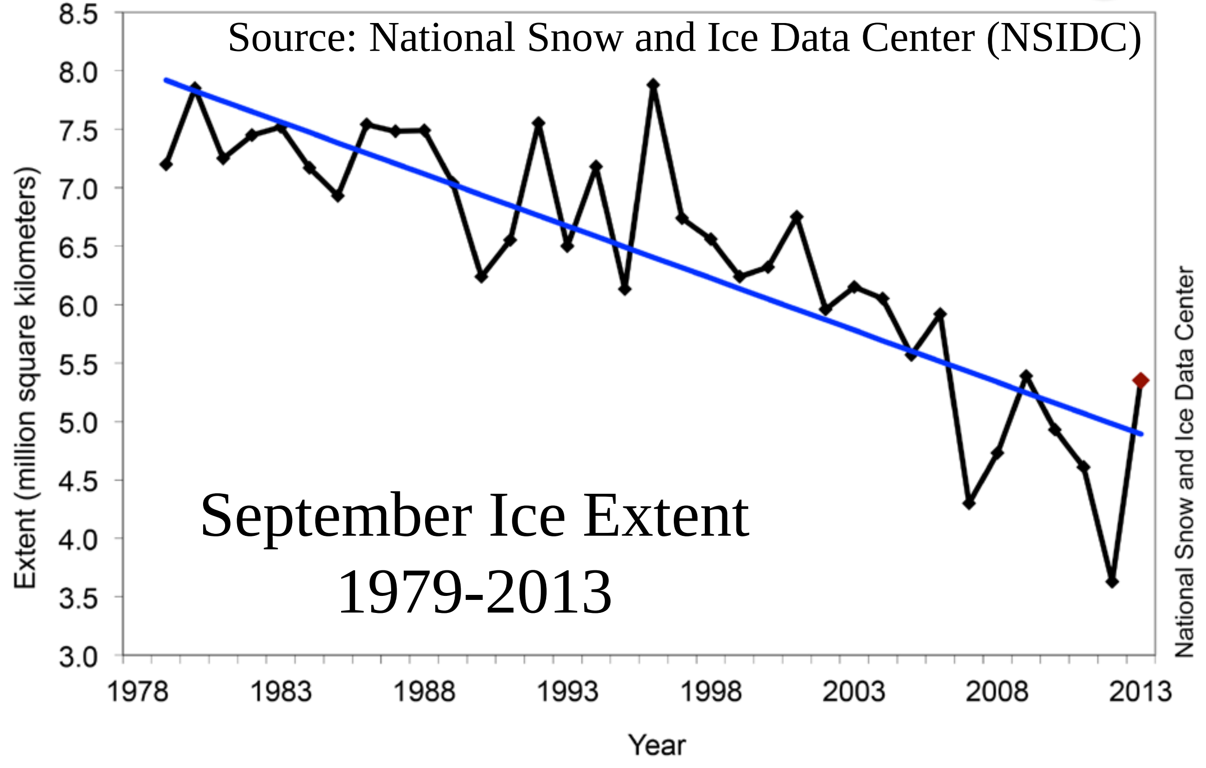
Sept 2012

3.6 million km^2

Since 1980:

- ~40% smaller Sept ice extent
- ~50% thinner ice pack
- Increasingly “younger” ice
- Earlier melt onset

Observed Sea Ice Change



Since 1980:

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- ~50% thinner ice pack
- Increasingly "younger" ice
- Earlier melt onset

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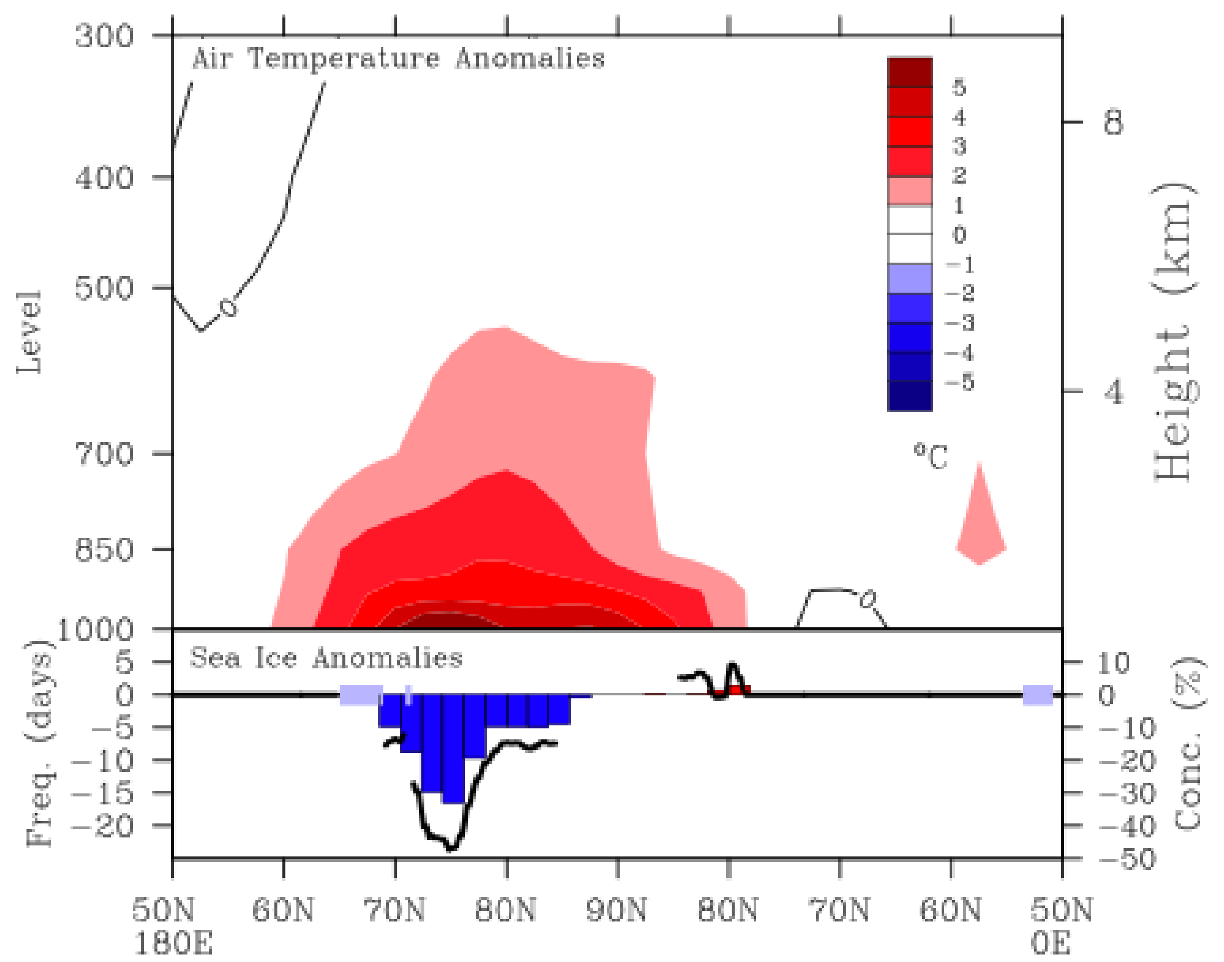
Climate changes associated with sea ice loss Observations of emerging Arctic Amplification

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

Sept Sea Ice Anomalies



(Serreze et al., 2008)

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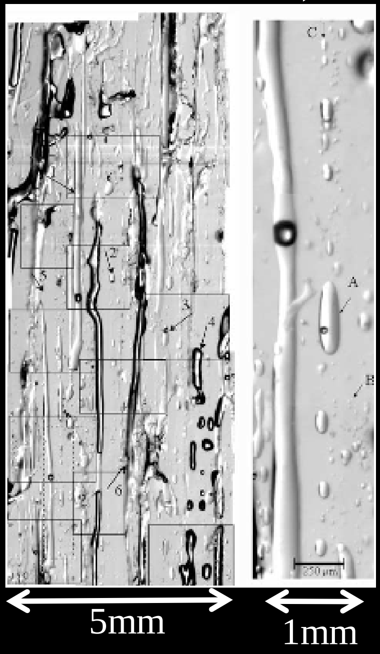
From: Feltham, 2008
(photos by Hajo Eicken)

(from Light, Maykut, Grenfell, 2003)



Sea Ice

- Composed of floes (can freeze to form a continuous cover)
- Typical thickness of meters
- Riddled with cracks and ridges
- Complex mosaic of ice types
- Inclusions of brine, gas, impurities

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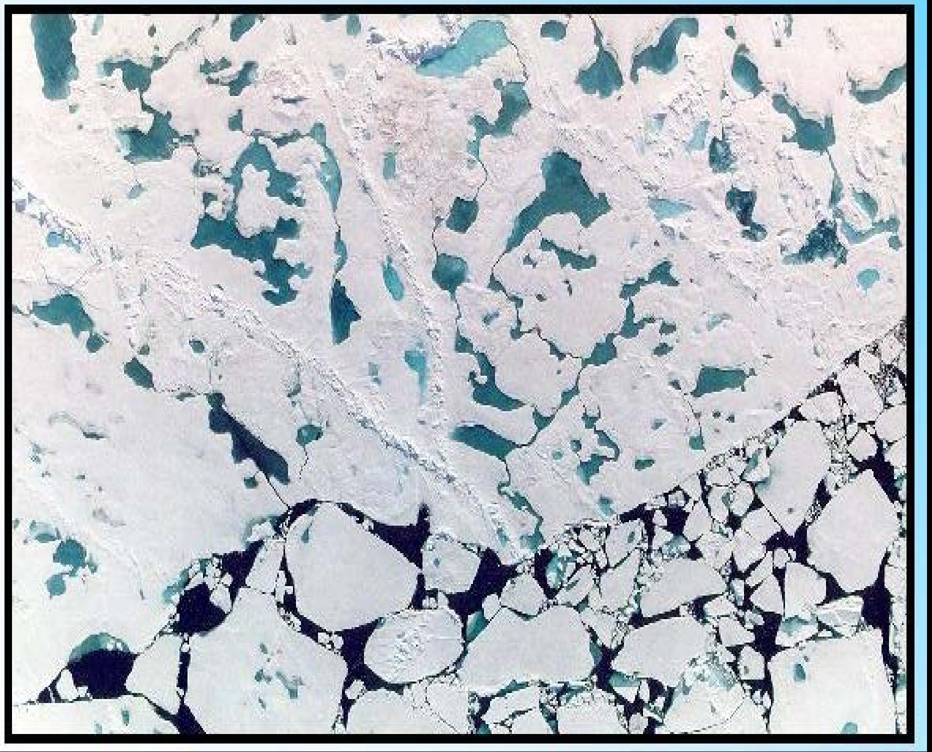
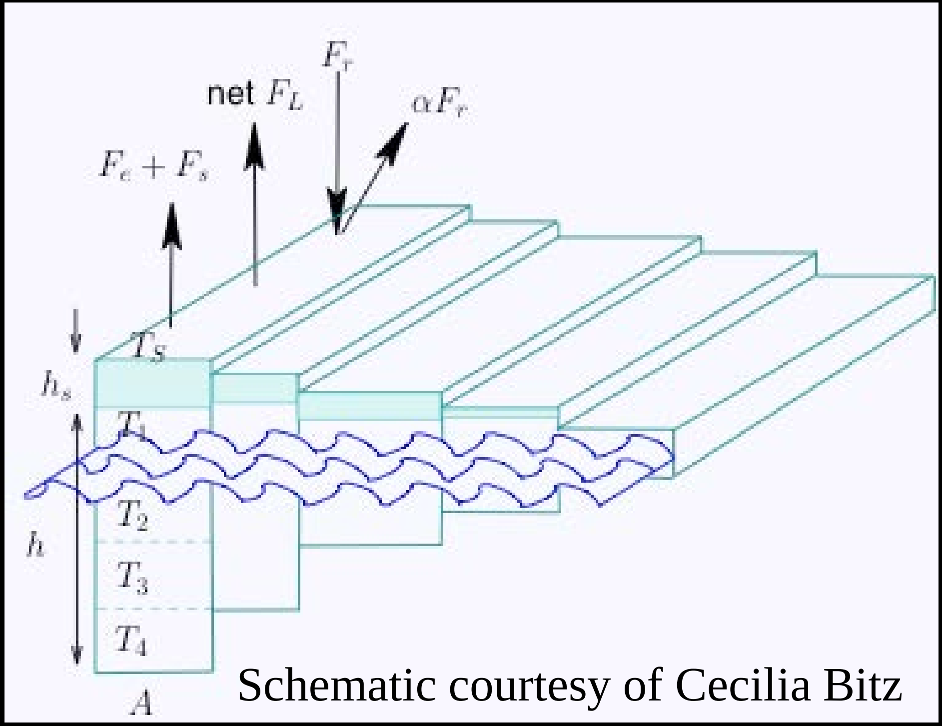
High spatial heterogeneity in sea ice

- Determined by thermodynamics, dynamics and mechanical redistribution (e.g Thorndike et al, 1975)
- Influences surface fluxes, ice mass balance
- Has the potential to modify feedbacks



440 m

Photo courtesy of Don Perovich

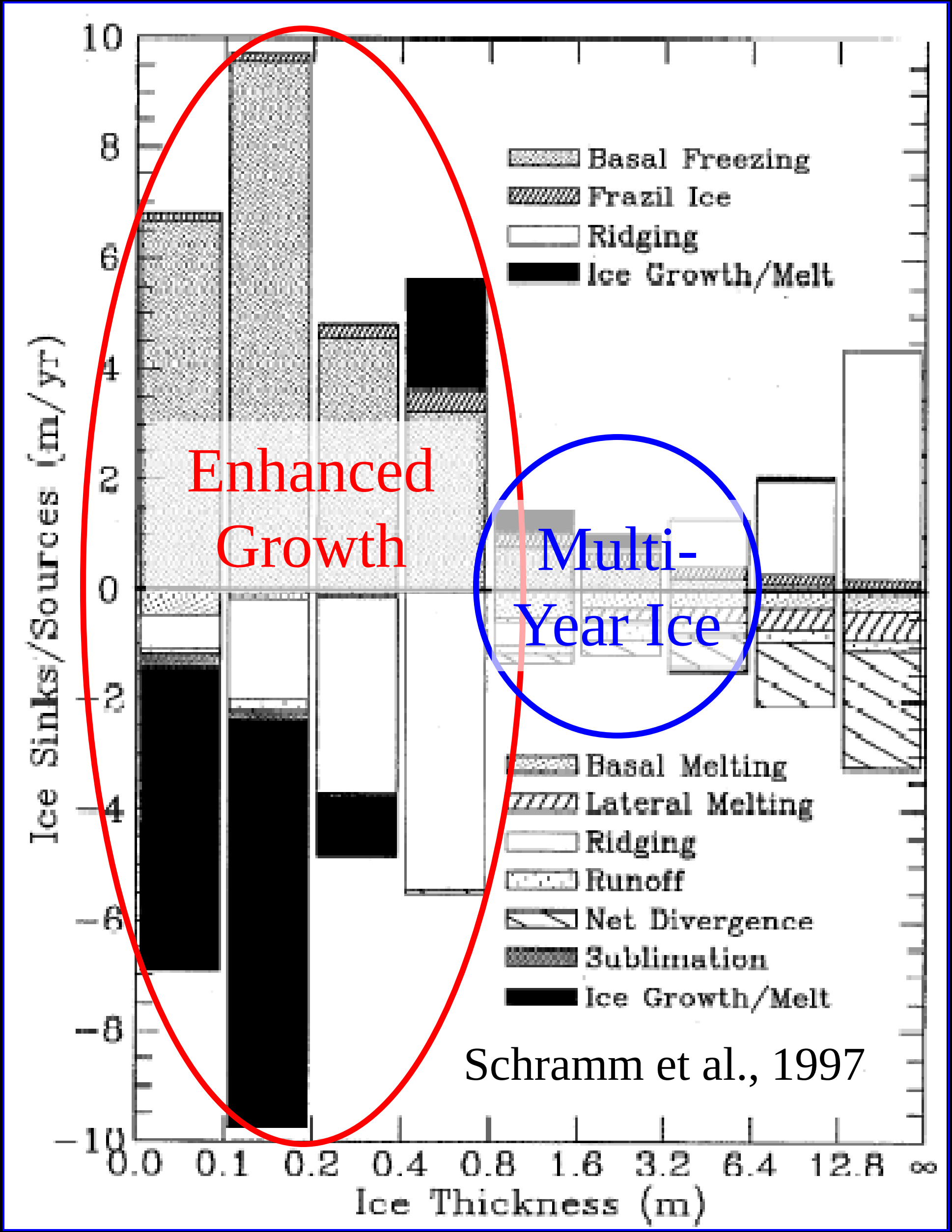


Schematic courtesy of Cecilia Bitz

Collaborators: C. Bitz, E. Hunke, B. Lipscomb, J. Schramm

Influence of including an Ice Thickness Distribution

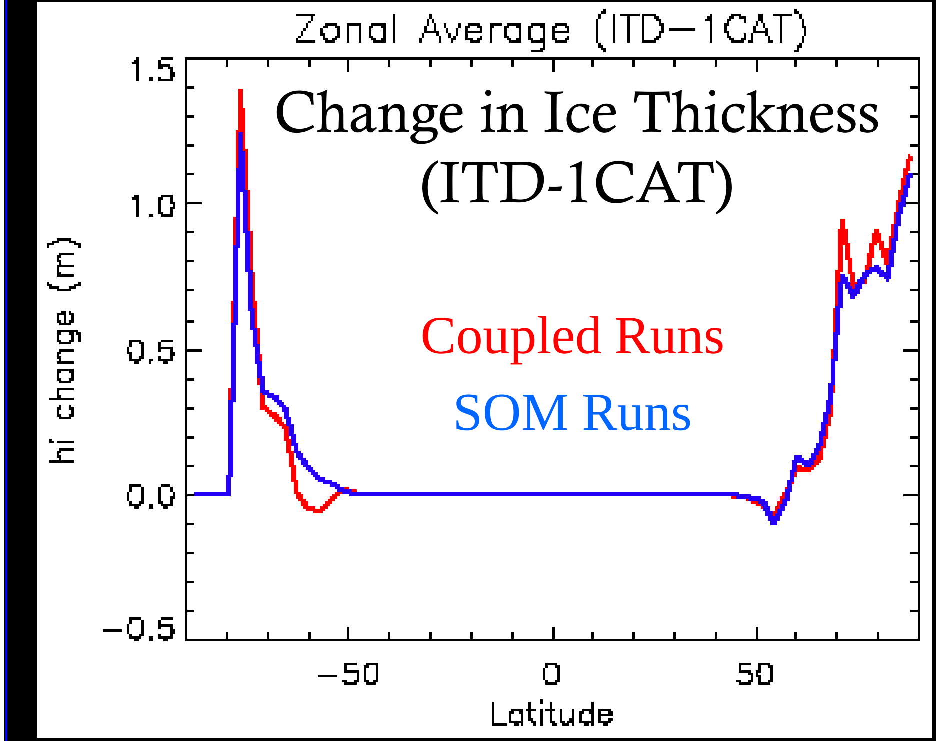
Mean Conditions



Enhanced Growth

Multi-Year Ice

Schramm et al., 1997



Zonal Average (ITD−1CAT)

Change in Ice Thickness (ITD-1CAT)

Coupled Runs

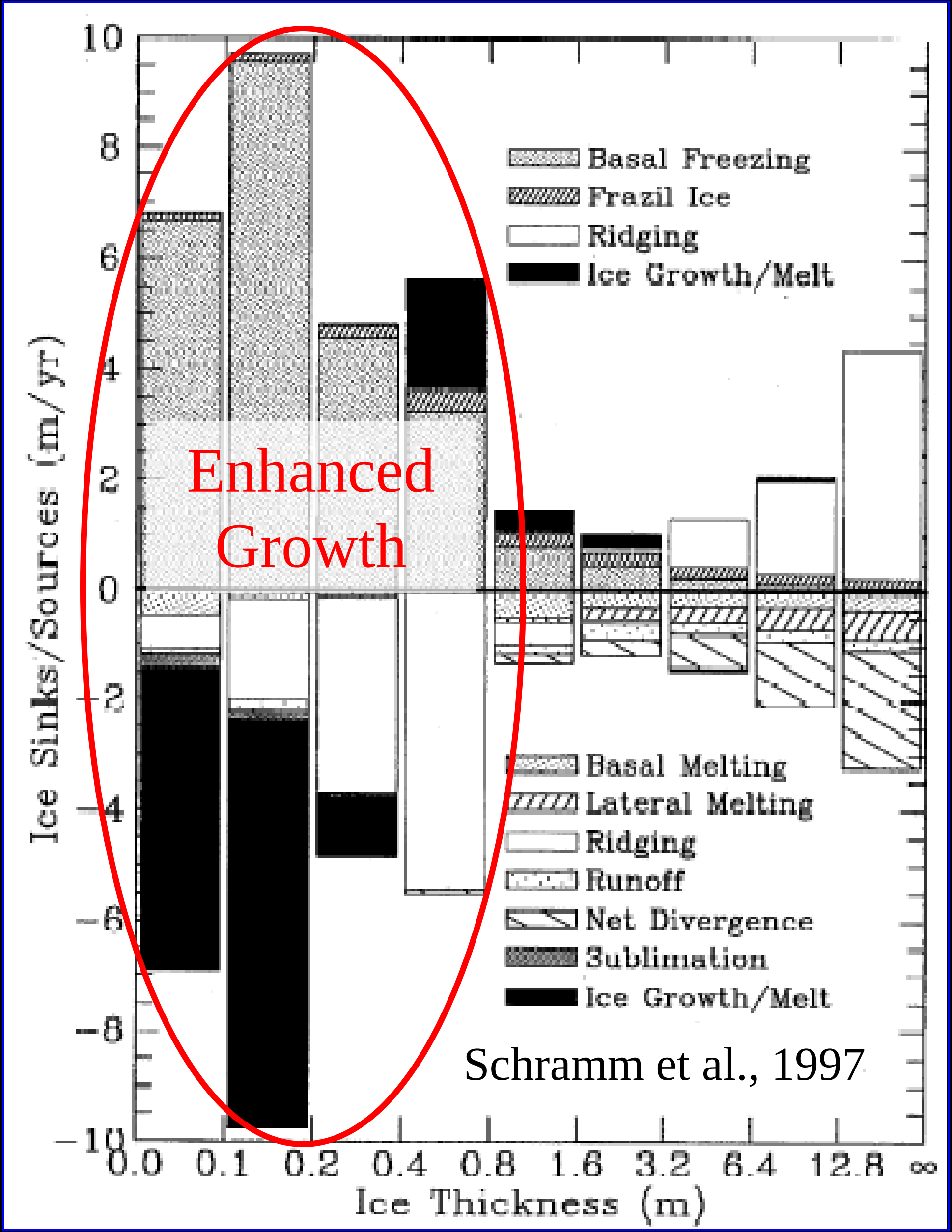
SOM Runs

(Holland et al., 2006)

CCSM3 Results

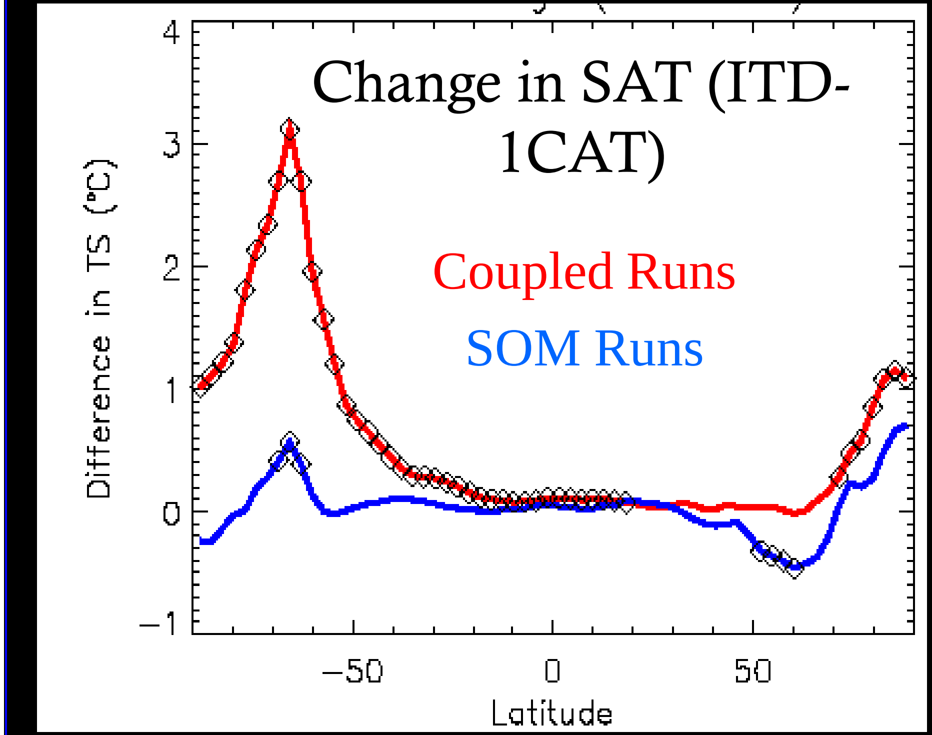
Influence of Ice Thickness Distribution

Mean Conditions



Enhanced Growth

Schramm et al., 1997

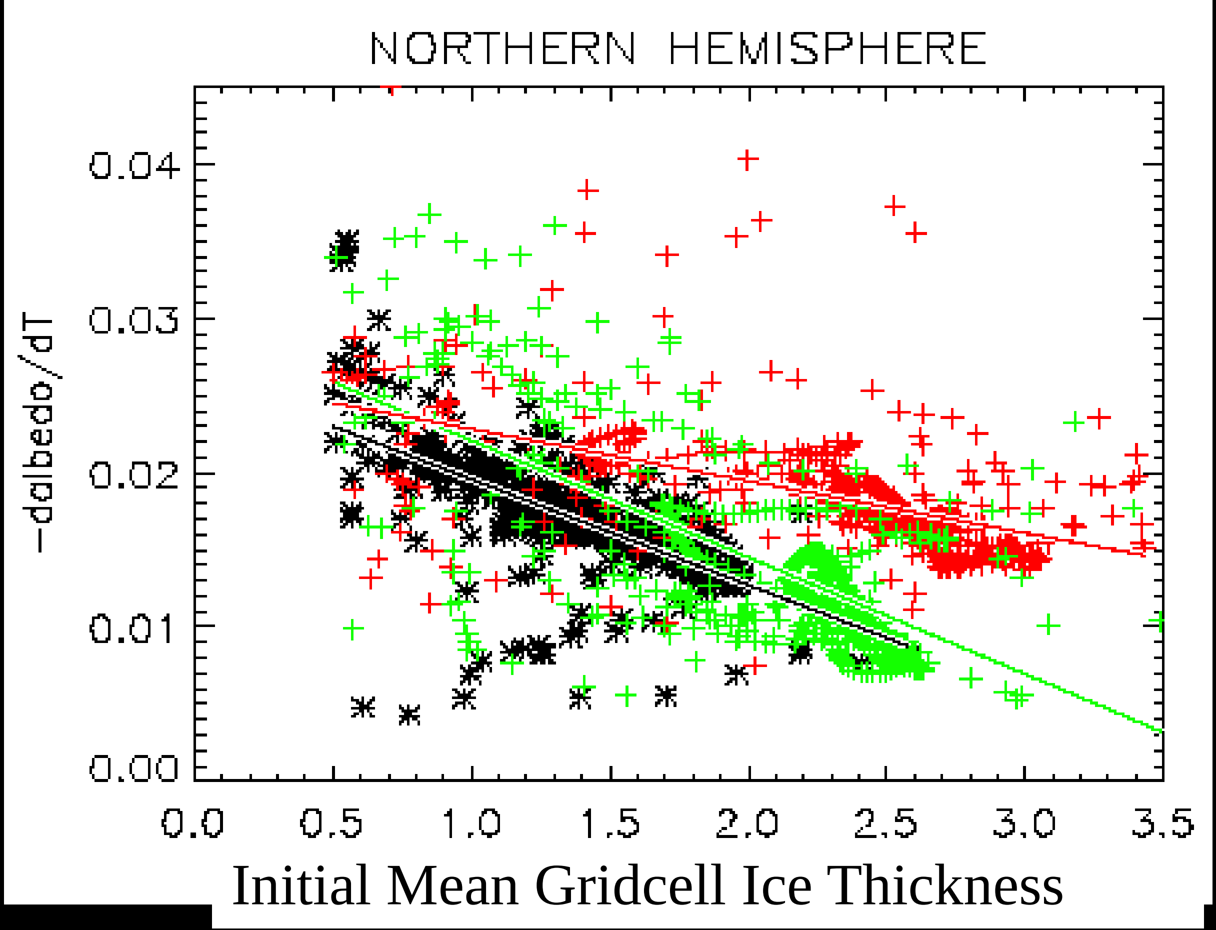

Change in SAT (ITD-1CAT)

(Holland et al., 2006)

Coupled response is larger because ocean heat transport increases

Arctic Surface Albedo Feedback Analysis

Change in surface albedo per temperature change



Response to CO_2 Doubling

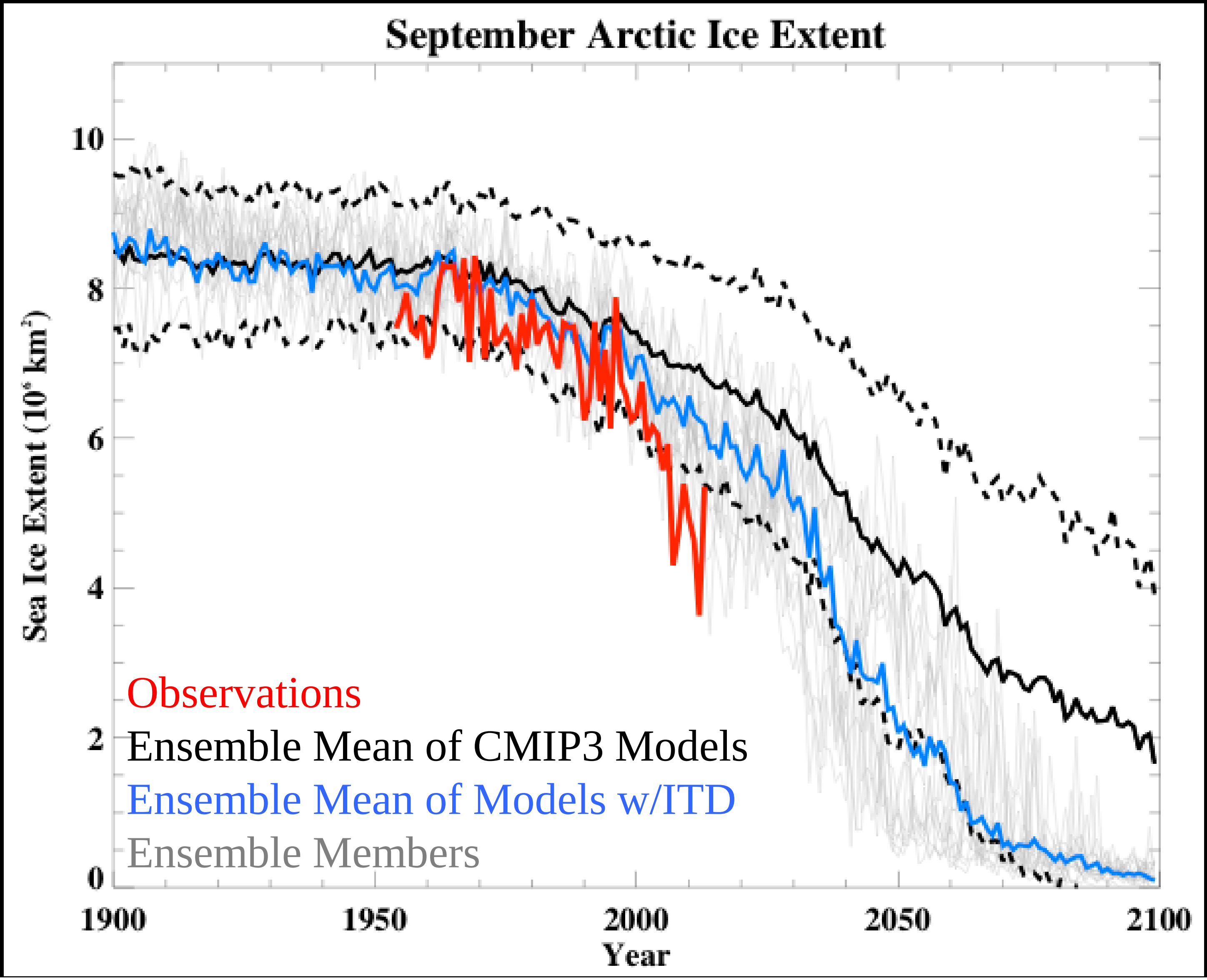
ITD (5 cat)
1 cat.
1cat tuned

Larger albedo change for thinner initial ice

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

Suggests **surface albedo feedback enhanced** with an ITD

CMIP3 Sea Ice Projections



Stroeve, Holland, Meier, Scambos, Serreze, Arctic sea ice decline: Faster than forecast, GRL, 2007

(Figure updated with observations through 2013)

CCSM4/CESM1 Albedo Developments

Collaborators: D. Bailey, B. Briegleb, B. Light, E. Hunke

Melt Pond Parameterization

- Influences radiation
- Pond volume depends on surface meltwater, assuming a runoff fraction

(NASA GSFC, ICESCAPE project)

Black carbon/Dust

- Aerosol deposition/cycling
- Account for black carbon, dust - deposited & modified by melt and transport

(Credit: Mark Dennett, NOAA)

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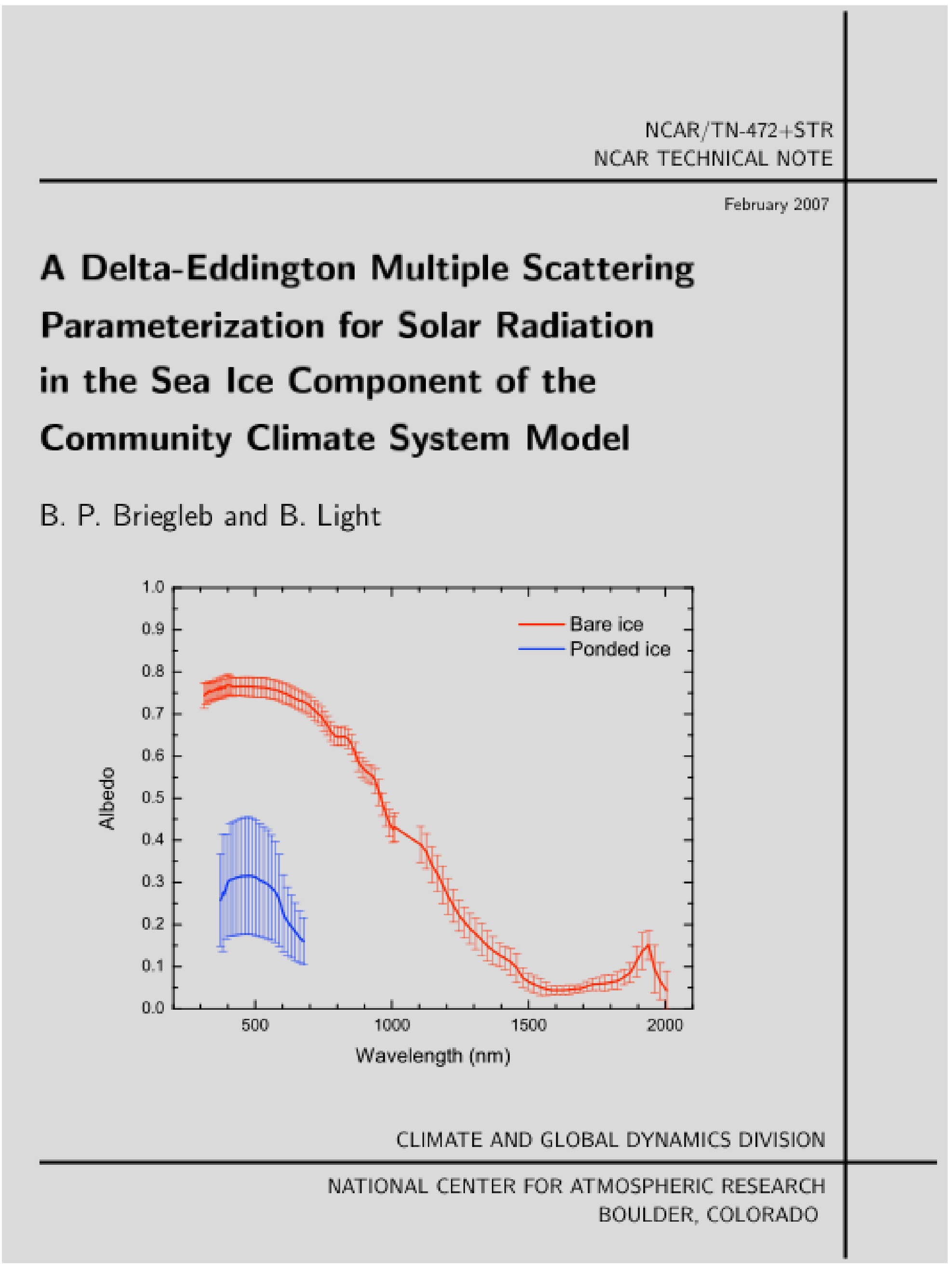
New Solar Radiation parameterization



NCAR/TN-472+STR
NCAR TECHNICAL NOTE

February 2007

A Delta-Eddington Multiple Scattering Parameterization for Solar Radiation in the Sea Ice Component of the Community Climate System Model

B. P. Briegleb and B. Light

CLIMATE AND GLOBAL DYNAMICS DIVISION

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
BOULDER, COLORADO

<u>Better physics:</u>

- makes use of inherent optical properties to define scattering and absorption of snow, sea ice and included absorbers

<u>More flexible</u>

- Explicitly allows for included absorbers (black carbon, dust, algae, ponds, etc.)

Radiative Forcing - Ponds

Radiative Forcing in sea ice defined as

$$R_{SW} = SW_A - SW_X$$

Net Shortwave All Surfaces

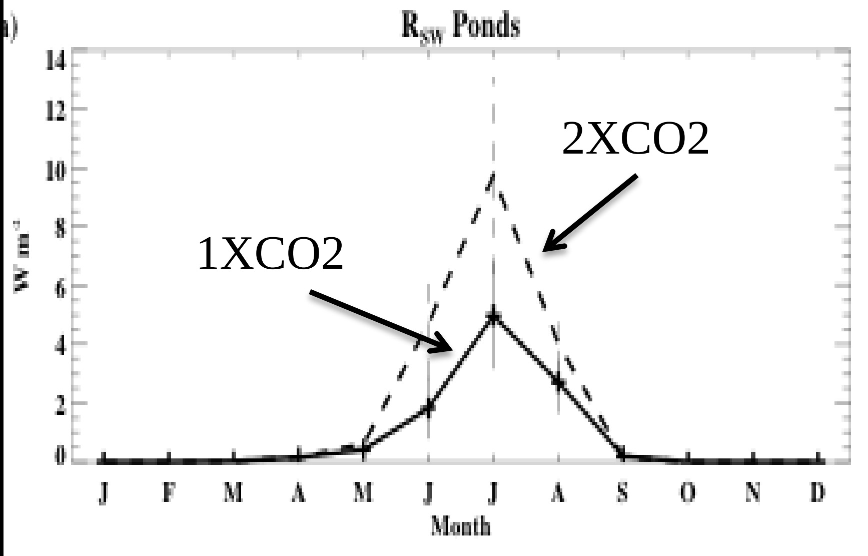
Net Shortwave Excluding Ponds

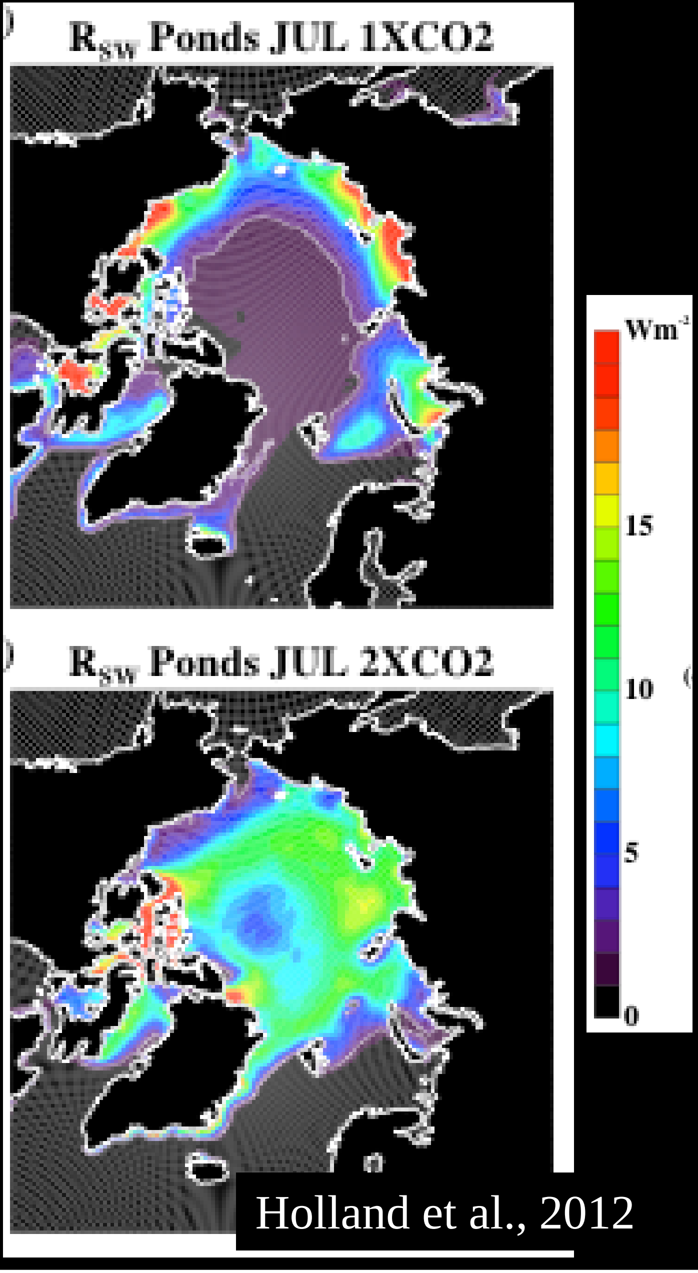
Ponds account for:

5/10 W/m^2 (1X/2XCO$_2$) Arctic avg July SW$_{net}$

Regionally, values can reach 20 W/m^2 (in July)

Forcing larger in 2XCO2 climate





Holland et al., 2012

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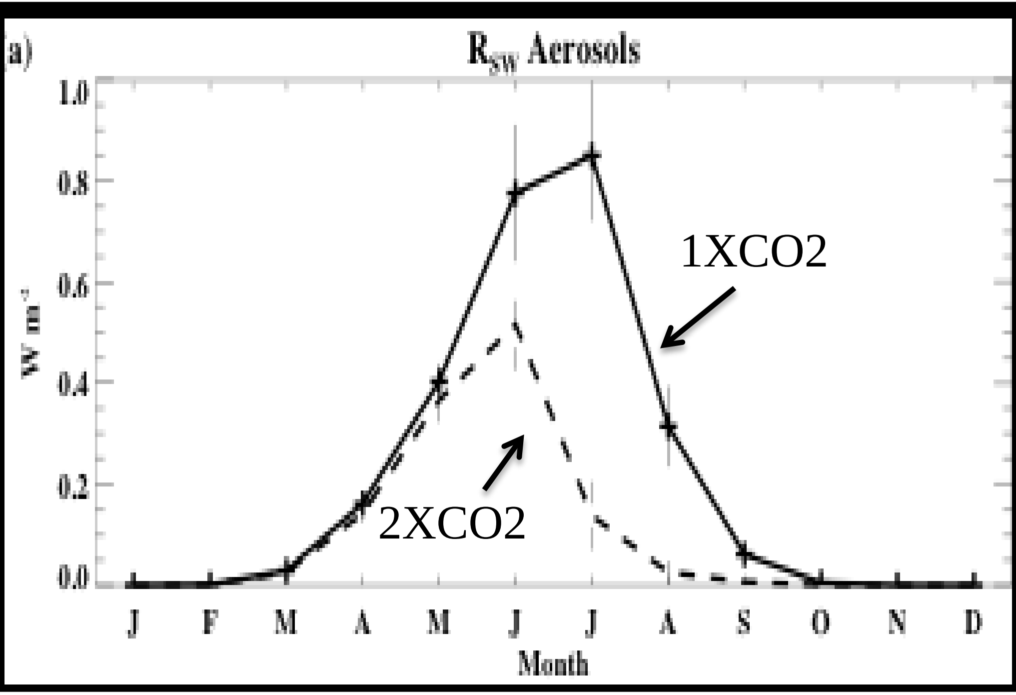
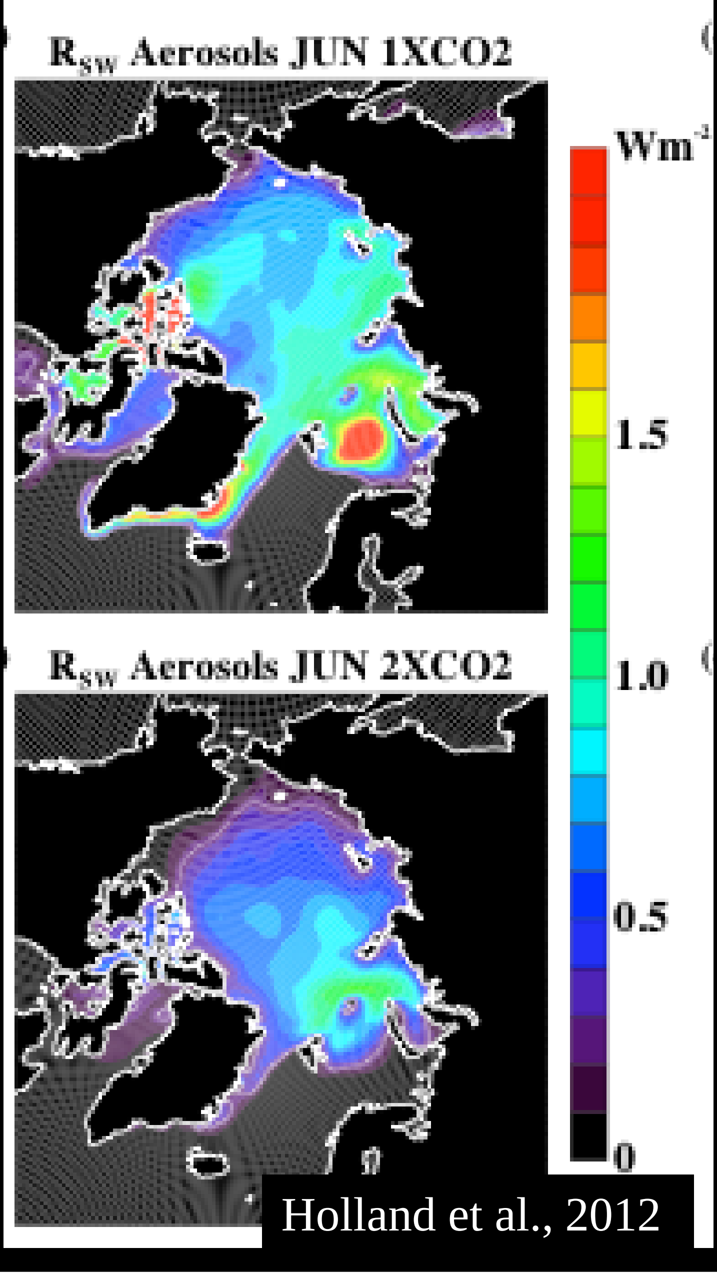
Radiative Forcing - Aerosols

Aerosols on sea ice (with 1850 deposition) account for:

- <1 W/m^2 Arctic Avg SW$_{net}$ for all months
- Regionally, values can reach 2 W/m^2 (in June, 1XCO$_2$)
- Aerosol forcing larger in 1XCO$_2$ climate





Holland et al., 2012

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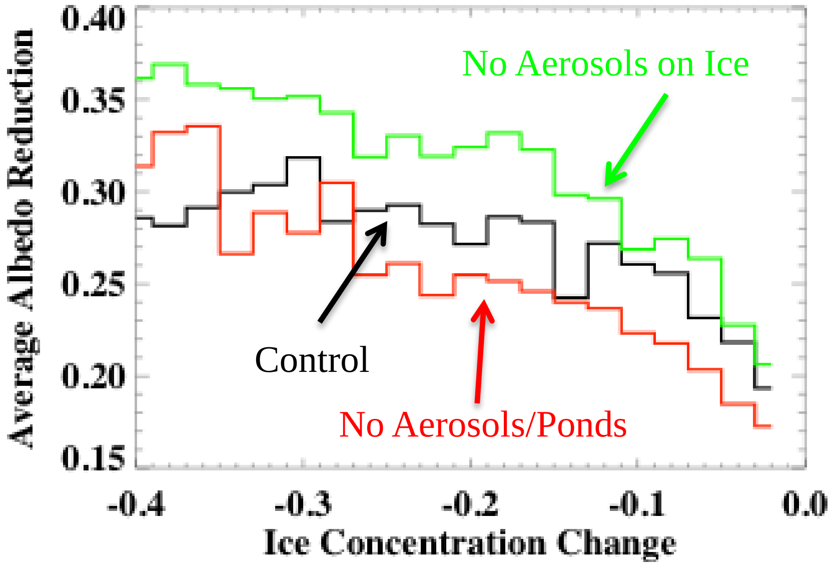
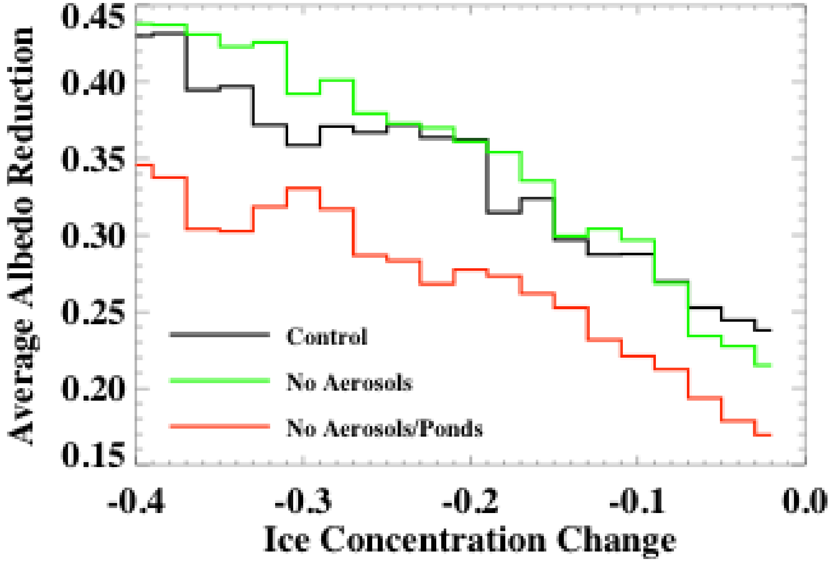
Surface Albedo Response

$2XCO_2$-$1XCO_2$

(a) July



(b) August



For regions with the same ice area change

July/August albedo change **larger when ponds included**

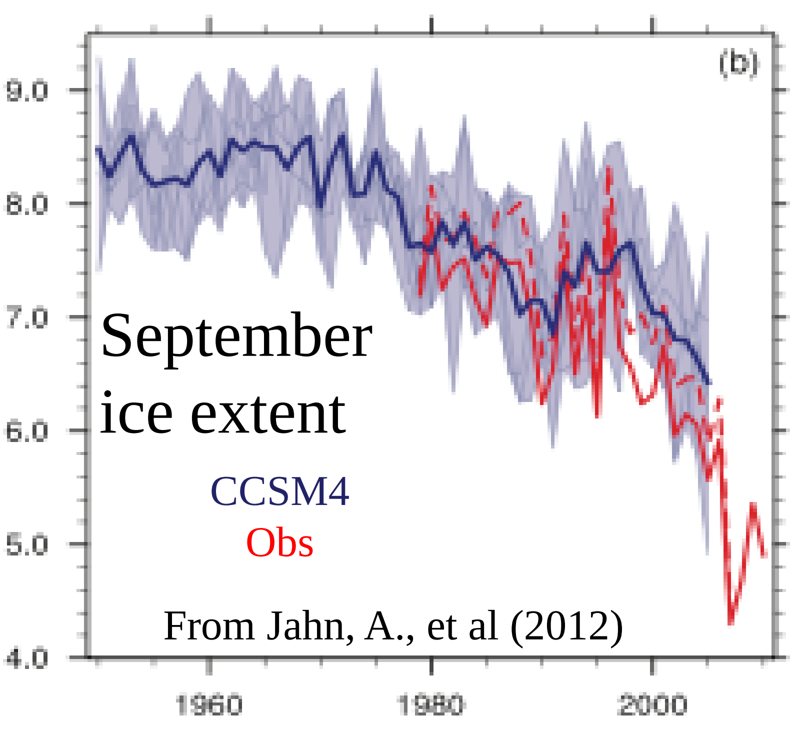
- Increased ponding in warm climate
- Stronger albedo feedback

July albedo change **smaller when aerosols included**

- Increased meltwater flushing of aerosols in warmer climate
- Weaker albedo feedback

Holland et al., 2012

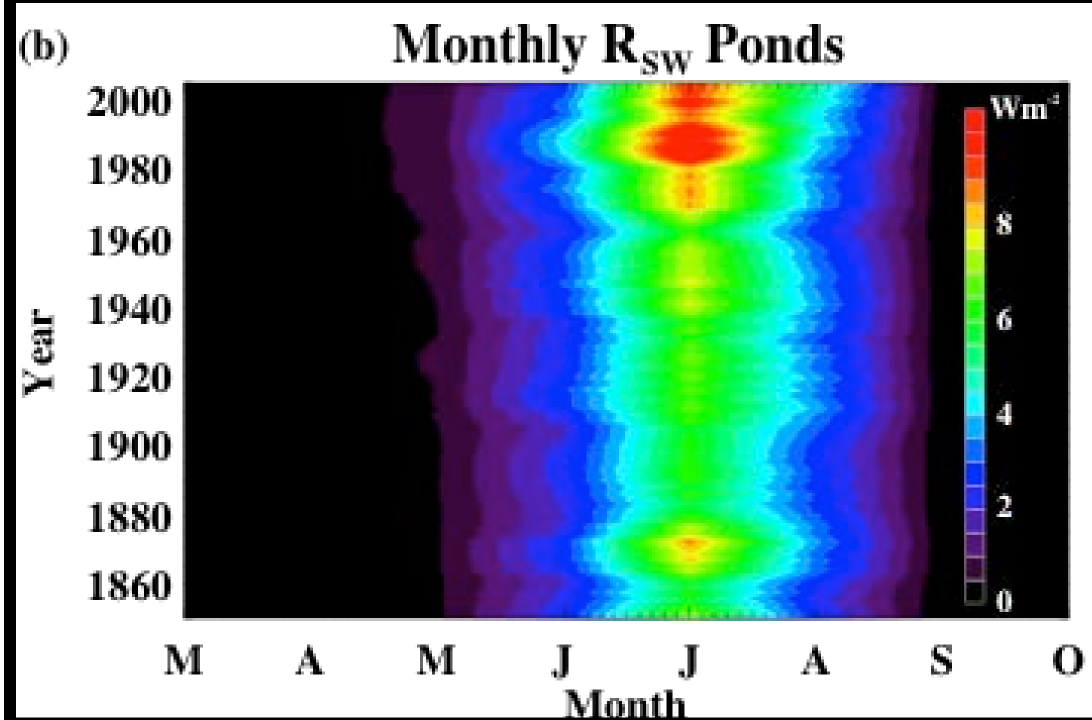
20th Century Change



From Jahn, A., et al (2012)

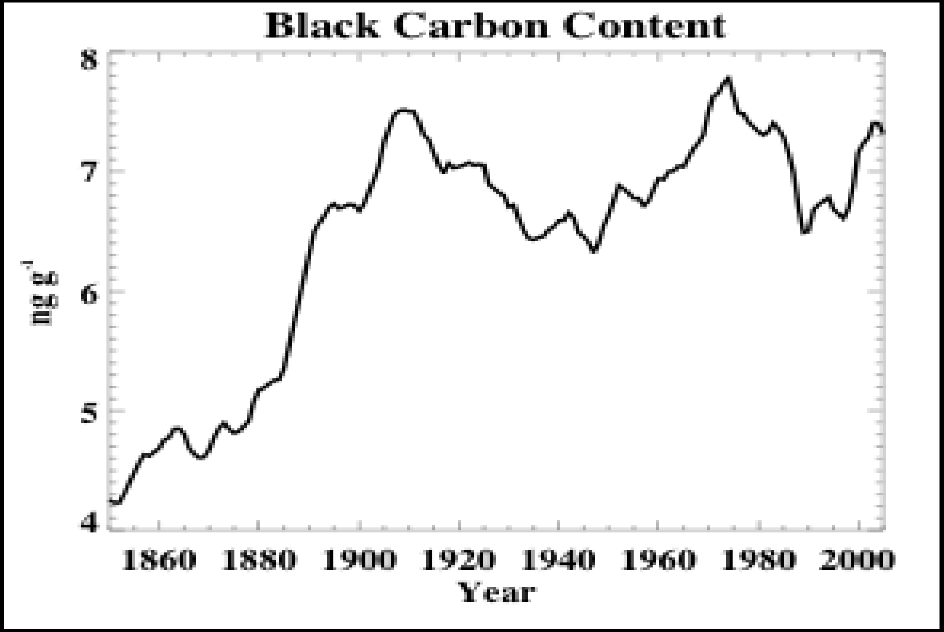
Solid red=NSIDC ice index
Dashed red from Comiso, 1999

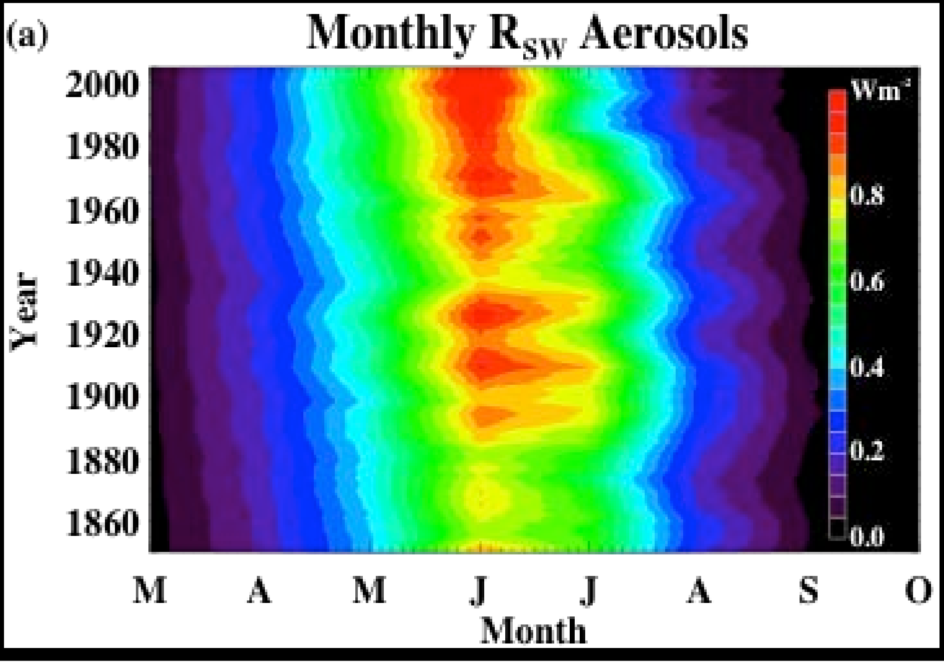
CCSM4 simulates significant Arctic ice loss over 20th century



With increased surface ice melt

- Melt pond concentrations increase
- Causing larger radiative forcing
- By 2000, ponds account for ~10 W/m^2 radiative forcing in July





20th Century Change – Black Carbon

Over 20th century on Arctic sea ice:

- Little secular black carbon content change after 1900
- Increased aerosol deposition balanced by increased meltwater flushing
- Aerosol forcing reaches ~1 W/m^2 in June by 2000

Holland et al., 2012

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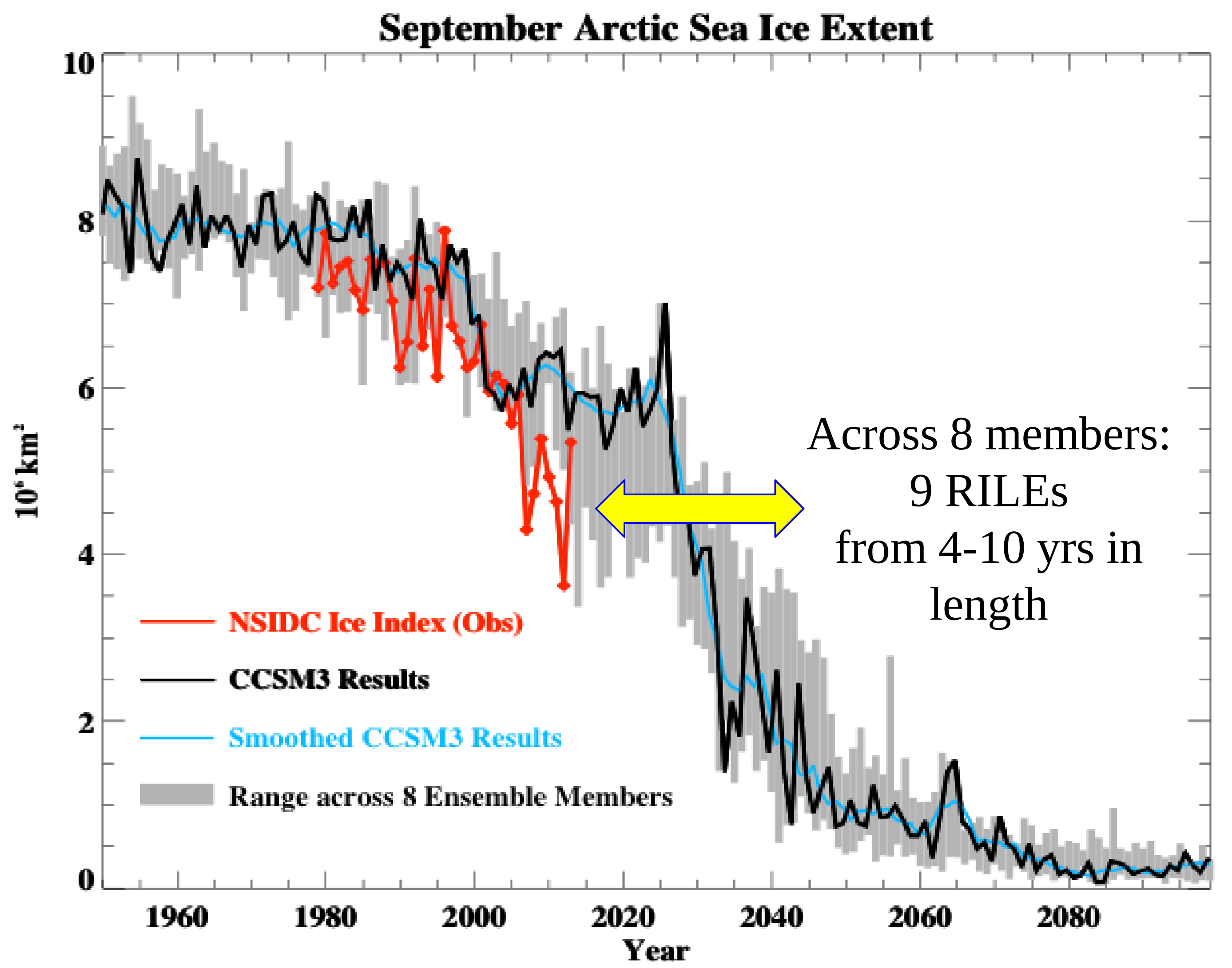
Understanding future ice loss

Role of intrinsic variability in midst of forced change



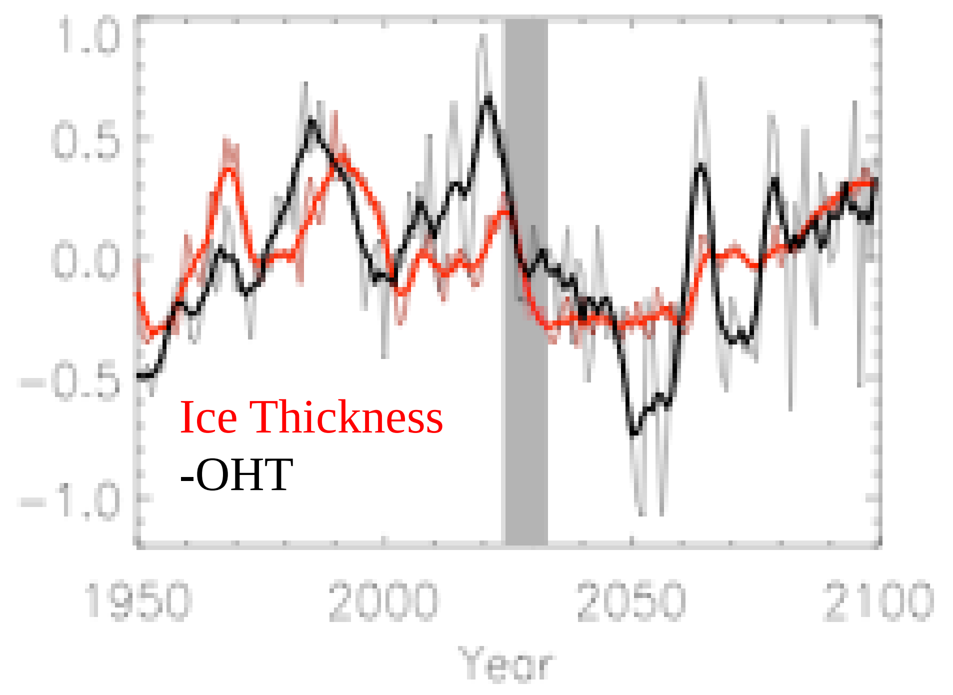
Across 8 members:
9 RILEs
from 4-10 yrs in
length

Rapid Ice
Loss Events
(RILEs)
in CCSM3

Updated from:
Holland, Bitz
and Tremblay
2006

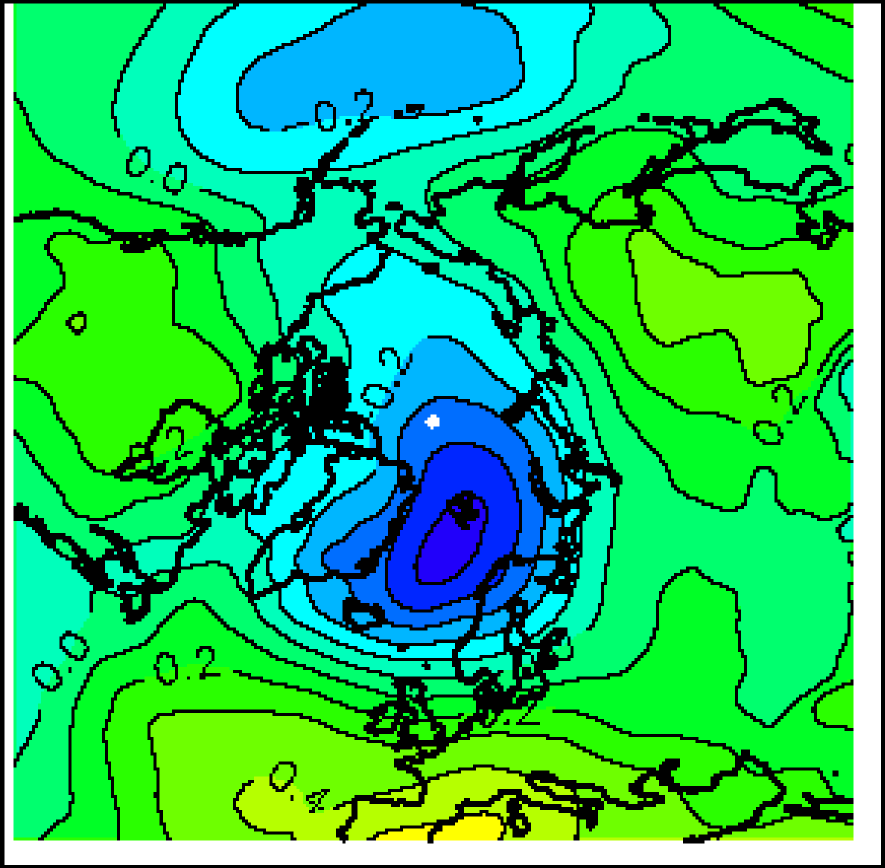
Understanding future ice loss

Role of intrinsic variability in midst of forced change



(Holland et al., 2006; Holland et al, 2008)

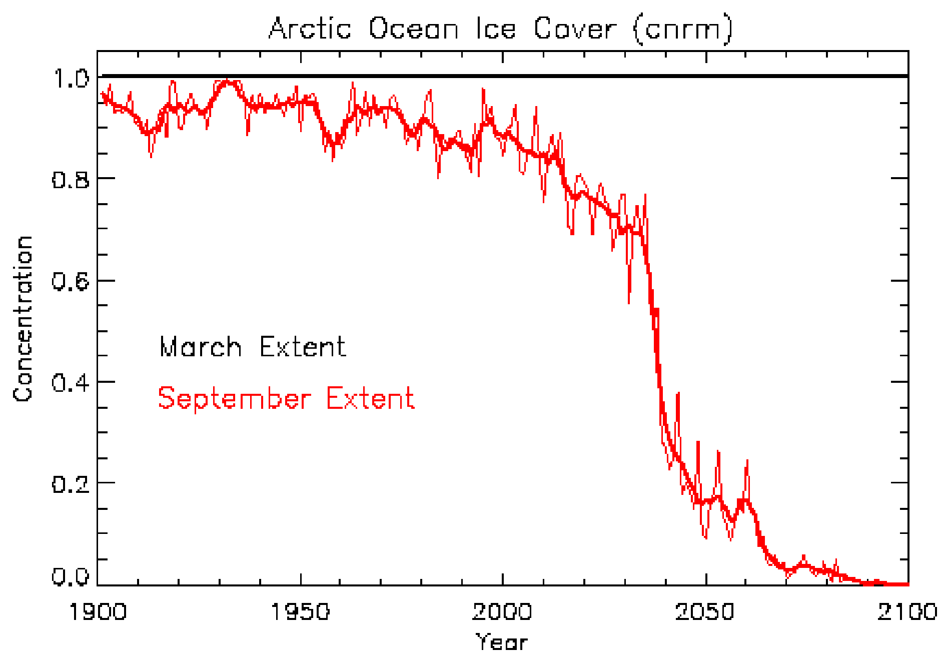
Correlation of detrended PSL with detrended Arctic OHT



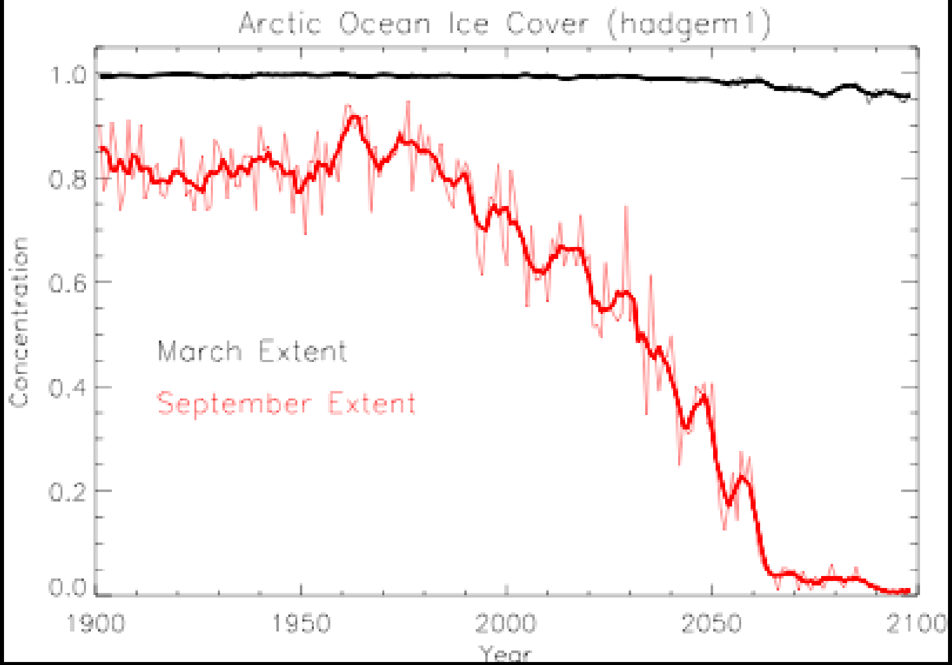
2000-2050; 8 ensemble members

Do other models simulate RILEs?

Some do…



Some don't…



From an analysis of 15 additional CMIP3 models:

- 50% of them simulate RILEs for some future forcing scenario.
- Rapid ice loss is more likely in simulations with higher anthropogenic forcing.

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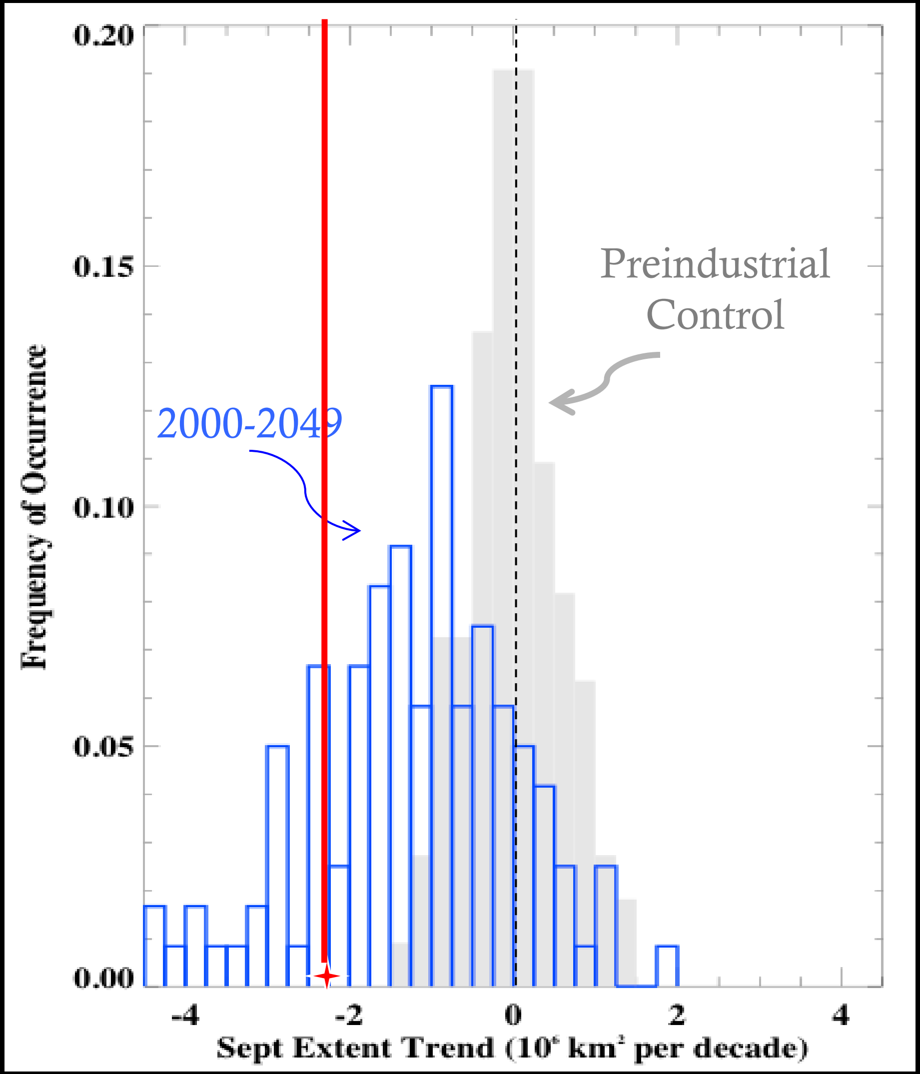
Future decadal Arctic sea ice variations



Results from CESM LE

(non-overlapping trends)

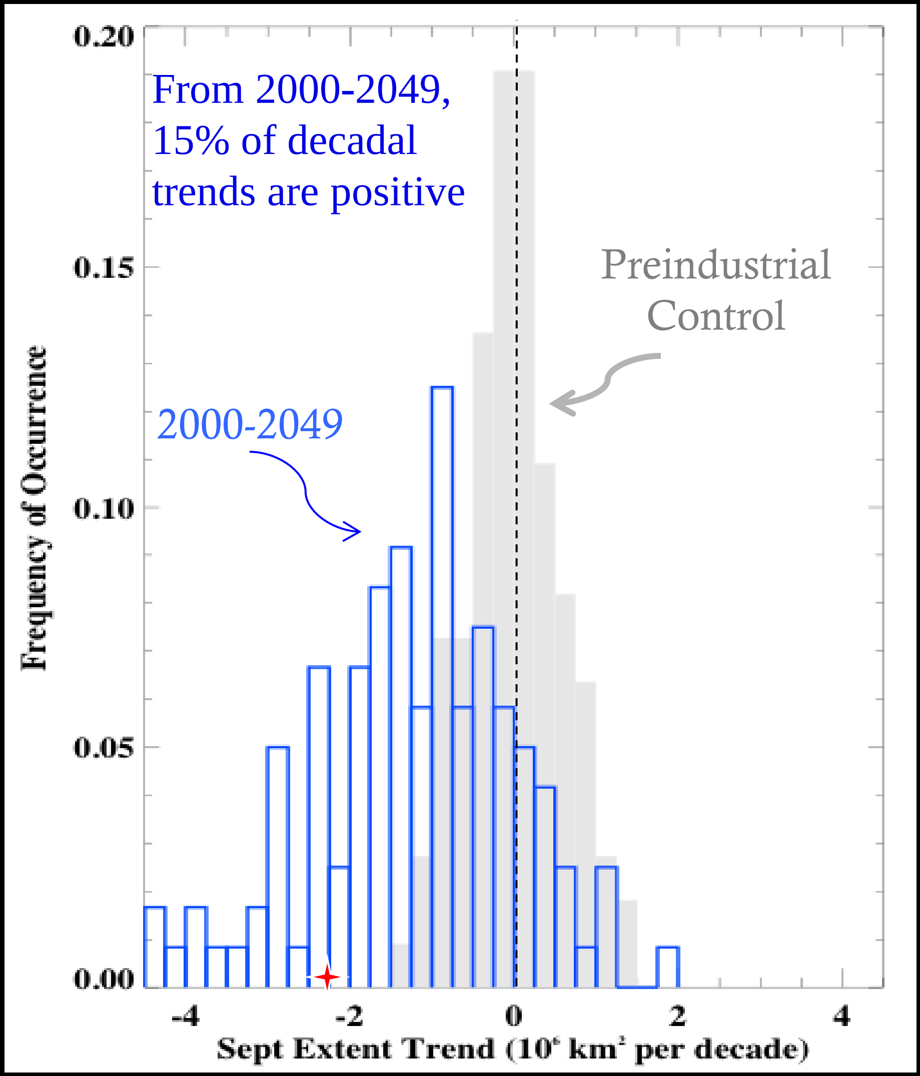
Collaborators: A. Jahn, J. Kay

Minimum observed decadal trend

- outside pre-industrial control distribution
- smaller than ~20% of simulated 2000-2049 trends

See also Kay et al., 2011

Future decadal Arctic sea ice variations


From 2000-2049, 15% of decadal trends are positive

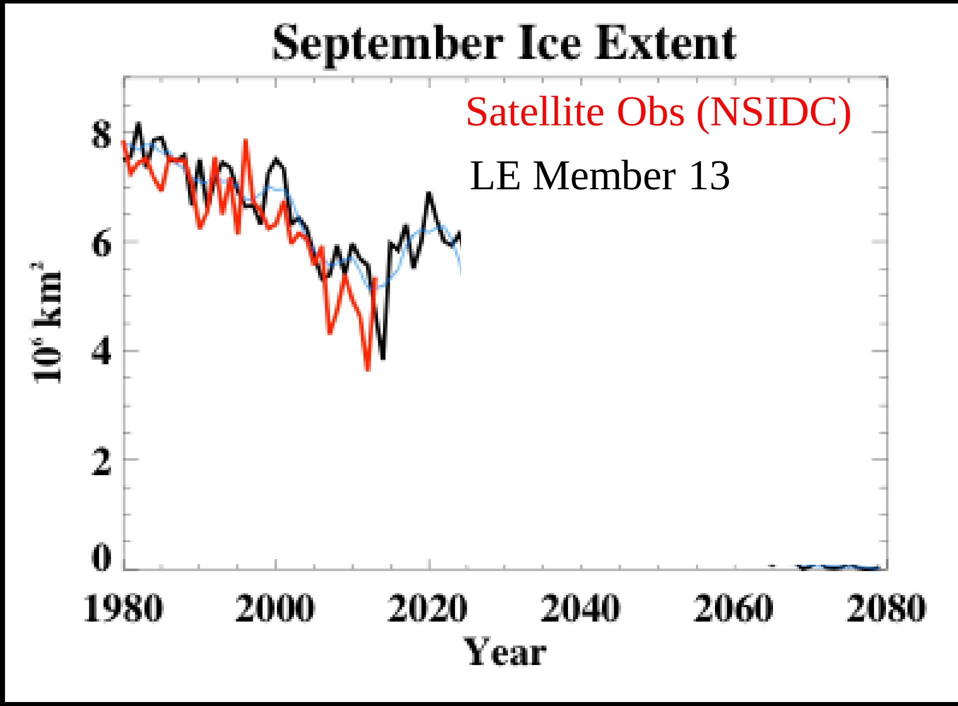
Preindustrial Control

2000-2049

Results from CESM LE

(non-overlapping trends)

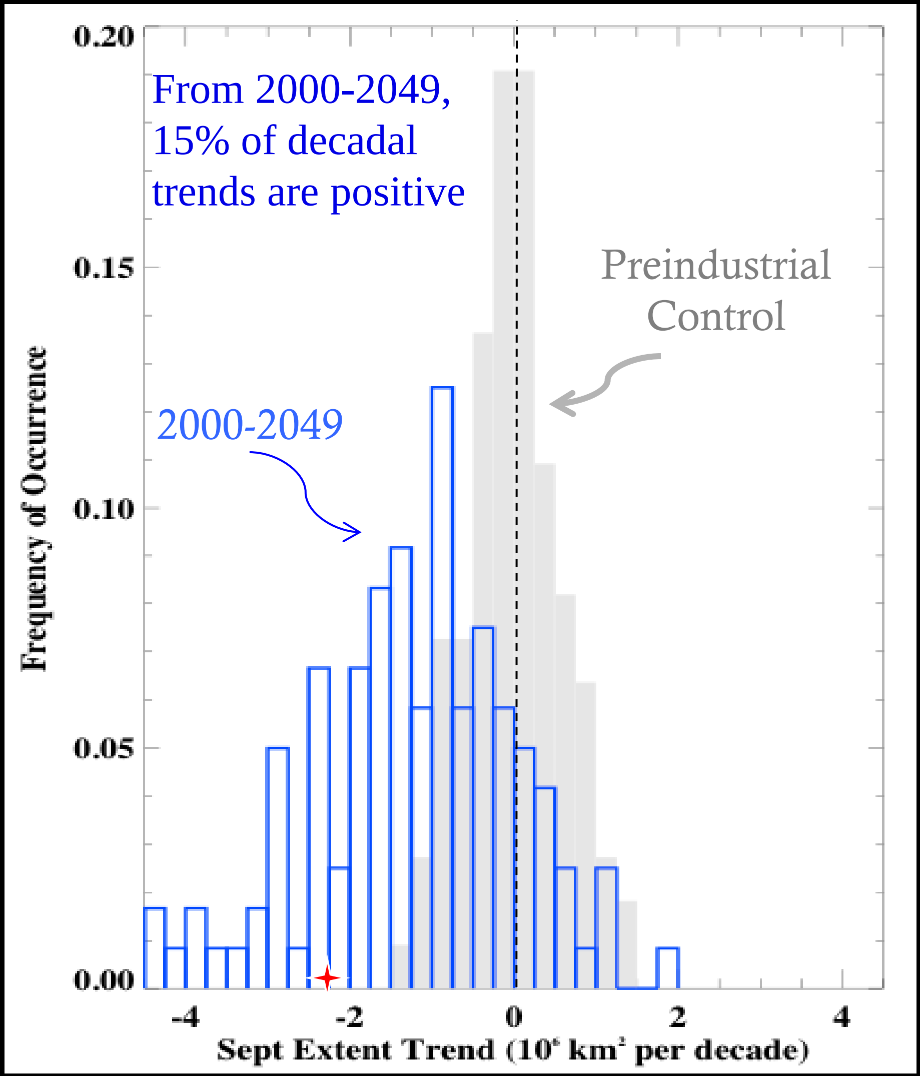
Collaborators: A. Jahn, J. Kay



While RILEs occur, decadal increases are also to be expected in a warming world

See also Kay et al., 2011

Future decadal Arctic sea ice variations



From 2000-2049, 15% of decadal trends are positive

Results from CESM LE

(non-overlapping trends)

Collaborators: A. Jahn, J. Kay

Initial analysis suggests no common relationship to major modes of variability during ice loss interruptions

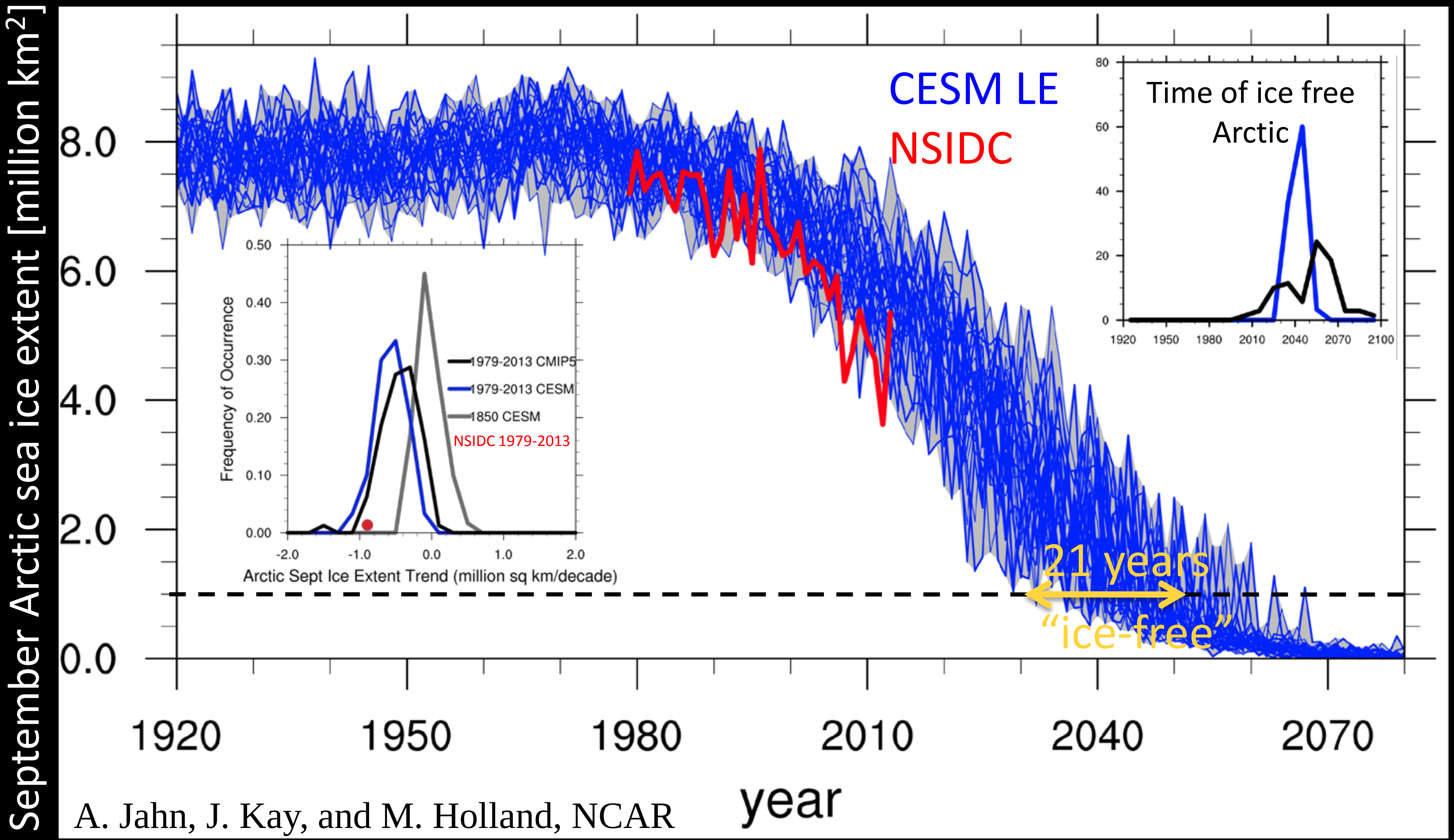
Suggests that many different processes can drive decadal-scale variations in the Arctic sea ice

While RILEs occur, decadal increases are also to be expected in a warming world

See also Kay et al., 2011

Sources of Uncertainty in Future Change

CESM Large Ensemble



A. Jahn, J. Kay, and M. Holland, NCAR

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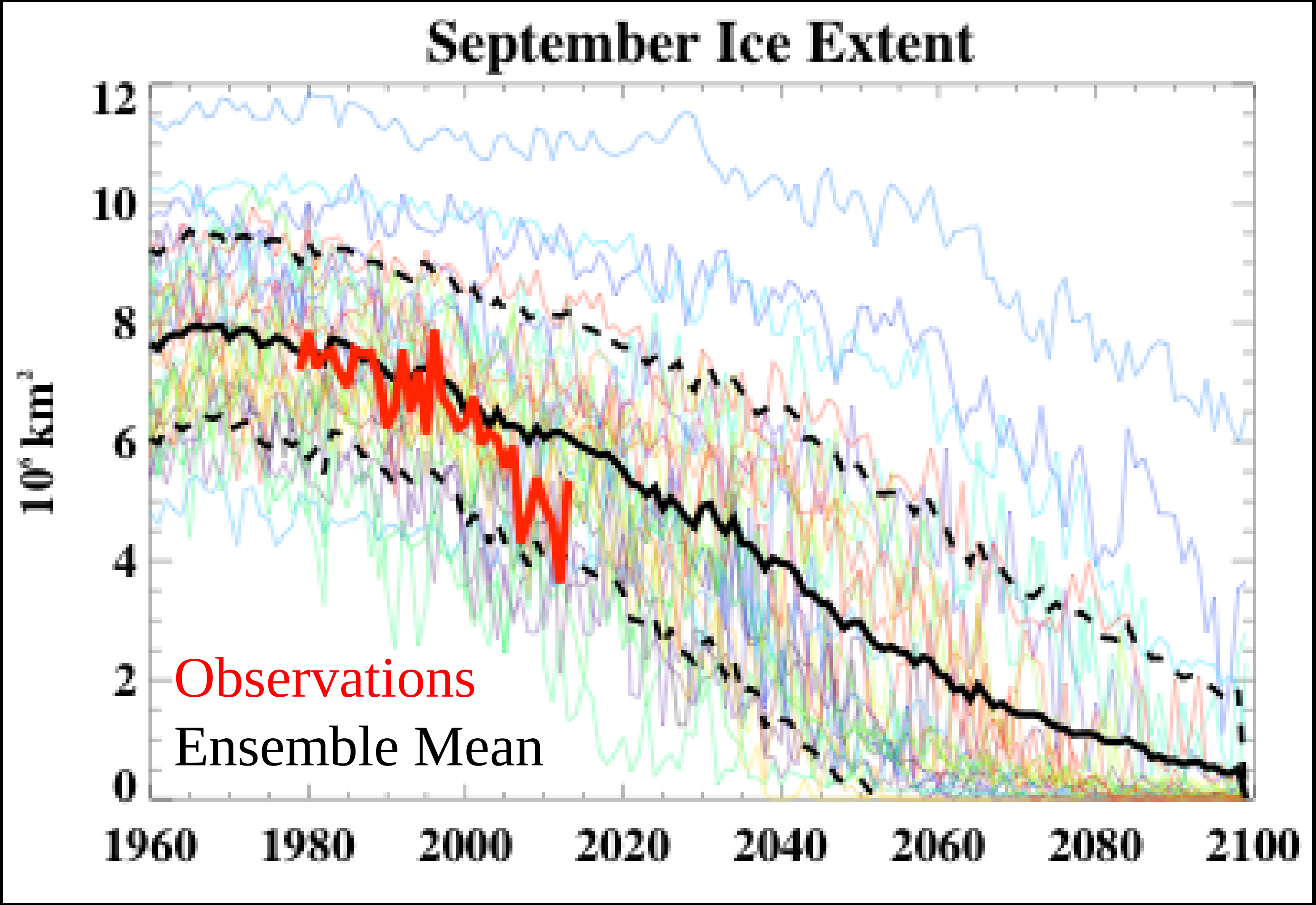
Sources of Uncertainty in Future Change

CMIP5 Multi-model Ensemble



CMIP5
RCP8.5

(Timeseries courtesy of Andy Barrett and Julienne Stroeve, NSIDC)

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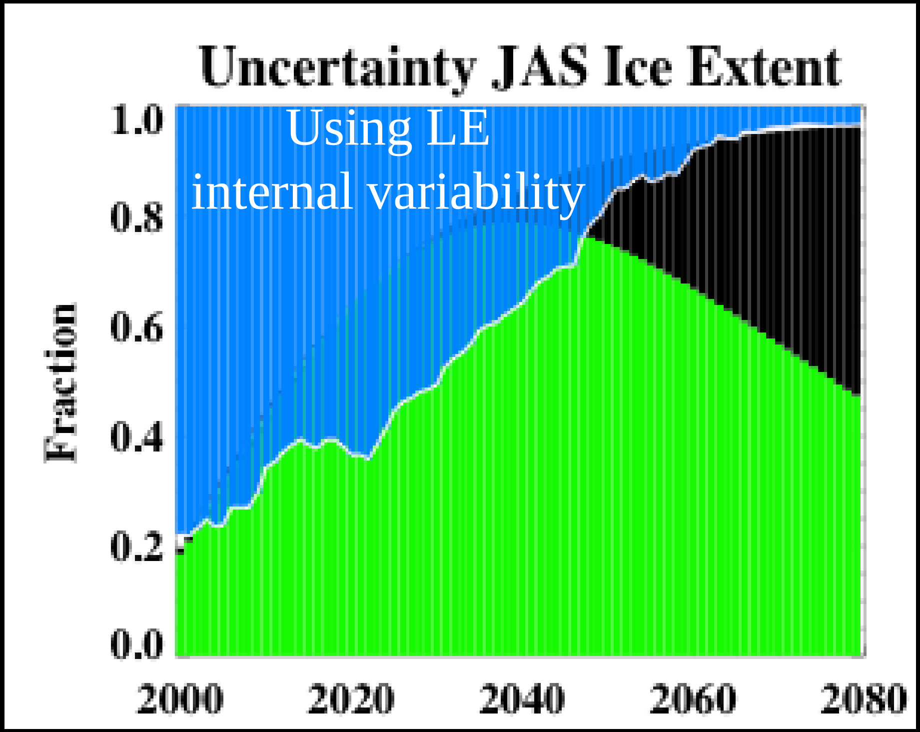
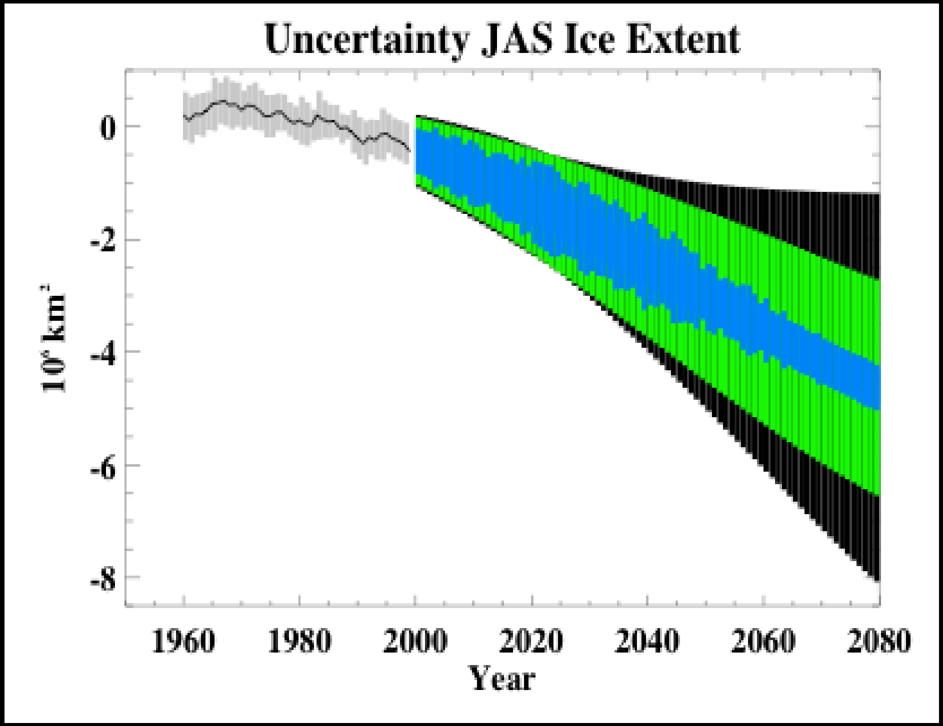
Sources of Uncertainty in Future Change





Uncertainty in future change in JAS Ice Extent relative to 2000 from:

Internal (Natural) Variability
Model Structure
Forcing Scenario

(Following the method of Hawkins and Sutton, 2009)

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Summary

- Sea ice model developments have improved the simulation of polar feedbacks within CESM
  - Ongoing sea ice developments are underway that will further enhance our predictive capability
- The availability of large ensemble simulations has enhanced our understanding of sources of uncertainty in future predictions
  - For Arctic sea ice, natural variability is considerable on multi-decadal timescales and limits the predictability of various aspects of sea ice loss

Questions?

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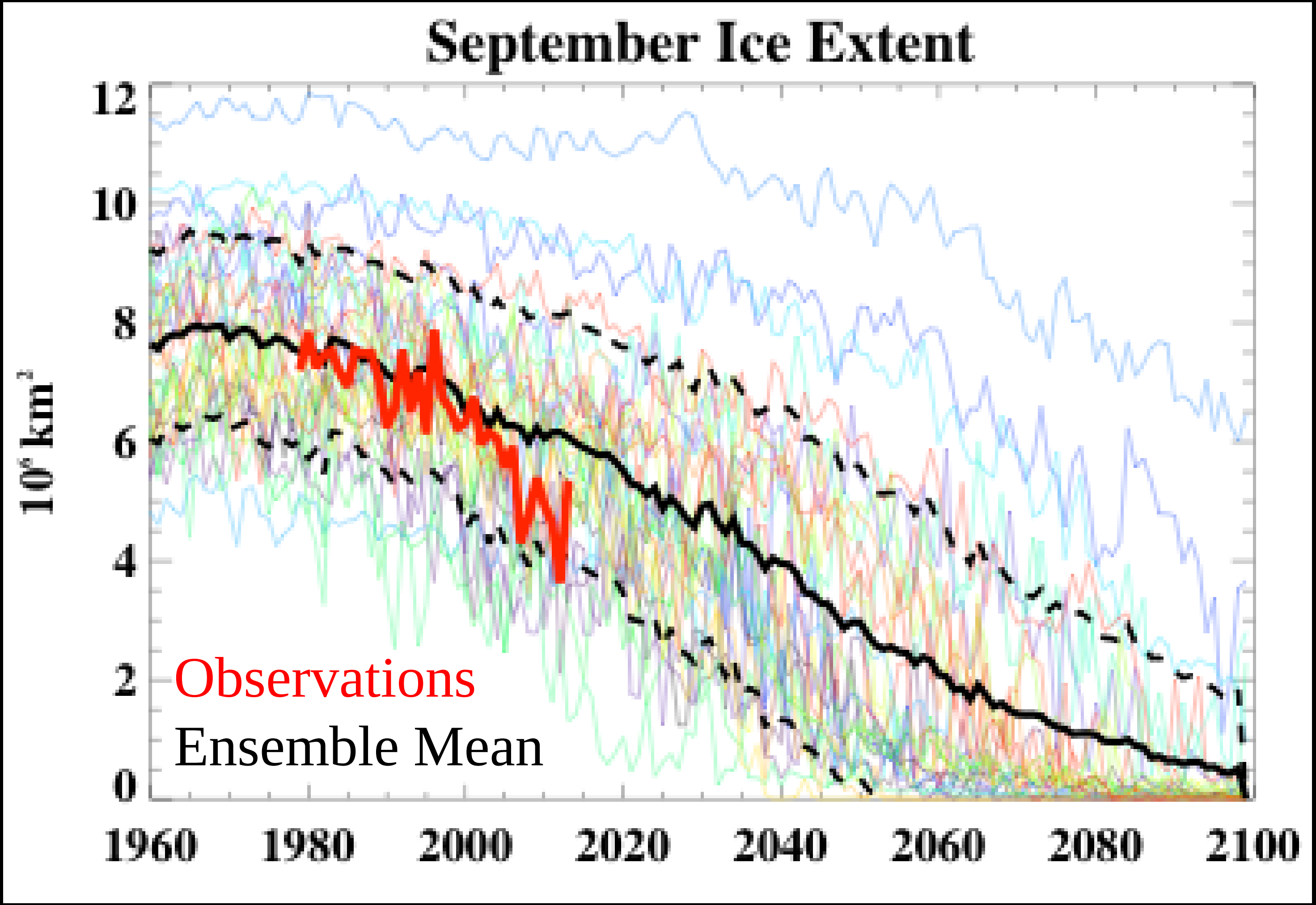
Sources of Uncertainty in Future Change

CMIP5 Multi-model Ensemble



CMIP5
RCP8.5

(Timeseries courtesy of Andy Barrett and Julienne Stroeve, NSIDC)

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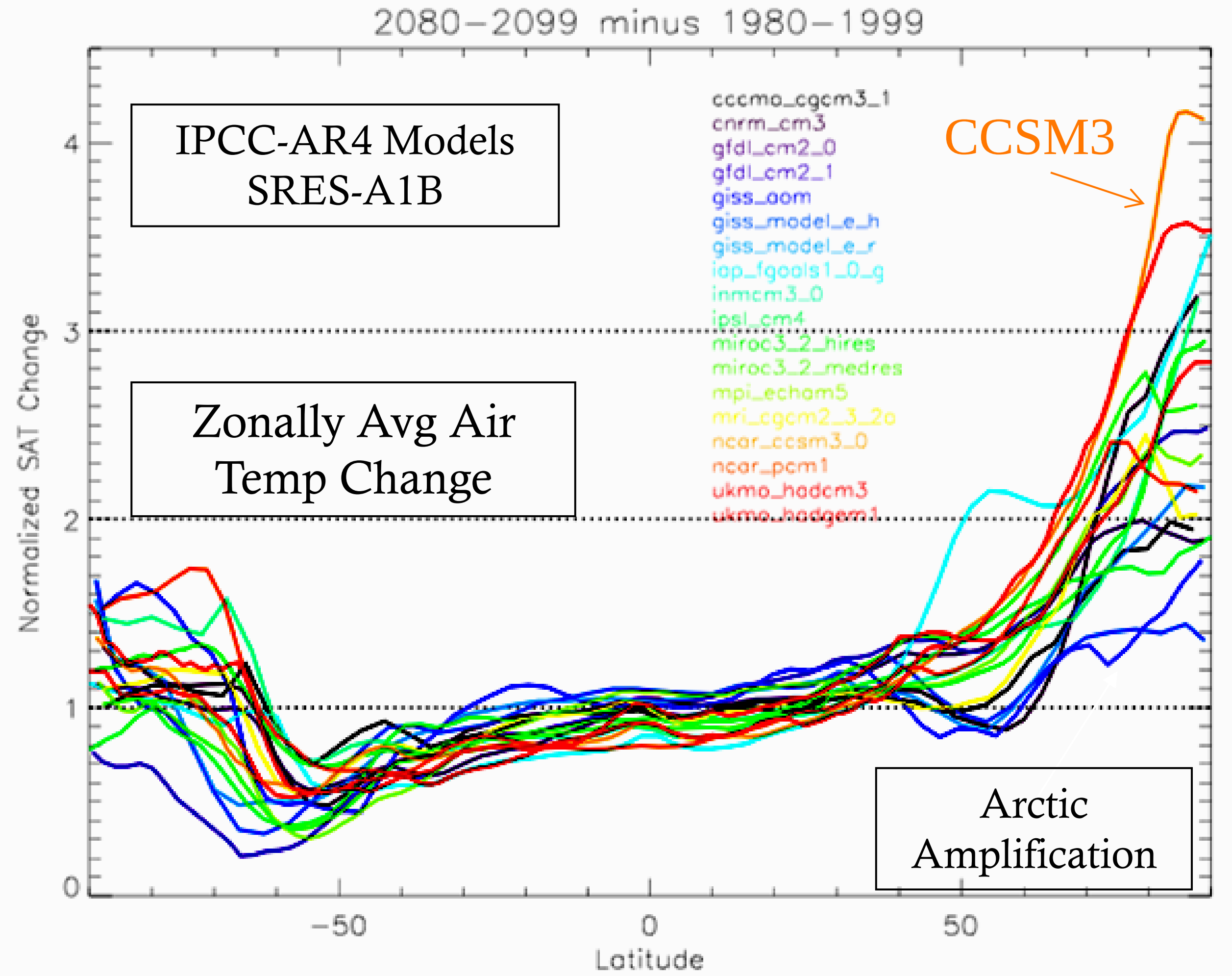
Arctic Amplification



(After Holland and Bitz, 2003)

CCSM3 had among the highest Arctic amplification from CMIP3 models

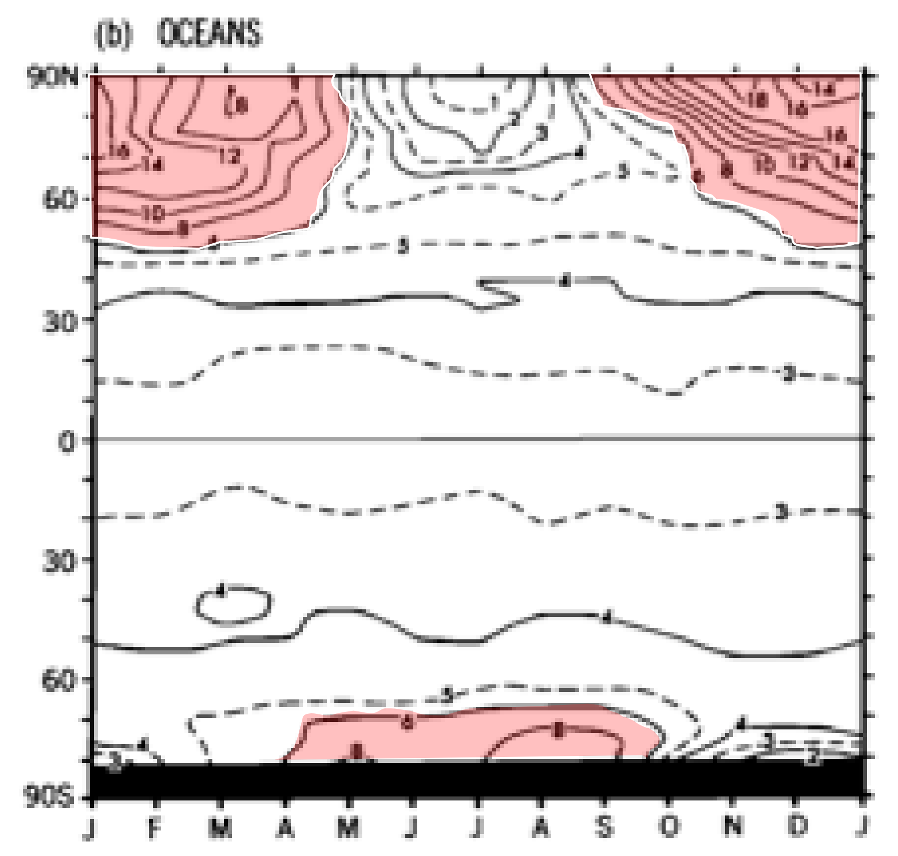
The inclusion of an ITD which enhances the albedo feedback may be one reason

But First…

- Some thoughts on CESM
- Some acknowledgments –
  - The amazing members of the Polar Climate Working Group
  - The incredible software engineers who make the model easy to use
  - The talented working group co-chairs who selflessly serve the project
  - The young scientists who breath new ideas into the project

Some modeling history

- Initial models (~1970s) had **no sea ice** component but raised albedo for cold (<-2C) wet surface areas
- In ~1980s **thermodynamic** sea ice components were included



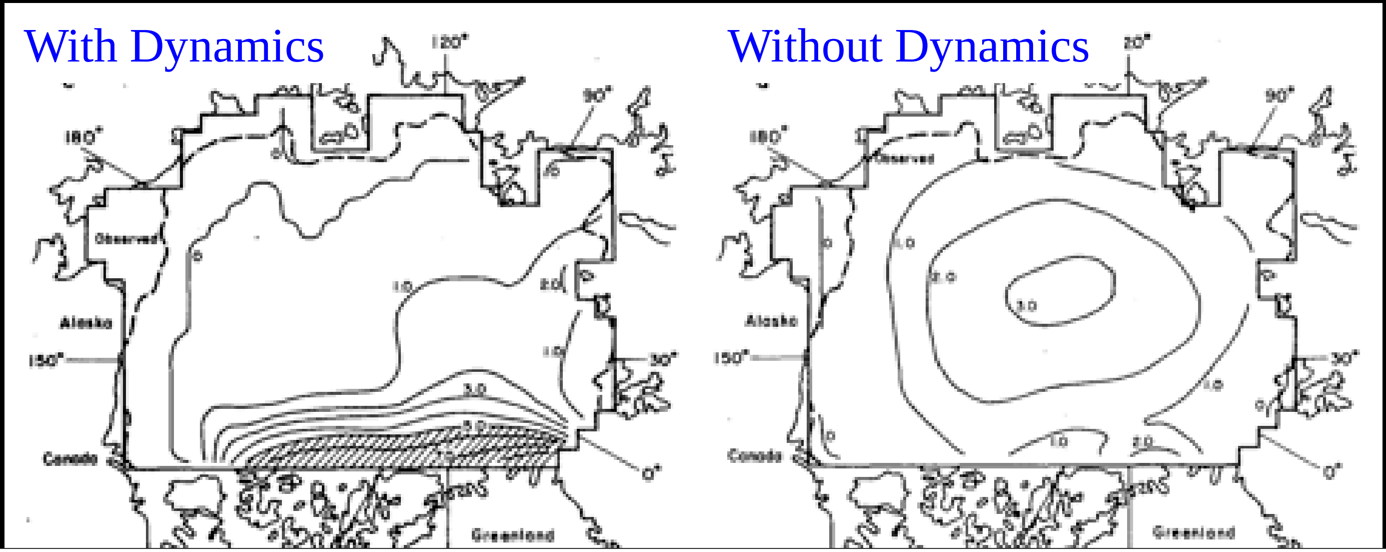
Surface Air Temperature Change 4XCO2-1XCO2

(From Manabe and Stouffer, 1980)

Atmosphere-Slab Ocn Model Runs

Some modeling history

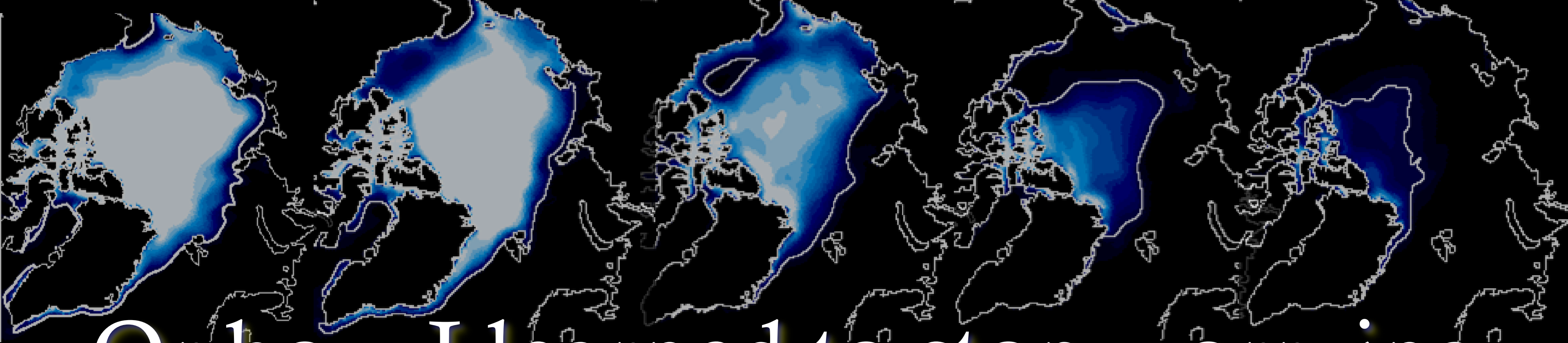
- Initial models (~1970s) had **no sea ice** component but raised albedo for cold (<-2C) wet surface areas
- In ~1980s **thermodynamic** sea ice components were included
- Coupled systems incorporated **dynamic** sea ice components (~1990s) of varying complexity


With Dynamics

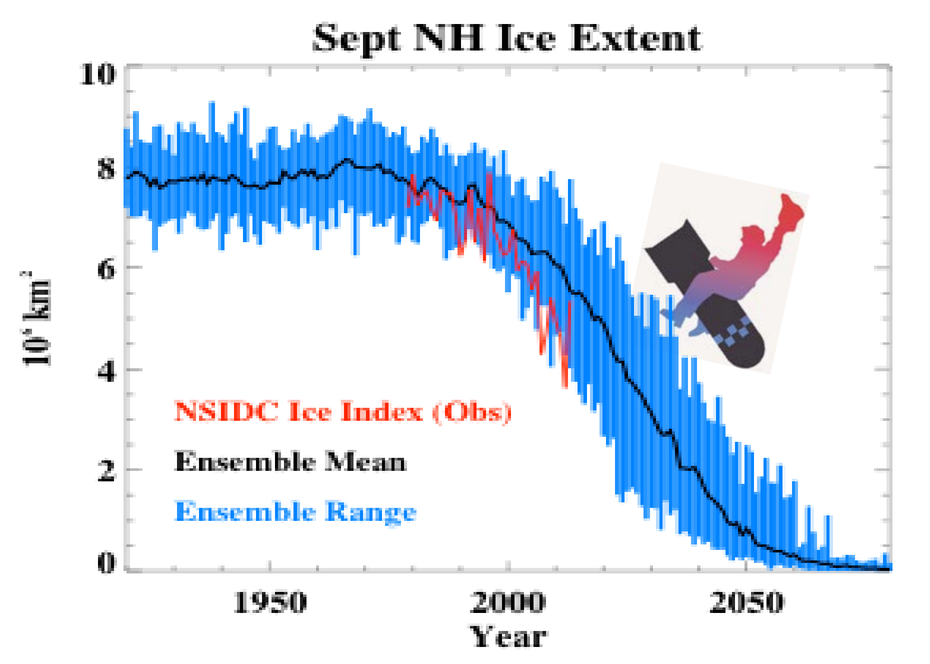
Without Dynamics

From Hibler, 1980 ice-only runs

Ice thickness pattern strongly influenced by dynamics



Or how I learned to stop worrying and love the decline



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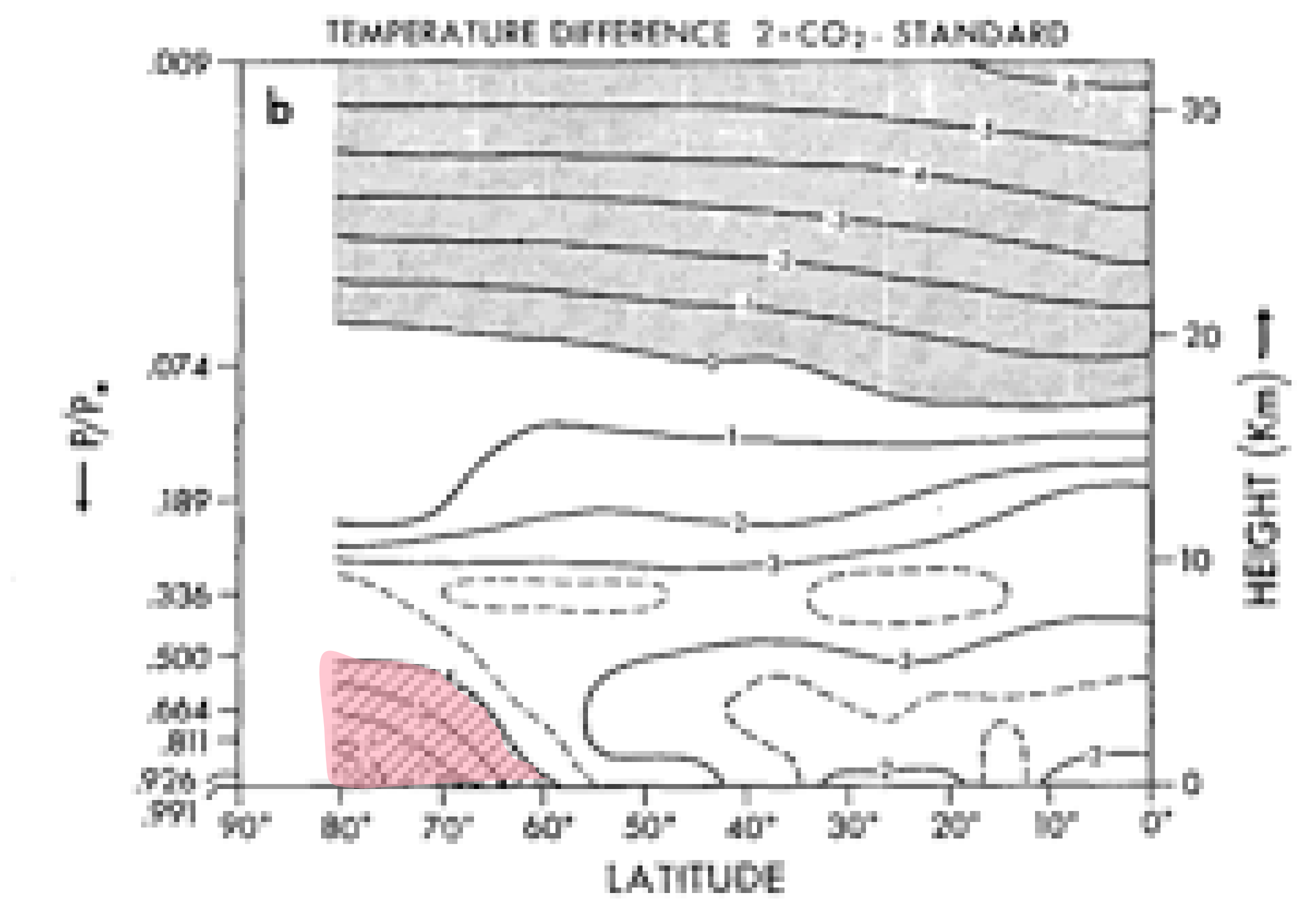
Some modeling history

- Initial models (~1970s) had **no sea ice** component but raised albedo for cold (<-2C) wet surface areas

Temperature response to CO2 doubling

(From Manabe and Weatherald, 1975)



Where we are today

- Most climate/earth system models include sea ice with:
  - A thermodynamic component $$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} k \frac{\partial T}{\partial z} + Q_{SW}$$
    - vertical heat transfer; vertical/lateral melt and growth rates
  - A dynamic component $$m \frac{\partial u}{\partial t} = -mfk \times u + \tau_a + \tau_o - mg \nabla H + \nabla \bullet \sigma$$
    - Ice motion; ice pack resists convergence/shear, freely diverges

- Some models include:
  - Ice Thickness Distribution $$\frac{\partial g}{\partial t} = -\frac{\partial}{\partial h}(fg) + L(g) - \nabla \bullet (vg) + \Psi(h,g,v)$$
    - Subgridscale parameterization
    - Accounts for high spatial heterogeneity
    - Redistribution resulting from ridging/rafting

- Parameterization improvements continually being developed
  - For example, the surface albedo treatment

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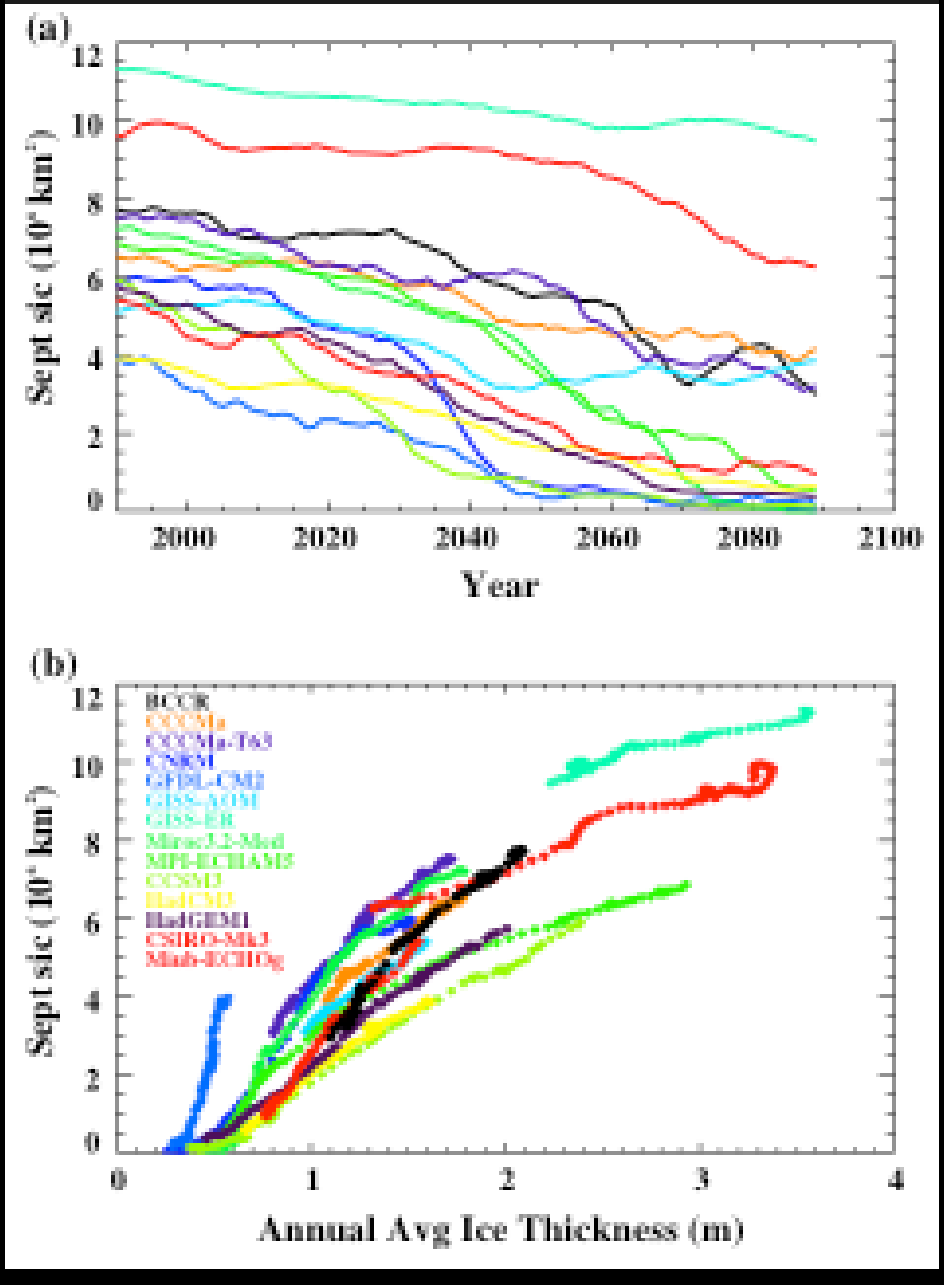
Where are we heading?

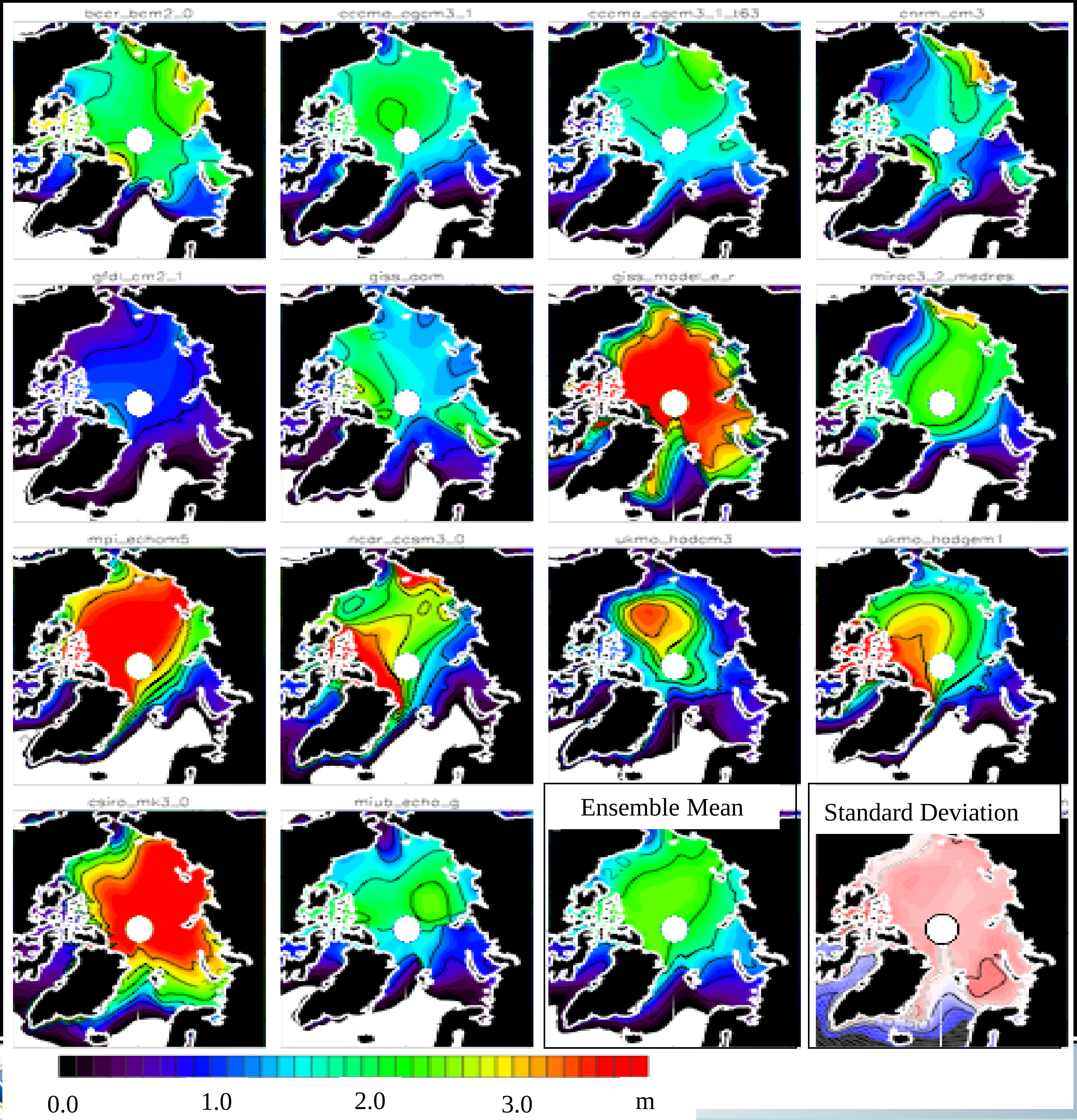
- Prognostic salinity
- Biogeochemistry
- More sophisticated melt pond modeling
- Snow model improvements
- Improved ice-ocean coupling

Much of this work is being done by collaborators at DOE Labs (primarily LANL) and Universities.



CMIP3 models projected September Arctic ice extent

CMIP3 model September Arctic ice extent versus ice thickness



CMIP3 Simulated Ice Thickness Climatology

1980-1999

Thickness varies considerably across models

Differences in mean and distribution

Largest inter-model scatter is in the Barents Sea region

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Influence of ITD on climate response: 2XCO2 Climate Change Integrations

CCSM3 Simulations to study influence of ITD on climate feedbacks

- SOM runs with 1 and 5 ice categories
- Additional SOM 1 ice category tuned run which has a similar ice thickness to the SOM-ITD run
- Limited ocean feedbacks present

Will show analysis of

- positive surface albedo feedback
- ~~negative ice thickness-ice growth rate feedback~~
- ~~Negative ice strength feedback~~

(Holland et al., 2006)

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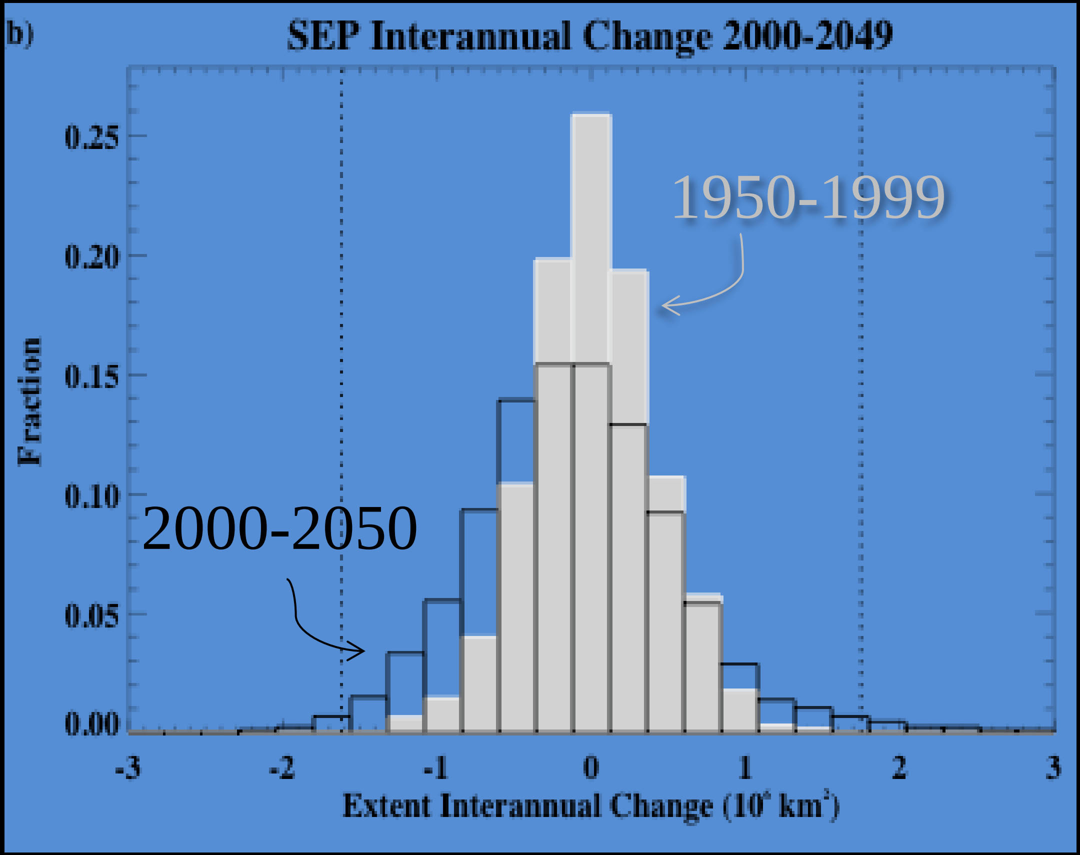
Changing interannual Arctic sea ice variability



September annual change

On annual timescales: Climate models suggest a greater frequency of "extreme" ice events

Greater frequency of both extreme decreases AND INCREASES

(Holland et al., 2008; Kay et al., 2011)

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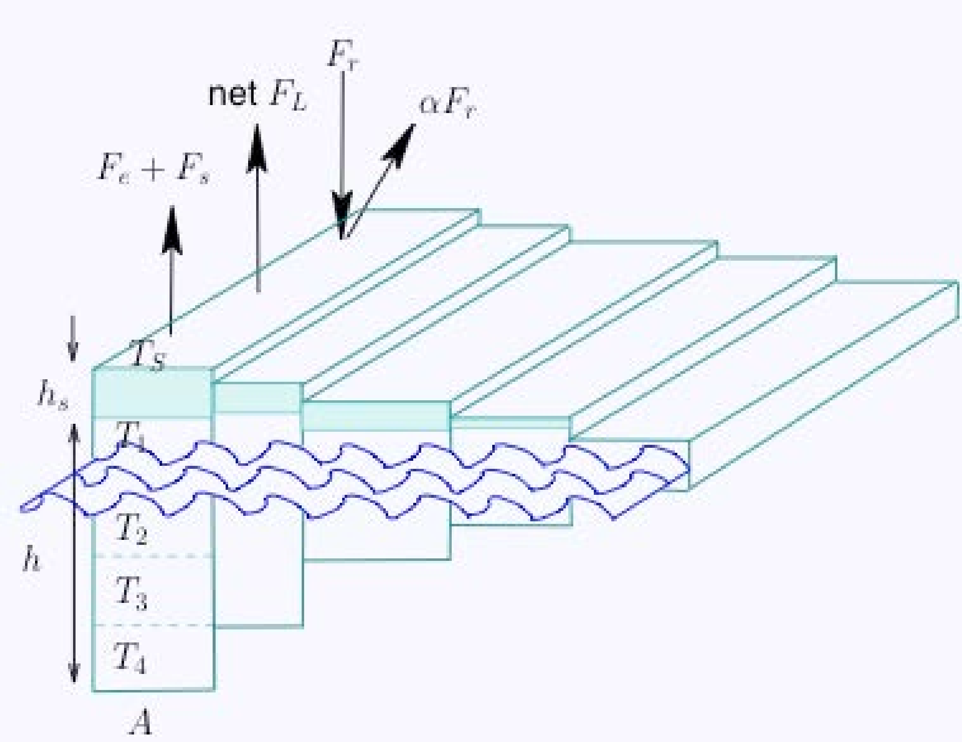
- **Ice thickness distributions** were introduced into some coupled models (~2000s)

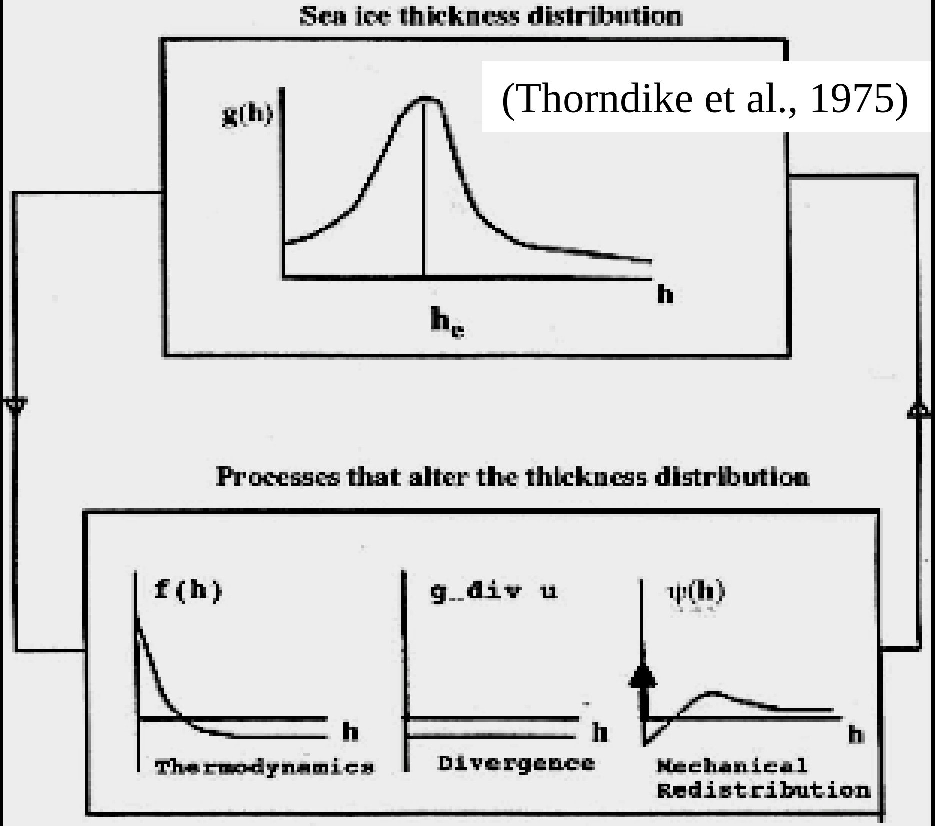
Motivation

Observations: Sea ice has high spatial heterogeneity

Modeling: Thorndike et al. (1975) had developed an ice thickness distribution model which was being used in ice-only studies



Schematic courtesy of Cecilia Bitz



Some closing thoughts

- Sea ice simulation strongly influenced by other aspects of simulated high latitude climate
- Numerous aspects of sea ice modeling remain challenging/uncertain
  - Relatively simple snow modeling, characterization of mechanical redistribution, melt pond formation
- Nevertheless climate models have shed much light on
  - the influence of sea ice on climate,
  - expectations of future ice variability and change
- Continued validation with observational data (not just mean state – but variability, statistical relationships) is needed to further our ability and confidence in models

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Schramm, J.L., Holland, M.M., Curry, J.A., and E.E. Ebert, 1997: Modeling the thermodynamics of a sea ice thickness distribution 1. Sensitivity to ice thickness resolution, *J. Geophys. Res*

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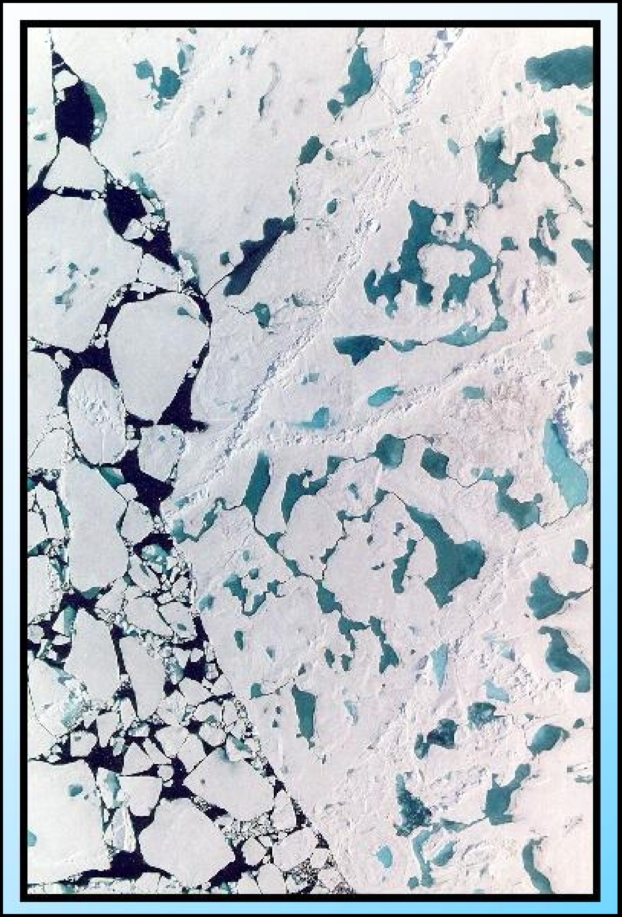
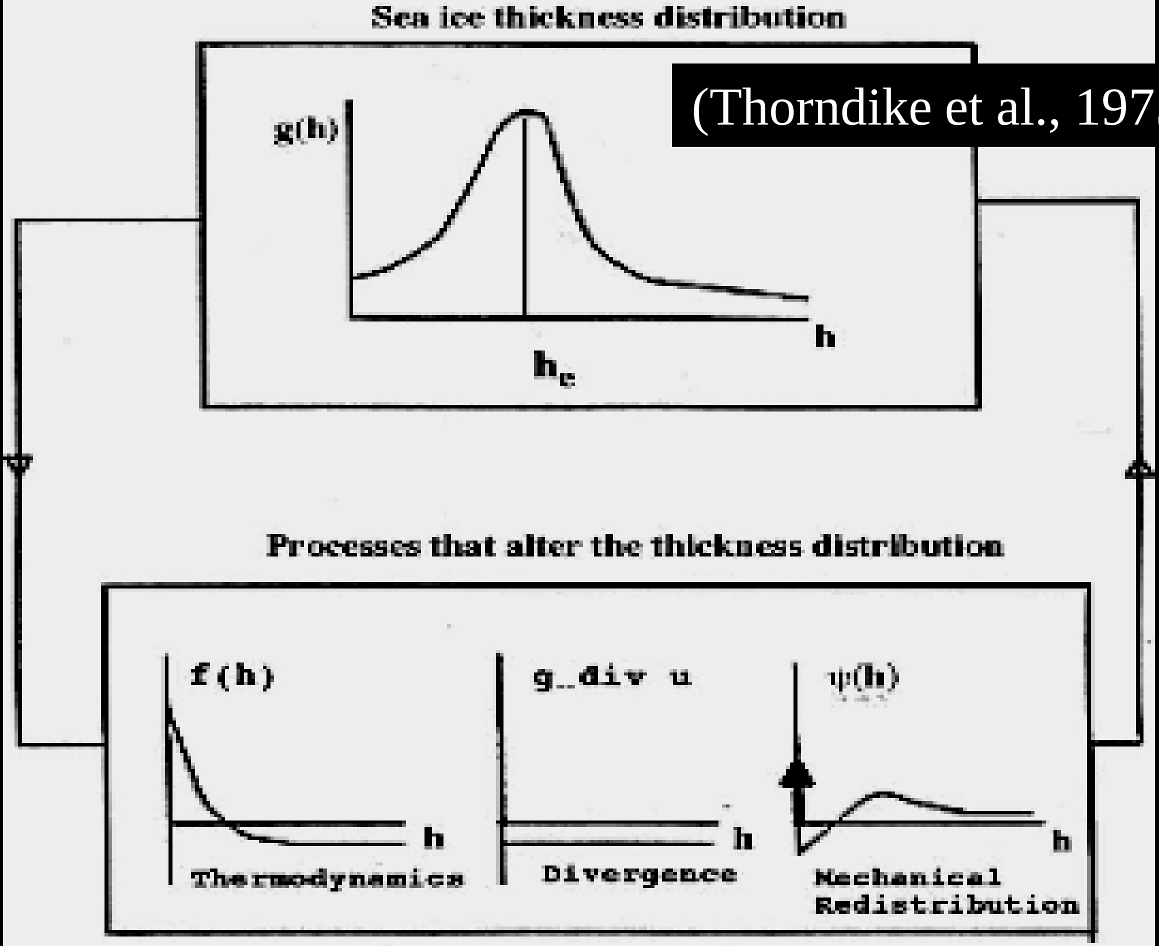
Sea Ice Model - Dynamics

- 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

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

Ice Thickness Distribution





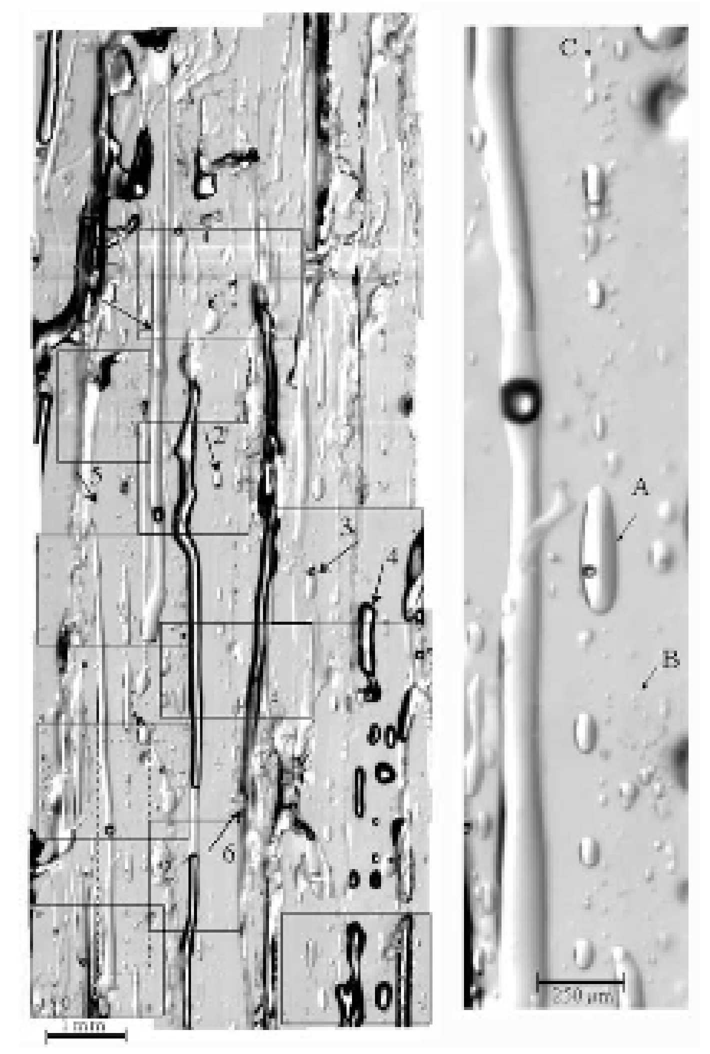
(Thorndike et al., 1975)

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

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

Thermodynamics Vertical heat transfer

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

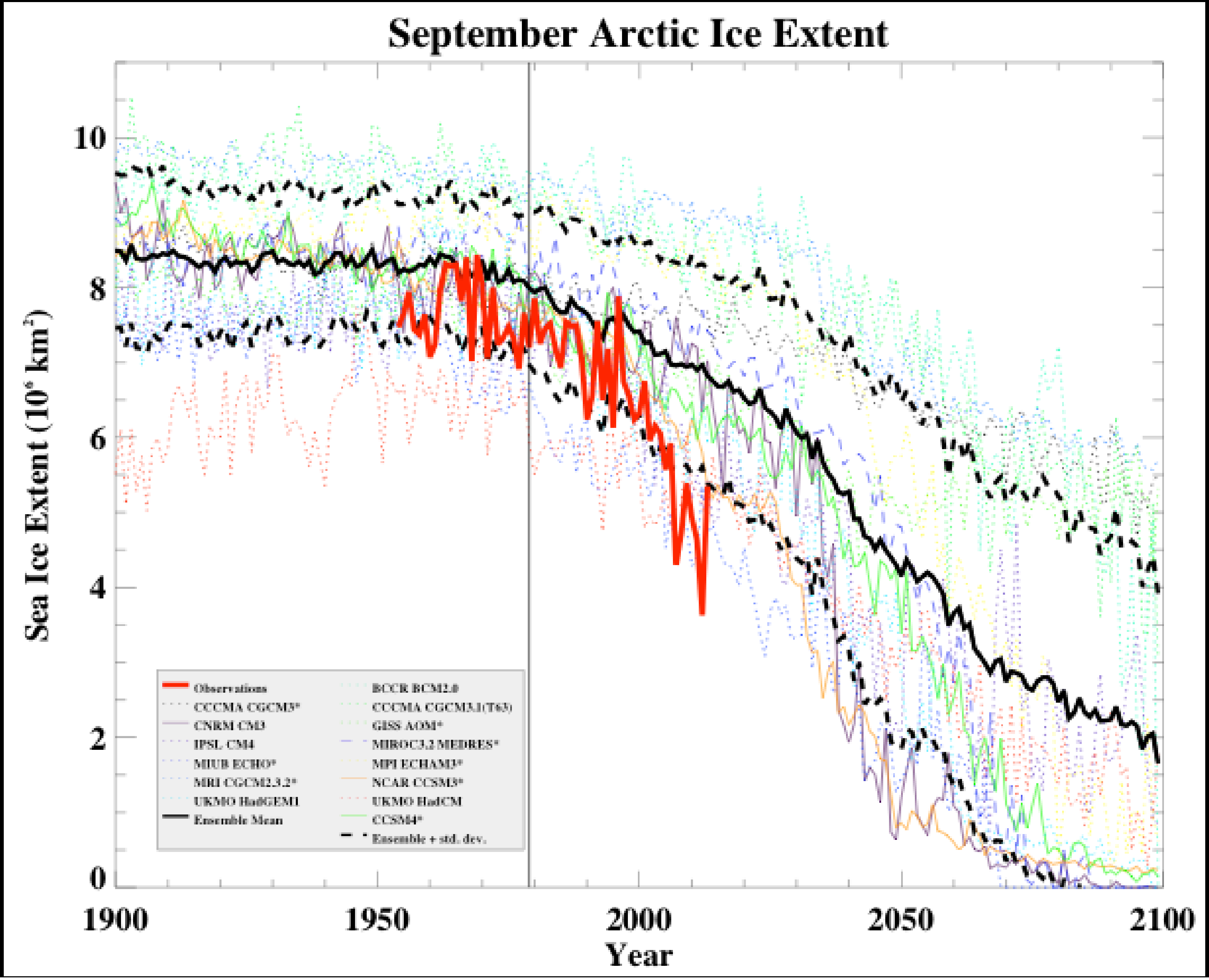


- Assume brine pockets are in thermal equilibrium with ice
- Heat capacity and conductivity are functions of T/S of ice
- Assume constant salinity profile
- Assume non-varying density
- Assume pockets/channels are brine filled
- $$Q_{SW} = -\frac{d}{dz} I_{SW} e^{-\kappa z} \quad \text{where} \quad I_{SW}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

2003)

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

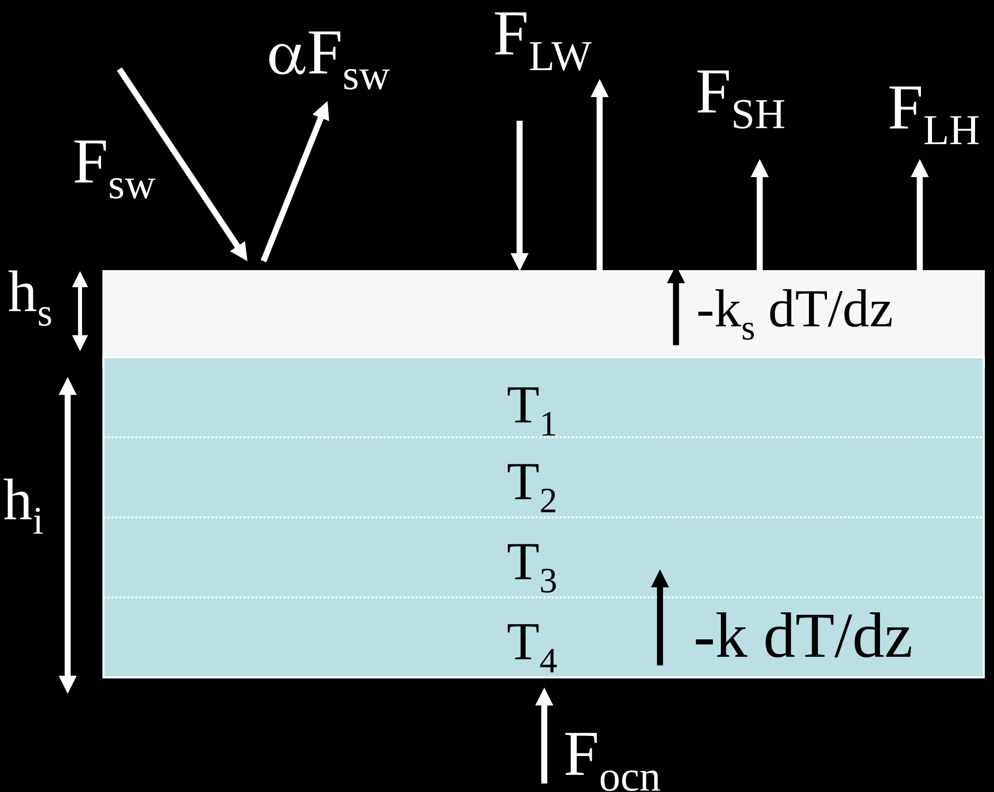
CMIP3 Sea Ice Projections



Stroeve, Holland, Meier, Scambos, Serreze, Arctic sea ice decline: Faster than forecast, GRL, 2007

(Figure updated with observations through 2013)

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

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

Ice Thickness Distribution

Ice thickness distribution g(x,y,h,t) evolution equation from Thorndike et al. (1975)

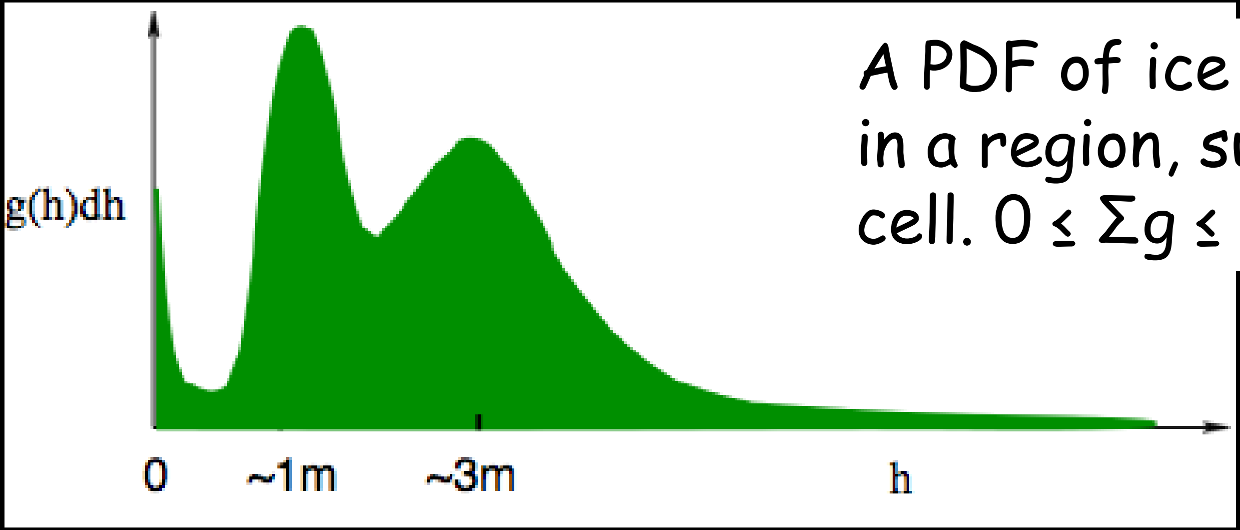
$$\frac{\partial g}{\partial t} = -\frac{\partial}{\partial h}(fg) + L(g) - \nabla \cdot (\vec{v}g) + \Psi(h,g,\vec{v})$$

Ice Growth

Lateral Melt

Convergence

Mechanical Redistribution



A PDF of ice thickness h in a region, such as a grid cell. $0 \leq \Sigma g \leq 1$

g(h)dh is the fractional area covered by ice of thickness h to h+dh

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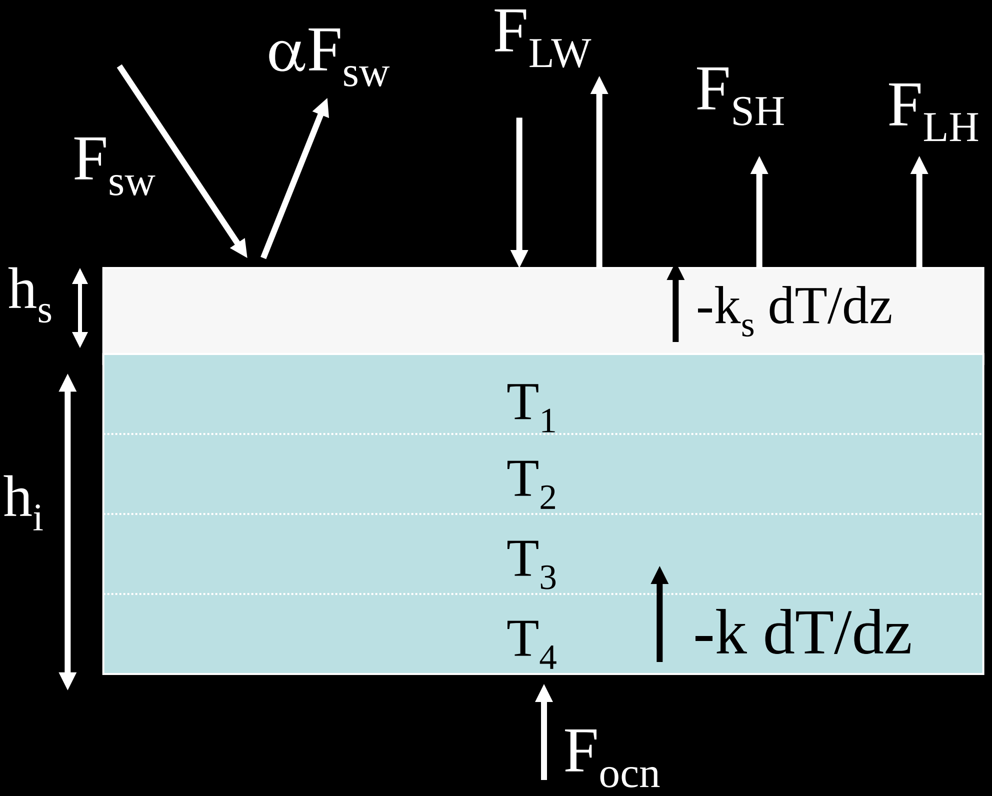
- Ice treated as a continuum with an effective large-scale rheology describing the relationship between stress and deformation
- Ice freely diverges (no tensile strength)
- Ice resists convergence and shear

(e.g. Hibler, 1979)

$$\underset{\substack{\uparrow \\ \text{Total derivative}}}{m\frac{Du}{Dt}} = \underset{\substack{\uparrow \\ \text{Coriolis}}}{-mfk \times \mathbf{u}} + \underset{\substack{\uparrow \\ \text{Air} \\ \text{stress}}}{\boldsymbol{\tau}_a} + \underset{\substack{\uparrow \\ \text{Ocean} \\ \text{stress}}}{\boldsymbol{\tau}_w} - \underset{\substack{\uparrow \\ \text{Sea Surface} \\ \text{Slope}}}{mg_r\nabla Y} + \underset{\substack{\uparrow \\ \text{Internal} \\ \text{Ice Stress}}}{\nabla \cdot \sigma}$$

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)

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

Balance of fluxes at ice base

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

Allows us to compute surface melt (snow or ice), ice basal melt and ice growth

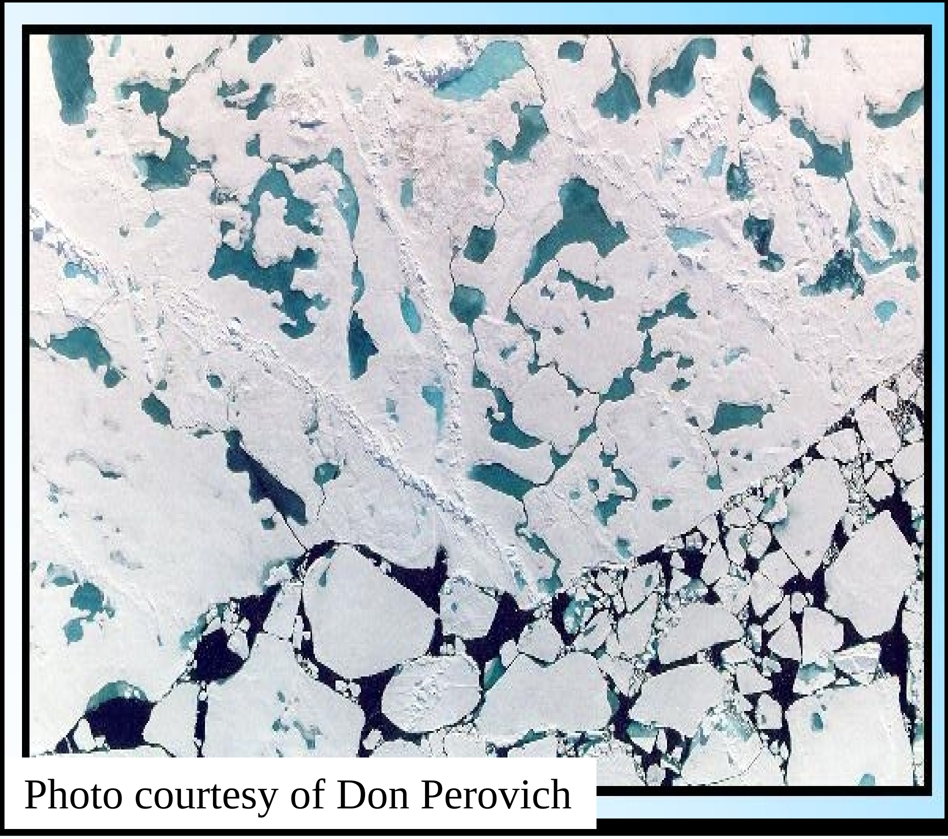
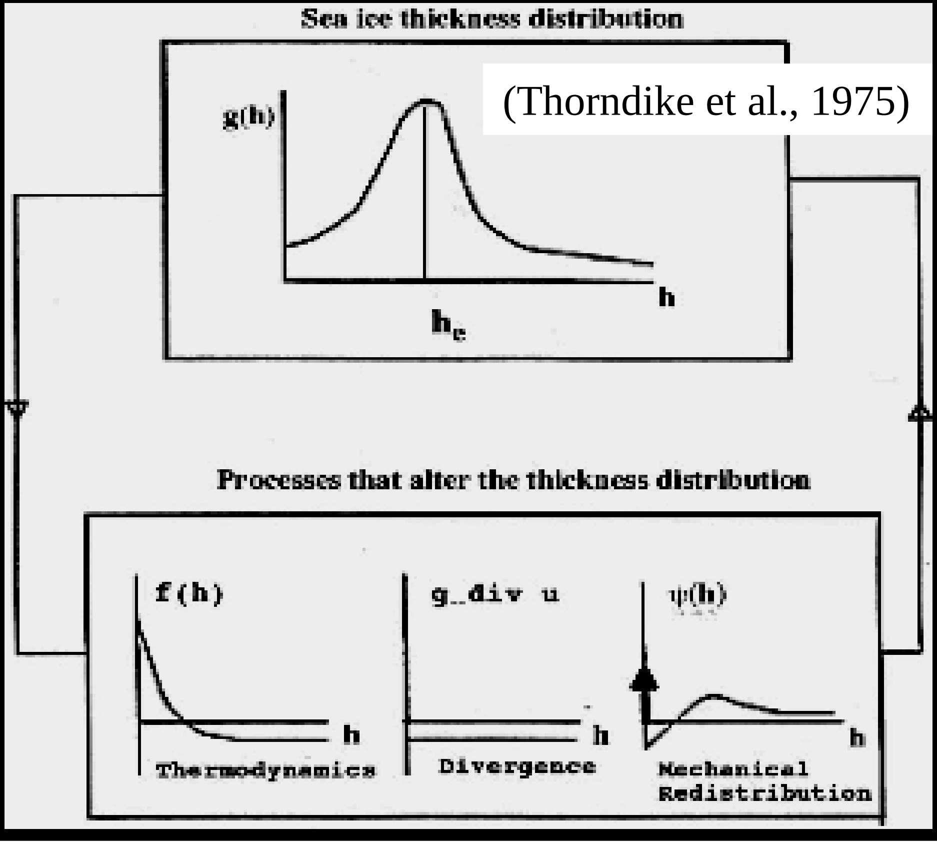
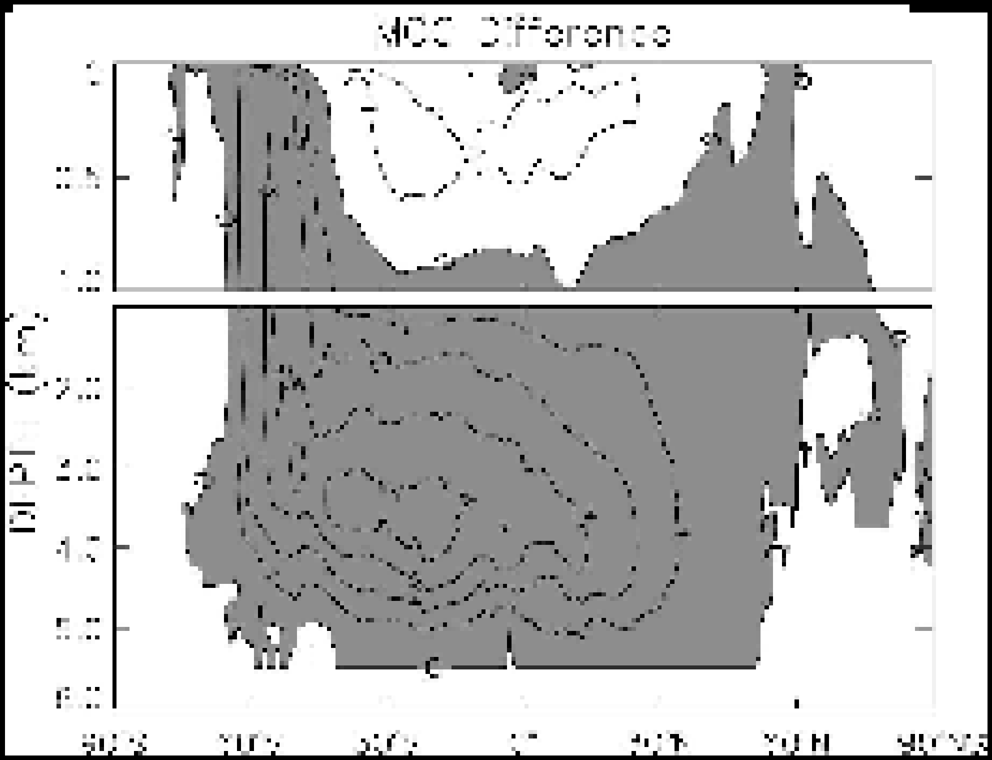


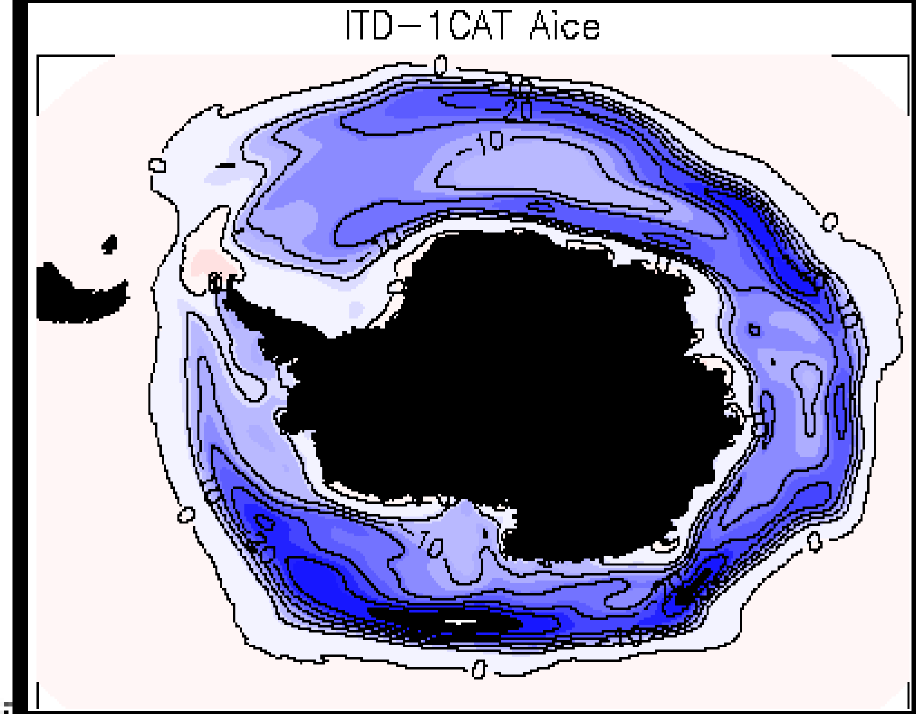
Photo courtesy of Don Perovich



(Thorndike et al., 1975)

ITD Influence on Mean Conditions





In the southern hemisphere, the ITD:

1. Modified ocn circulation/heat transport
2. Resulting in less extensive ice

CCSM3
Results

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