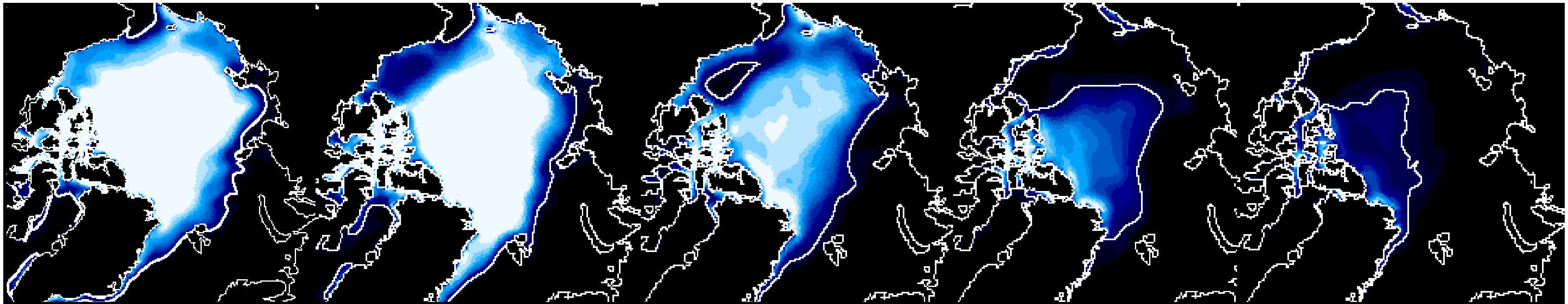
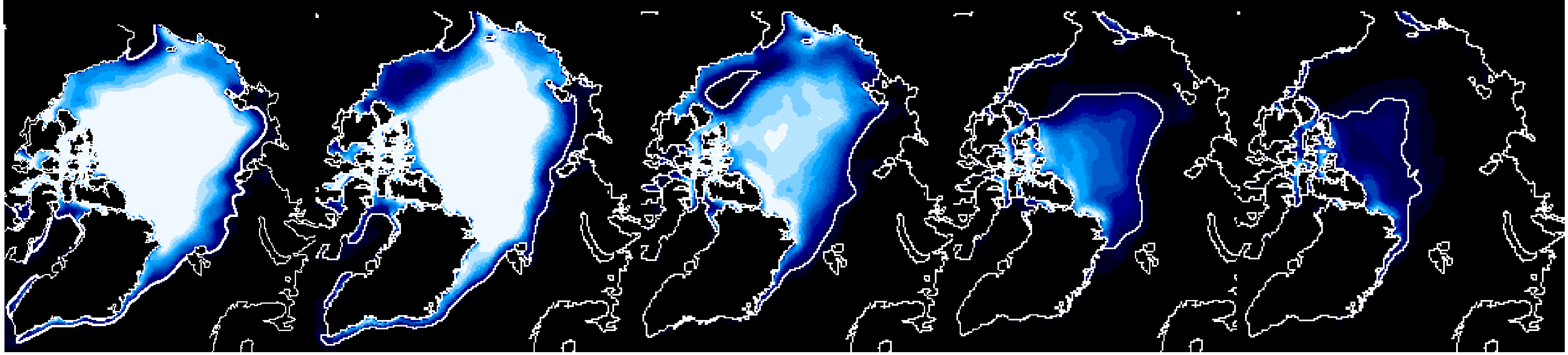


The forcings and feedbacks of rapid Arctic sea ice loss

Marika Holland, NCAR

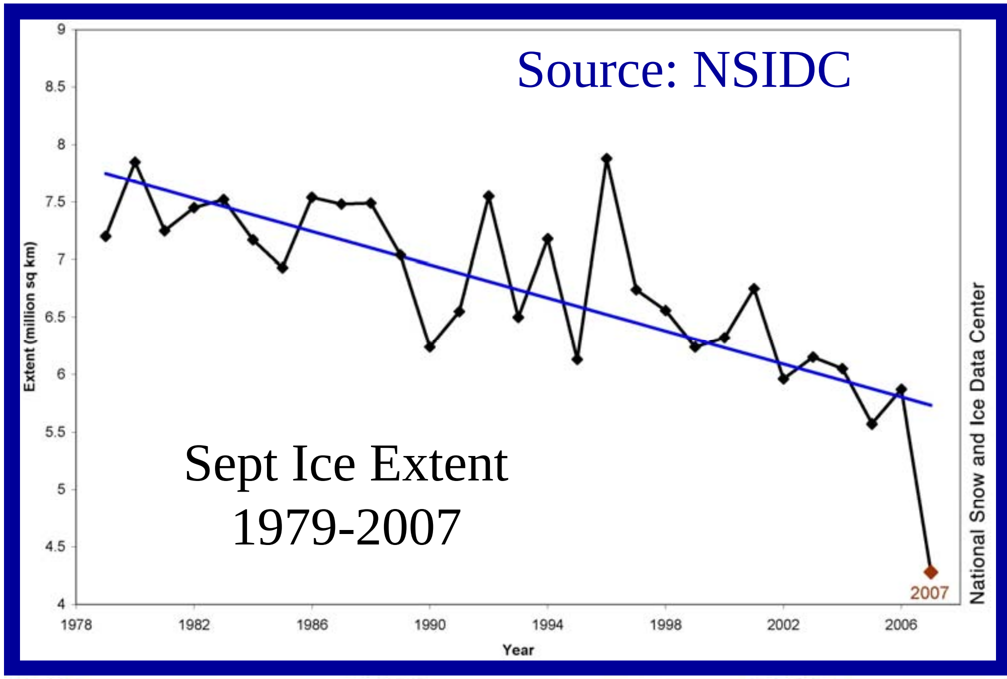
With: C. Bitz (U.WA), B. Tremblay (McGill), D. Bailey (NCAR), J. Stroeve (NSIDC), M. Serreze (NSIDC), D. Lawrence (NCAR), S Vavrus (U. Wisc)



Outline

1. Observed sea ice change
2. Projected change in CCSM3 summer Arctic ice cover
    - Possibility of abrupt transitions
    - Mechanisms driving change
    - Possible "Tipping Point" behavior?
3. Projections from other climate models
4. Conclusions

Arctic summer sea ice



The New York Times

Arctic Melt Unnerves the Experts

Andy Armstrong/National Oceanic and Atmospheric Administration

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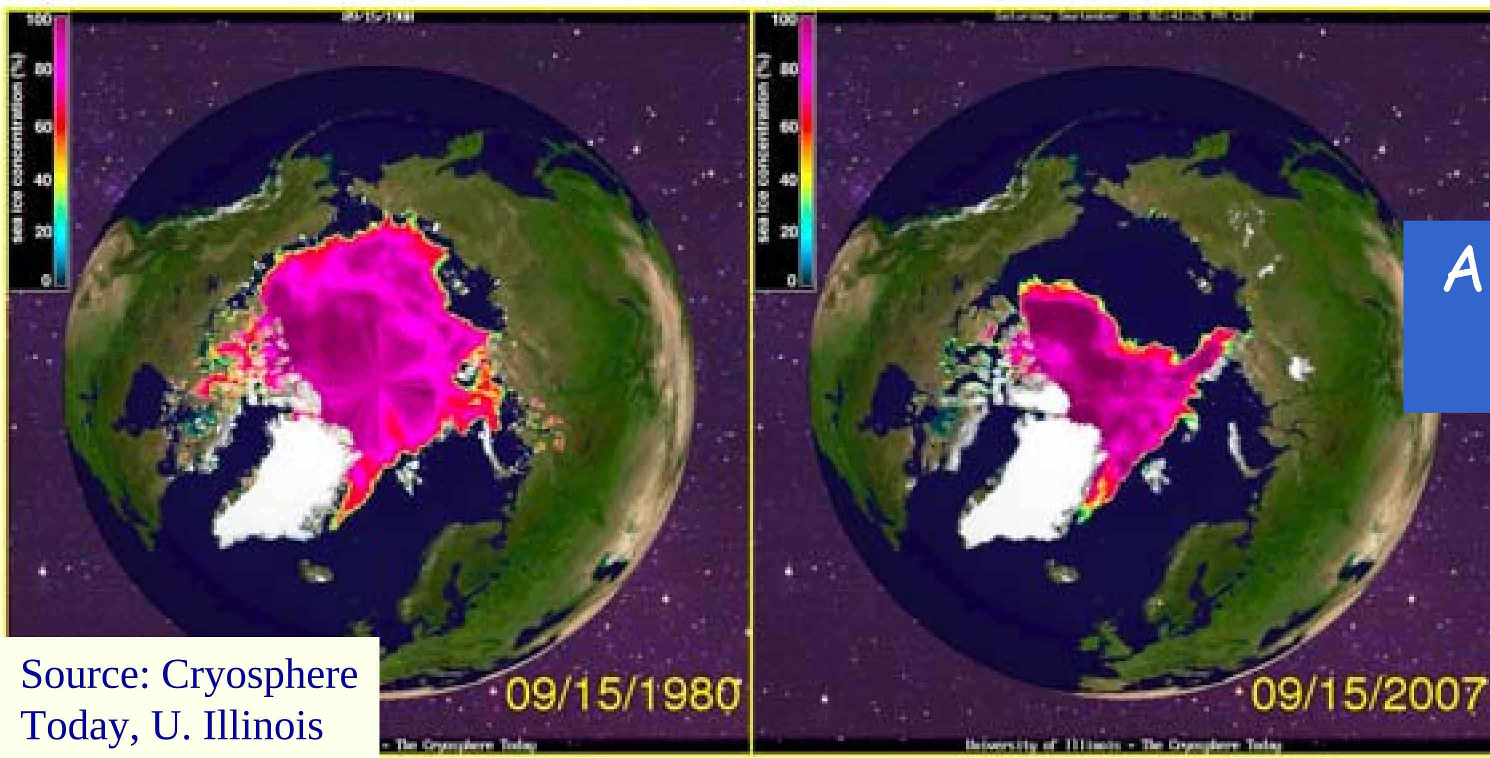
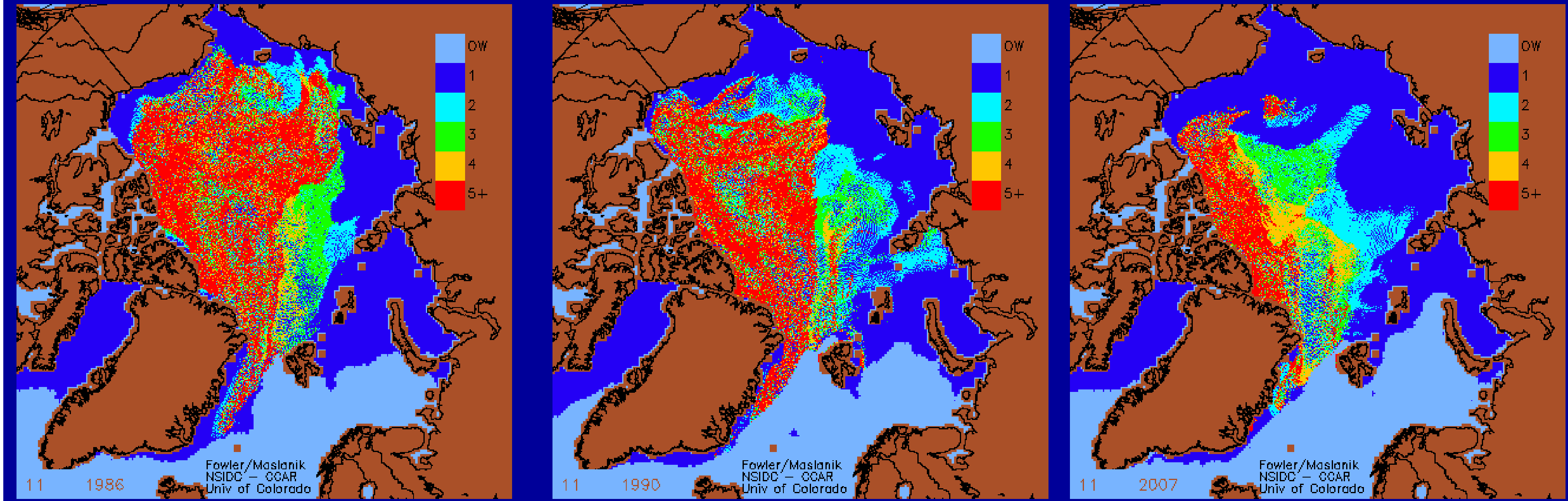


Source: Cryosphere Today, U. Illinois

Transition Towards Younger Ice

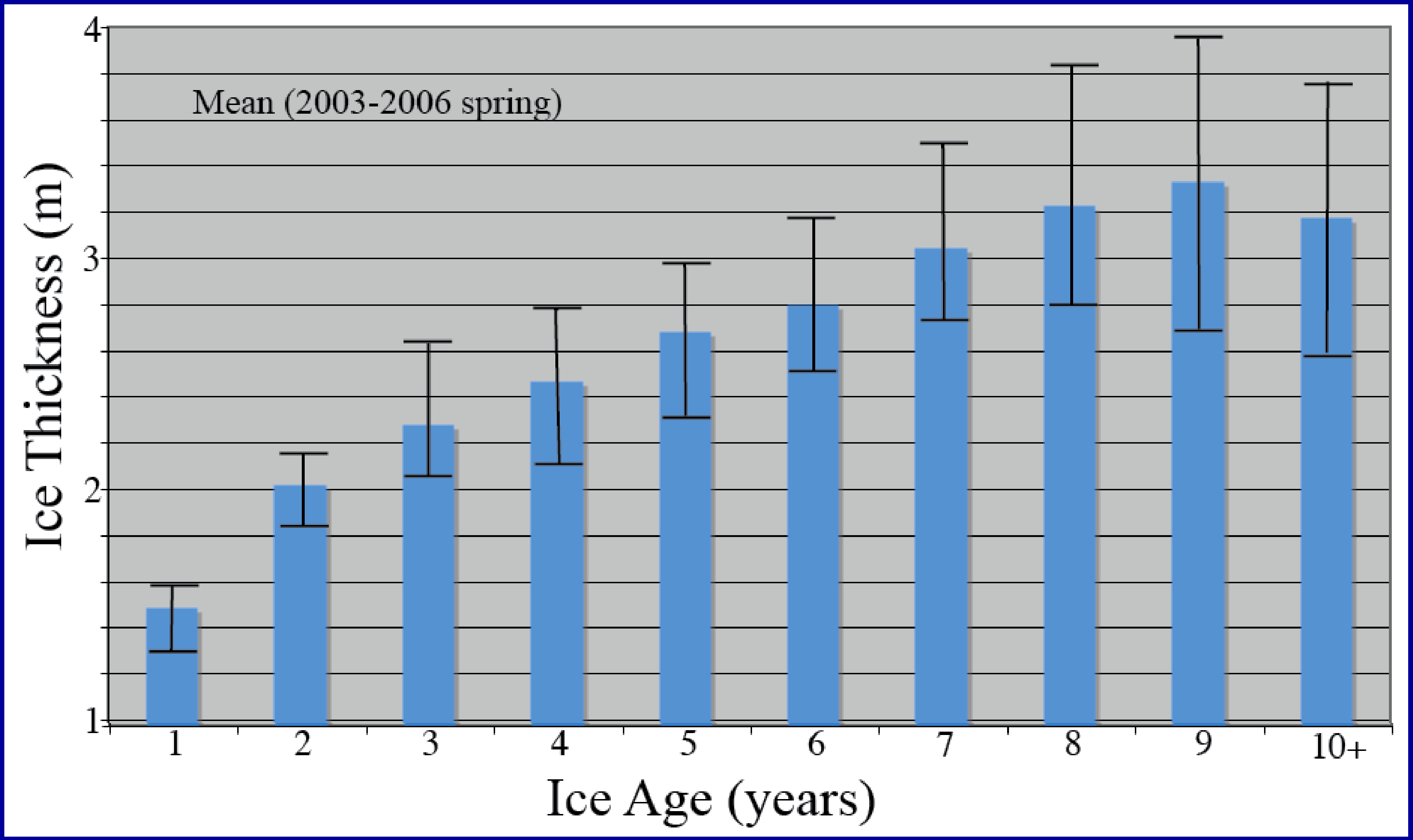
- Ice age tracking algorithm from C. Fowler and J. Maslanik
- By 2007 ice 5 years or older makes up only 10% of the perennial ice pack.



Spring 1986 Spring 1990 Spring 2007

Maslanik et al., 2007

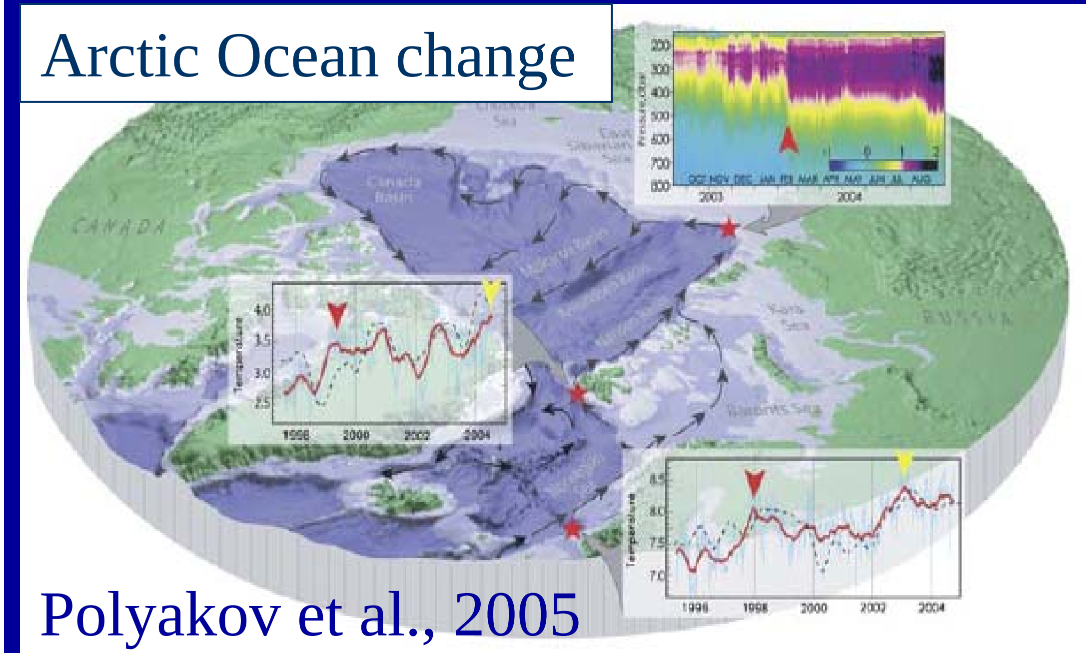
Younger Ice generally Thinner Ice

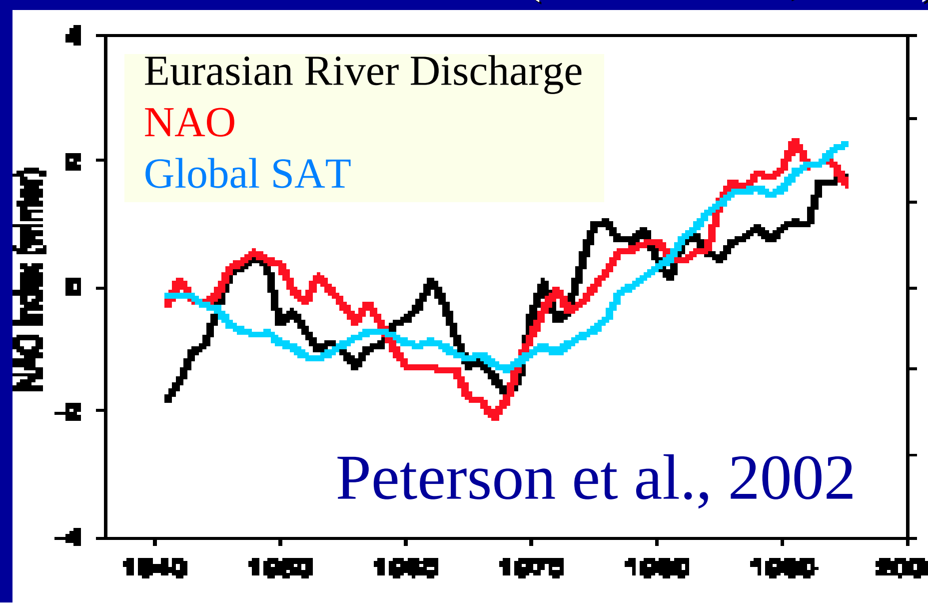


Maslanik et al., 2007

- Comparison between ice age and thickness from 4 years of spring ICESat GLAS-derived thickness fields from J. Zwally and D. Yi.
- Results suggest a decrease in mean thickness from 2.6 m in March 1987 to 2.0 m in March 2007

Ice Loss Just One Aspect of a Changing Arctic





Arctic change:
The poster child for global climate change

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'Arctic is screaming,' say scientists seeing new data; worry over 'tipping point'

The Associated Press — Published: December 12, 2007

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WASHINGTON: An already relentless melting of the Arctic greatly accelerated during the Northern Hemisphere's hot summer months, a warning sign that some scientists worry could mean global warming has passed an ominous tipping point. One is even speculating that summer sea ice would be gone in five years.

Greenland's ice sheet melted nearly 19 billion tons (17.25 metric tons) more than the previous high mark, and the volume of Arctic sea ice at summer's end was half what it was just four years earlier, according to new NASA satellite data obtained by The Associated Press.

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ENVIRONMENT SUMMIT-Arctic thaw may be at "tipping point"

Fri Sep 28, 2007 8:33am EDT

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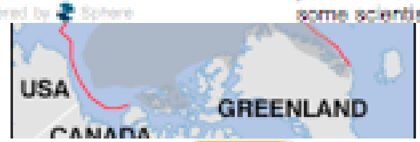
World sea levels to rise 1.5m by 2100: scientists
15 Apr 2008

By Alister Doyle, Environment Correspondent

OSLO, Sept 28 (Reuters) - A record melt of Arctic summer sea ice this month may be a sign that global warming is reaching a critical trigger point that could accelerate the northern thaw, some scientists say.



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Arctic ice hits 'tipping point'

By Roger Highfield, Science Editor
Last Updated: 12:01am GMT 16/03/2007

Dwindling Arctic sea ice may have reached a 'tipping point' that could make British winters even wetter, according to researchers.

Arctic sea ice levels naturally ebb and flow throughout the year and are always lowest in September. But September 2005 marked their lowest level in 50 years and satellite data show average September sea ice extent down by 8.6 per cent per decade and accelerating.

Some computer models even predict an ice-free Arctic Ocean in September by 2050.

Research Questions

- What is the potential for future rapid Arctic summer ice loss?
- What forcings/feedbacks are implicated in rapid ice loss?
- Does rapid summer ice loss result from “threshold-type” (tipping point) behavior?
- What are the impacts of rapid ice loss on other aspects of the Arctic system?

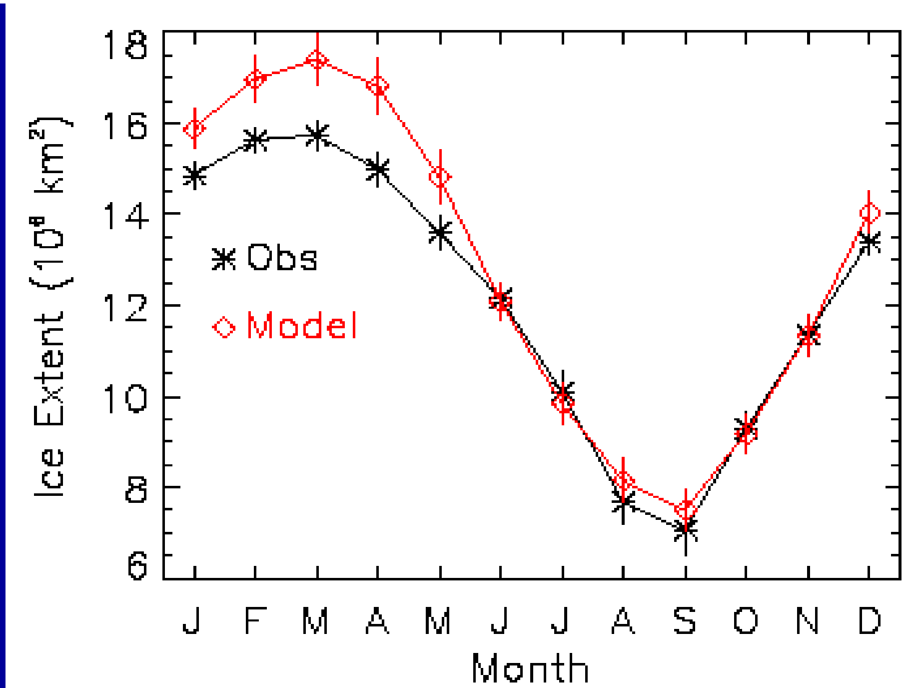
CCSM3 IPCC Model Simulations

20th century runs

- branched from 1870 control run
- include variations in sulfates, solar input, volcanoes, ozone, GHGs (CO_2, CH_4, N_2O), Halocarbons (CFCs), black carbon

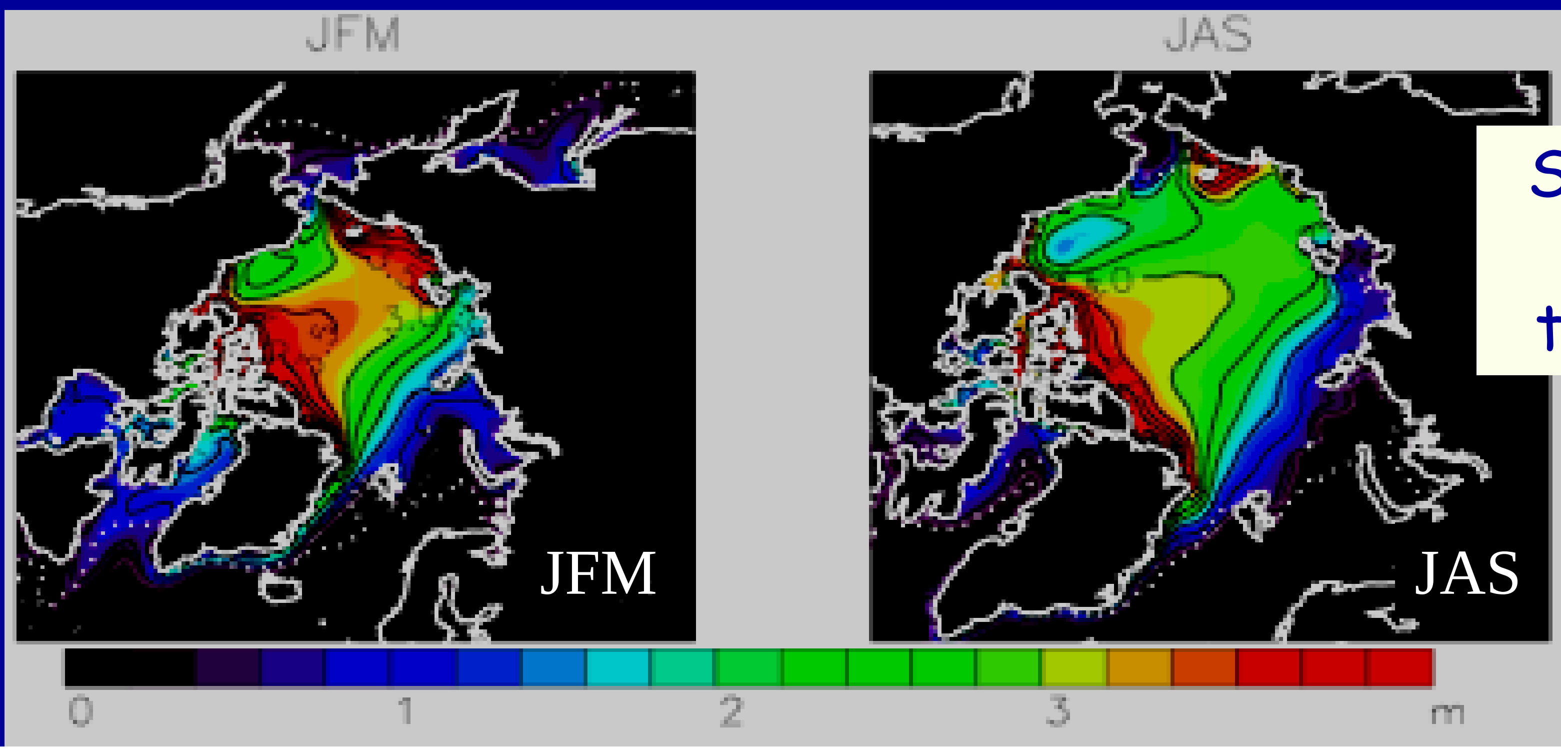
21st century runs

- *A1B scenario*: rapid economic growth; global population that peaks mid-century; rapid introduction of new and more efficient technologies; balance across fossil/non-fossil energy sources.



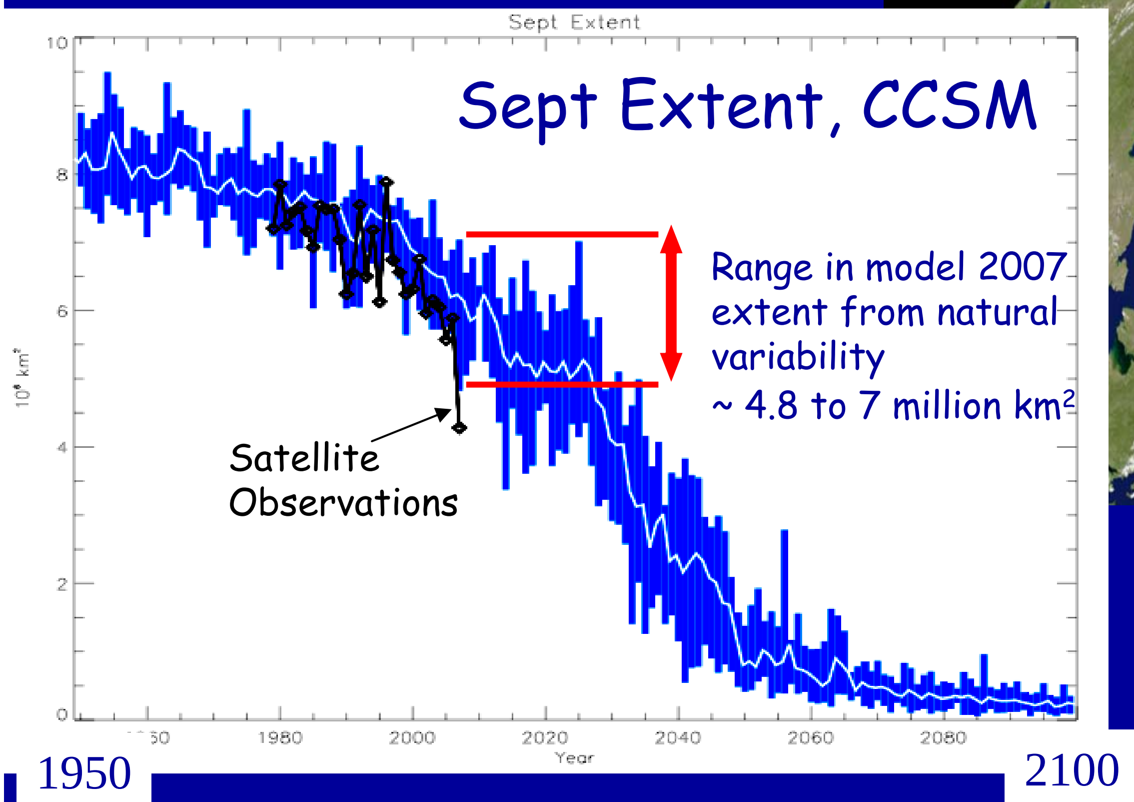
Ice Extent Annual Cycle

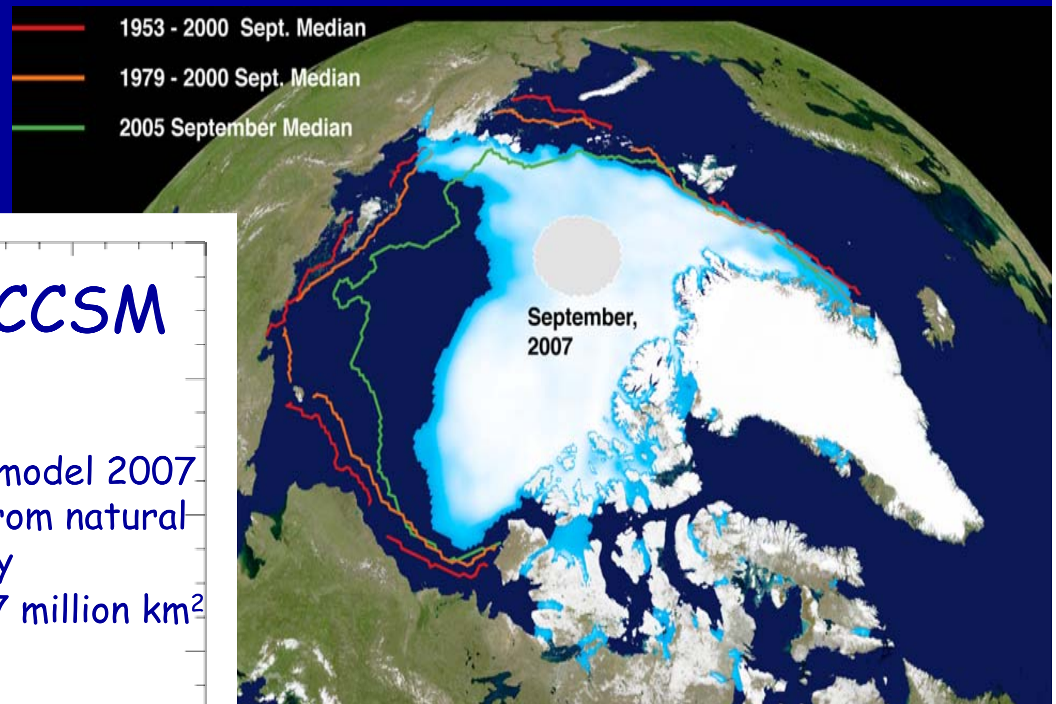
CCSM3 Arctic Sea Ice 1979-1999 Average



Simulated ice thickness

Simulated change over historical record





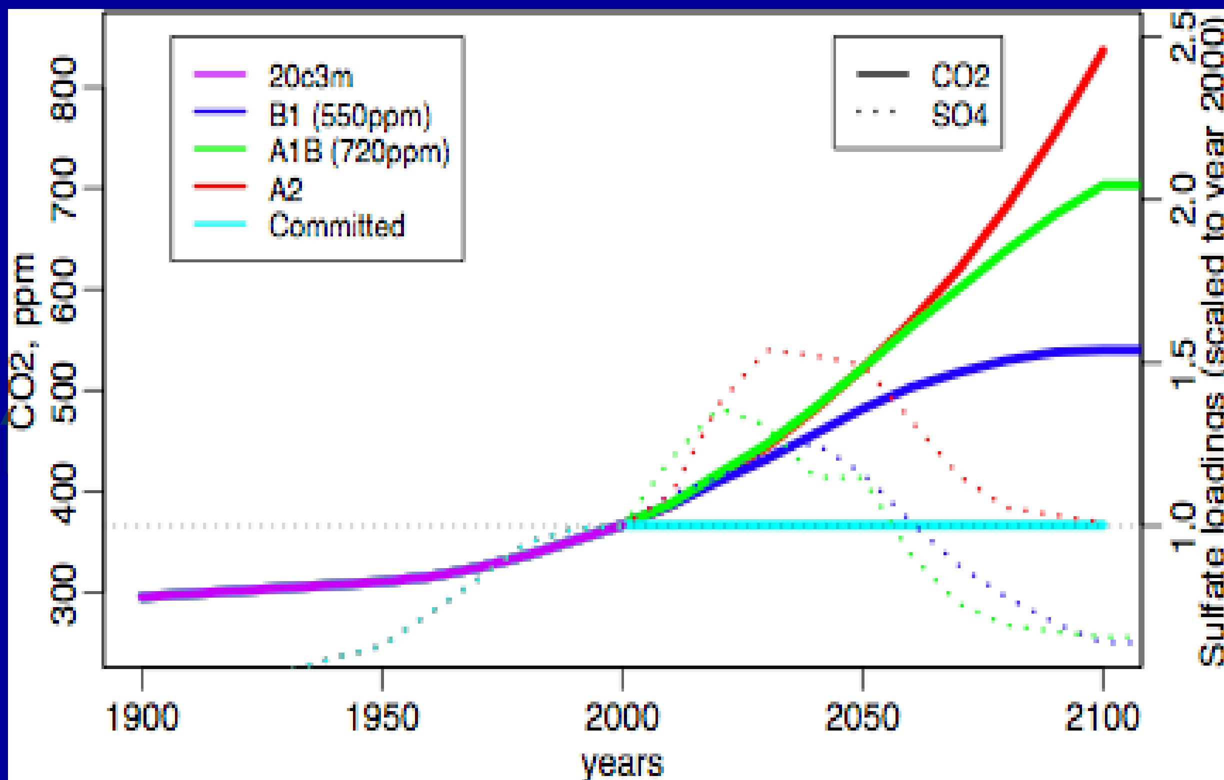
Simulated trend generally consistent with observed loss

CCSM3 does not obtain 2007-like conditions until 2013

Simulated natural variability is considerable and comparable to obs

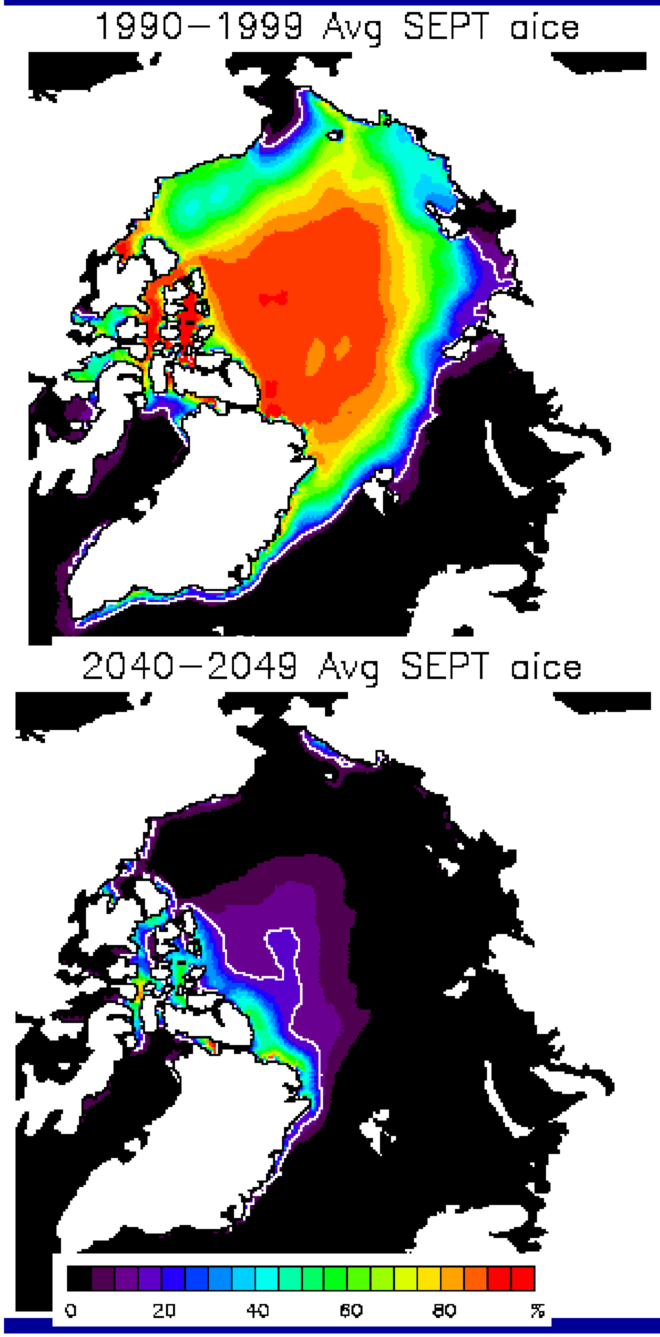
Future climate scenarios

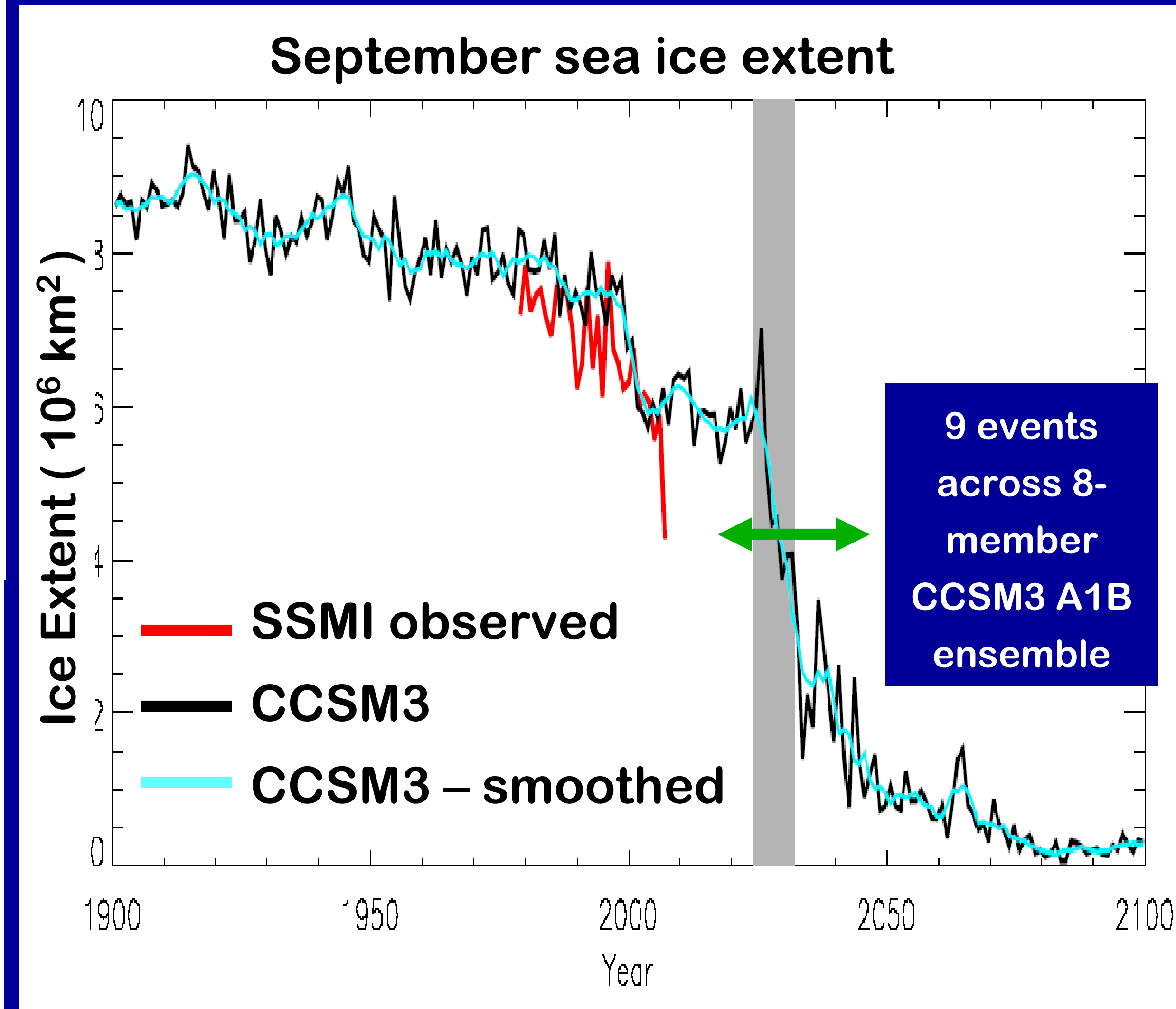
- Relatively gradual forcing.
- Relatively gradual response in global air temperature



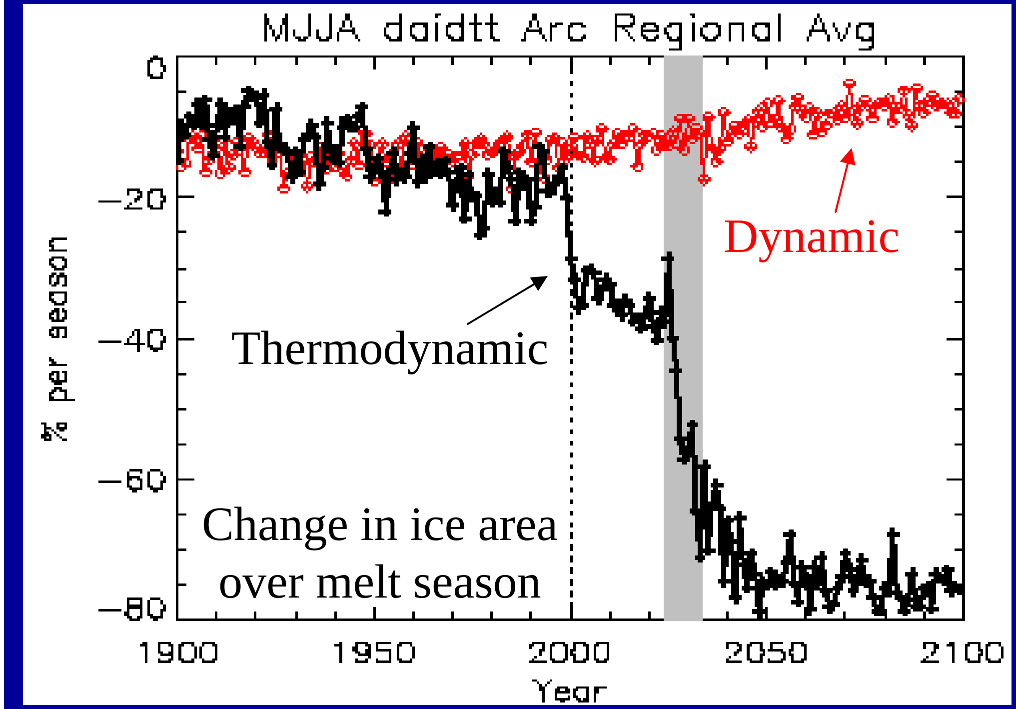
IPCC-AR4

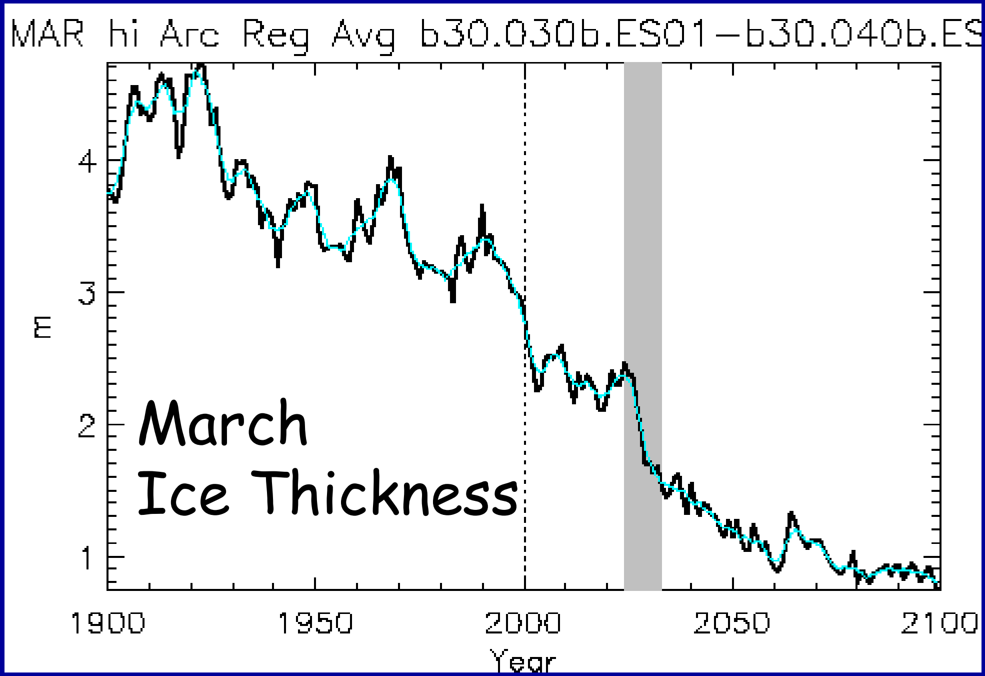
Abrupt reductions in the September sea ice cover





Holland et al., 2006



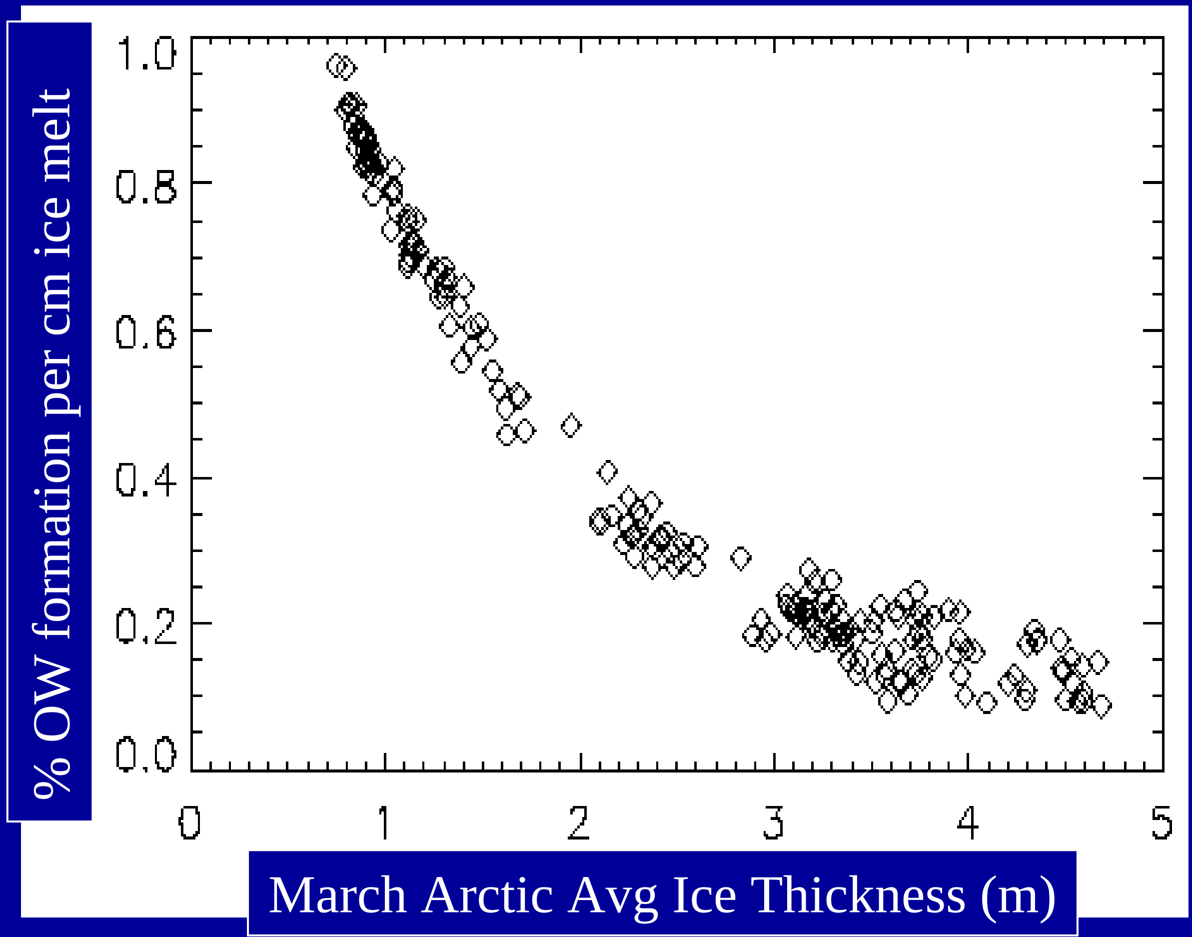


Forcing of the Abrupt Change

- Change is driven thermodynamically
- Dynamics plays a small stabilizing role

- Ice melt rates directly modify ice thickness
- Ice thickness shows large drop associated w/ event
- This change is similar to earlier reductions in 20th century that had little ice extent change.

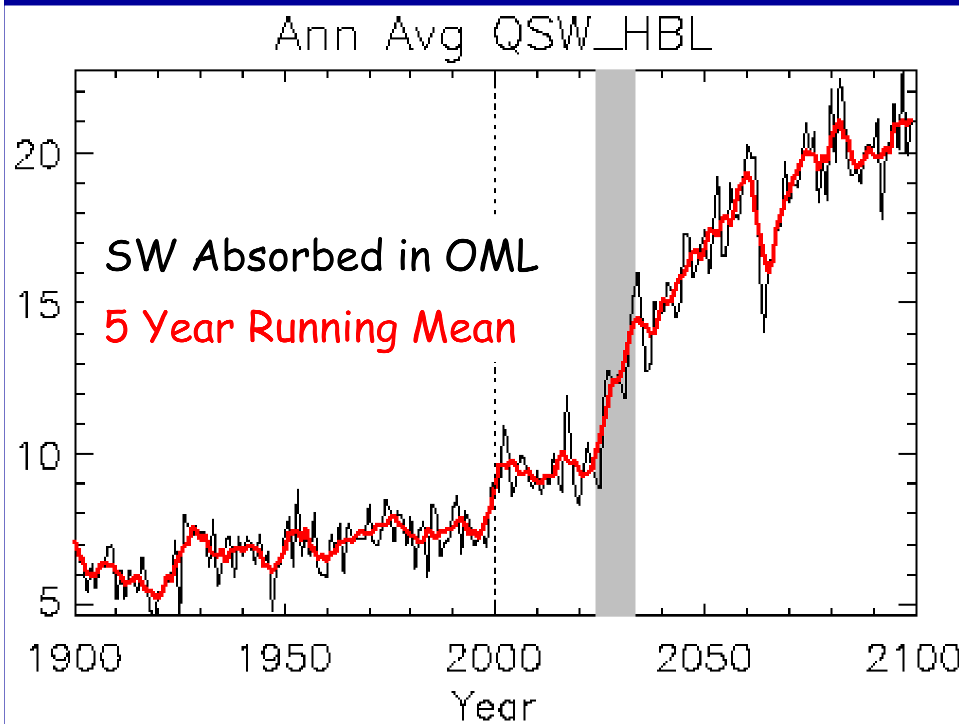
Processes contributing to abrupt change

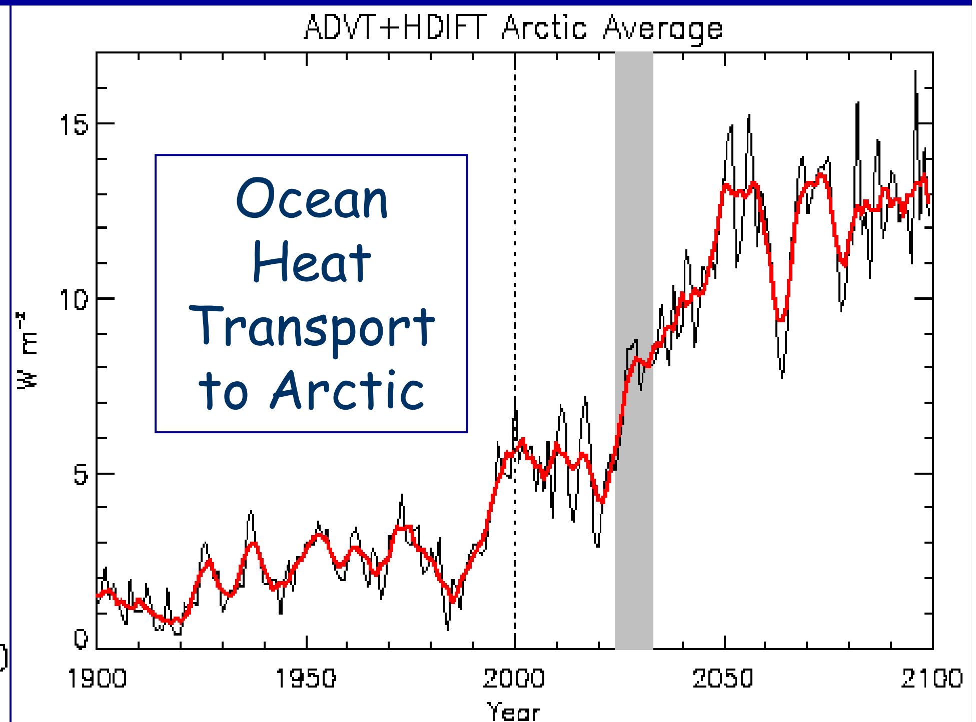


Increased efficiency of OW production for a given ice melt rate

- As ice thins, vertical melting more efficiently produces open water
- Relationship with ice thickness is non-linear

Processes contributing to abrupt change





Albedo Feedback

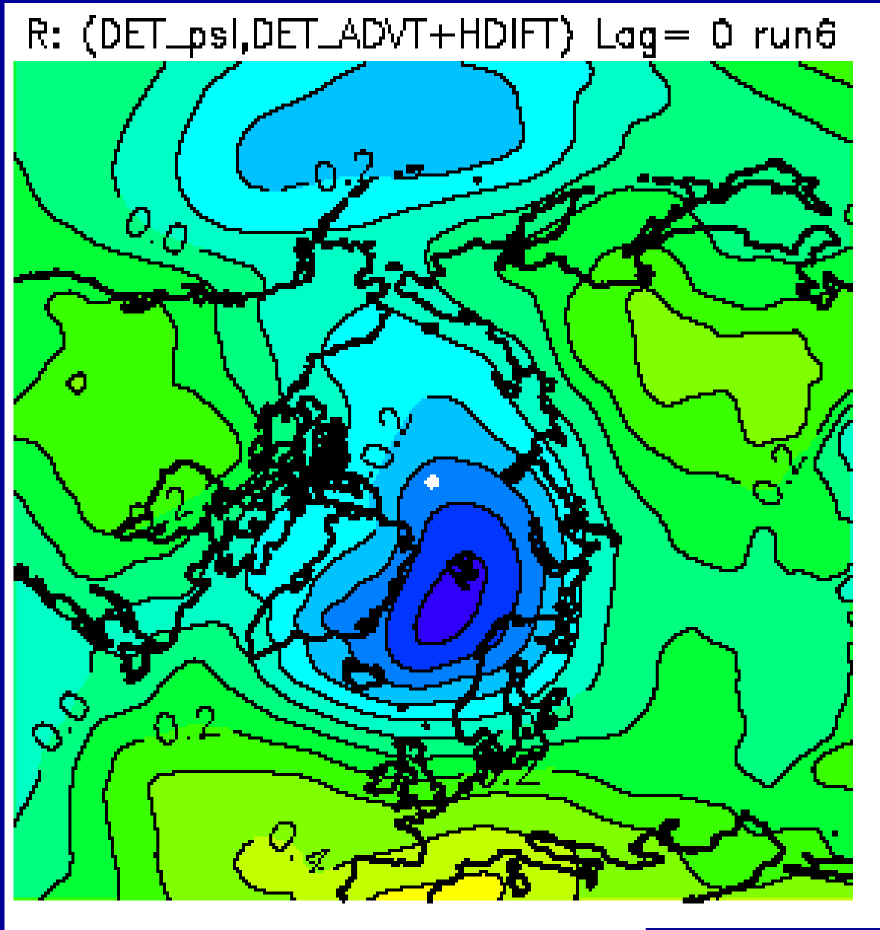
Increases in absorbed solar radiation as the ice recedes.

Contributes to increased basal melting

Increases in ocean heat transport over abrupt transition.

Contributes to increased basal melting and provides a possible “trigger” for the event.

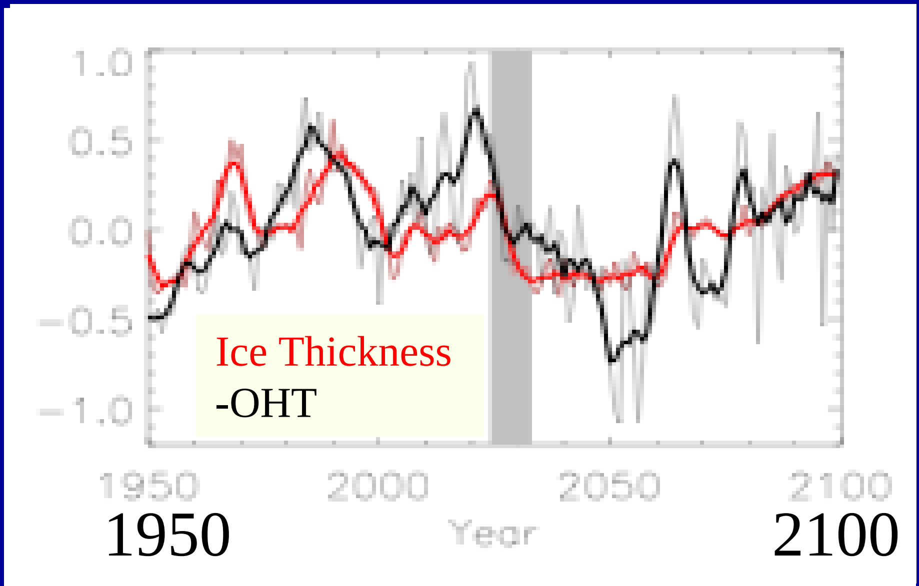
Both trend and shorter-timescale variations in OHT appear important

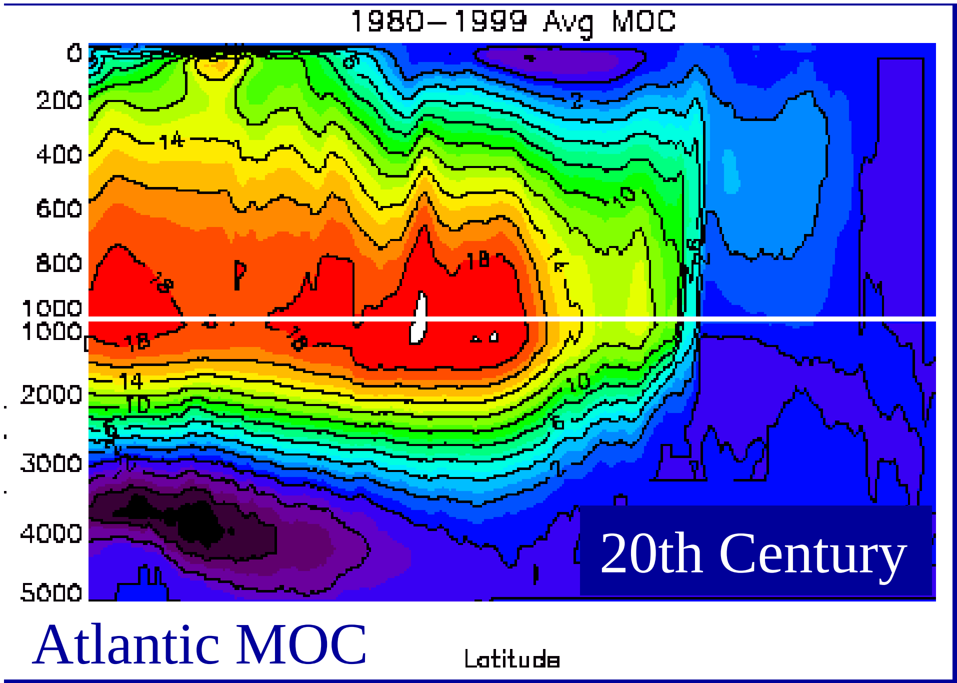


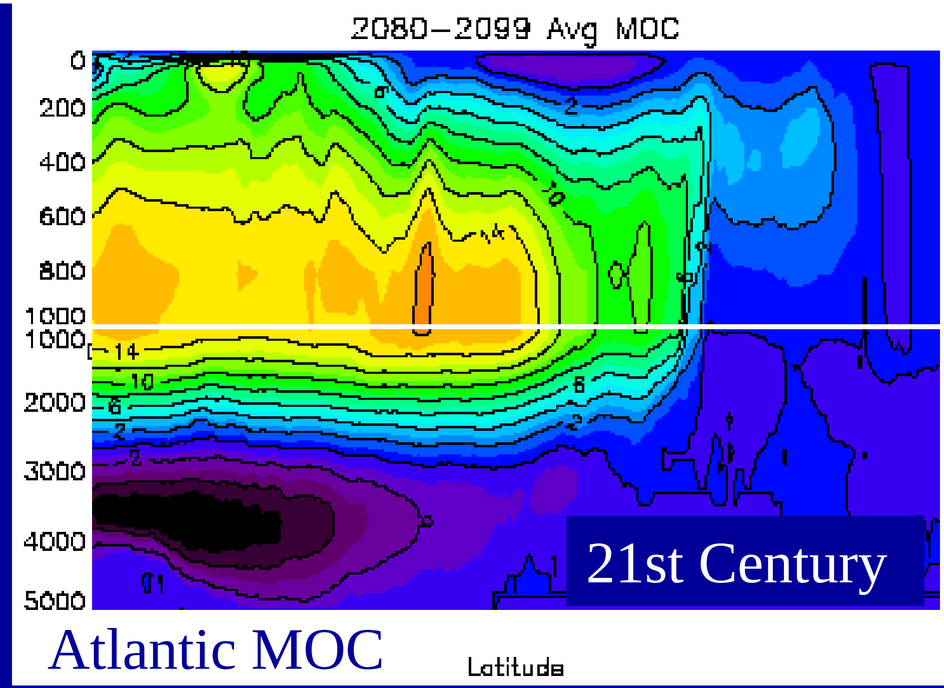
(Holland et al, in press)

OHT "natural" variations lead changes in ice cover

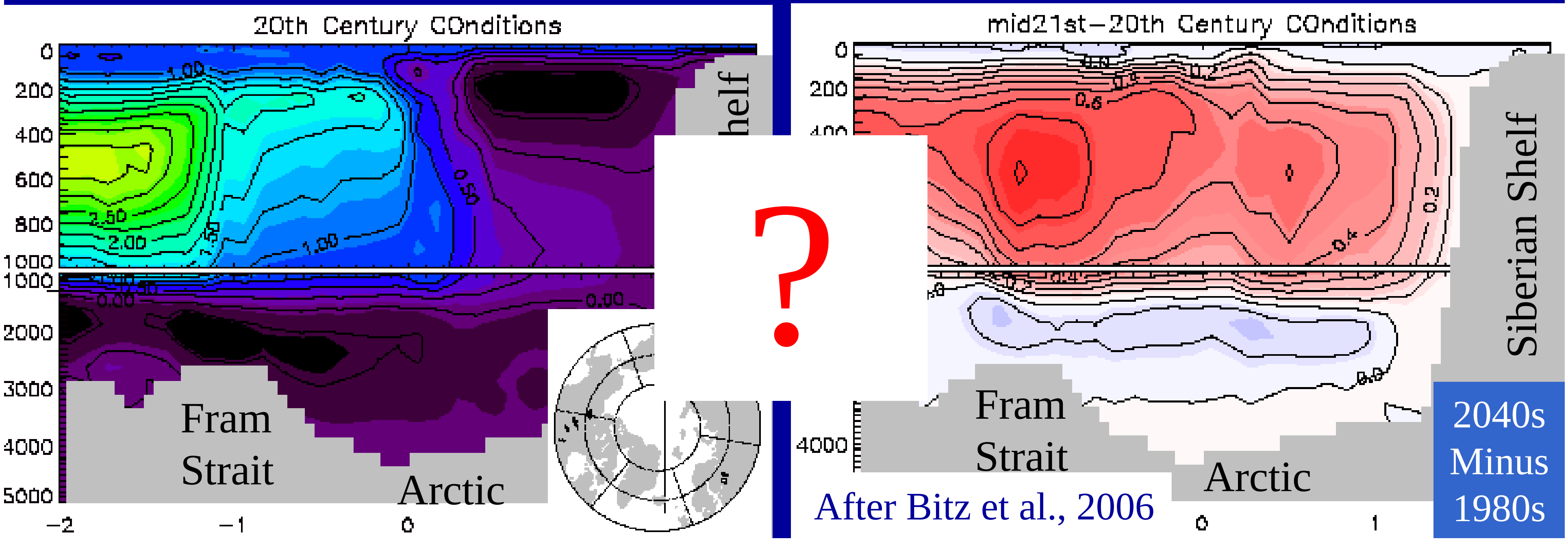
Correlated to an NAO-type pattern in SLP







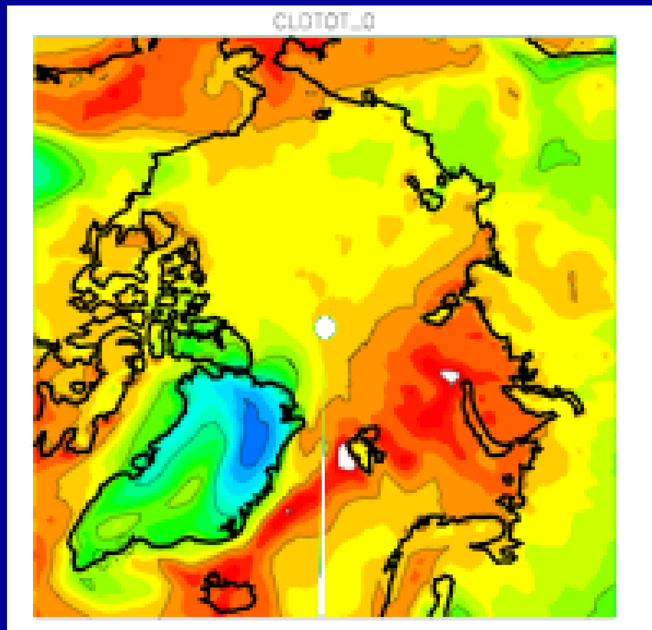
OHT Trend



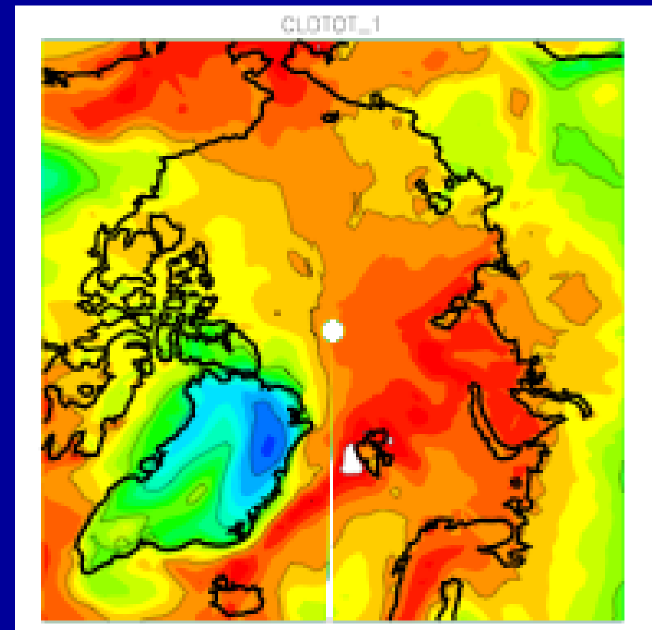
After Bitz et al., 2006

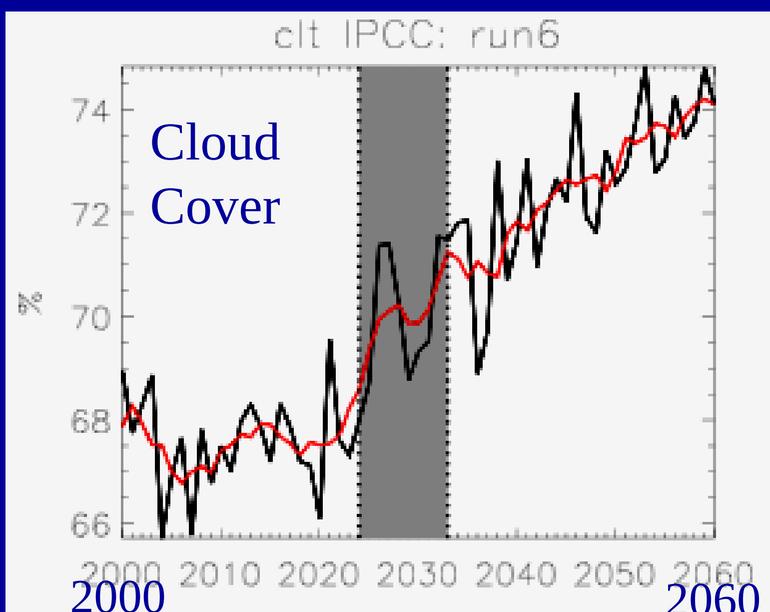
A possible role for cloud feedbacks?

Cloud cover before event

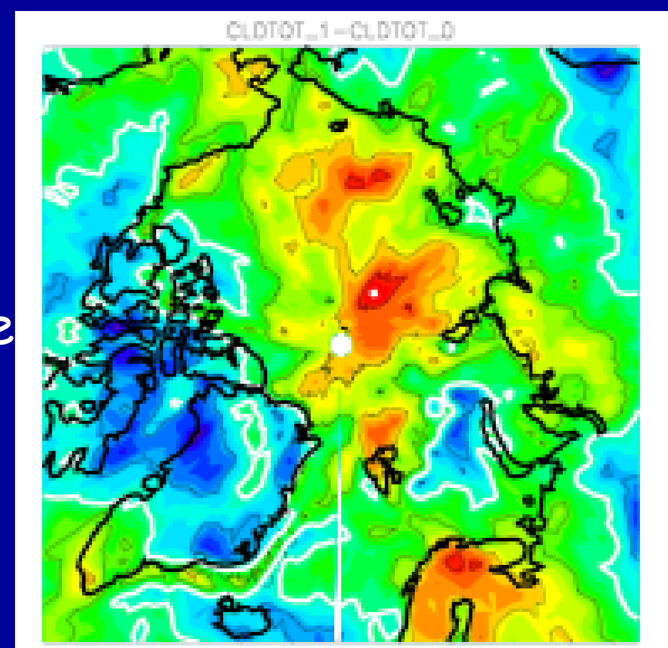


Cloud cover after event

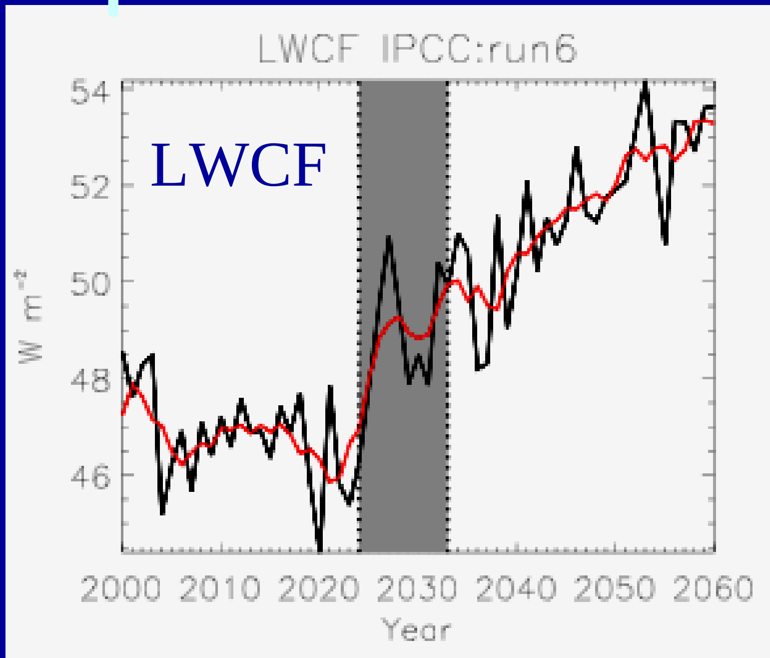


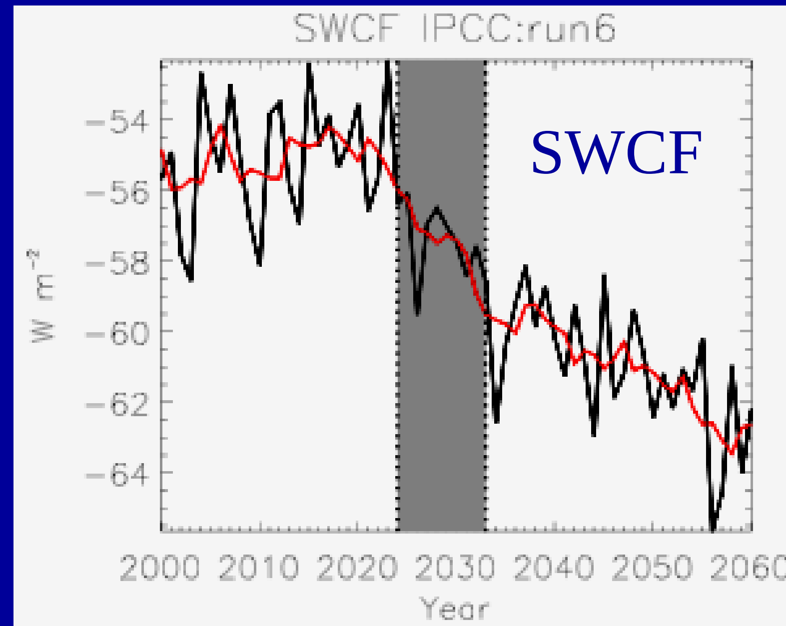


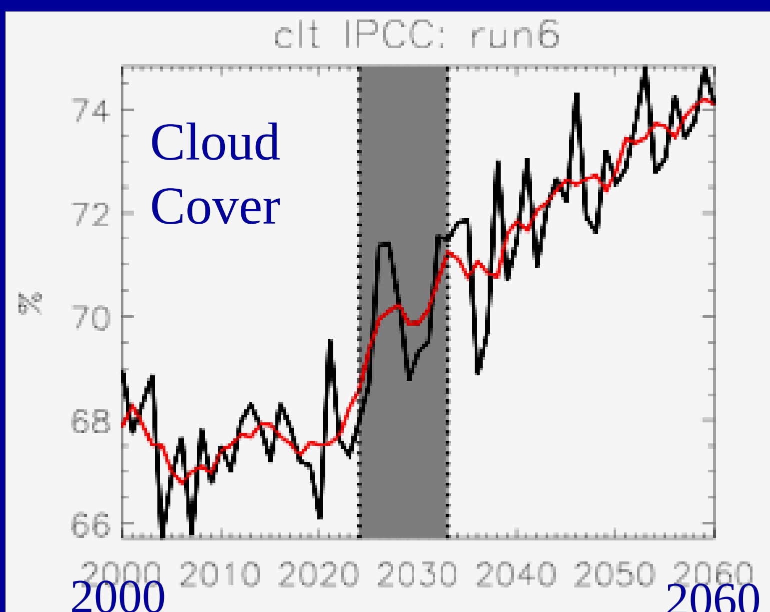
Cloud cover difference



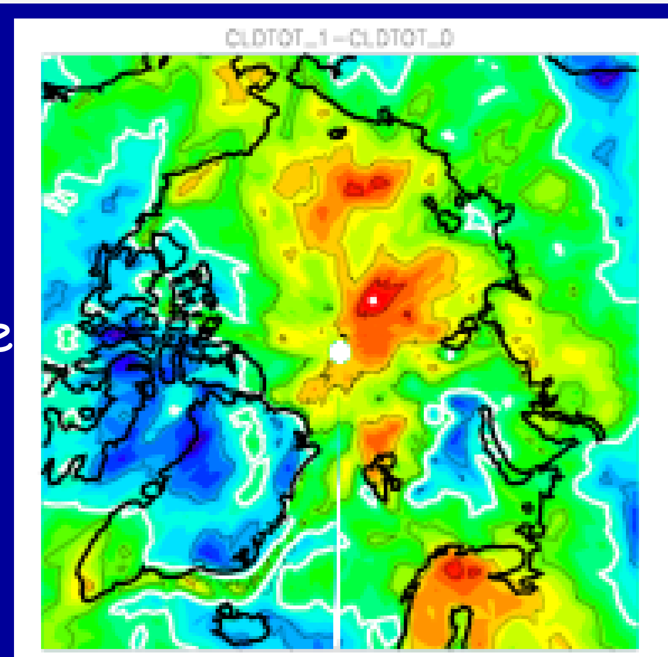
A possible role for cloud feedbacks?







Cloud cover difference



Mechanisms Driving Abrupt Transition

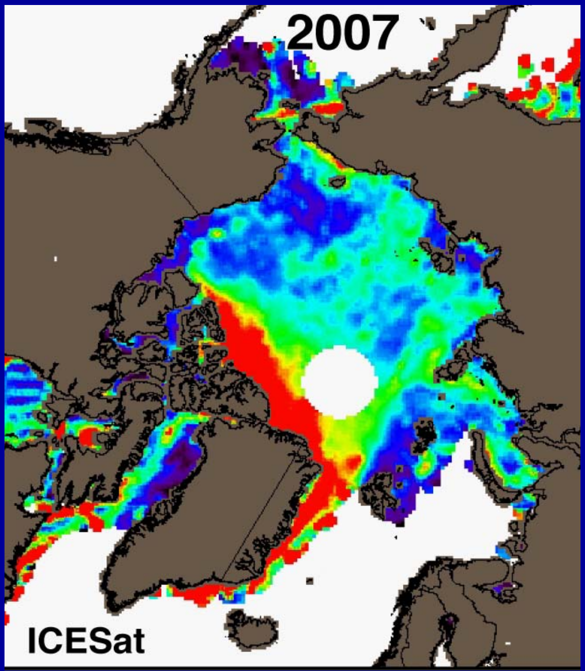
1. Transition of ice to a more vulnerable state
   - thinning of the ice
2. A Trigger - (Natural?) rapid increases in OHT.
   - Other natural variations could potentially play the same “triggering” role
3. Positive feedbacks that accelerate the retreat
   - Surface albedo feedback
   - OHT feedbacks? Mechanisms not fully understood.
   - Possible cloud feedbacks under investigation

Similar mechanisms at work for abrupt events in other ensemble members
Relative importance of various factors differs among events

Conditions implicated in 2007 ice loss

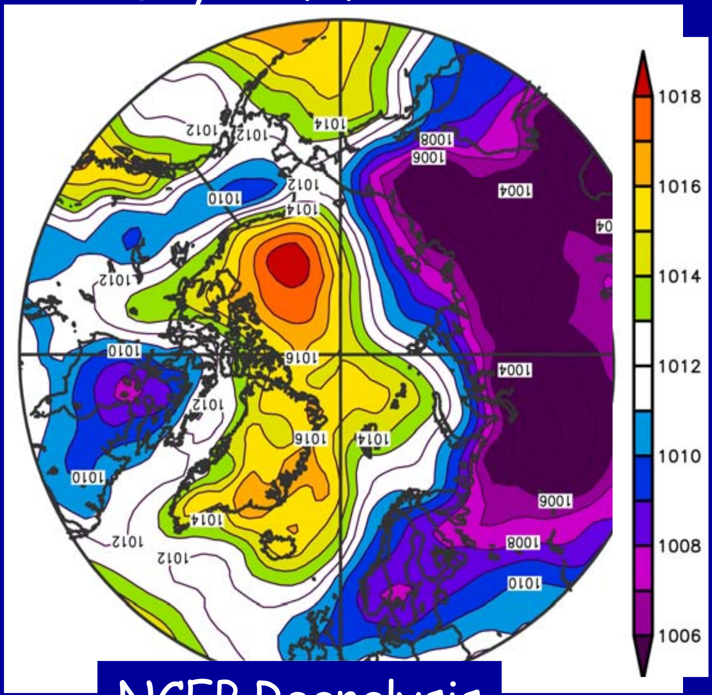
1. Thinning of ice to a more vulnerable state
2. A Trigger - anomalous high pressure over Beaufort Sea
   - Other associated variations possibly played a role
3. Positive feedbacks that could accelerate future retreat
   - Surface albedo feedback

Ice Thickness



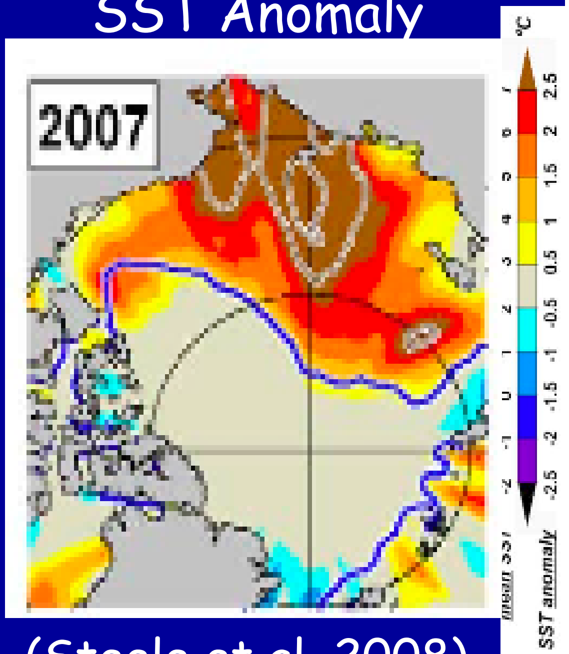
(Stroeve et al., 2008)

SLP, Summer 2007



NCEP Reanalysis

SST Anomaly



(Steele et al, 2008)

Is simulated Rapid Ice Loss a consequence of "Tipping Point" behavior?

Role of forced versus natural change

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Ensemble Mean
Sept Extent
"Forced Response"

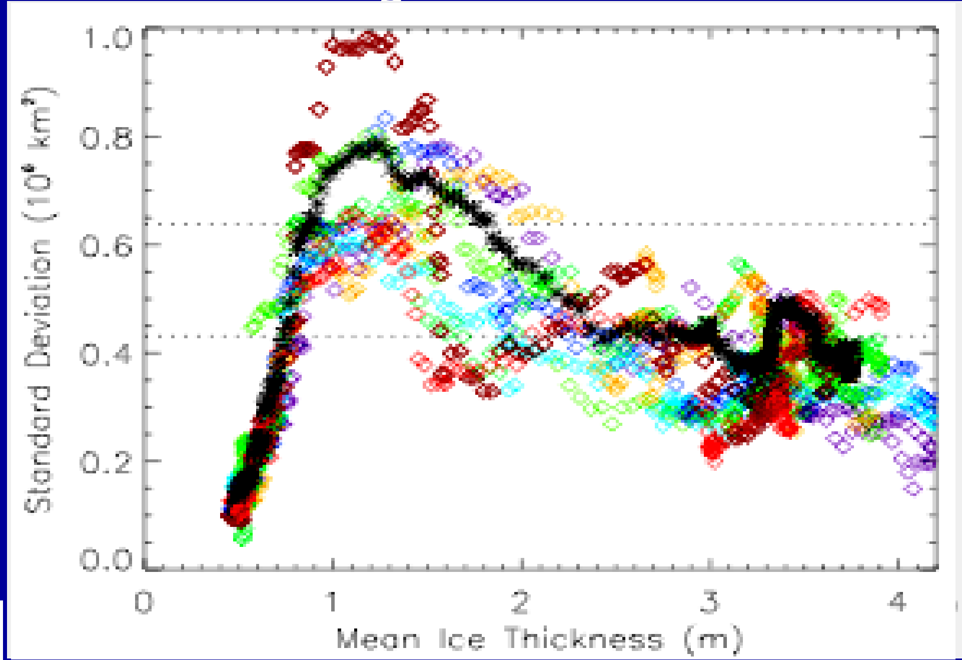
1900 2100

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Extent with Ensemble
Mean Removed

1900 2100

30 Yr Running Standard Deviation

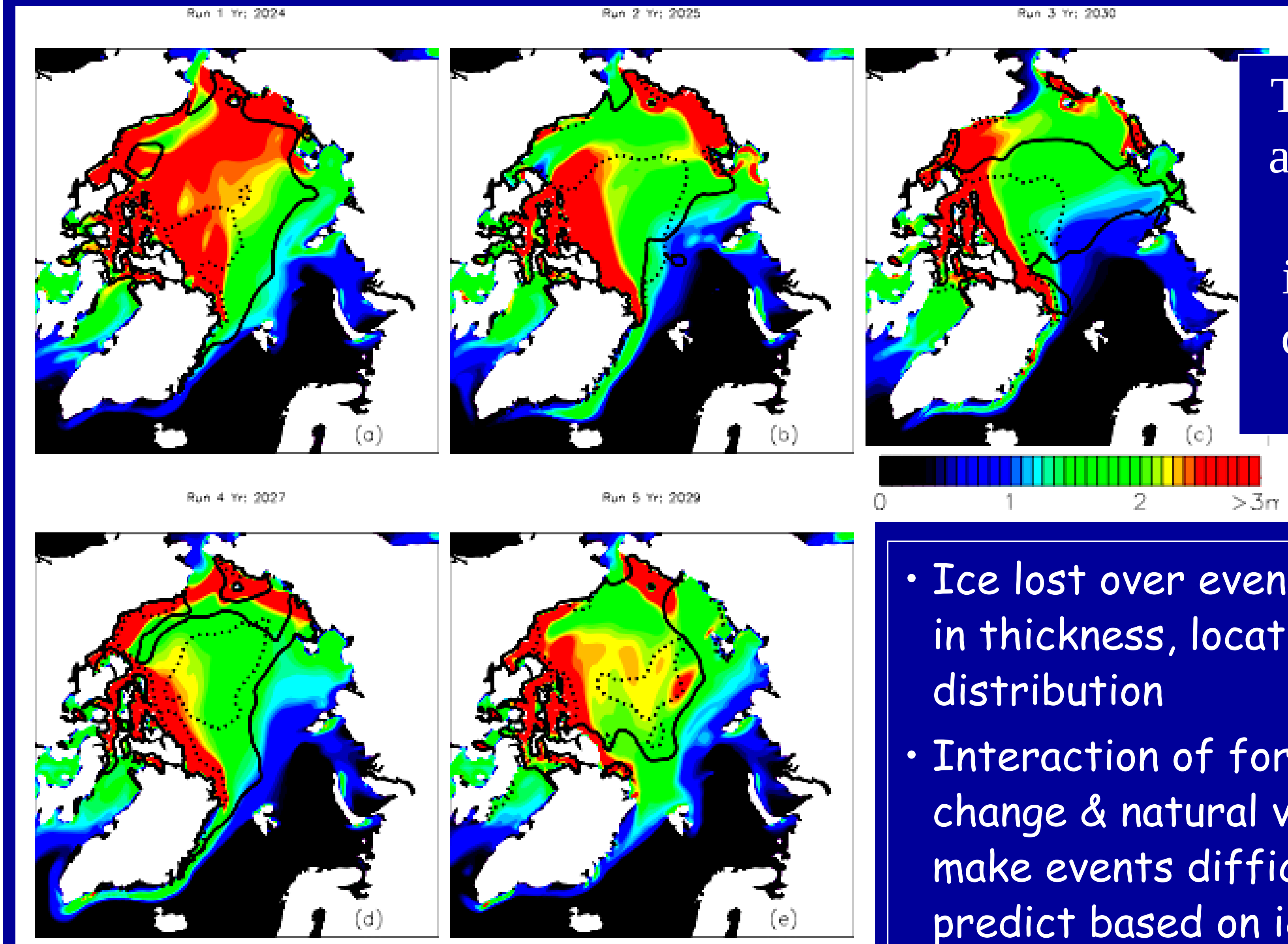


As ice thins, the "natural" variability in extent increases

A combination of large "forced" change and large intrinsic variability necessary

(Holland et al., in press)

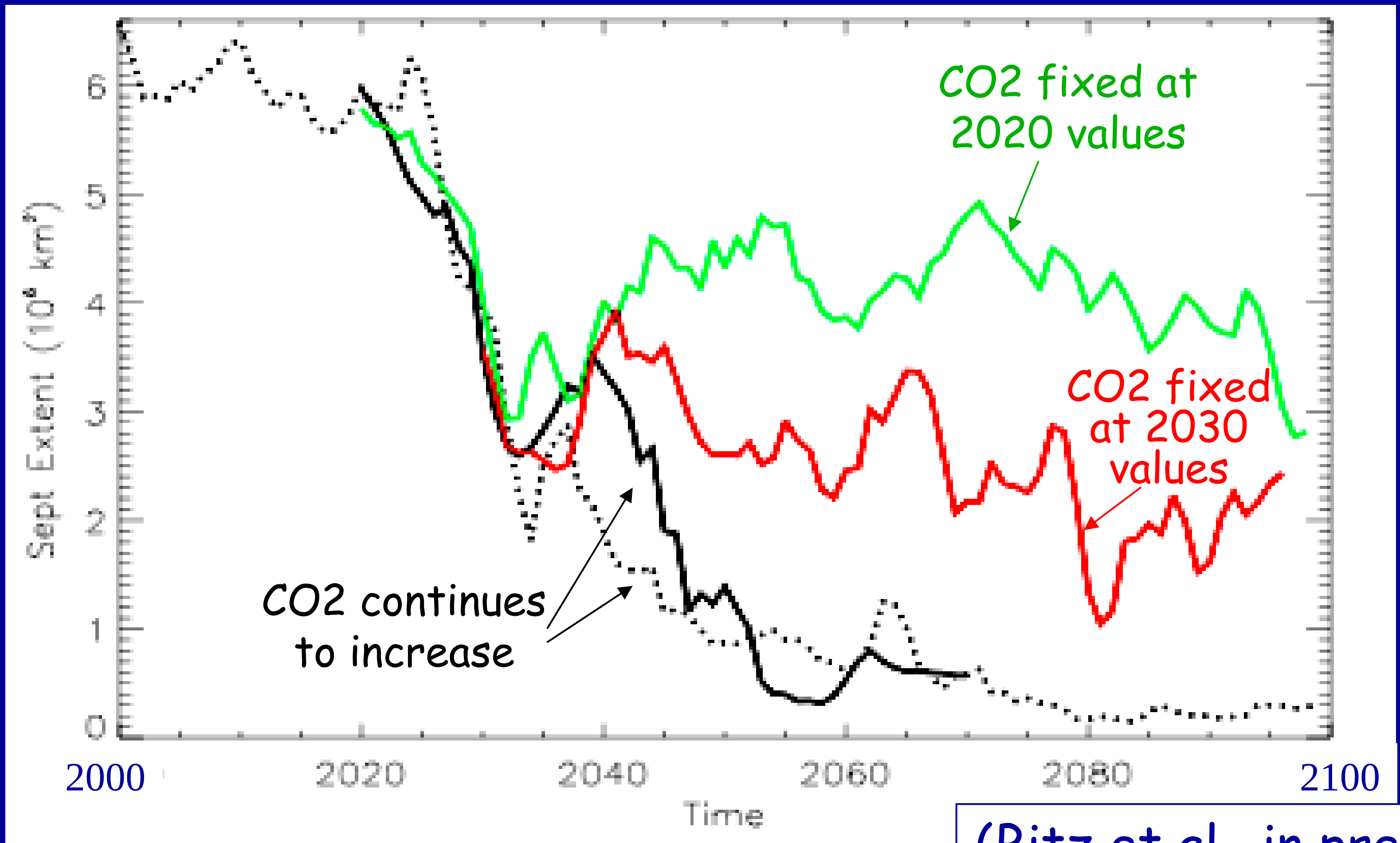
Searching for a “critical” ice threshold



Thickness and extent of ice at initiation of abrupt retreat

- Ice lost over events varies in thickness, location, distribution
- Interaction of forced change & natural variations make events difficult to predict based on ice state

If fix CO2, does ice continue to retreat?



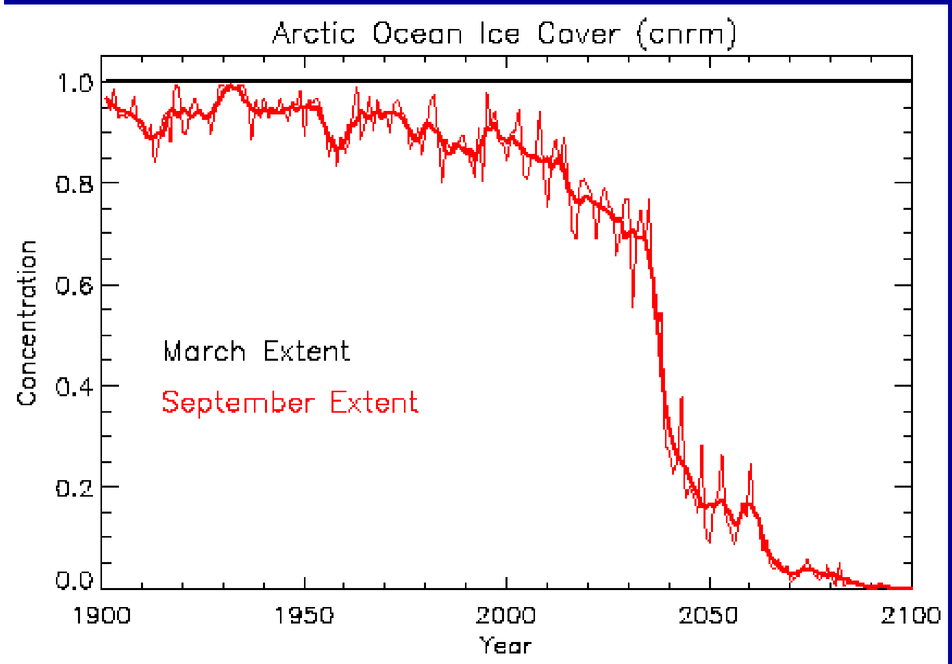
(Bitz et al., in prep)

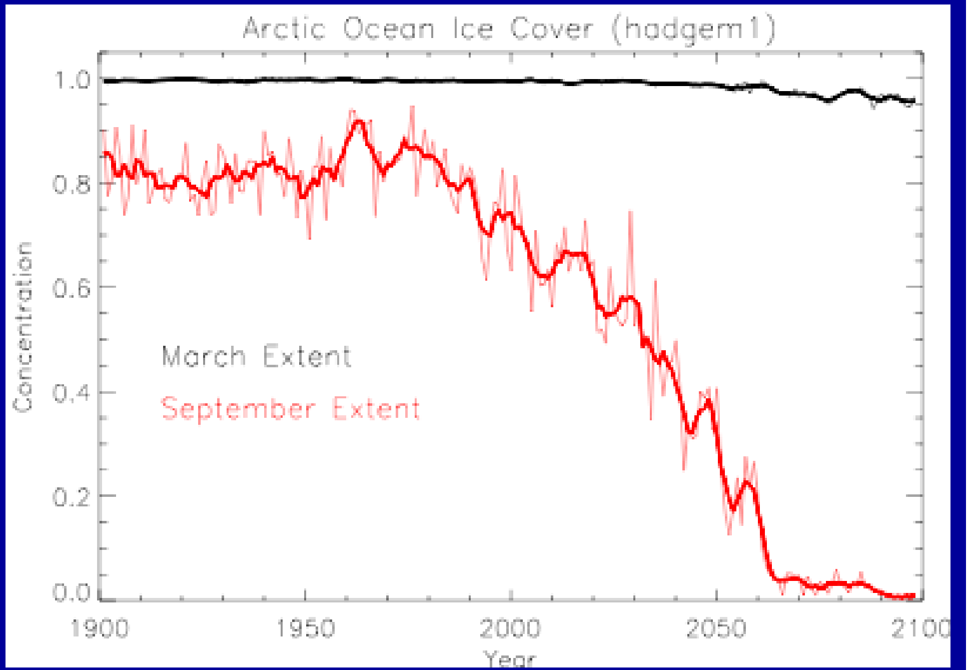
Model results suggest

- that sea ice may not go seasonally ice-free if no continued increases in CO2
- Strongly suggests this is not Tipping Point behavior!

Do other models have abrupt transitions?

Some do… Some don't…



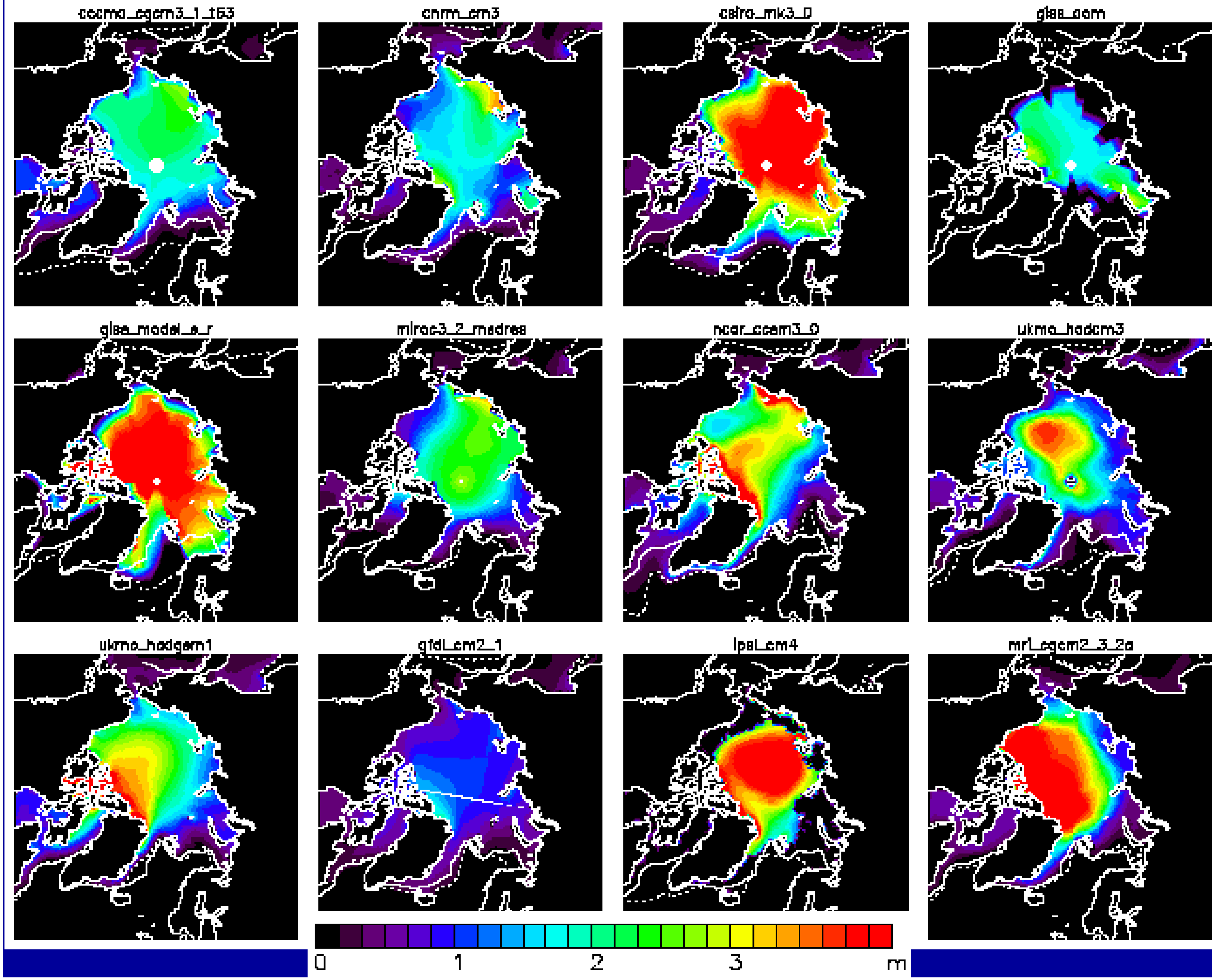


From an analysis of 15 additional IPCC-AR4 models, we find that 50% of them simulate abrupt reductions for some future forcing scenario. Rapid ice loss is more likely in simulations with higher anthropogenic forcing.

Data from IPCC AR4 Archive at PCMDI

Is it possible to identify why various models exhibit differences in their possible future abrupt ice retreat?

Simulated late 20th century ice conditions



Ann avg 1980-1999 ice thickness

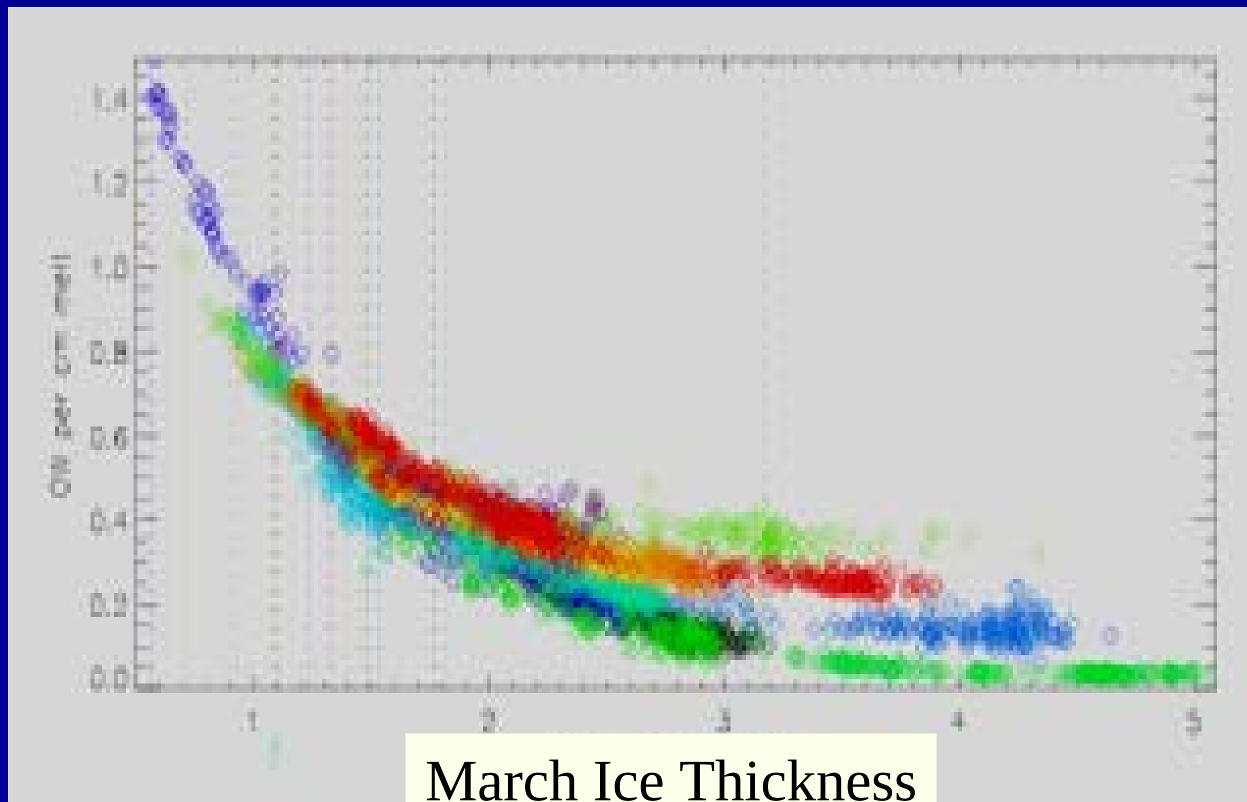
IPCC AR4

Dash=March extent

White=Obs Extent

OW production and ice thickness

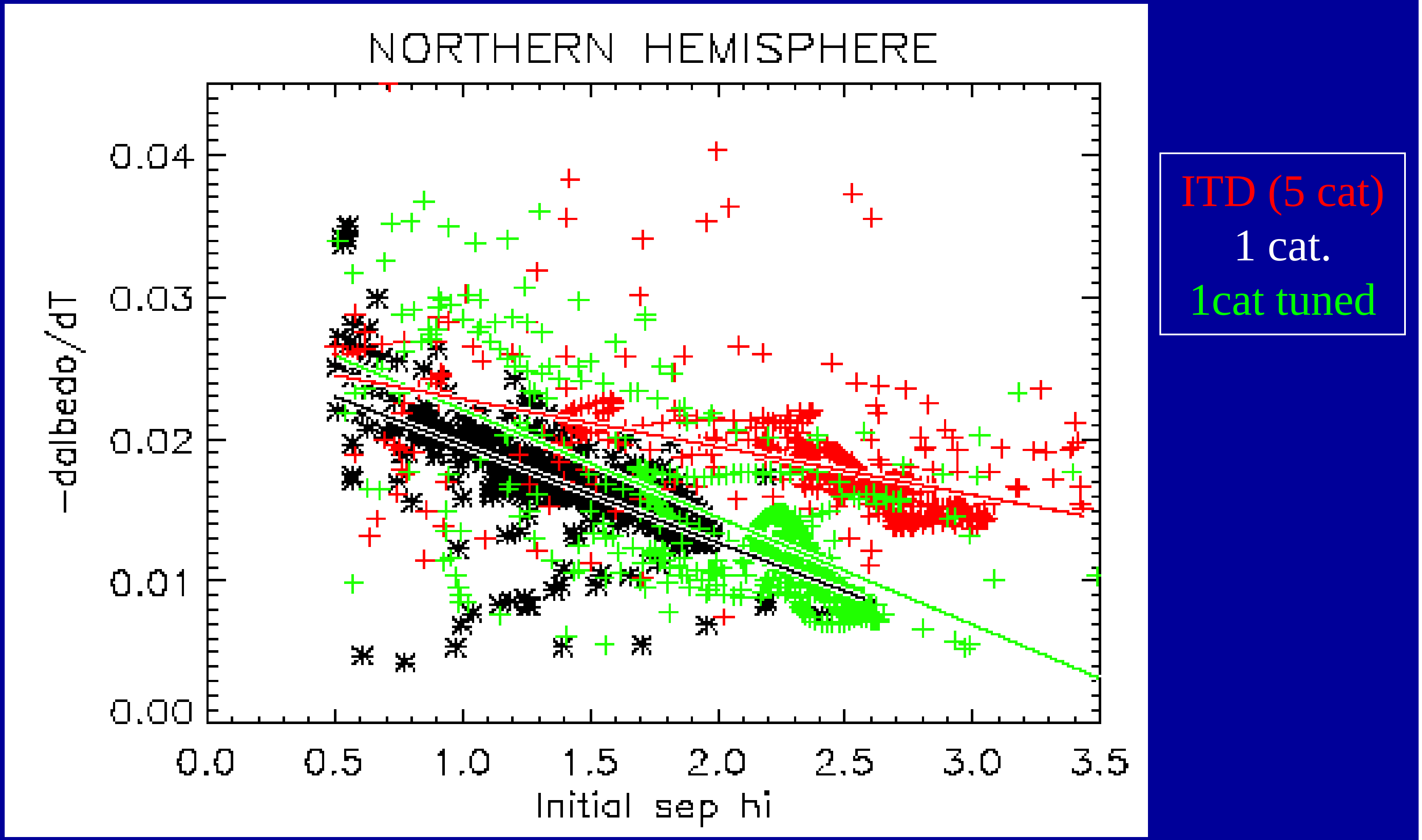
OW formed per cm ice melt



March Ice Thickness

The percent of models with abrupt retreat increases if models with unrealistic present-day ice thickness and/or extent are excluded from the analysis.

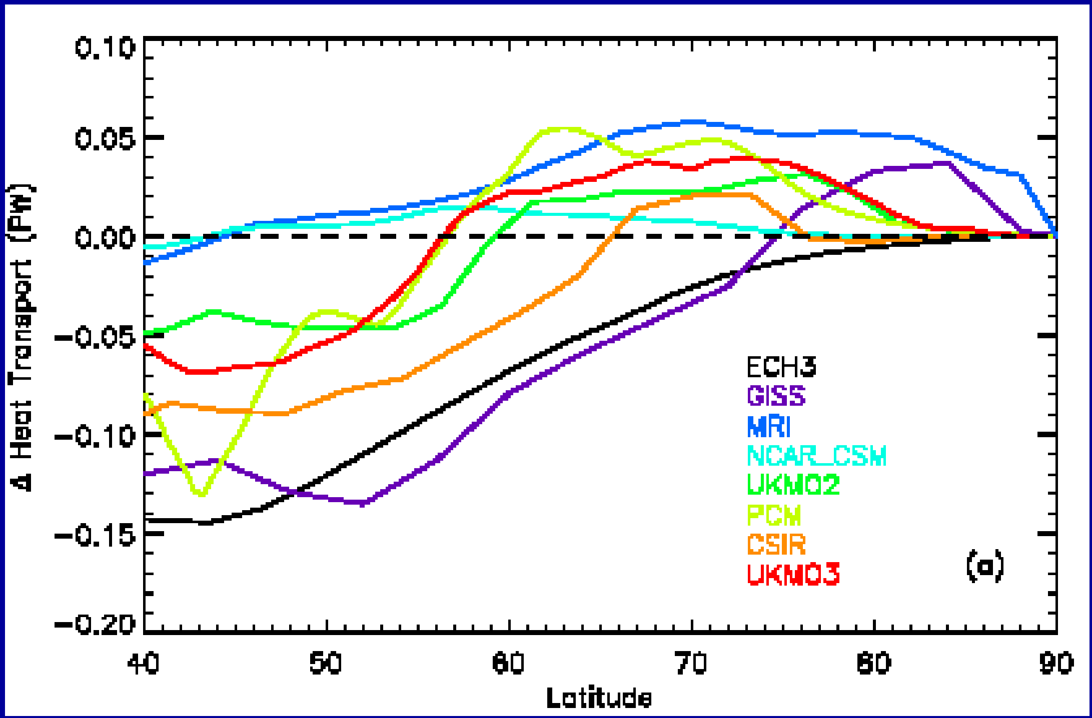
Feedback Strength and Model Parameterizations



(Holland et al., 2006)

For example, studies suggest that including a subgridscale ice thickness distribution enhances the albedo feedback

Increases in Ocean Heat Transport to the Arctic



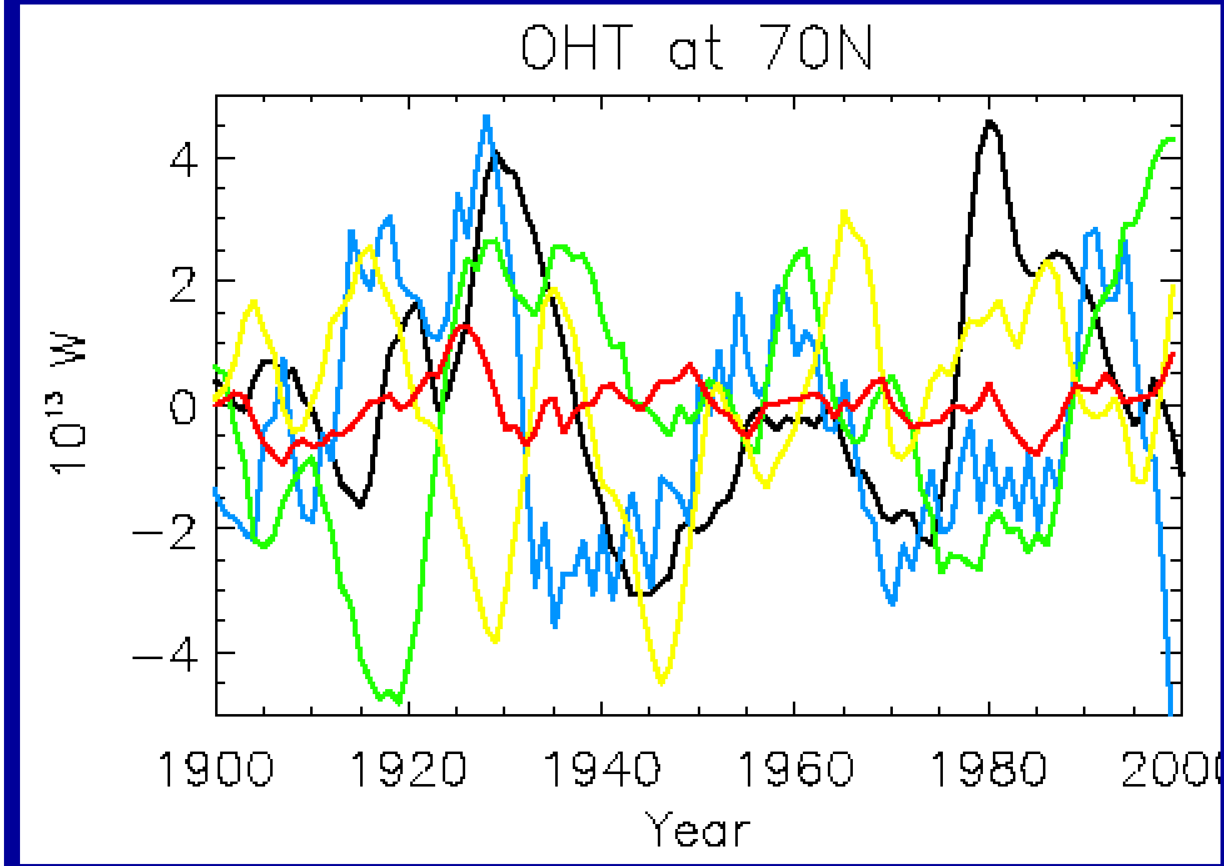
Change in OHT
2XCO2-present day

Change in poleward ocean heat transport at 2XCO2 conditions in CMIP2 models

OHT increases to the Arctic are common in climate models but vary considerably in their magnitude

(From Holland and Bitz, 2003)

Aspects of the Model's Internal Variability

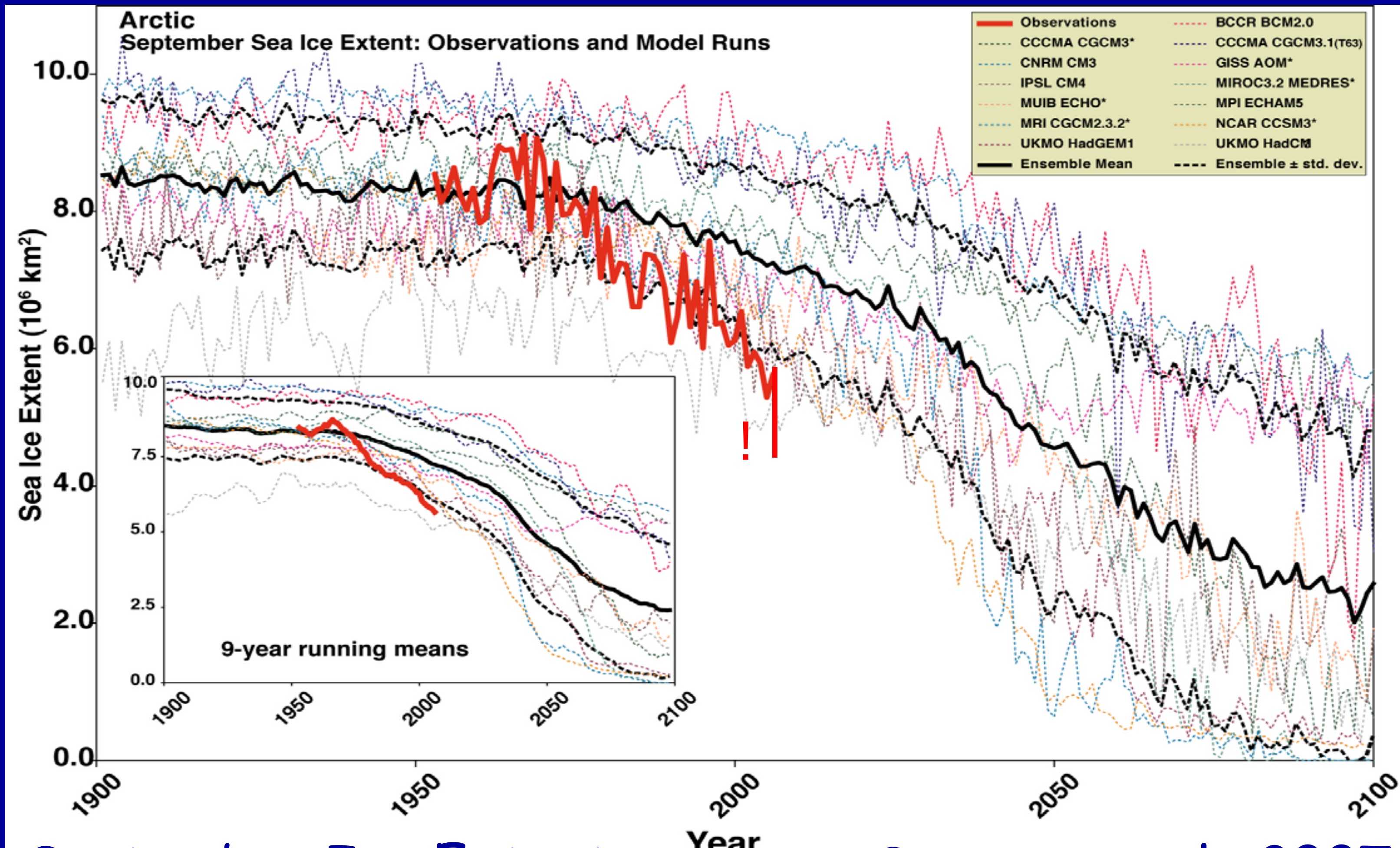


Model	Standard Deviation
Model 1	1.93
Model 2	1.90
Model 3	1.72
Model 4	1.68
Model 5	0.42

Is it possible to identify why some do and some do not?

- No easily identifiable single factor
- A combination of multiple things, including
  - Model parameterizations
  - Initial conditions
  - Internally generated model variability

IPCC-AR4 climate model projections



September Ice Extent Stroeve et al., 2007

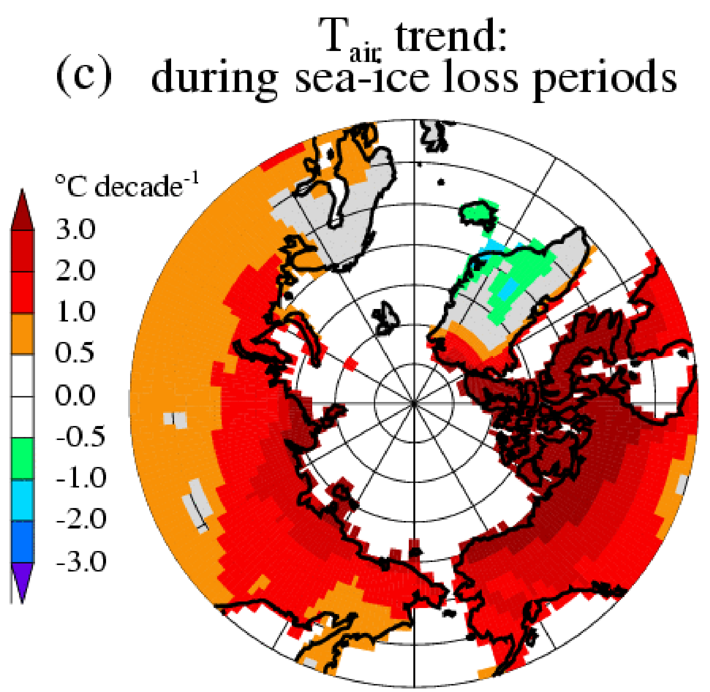
Large range in simulated ice extent and extent loss

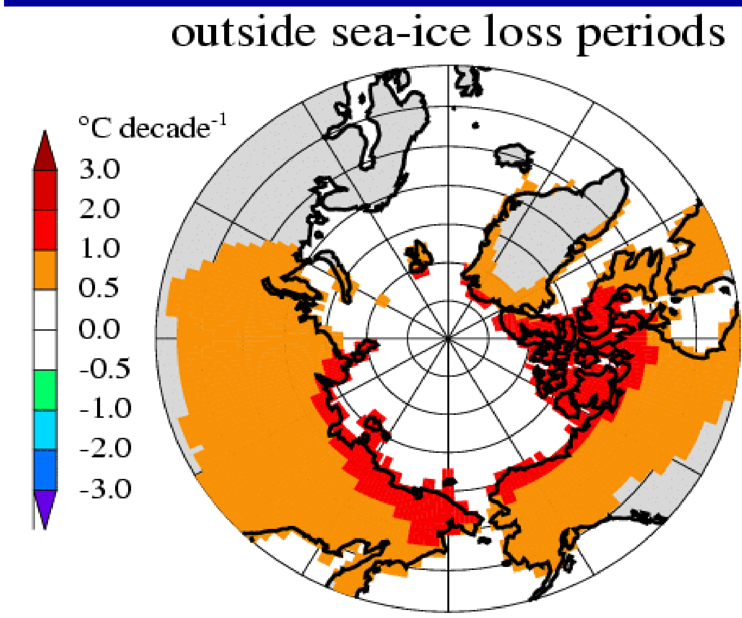
Models generally conservative compared to observations

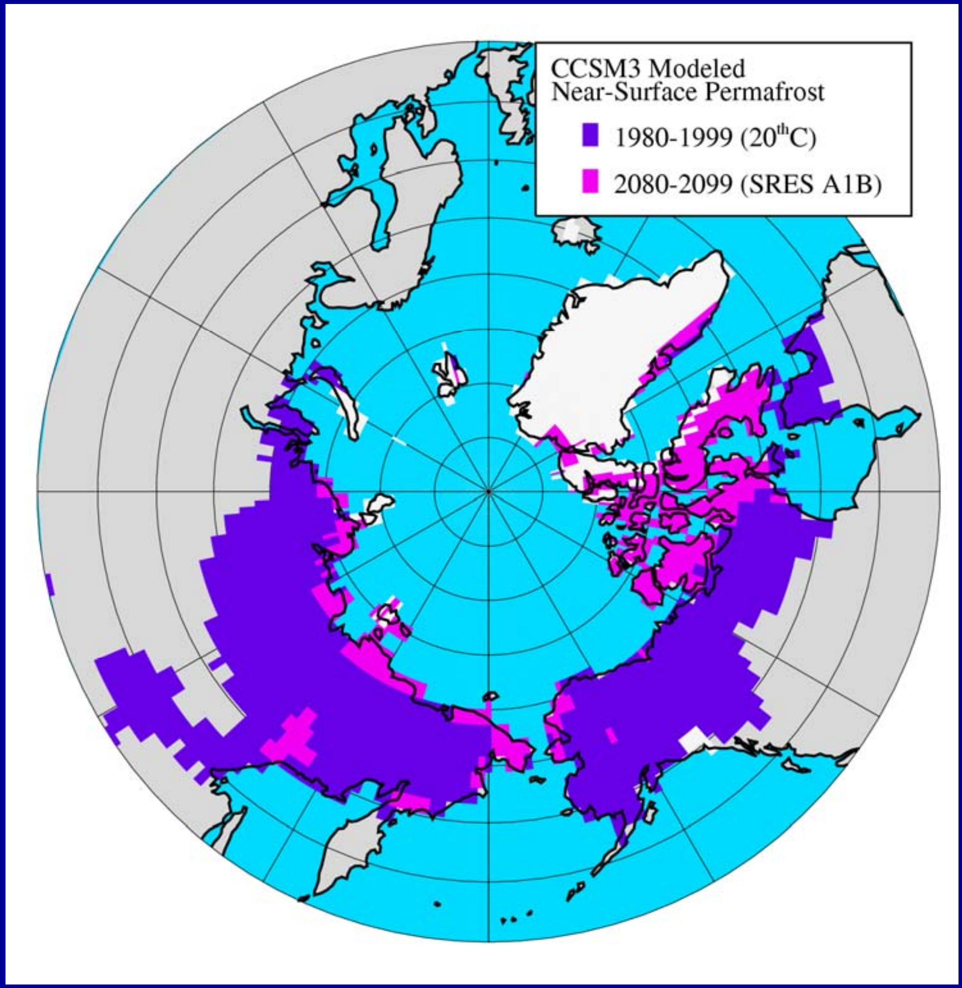
Continued Research: Remaining Questions

- Role of other forcings/feedbacks - Clouds, atmospheric circulation variations
- Model depiction of certain processes - OHT/ice interactions, Arctic ocean structure
- Mechanisms driving some of the changes - Arctic long-term OHT increase, cloud response
- Importance of neglected processes - e.g., methane release?

Associated Permafrost Retreat







Lawrence et al., in press

Conclusions

- Abrupt summer sea ice reductions are common in future climate projections (in one model analyzed)
- In most extreme case, retreat from near-present day to near-ice free Septembers in ~10 yrs
- The transitions result from:
  - A vulnerable, thin ice state: Increased OW per melt rate
  - A trigger: Increased OHT (natural variability?)
  - Accelerating feedbacks: Albedo change/OHT?/Clouds?
- Rapid ice loss results from interaction of natural variability and anthropogenic change
- Little indication that these are a "tipping point" response
- Models differ on simulation of abrupt summer ice loss

Questions?