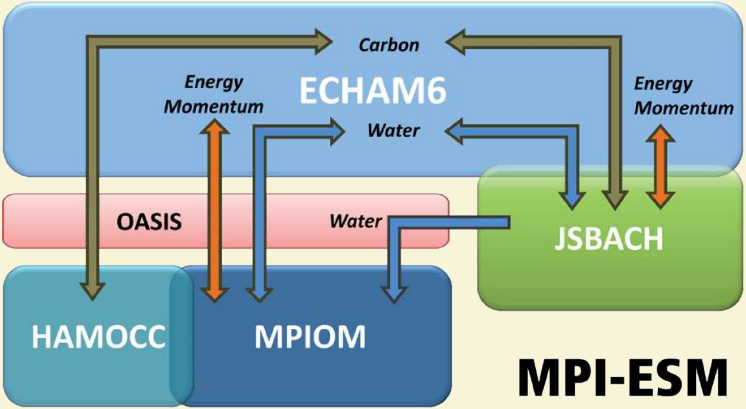
What do climate models need sea ice for?

A visit to the engine room

Overview

1. How do we build a climate model?
2. How well must sea ice be represented in climate models?
3. Understanding the limited importance of sea ice
4. Concluding remarks

The building blocks of MPI-ESM



Giorgetta et al., 2013

The MPI atmosphere model ECHAM6

Some of our explicit equations

- Navier Stokes equation
- Clausius Clapeyron equation
- Conservation laws (water, energy, momentum, carbon)

Some of our parameterisations

- Formation of clouds
- Interactions of clouds with radiation
- Gravity wave drag
- Turbulent boundary layer

The MPI ocean model MPIOM

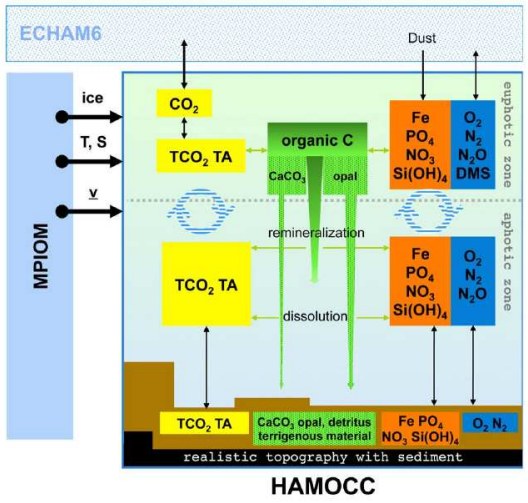
Some of our explicit equations

- Navier Stokes equation
- Equation of state of sea water
- Conservation laws (water, energy, momentum, carbon)

Some of our parameterisations

- Vertical and horizontal impact of eddies
- Slope convection

The MPI ocean biogeochemistry model HAMOCC



Ilyina et al., 2013

The MPI land model JSBACH

Some of our parameterisations

- Vegetation classes
- Soil moisture
- Fire

The MPI sea-ice model

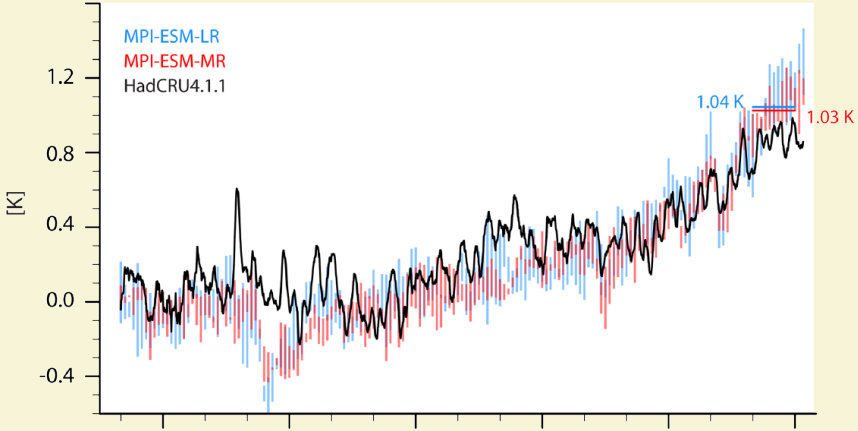
Some of our explicit equations

- Vertical heat transport (simplified)
- Conservation of salt, water, energy

Some of our parameterisations

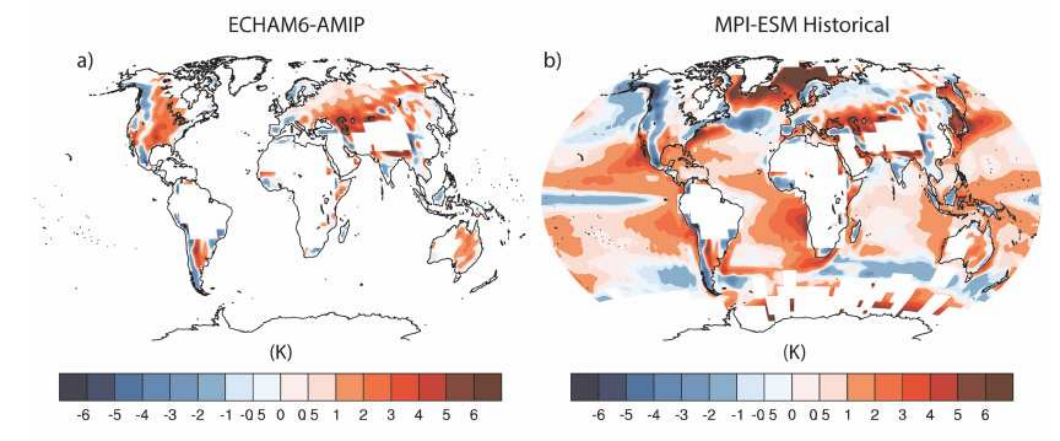
- Viscous-plastic rheology (Hibler)
- Virtual ice-thickness distribution (Hibler)
- Surface albedo (melt ponds, snow)
- Roughness

Global mean temperature



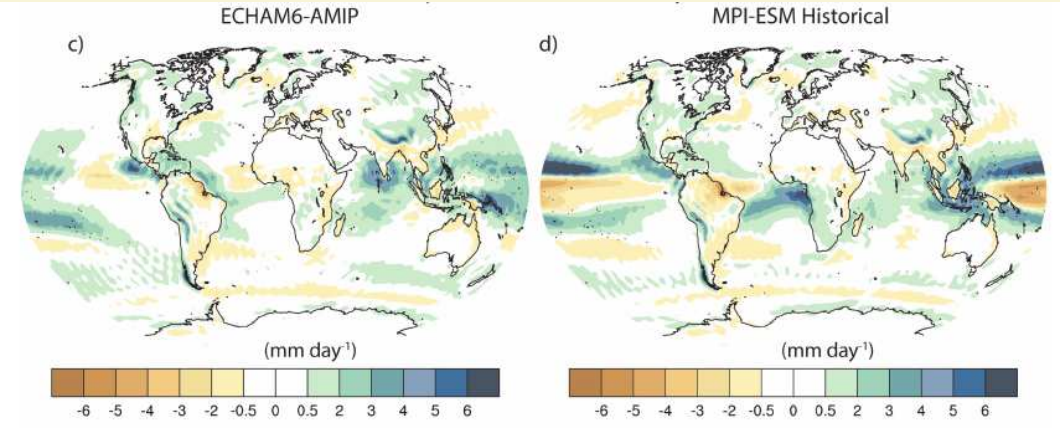
Giorgetta et al., JAMES, 2013

Regional biases of temperature



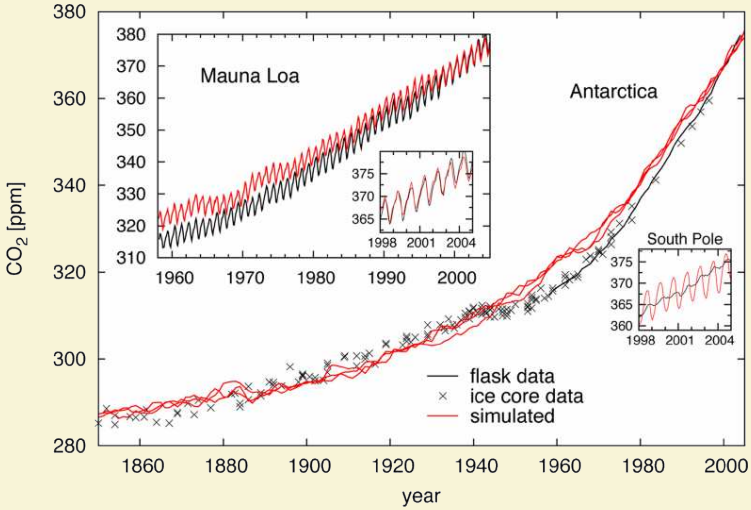
Giorgetta et al., JAMES, 2013

Regional biases of precipitation



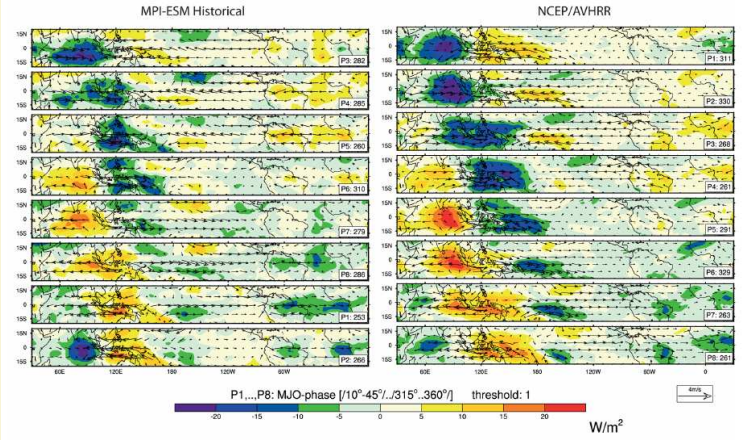
Giorgetta et al., JAMES, 2013

Atmospheric CO_2



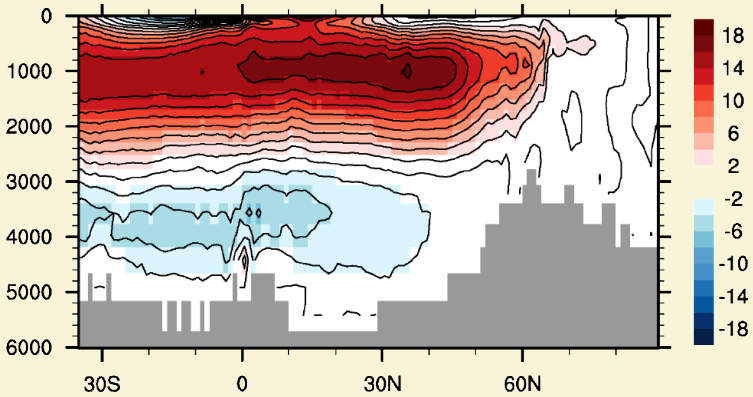
Giorgetta et al., JAMES, 2013

Madden-Julian-Oscillation



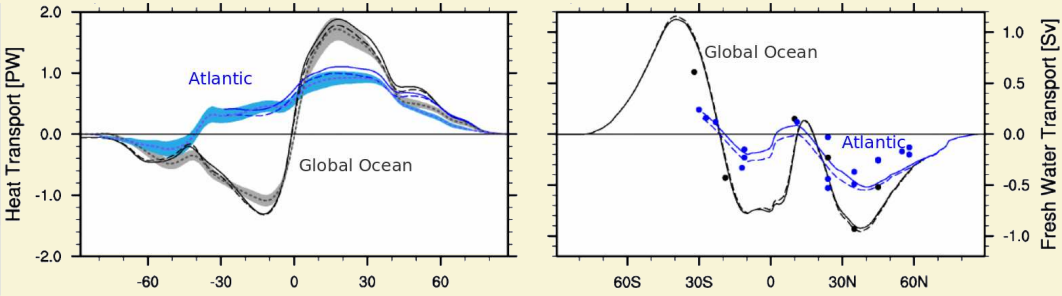
Giorgetta et al., JAMES, 2013

Meridional overturning circulation



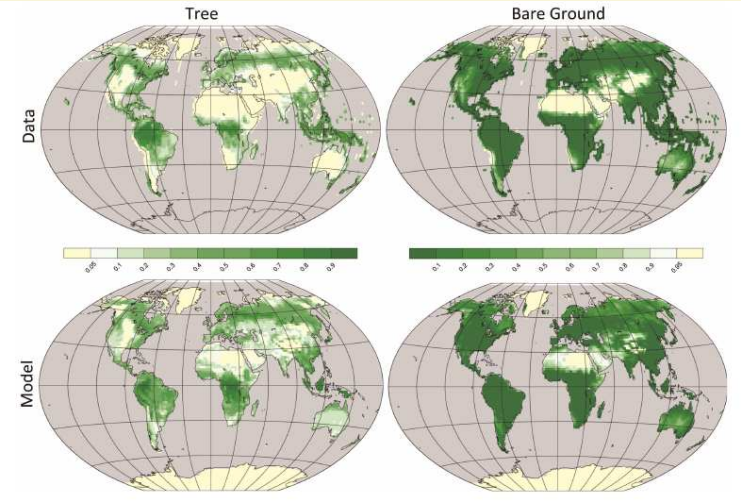
Jungclaus et al., JAMES, 2013

Meridional heat and freshwater transport in the ocean



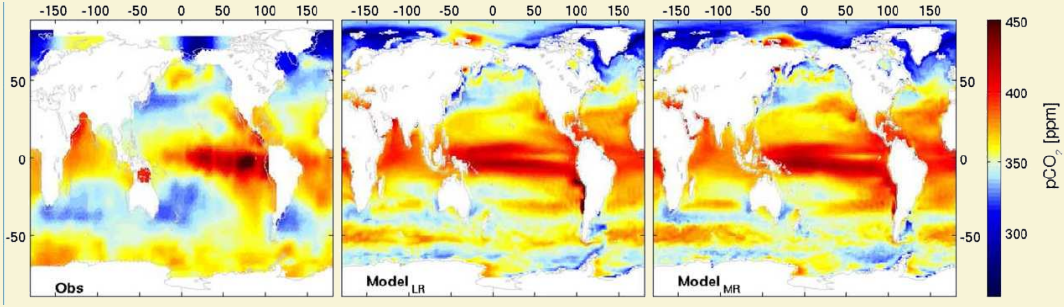
Jungclaus et al., JAMES, 2013

Land cover



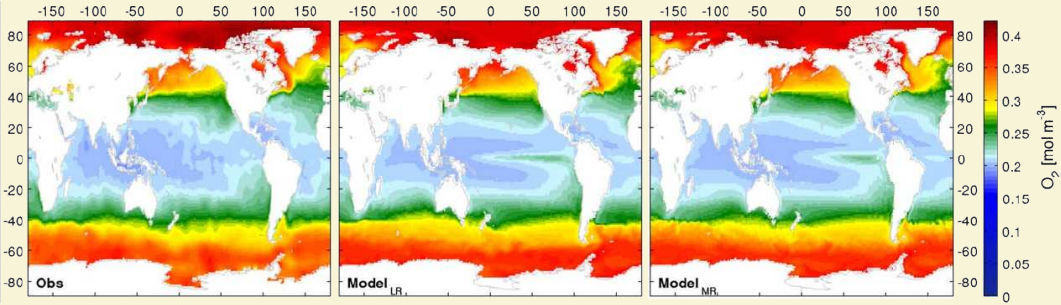
Brovkin et al., JAMES, 2013

Oceanic CO_2 distribution



Ilyina et al., JAMES, 2013

Oceanic O_2 distribution



Ilyina et al., JAMES, 2013

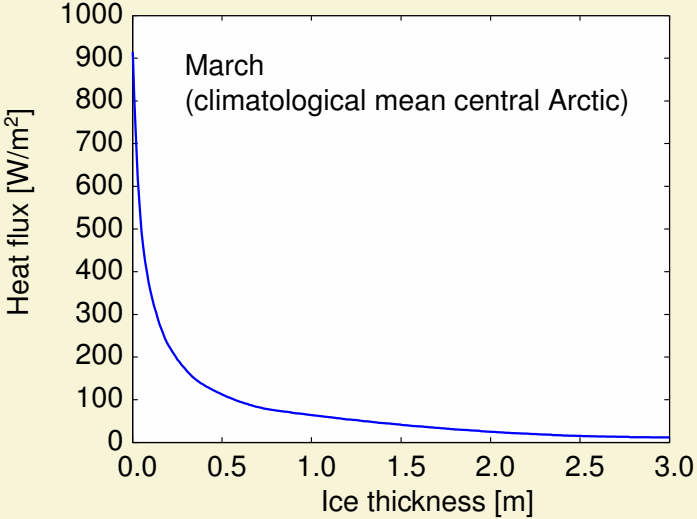
Overview

Why is sea ice important for the climate system

Main impact on ocean and atmosphere

- Sea ice changes the heat exchange between ocean and atmosphere
- Sea ice changes the salinity structure of the ocean
- Sea ice changes the energy balance of the atmosphere and contributes to Polar Amplification

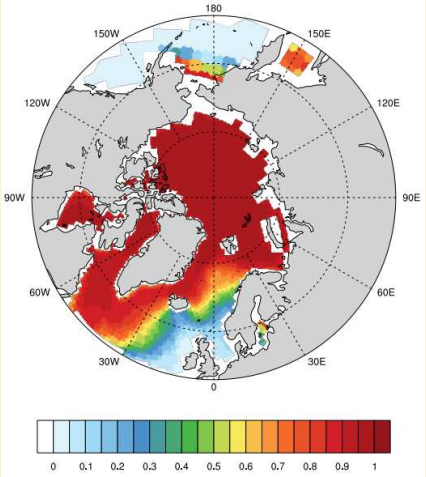
1. Heat exchange between atmosphere and ocean



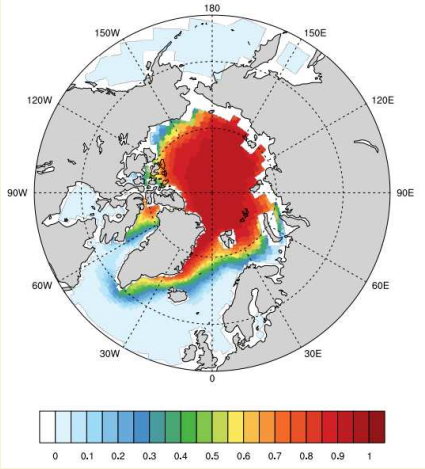
After *Maykut*, JGR, 1982

Coupled model simulation with excessive sea ice

Sea ice coverage in March

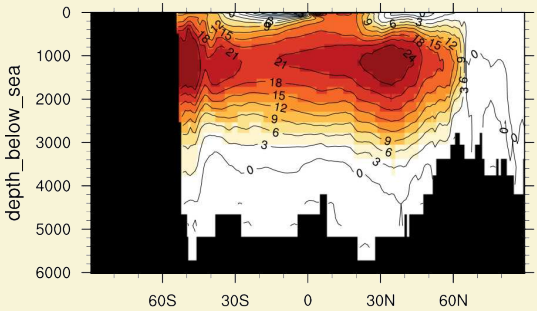


Sea ice coverage in September

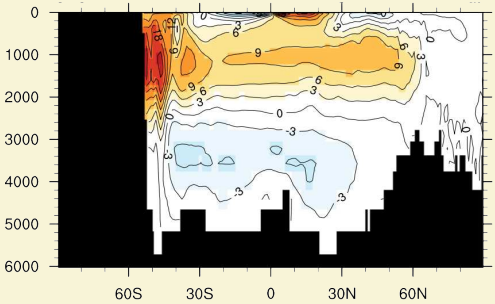


Coupled model simulation with excessive sea ice

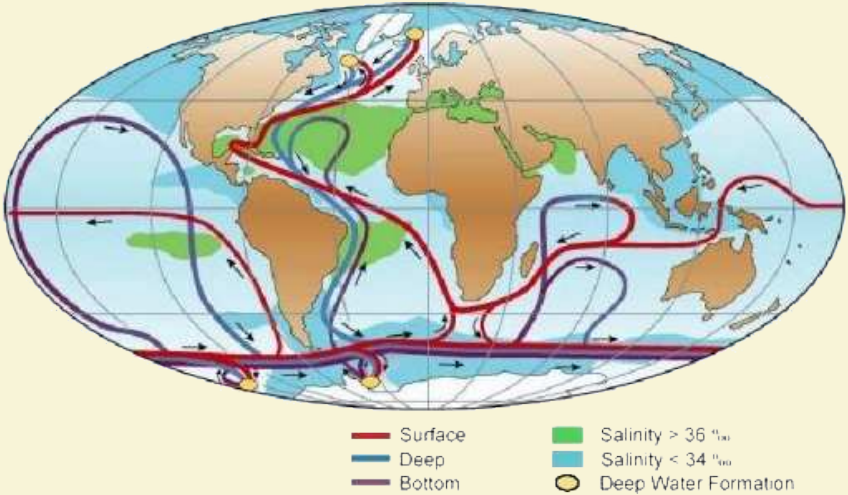
MOC in simulation with normal sea ice



MOC in simulation with too much sea ice

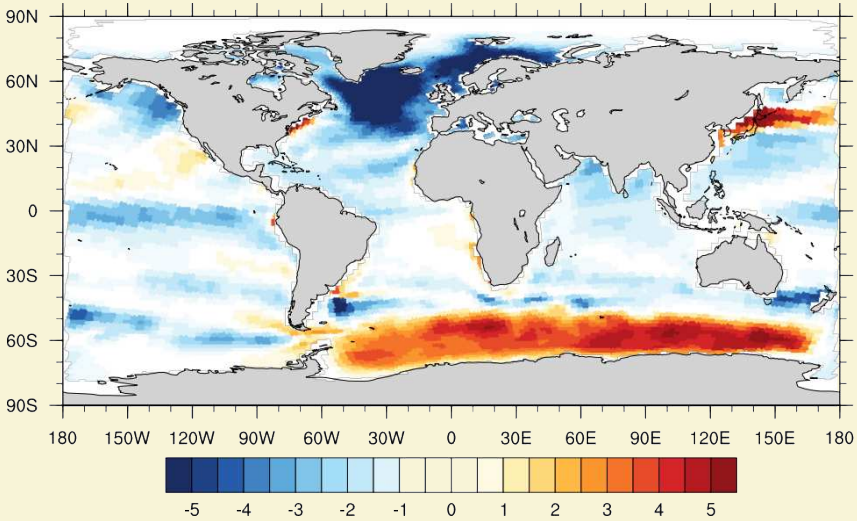


The Thermohaline Circulation III

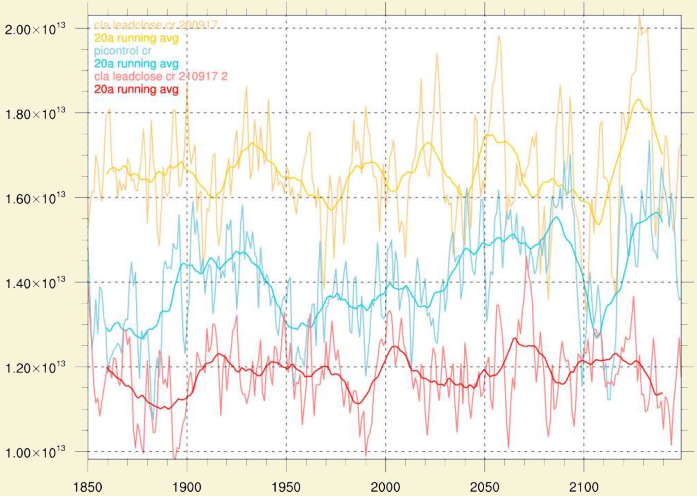


Rahmstorf, Nature, 2002

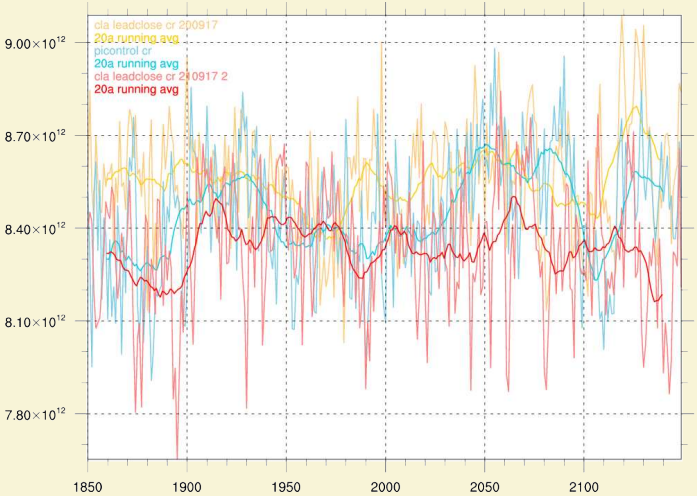
Coupled model simulation with excessive sea ice



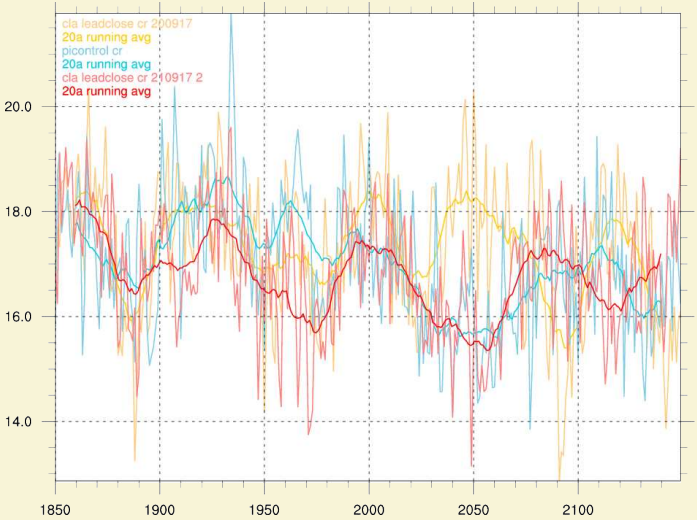
Sea-ice volume induced by changes in lead-close parameter



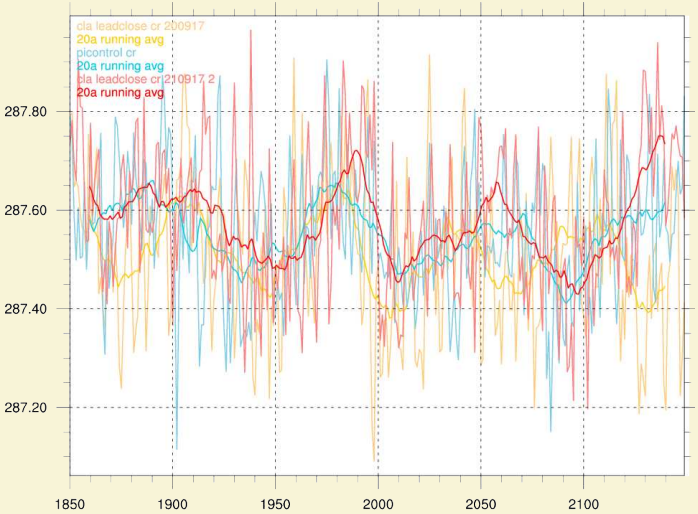
Sea-ice extent induced by changes in lead-close parameter



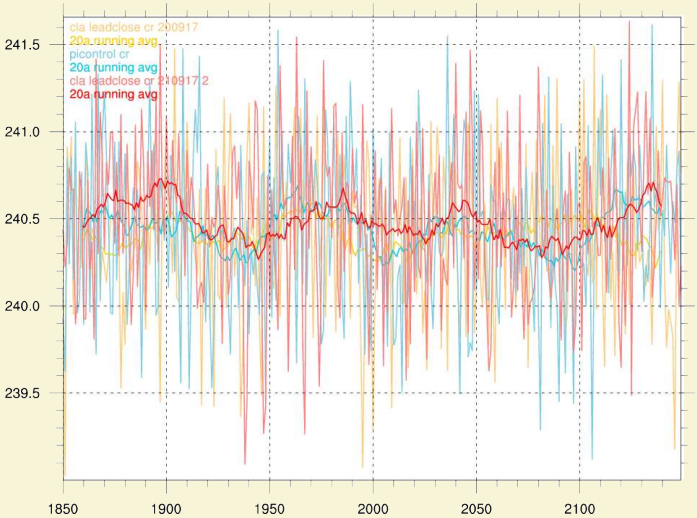
MOC induced by changes in lead-close parameter



2m air temperature induced by changes in lead-close parameter



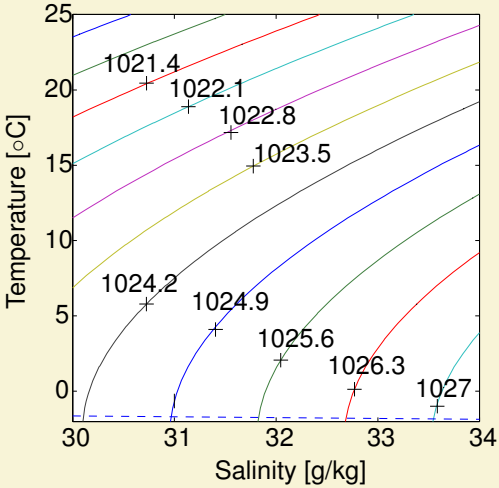
Outgoing SW radiation induced by changes in lead-close parameter



Importance of sea ice for heat exchange

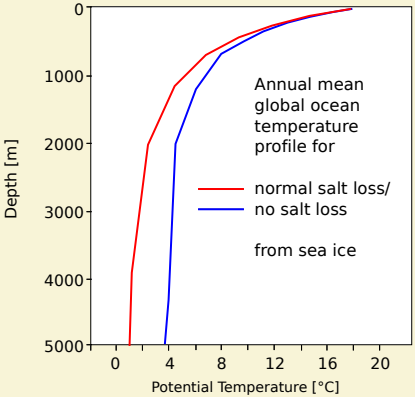
- Excessive sea ice can substantially alter the meridional overturning circulation (MOC) of the Atlantic Ocean
- Too little sea ice has only a minor impact on the MOC or atmospheric temperatures

2. Salt release into underlying ocean



Ocean convection

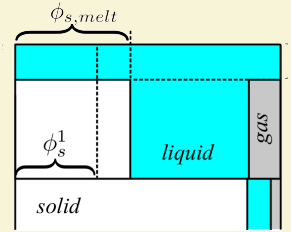
Salt loss from sea ice changes deep convection in Southern Ocean



Stössel et al., JPO, 2002

1. What is the salinity of first-year sea ice?

2. Model

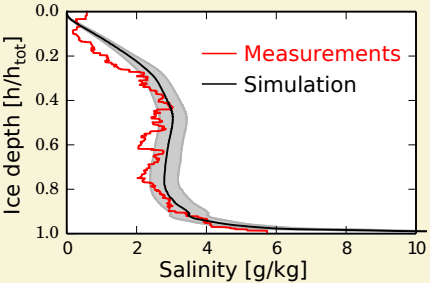


Salt loss is given by gravity drainage described by a Rayleigh number

$$Ra = \frac{\rho_{br}\beta\Delta S_{br} g h \Pi(\overline{\phi})}{\kappa\mu}$$

3. Measurements

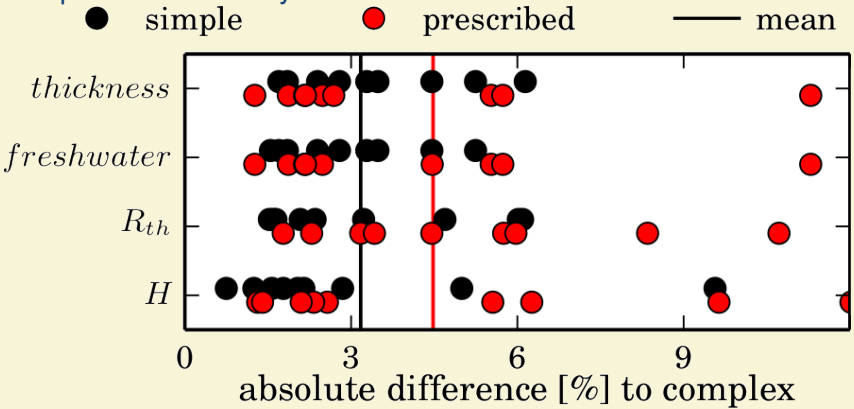
4. Comparison



Griewank and Notz, *J. Geophys. Res.*, 2014, *The Cryosphere*, 2015

Comparison of complex scheme with prescribed salinity profile

Difference after 4.5 years of simulation between complex scheme, simple scheme, and prescribed salinity

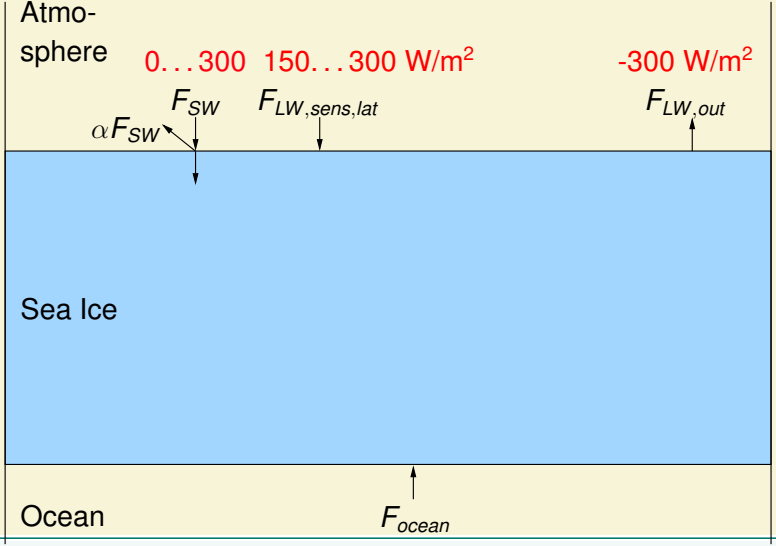


Griewank and Notz, *J. Geophys. Res.*, 2014, *The Cryosphere*, 2015

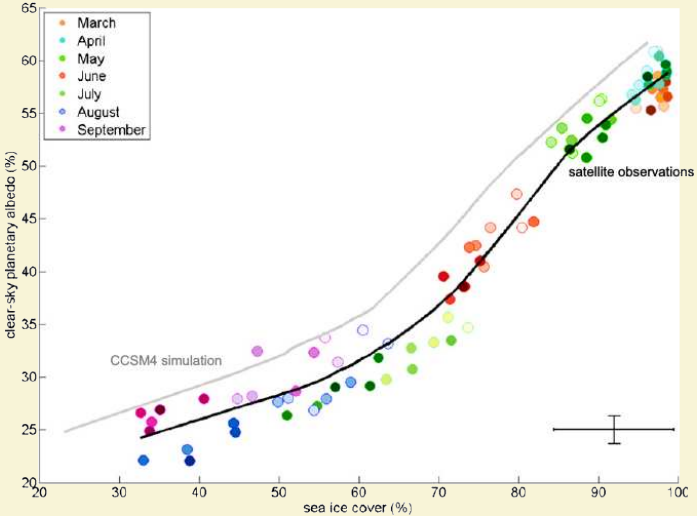
Importance of sea ice for salt release

- Salt release from sea ice is important for a reasonable simulation of the Southern Ocean
- A prescribed salinity profile might be good enough for most purposes
- Biases caused by lack of resolved eddies, under-ice shelf circulation, and iceberg freshwater discharge are likely more important for model biases in the Southern Ocean

3. Heat balance of the atmosphere

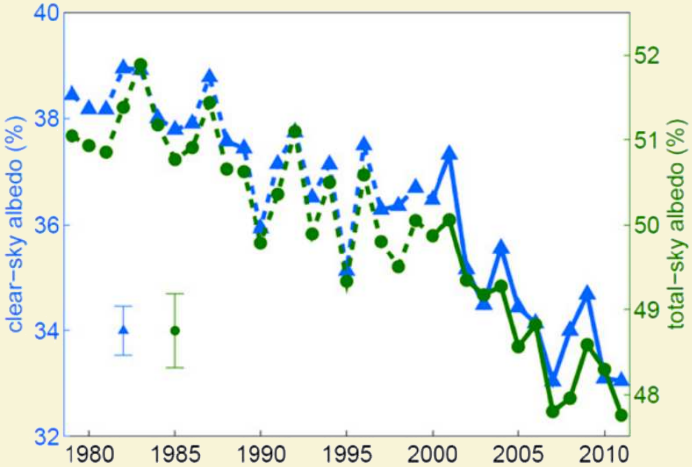


Changes in albedo



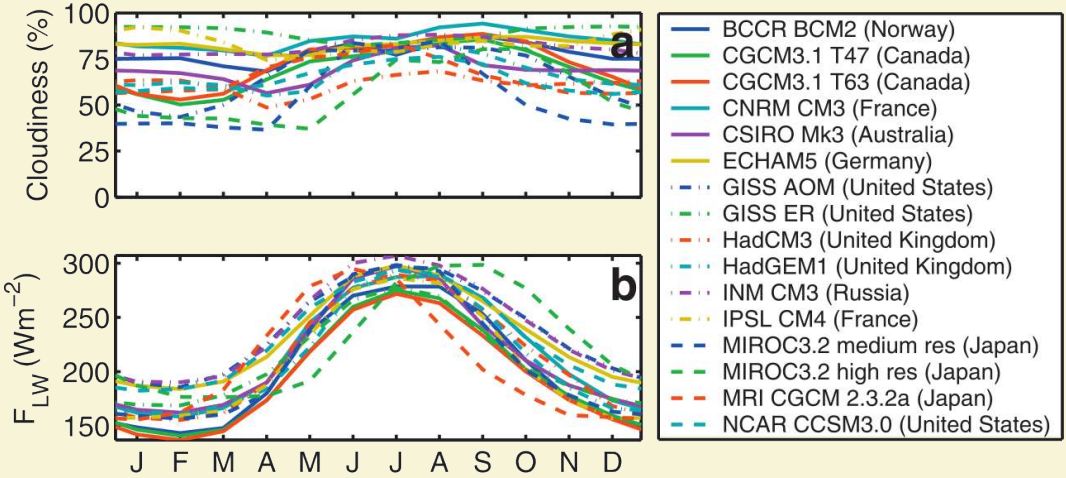
Pistone et al., 2014

Changes in albedo



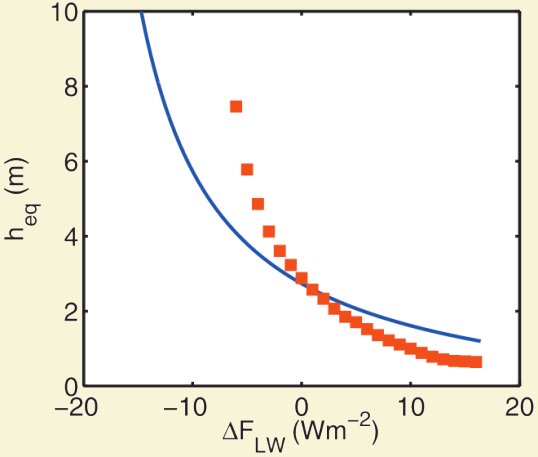
Pistone et al., 2014

Impact of albedo change in a simplified setup



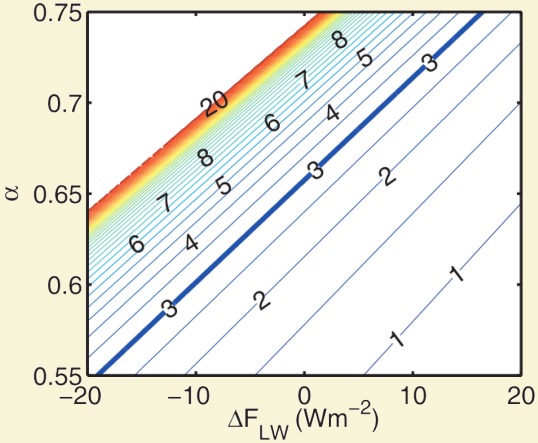
Eisenman et al., 2007

Impact of albedo change in a simplified setup



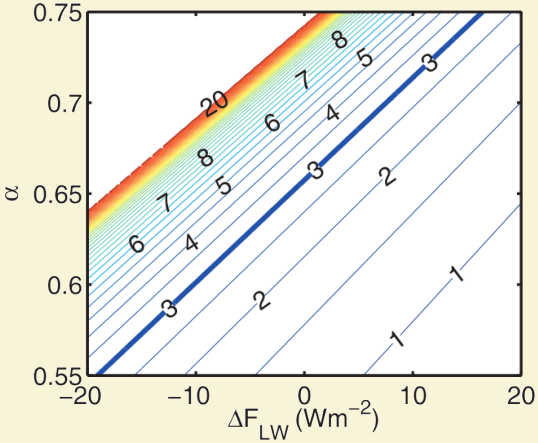
Eisenman et al., 2007

Impact of albedo change in a simplified setup



Eisenman et al., 2007, DeWeaver et al., 2008

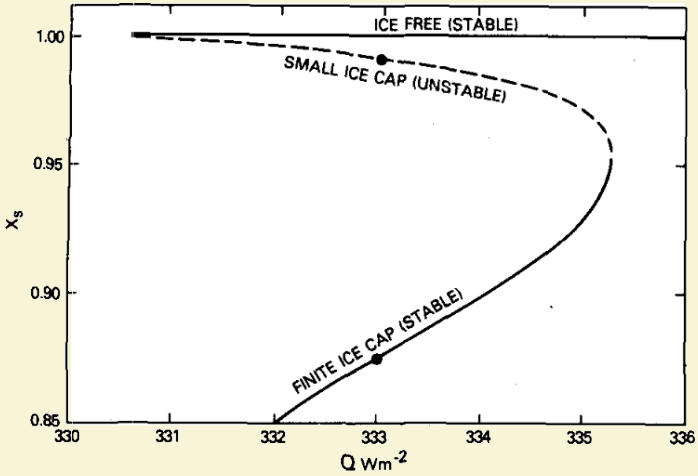
Impact of albedo change in a simplified setup



But Holland et al. (2006) only find a change in ice thickness from 1.95 m to 2.5 m

Eisenman et al., 2007, DeWeaver et al., 2008

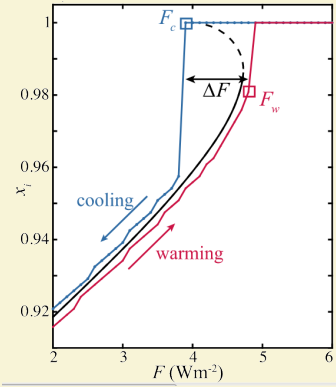
The small ice cap instability



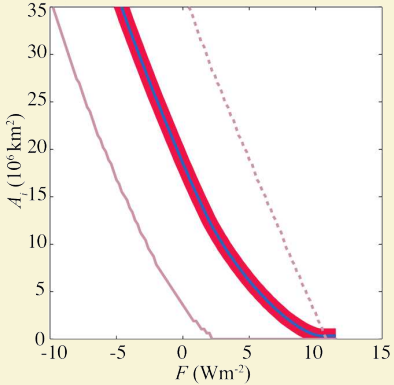
North, 1984

Instability only occurs in very simple models

Hysteresis in very simple Energy-balance model

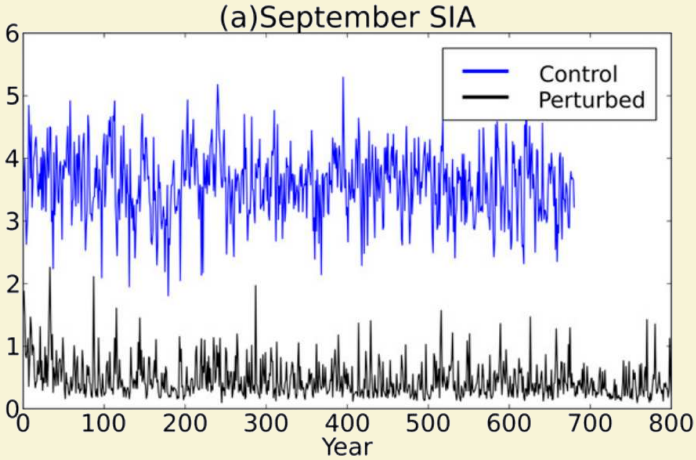


No hysteresis in model with seasonal cycle and meridional heat transport



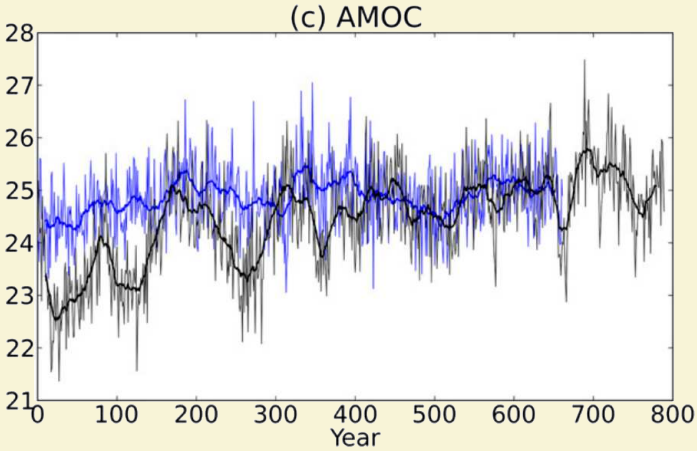
Wagner and Eisenman, 2015

Impact of changes in albedo



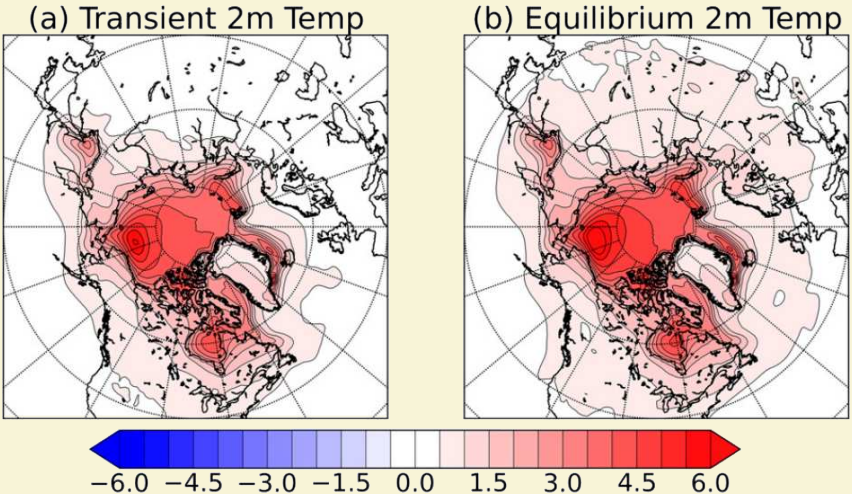
Blackport and Kushner, 2014

Impact of changes in albedo



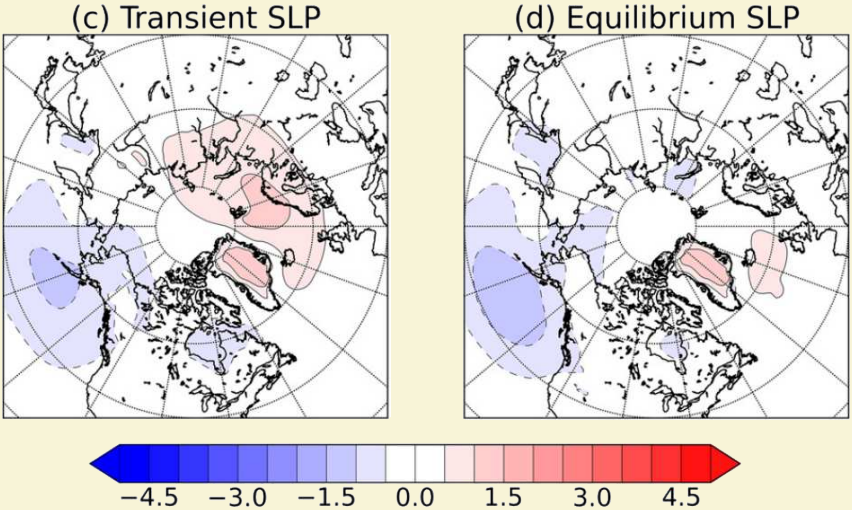
Blackport and Kushner, 2014

Impact of changes in albedo



Blackport and Kushner, 2014

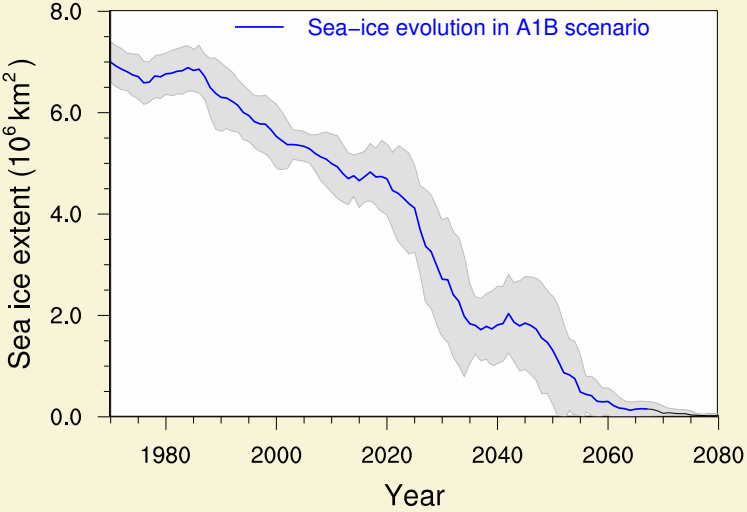
Impact of changes in albedo



Blackport and Kushner, 2014

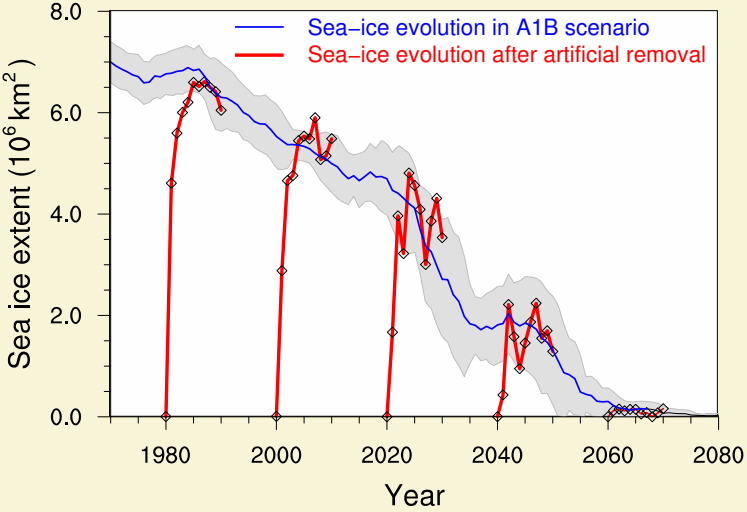
Overview

ECHAM5/MPI-OM modelled sea-ice evolution



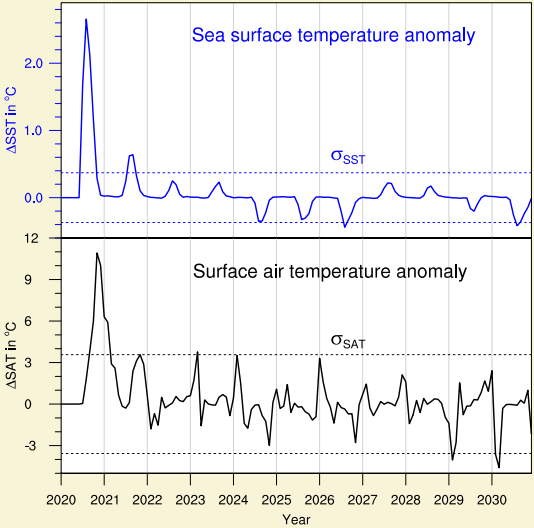
Tietsche et al., GRL., 2011

Sea ice recovers efficiently after complete removal



Tietsche et al., GRL., 2011

Surface temperature anomalies

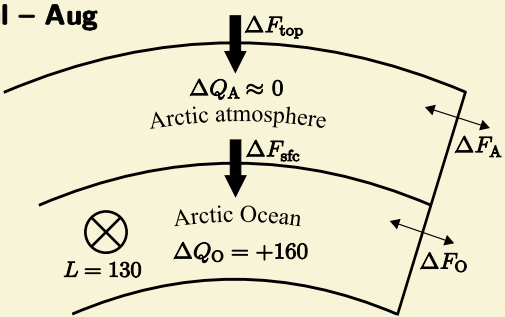


Tietsche et al., GRL., 2011

Heat budget

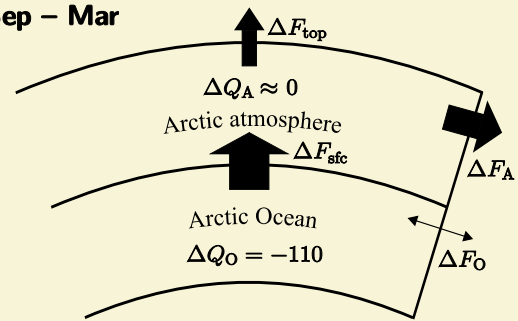
Heat budget summer

Jul – Aug



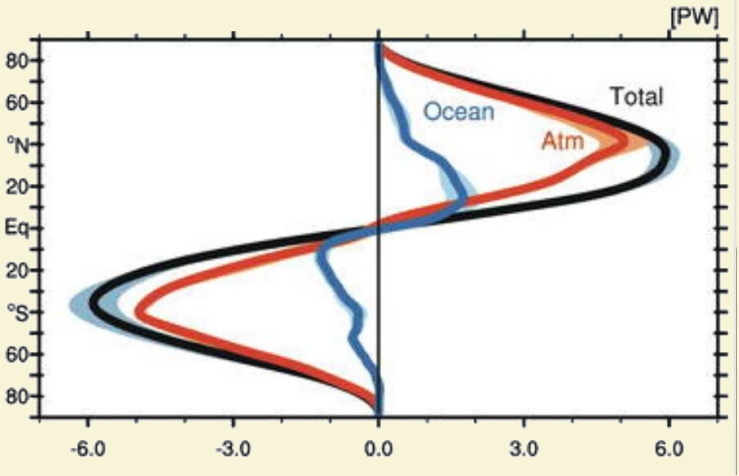
Heat budget winter

Sep – Mar



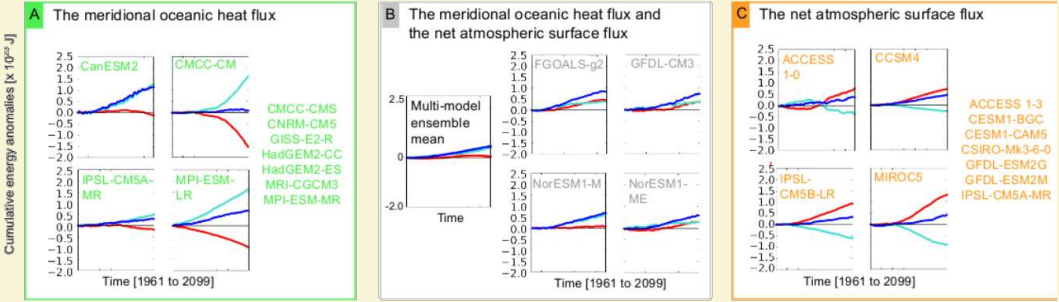
Tietsche et al., GRL., 2011

What provides the energy for the Arctic-Ocean warming?



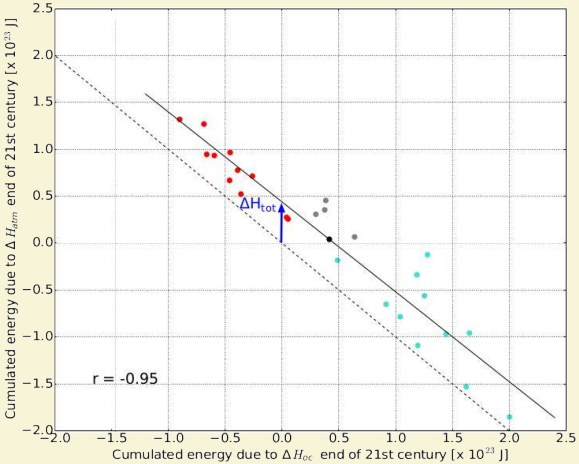
Fasullo and Trenberth, 2008

What provides the energy for the Arctic-Ocean warming?



Burgard and Notz, GRL, 2017

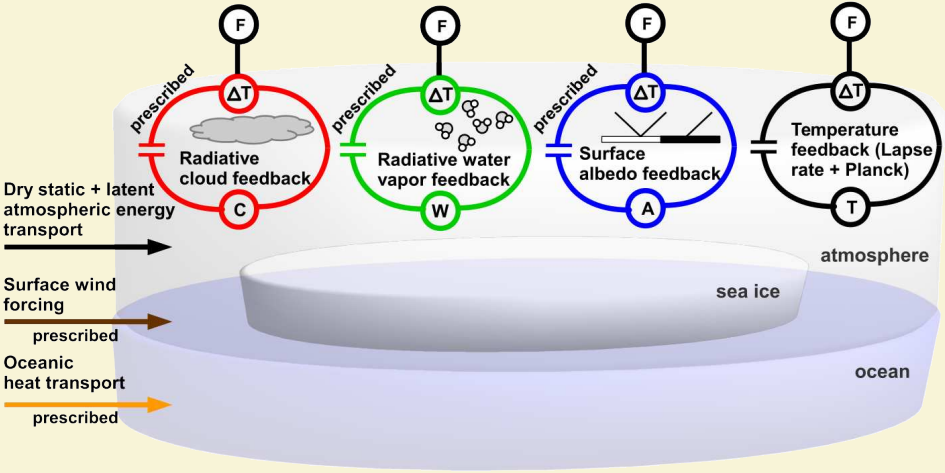
What provides the energy for the Arctic-Ocean warming?



The total heat transport into the Arctic is very similar across all models. → Bjerknes compensation

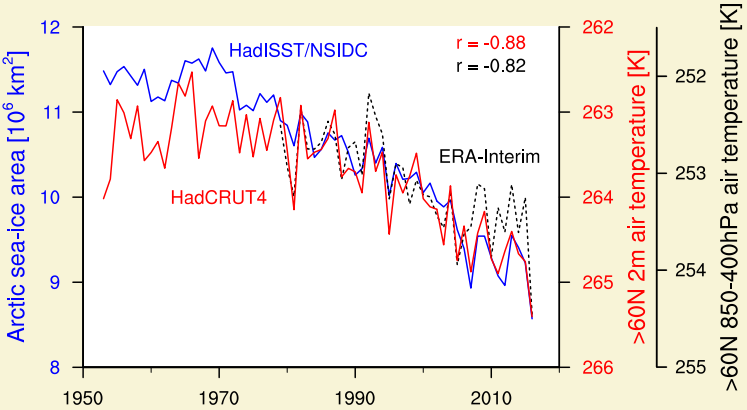
Burgard and Notz, GRL, 2017

Importance of sea ice for variability of sea ice



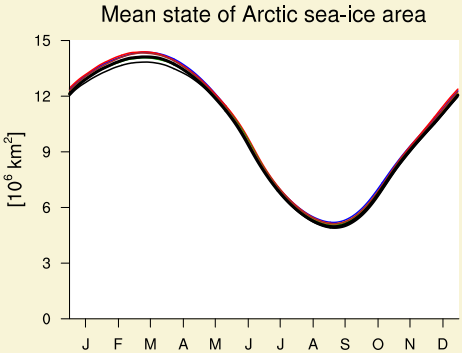
Olonscheck et al., in preparation

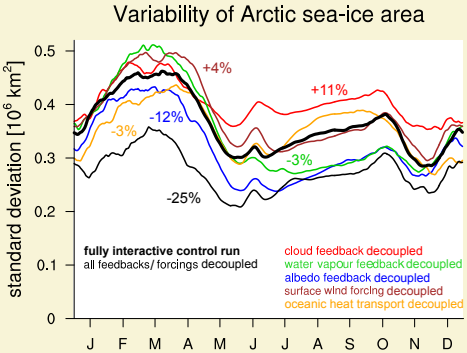
Importance of sea ice for variability of sea ice



Olonscheck et al., in preparation

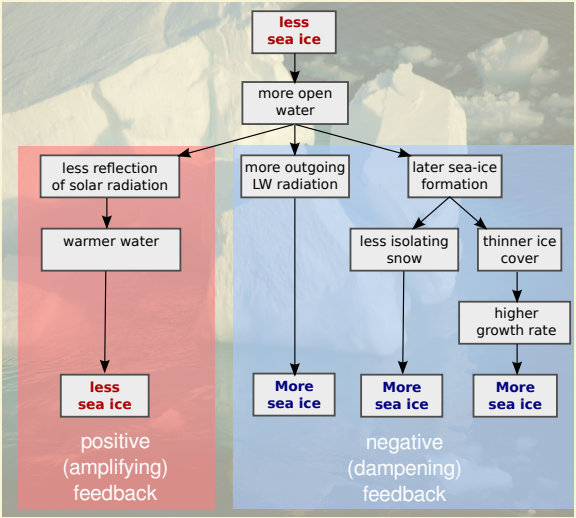
Importance of sea ice for variability of sea ice





Olonscheck et al., in preparation

Negative feedbacks dominate the evolution of sea ice



Therefore, uncoupled models usually overestimate the importance of changes in sea-ice code

Notz and Bitz, 2017

Impact of numerical roundoff errors on Arctic sea-ice prediction

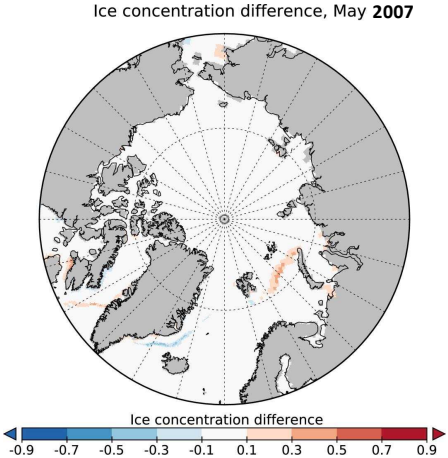
Two experiments with MPI-ESM-LR:

1.) Seasonal hindcast (single member) started on 1 May 2007

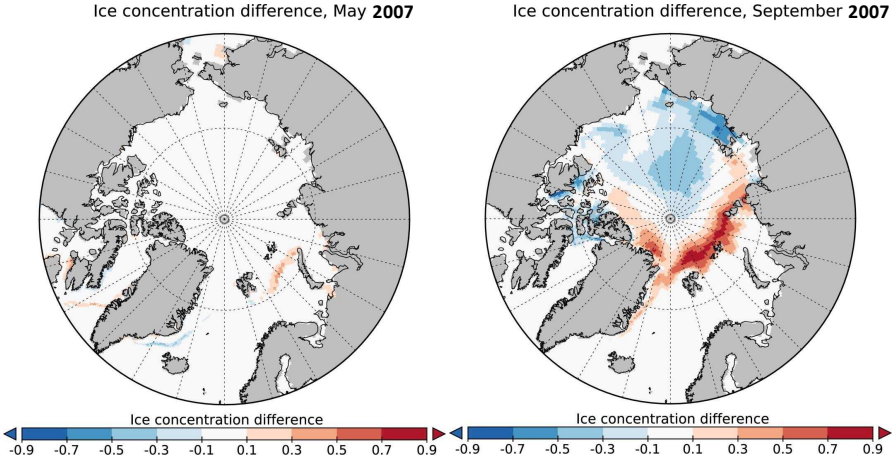
2.) Same as 1.) but with “disturbed” sea-ice concentration

“disturbed” = random number between -1e-12 and +1e-12 added to initial sea-ice concentration

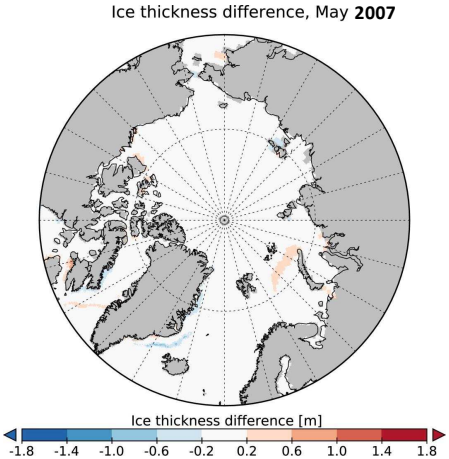
Sea-ice concentration

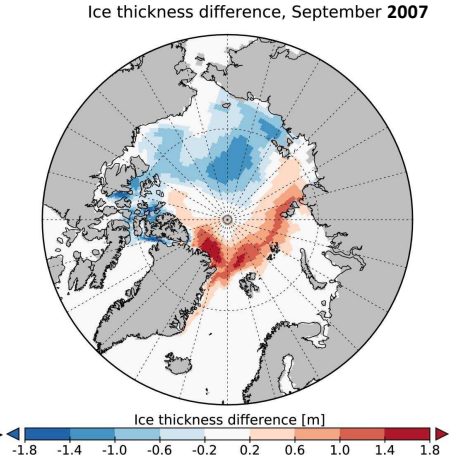


Sea-ice concentration



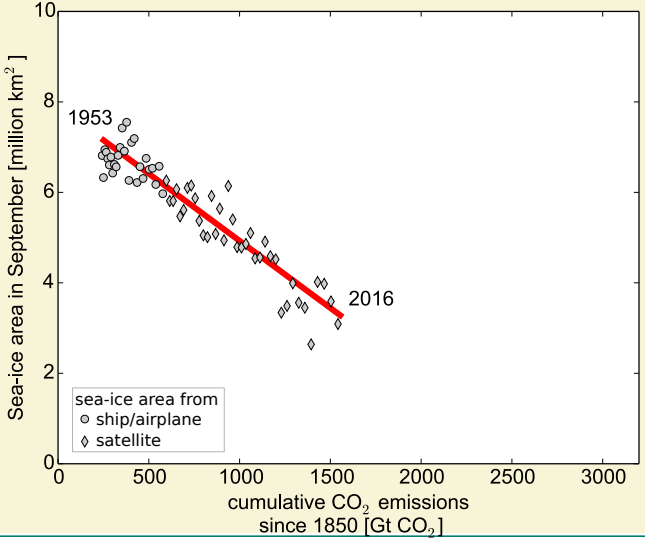
Sea-ice thickness





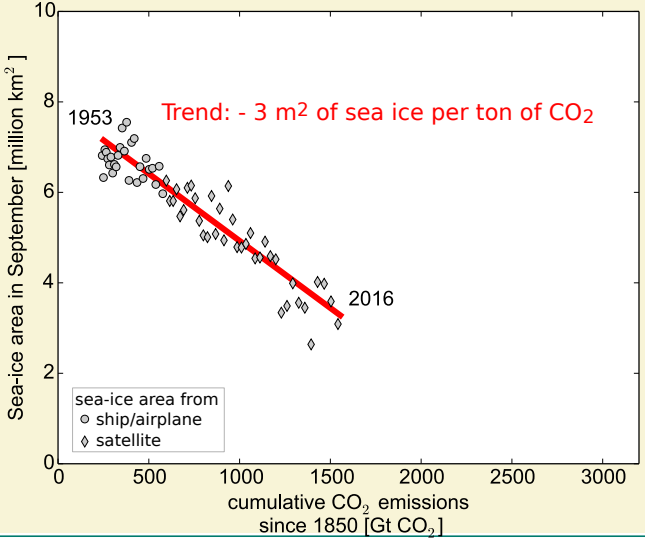
Overview

Sea-ice loss is primarily driven by CO_2 emissions



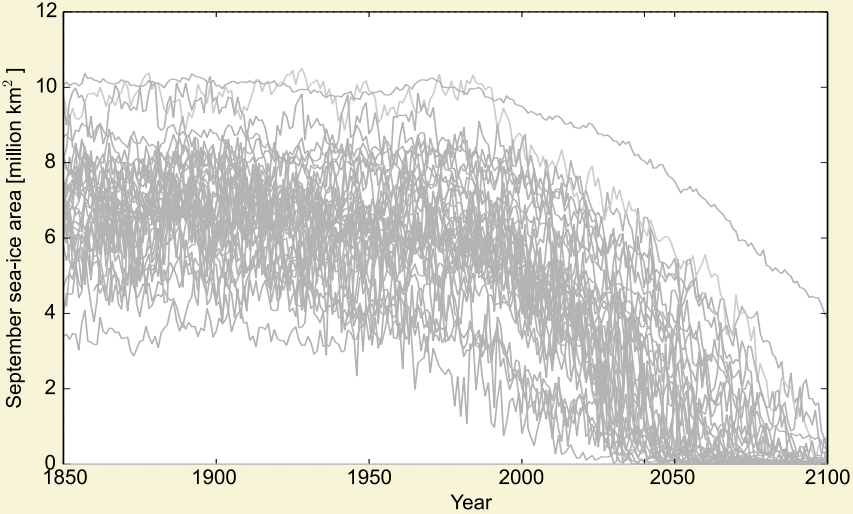
Notz and Stroeve, Science, 2016

Sea-ice loss is primarily driven by CO_2 emissions



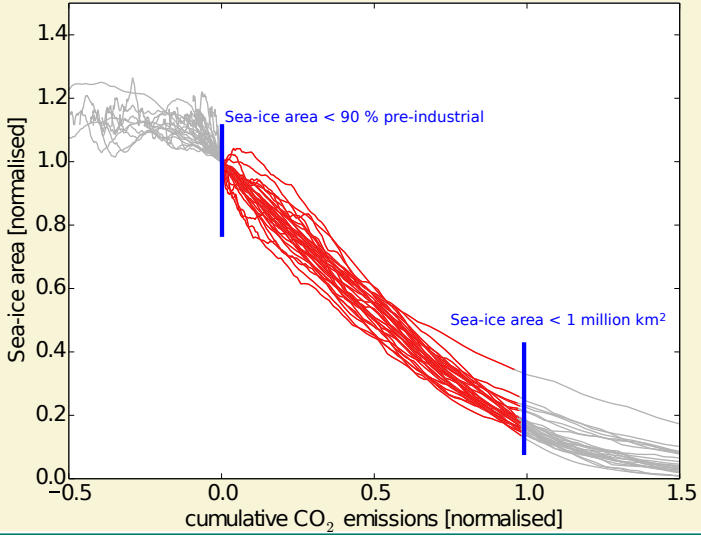
Notz and Stroeve, Science, 2016

Arctic summer sea ice in CMIP5 models



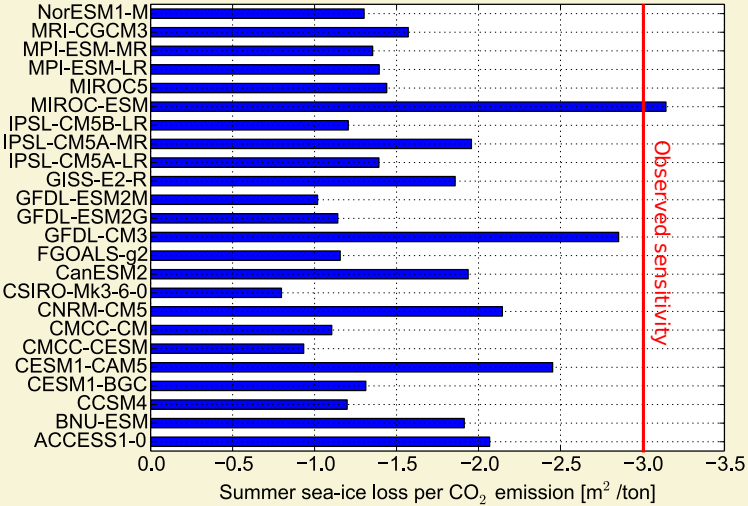
Notz and Stroeve, Science, 2016

Arctic summer sea ice in CMIP5 models



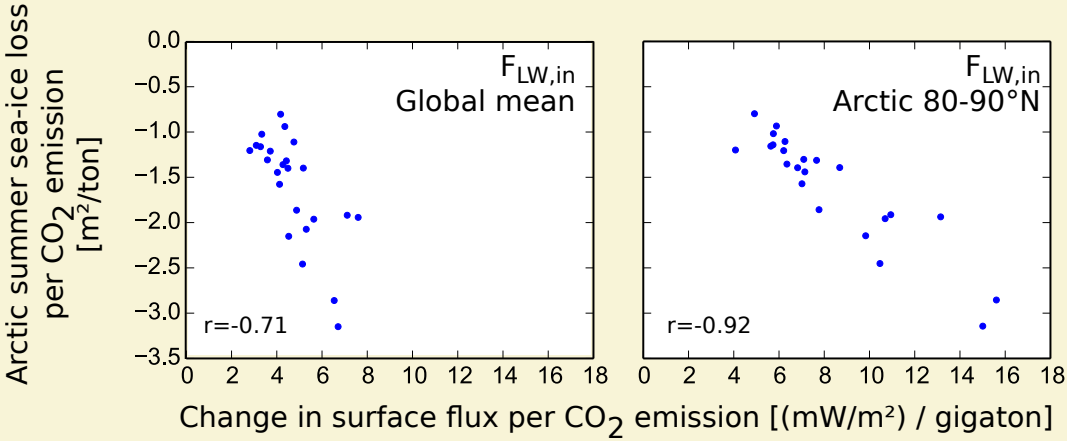
Notz and Stroeve, Science, 2016

Models underestimate observed sensitivity



Notz and Stroeve, Science, 2016

Relationship with incoming LW radiation is clear in models



Notz and Stroeve, Science, 2016

Summary

The importance of sea ice for the climate system...

- mostly derives from its impact on the ocean circulation. In particular, too much sea ice can slow down the oceanic overturning circulation
- is usually overestimated in uncoupled setups because negative feedbacks dominate sea-ice response
- is usually overestimated in coupled setups unless the model is re-tuned after changes to sea-ice code

Summary

The importance of sea ice for the climate system. . .

- mostly derives from its impact on the ocean circulation. In particular, too much sea ice can slow down the oceanic overturning circulation
- is usually overestimated in uncoupled setups because negative feedbacks dominate sea-ice response
- is usually overestimated in coupled setups unless the model is re-tuned after changes to sea-ice code

. . . and finally

- Understanding does not require the most realistic sea ice cover
- Not everything we do as scientists needs to be directly relevant for climate change. Sea ice simply is fascinating in its own right.