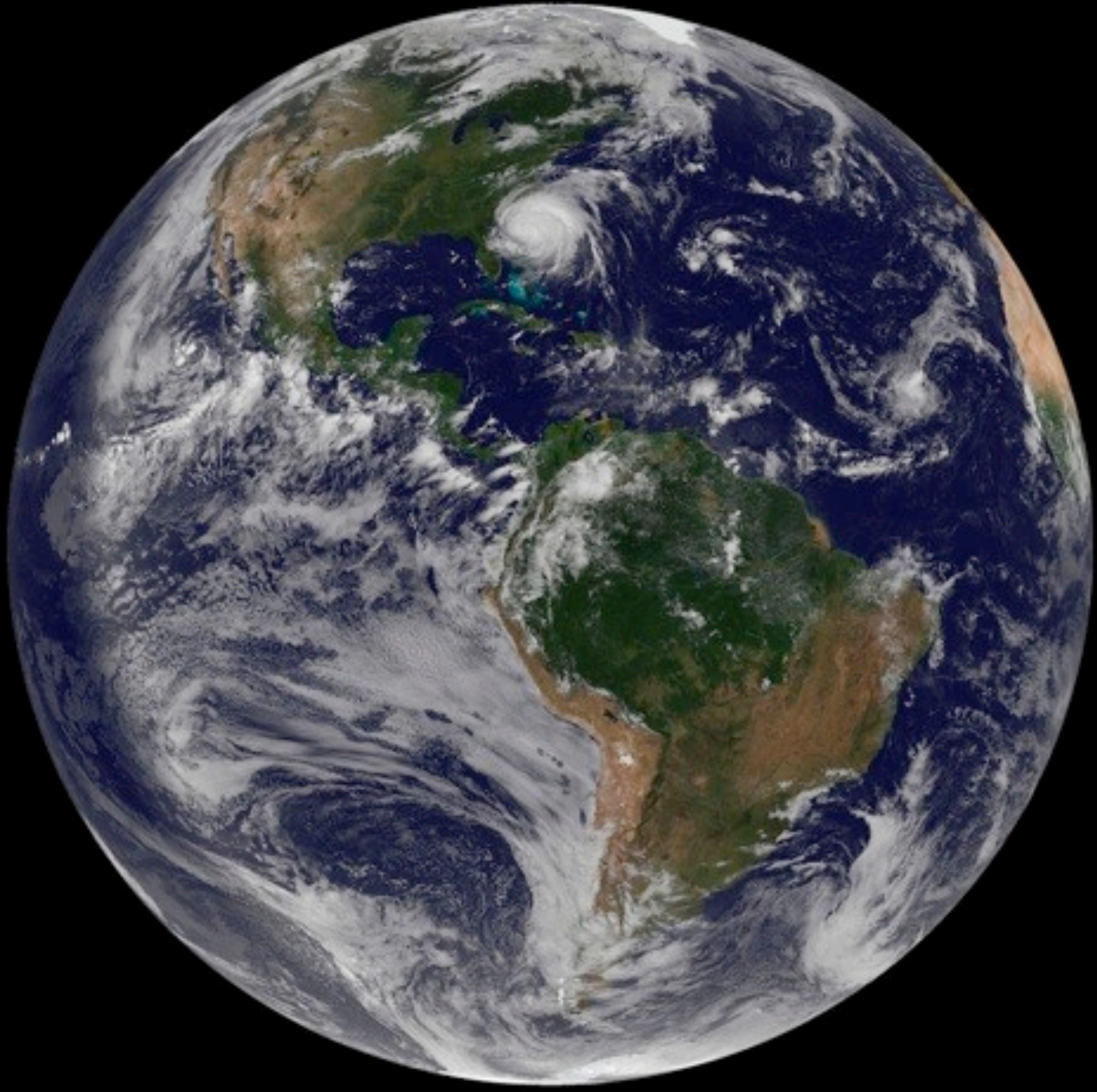
The Physical Climate System



Has a climate model ever made a demonstrably succesful prediction?

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The Effects of Doubling the CO_2 Concentration on the Climate of a General Circulation Model[1]

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(Manuscript received 6 June 1974, in revised form 8 August 1974)

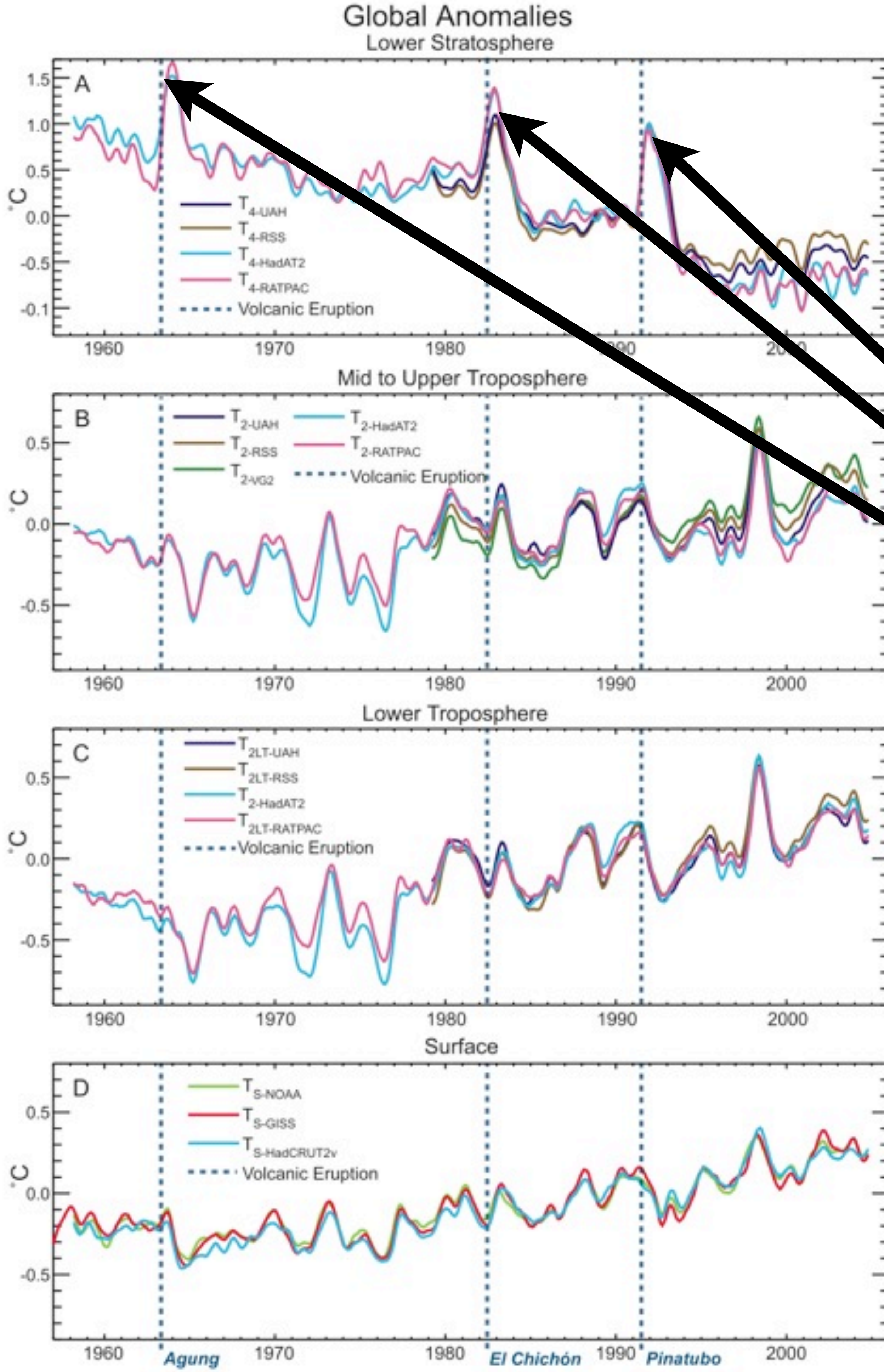
ABSTRACT

An attempt is made to estimate the temperature changes resulting from doubling the present CO_2 concentration by the use of a simplified three-dimensional general circulation model. This model contains the following simplifications: a limited computational domain, an idealized topography, no heat transport by ocean currents, and fixed cloudiness. Despite these limitations, the results from this computation yield some indication of how the increase of CO_2 concentration may affect the distribution of temperature in the atmosphere. It is shown that the CO_2 increase raises the temperature of the model troposphere, whereas it lowers that of the model stratosphere. The tropospheric warming is somewhat larger than that expected from a radiative-convective equilibrium model. In particular, the increase of surface temperature in higher latitudes is magnified due to the recession of the snow boundary and the thermal stability of the lower troposphere which limits convective heating to the lowest layer. It is also shown that the doubling of carbon dioxide significantly increases the intensity of the hydrologic cycle of the model.

Manabe & Wetherald predicted:

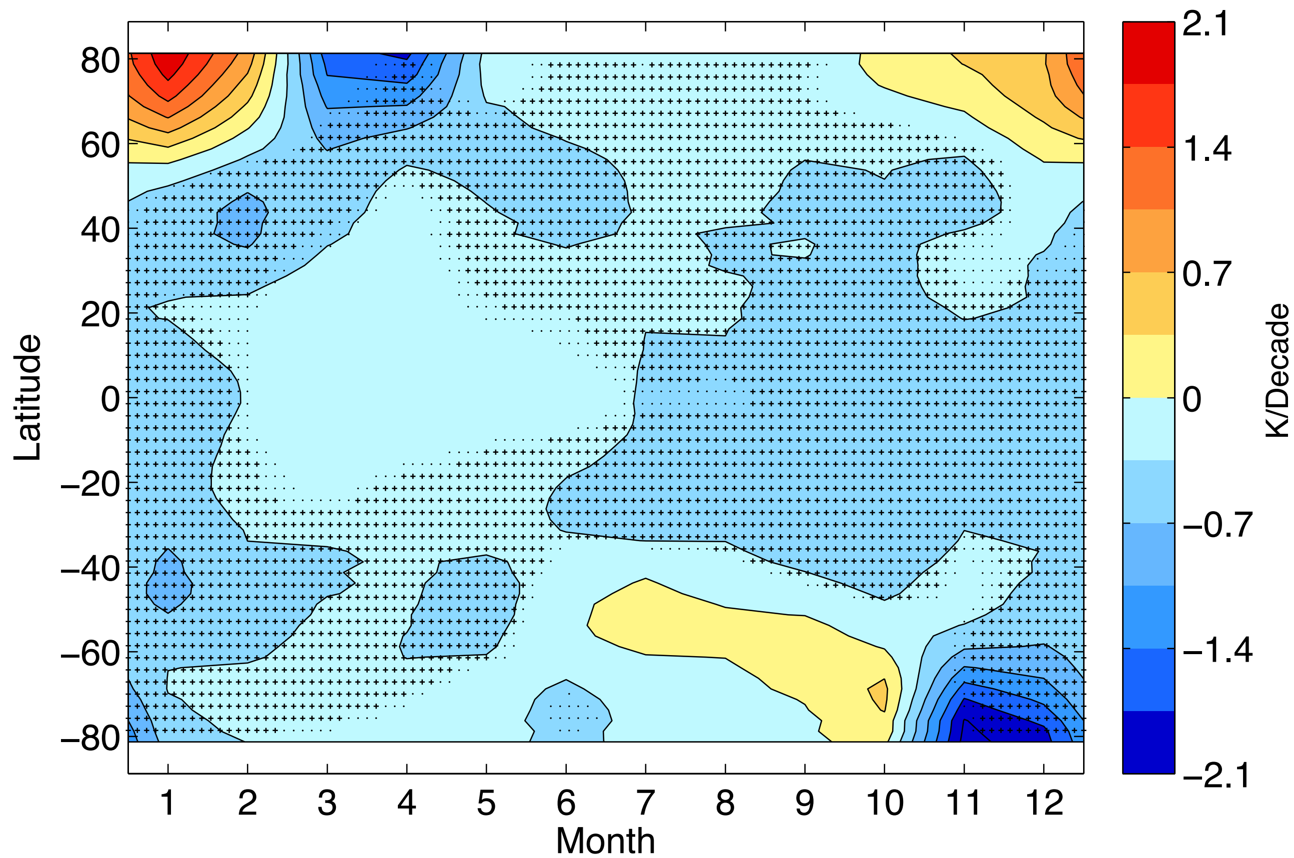
- **Warming lower atmosphere**
- **Greater warming near the poles**
- **Cooling stratosphere**
- **More rain and higher humidity**

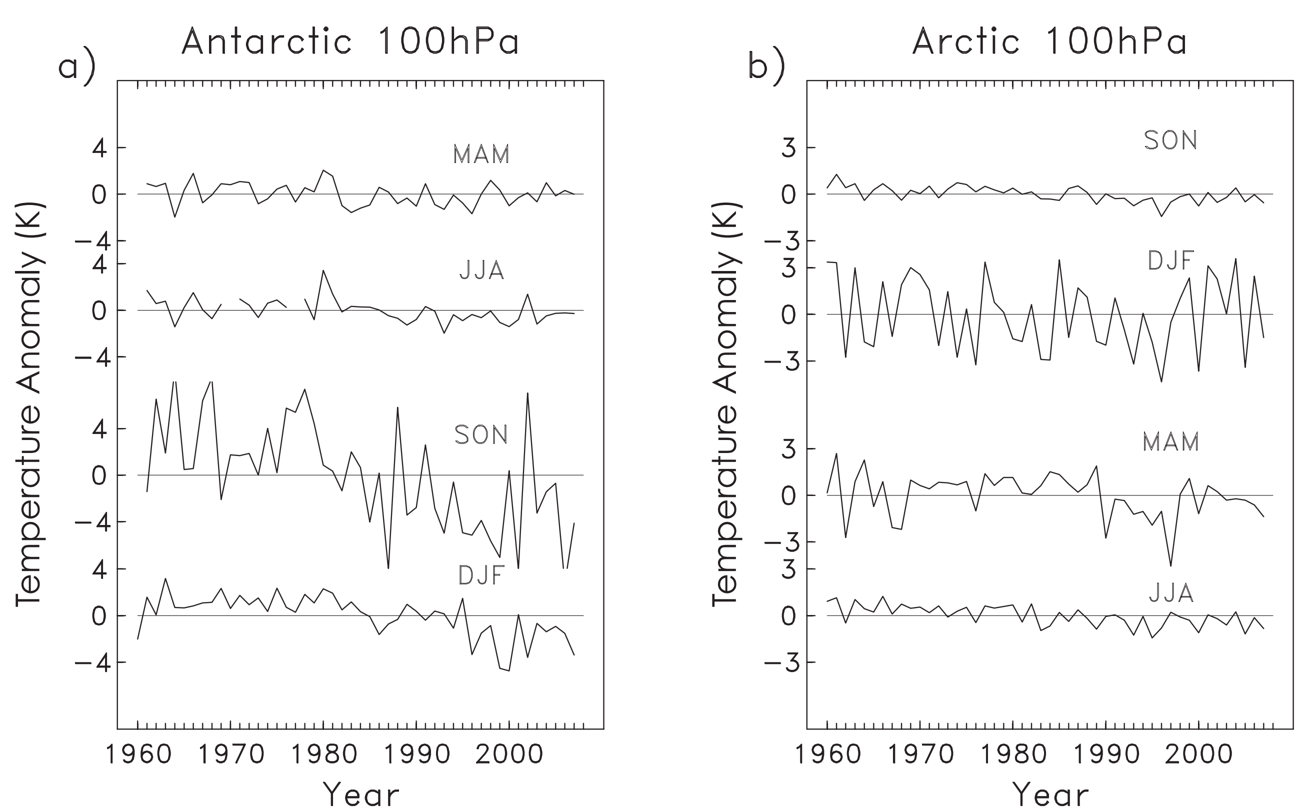
All of these things have now happened.



Stratospheric Cooling

Major volcanoes





Piers Forster et al. 2010

doi:10.1038/nature10556

Unprecedented Arctic ozone loss in 2011

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Chemical ozone destruction occurs over both polar regions in local winter–spring. In the Antarctic, essentially complete removal of lower-stratospheric ozone currently results in an ozone hole every year, whereas in the Arctic, ozone loss is highly variable and has until now been much more limited. Here we demonstrate that chemical ozone destruction over the Arctic in early 2011 was—for the first time in the observational record—comparable to that in the Antarctic ozone hole. Unusually long-lasting cold conditions in the Arctic lower stratosphere led to persistent enhancement in ozone-destroying forms of chlorine and to unprecedented ozone loss, which exceeded 80 per cent over 18–20 kilometres altitude. Our results show that Arctic ozone holes are possible even with temperatures much milder than those in the Antarctic. We cannot at present predict when such severe Arctic ozone depletion may be matched or exceeded.

Since the emergence of the Antarctic 'ozone hole' in the 1980s[1] and elucidation of the chemical mechanisms[2–5] and meteorological conditions[6] involved in its formation, the likelihood of extreme ozone depletion over the Arctic has been debated. Similar processes are at work in the polar lower stratosphere in both hemispheres, but differences in the evolution of the winter polar vortex and associated polar temperatures have in the past led to vastly disparate degrees of springtime ozone destruction in the Arctic and Antarctic. We show that chemical ozone loss in spring 2011 far exceeded any previously observed over the Arctic. For the first time, sufficient loss occurred to reasonably be described as an Arctic ozone hole.

Arctic polar processing in 2010–11

In the winter polar lower stratosphere, low temperatures induce condensation of water vapour and nitric acid (HNO_3) into polar stratospheric clouds (PSCs). PSCs and other cold aerosols provide surfaces for heterogeneous conversion of chlorine from longer-lived reservoir species, such as chlorine nitrate ($ClONO_2$) and hydrogen chloride (HCl), into reactive (ozone-destroying) forms, with chlorine monoxide (ClO) predominant in daylight[5,7].

In the Antarctic, enhanced ClO is usually present for 4–5 months (through to the end of September)[8–11], leading to destruction of most of the ozone in the polar vortex between ~14 and 20 km altitude[7]. Although ClO enhancement comparable to that in the Antarctic occurs at some times and altitudes in most Arctic winters[9], it rarely persists for more than 2–3 months, even in the coldest years[10]. Thus chemical ozone loss in the Arctic has until now been limited, with largest previous losses observed in 2005, 2000 and 1996[7,12–14].

The 2010–11 Arctic winter–spring was characterized by an anomalously strong stratospheric polar vortex and an atypically long continuously cold period. In February–March 2011, the barrier to transport at the Arctic vortex edge was the strongest in either hemisphere in the last ~30 years (Fig. 1a, Supplementary Discussion).

The persistence of a strong, cold vortex from December through to the end of March was unprecedented. In the previous years with most ozone loss, temperatures (T) rose above the threshold associated with chlorine activation (T_{act}, near 196 K, roughly the threshold for the potential existence of PSCs) by early March (Fig. 1b, Supplementary Figs 1, 2). Only in 2011 and 1997 have Arctic temperatures below T_{act} persisted through to the end of March, sporadically approaching a vortex volume fraction similar in size to that in some Antarctic winters (Fig. 1b). In 1996–97, however, the cold volume remained very limited until mid-January and was smaller than that in 2011 at most times during late January through to the end of March (Fig. 1b, Supplementary Figs 1, 2).

Daily minimum temperatures in the 2010–11 Arctic winter were not unusually low, but the persistently cold region was remarkably deep (Supplementary Figs 1, 2). Temperatures were below T_{act} for more than 100 days over an altitude range of ~15–23 km, compared to a similarly prolonged cold period over only ~20–23 km altitude in 1997; below ~19 km altitude, $T < T_{act}$ continued for ~30 days longer in 2011 than in 1997 (Supplementary Fig. 1b). In 2005, the previous year with largest Arctic ozone loss[7], $T < T_{act}$ occurred for more than 100 days over ~17–23 km altitude, but all before early March.

The winter mean volume of air in which PSCs may form (that is, with $T < T_{act}$), V_{psc}, is closely correlated with the potential for ozone loss[7,15–17]. In 2011, V_{psc} (as a fraction of the vortex volume) was the largest on record (Fig. 1c). Both large V_{psc} and cold lingering well into spring are important in producing severe chemical loss[7,15,16], and 2010–11 was the only Arctic winter during which both conditions have been met. Much lower fractional V_{psc} in 1997 than in 1996, 2000, 2005 or 2011 (Fig. 1c) is consistent with less ozone loss that year[16,17].

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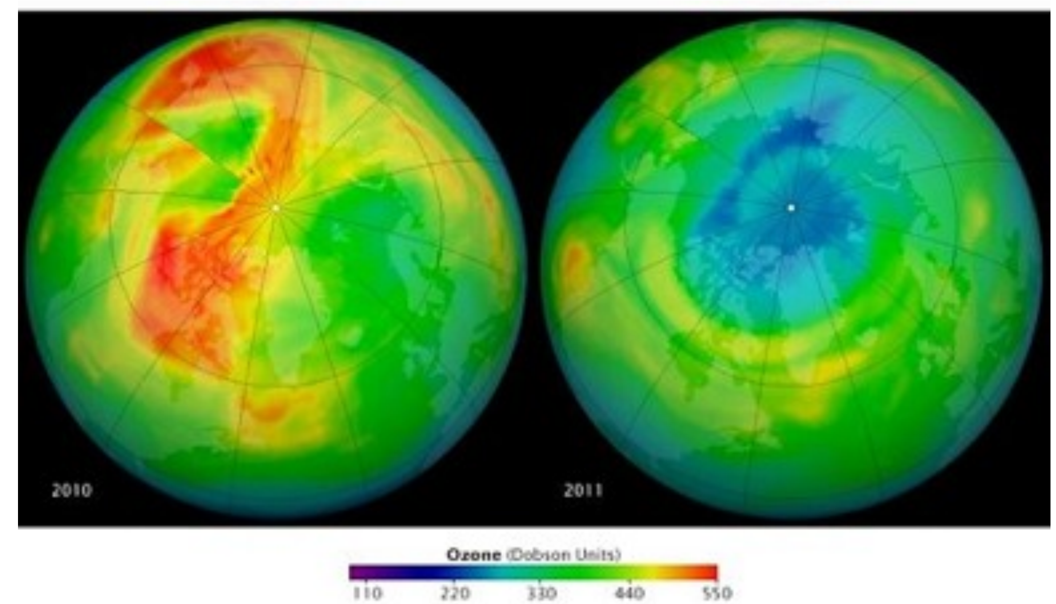


Stratosphere-troposphere coupling

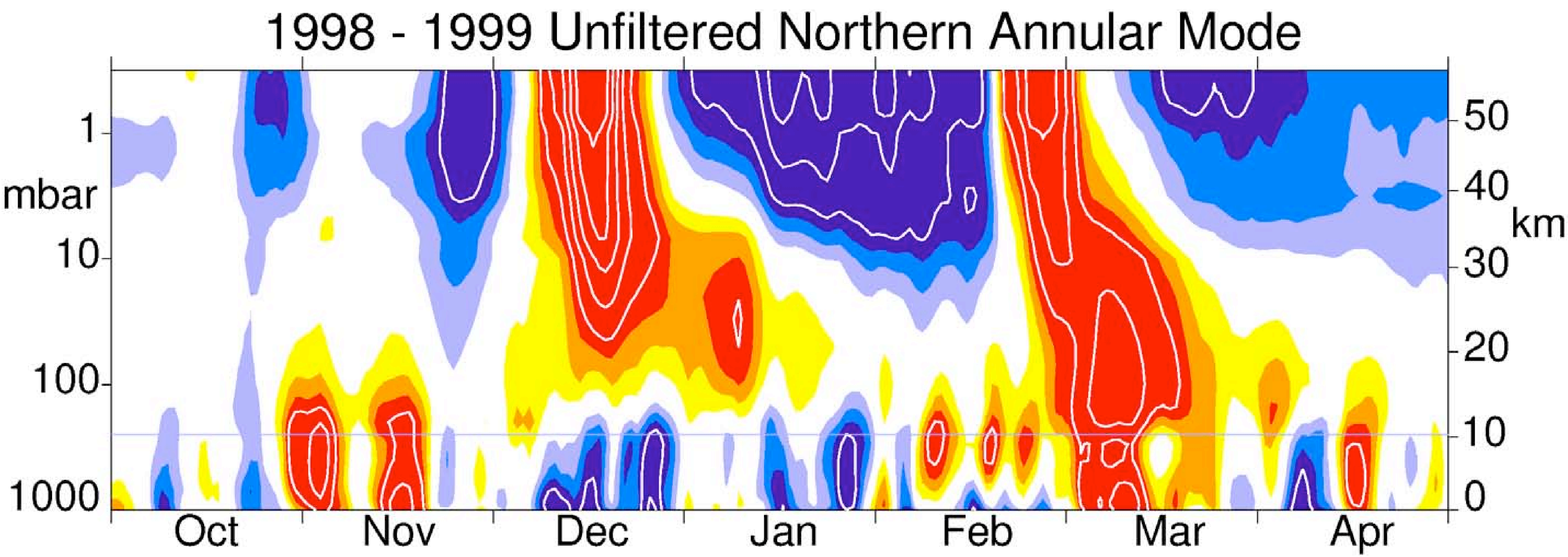
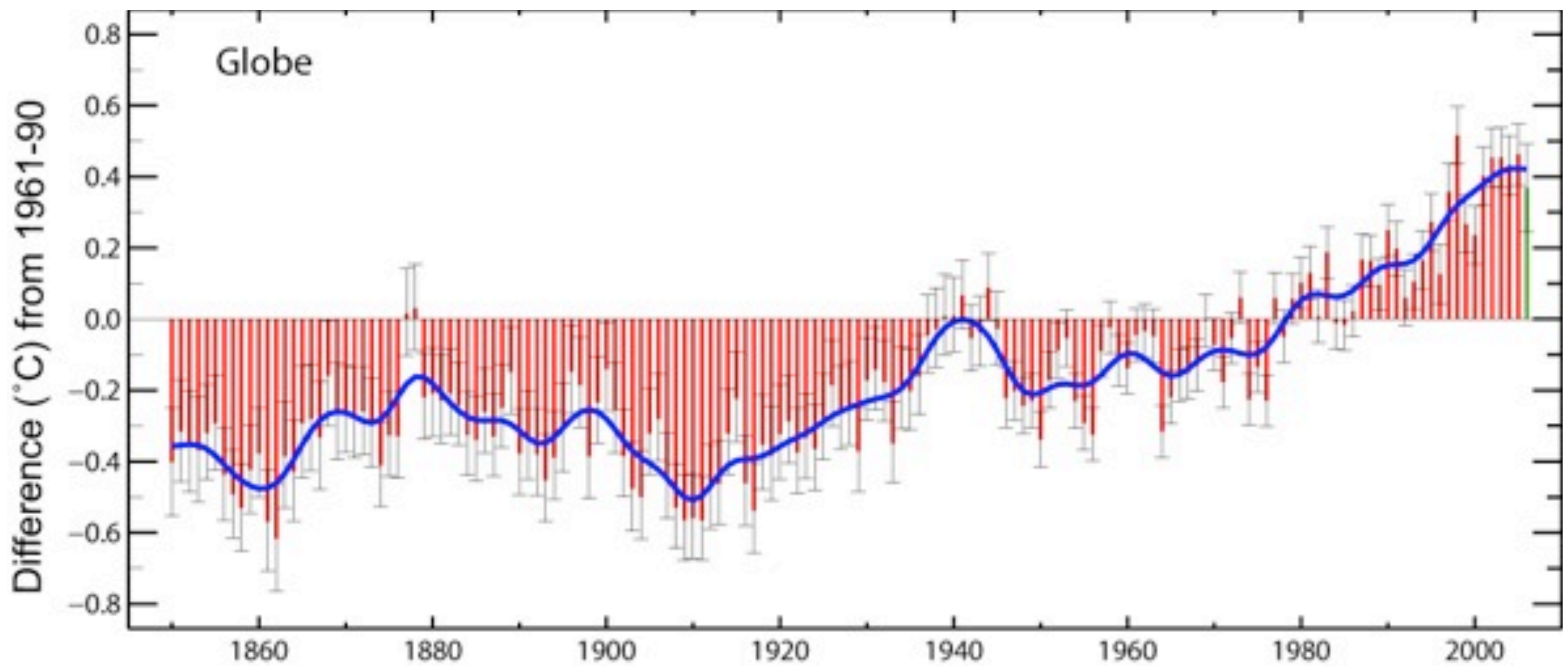
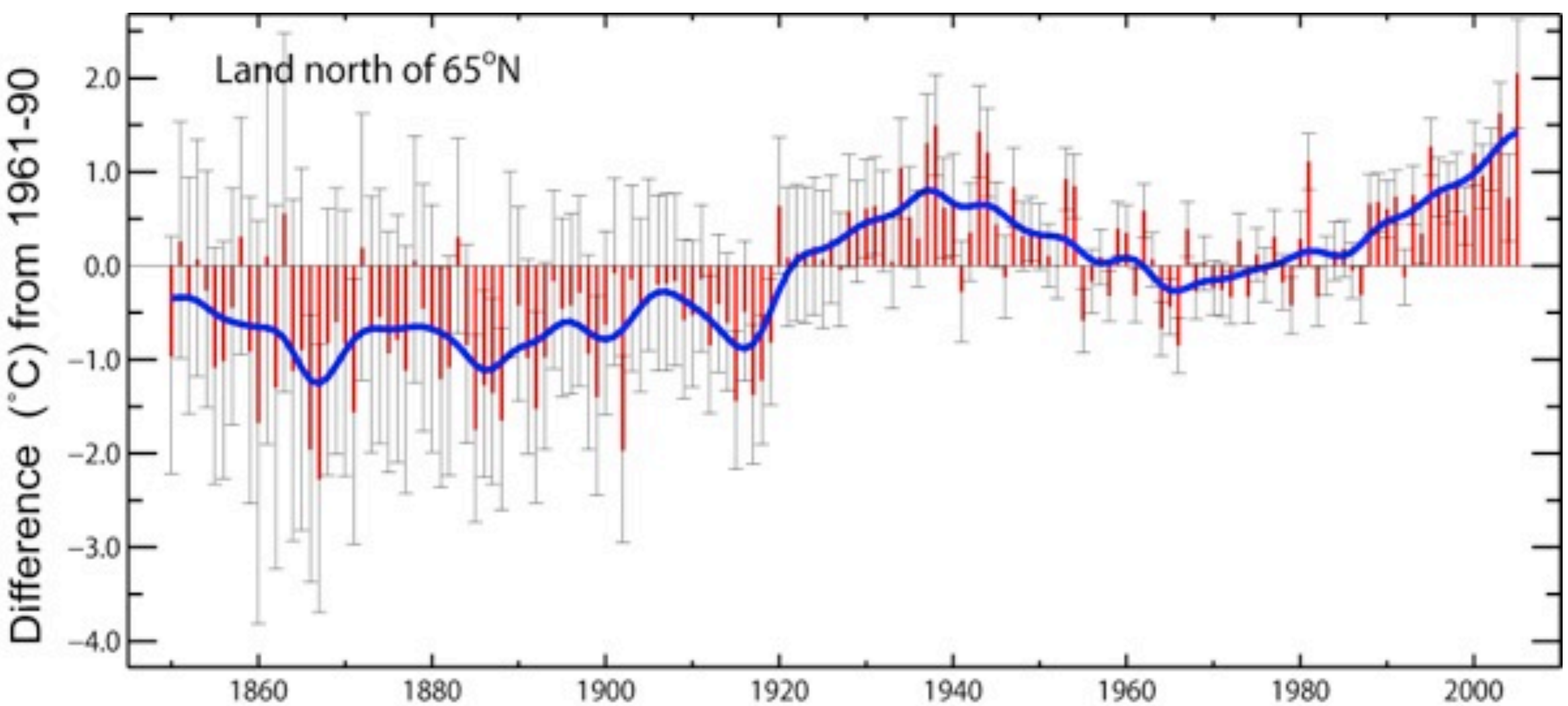


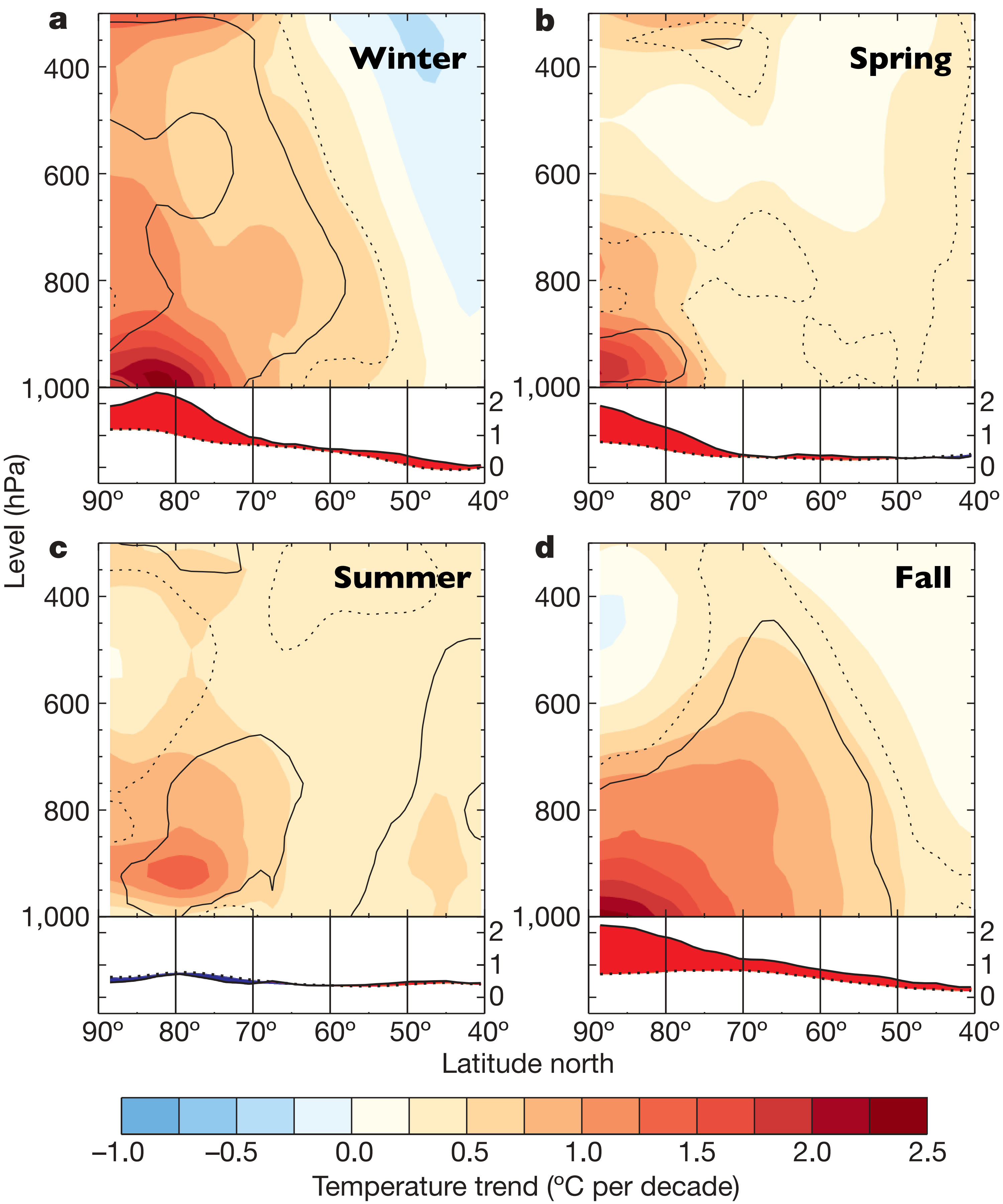
Figure from Mark Baldwin



Warming in the Arctic is roughly double that for the whole Earth.



Note different scales.

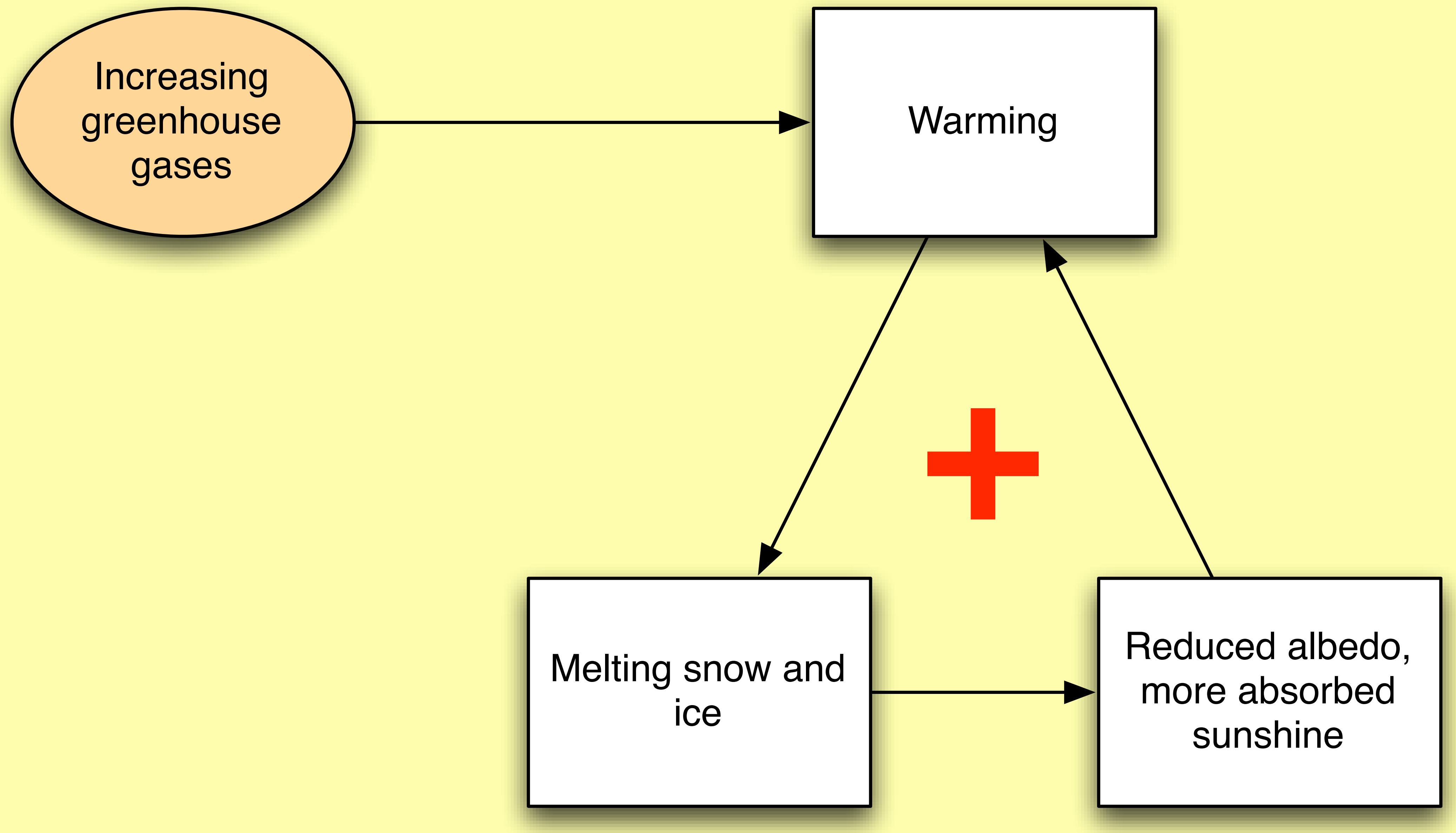


Screen & Simmonds, 2010

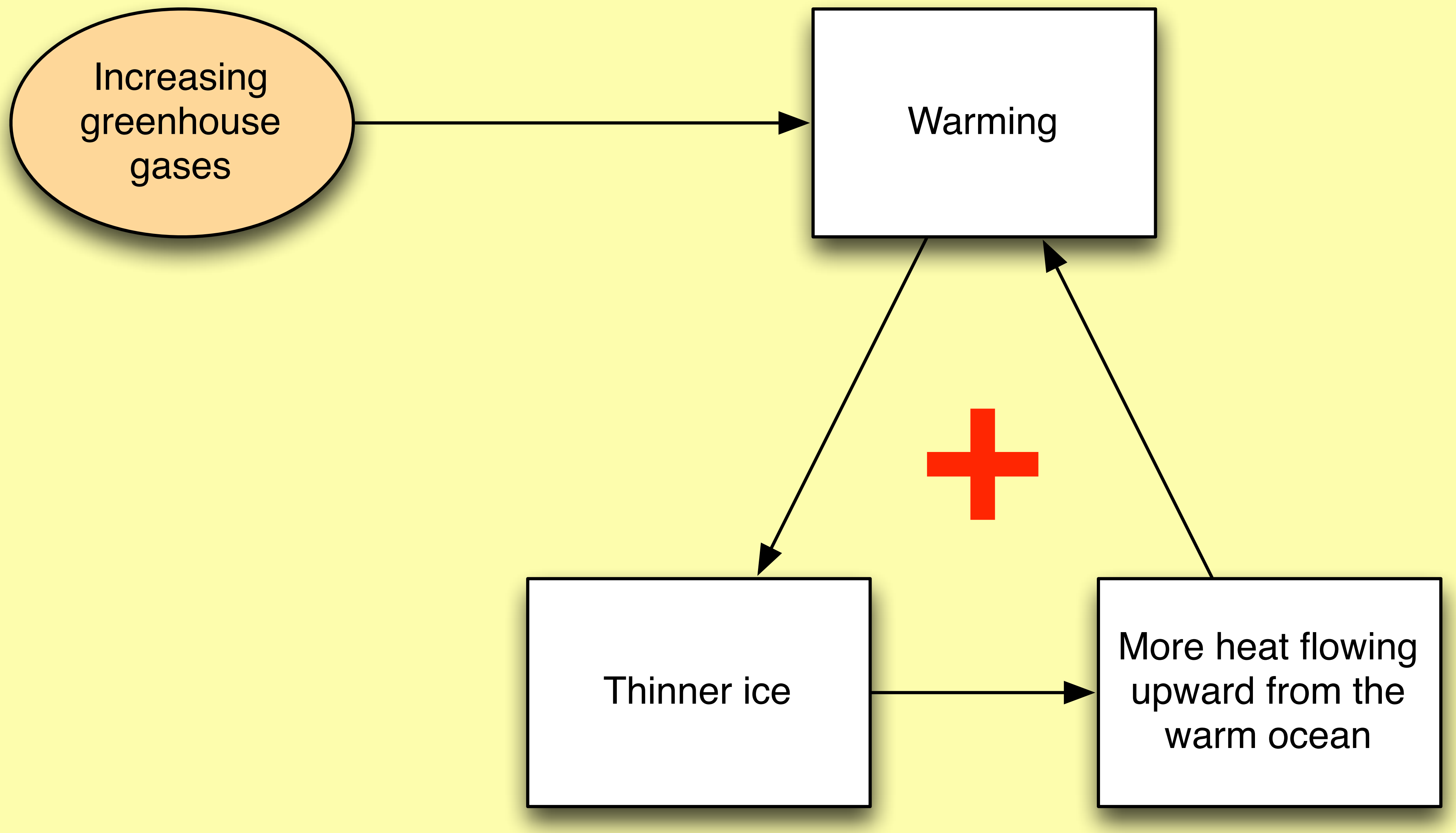
Sea ice

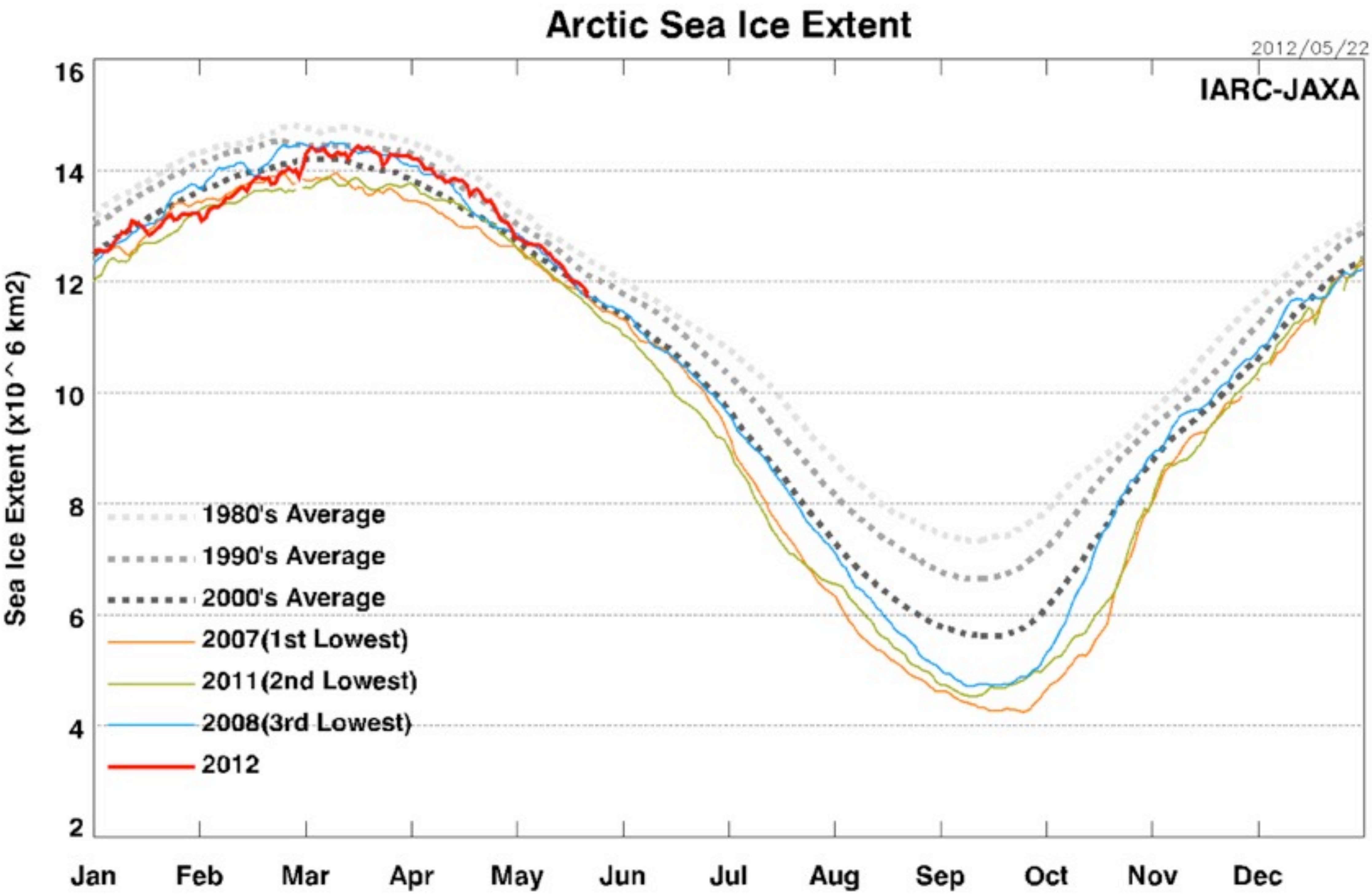
- **Reflects sunlight**
- **Blocks heat exchange between the ocean below and the air above**

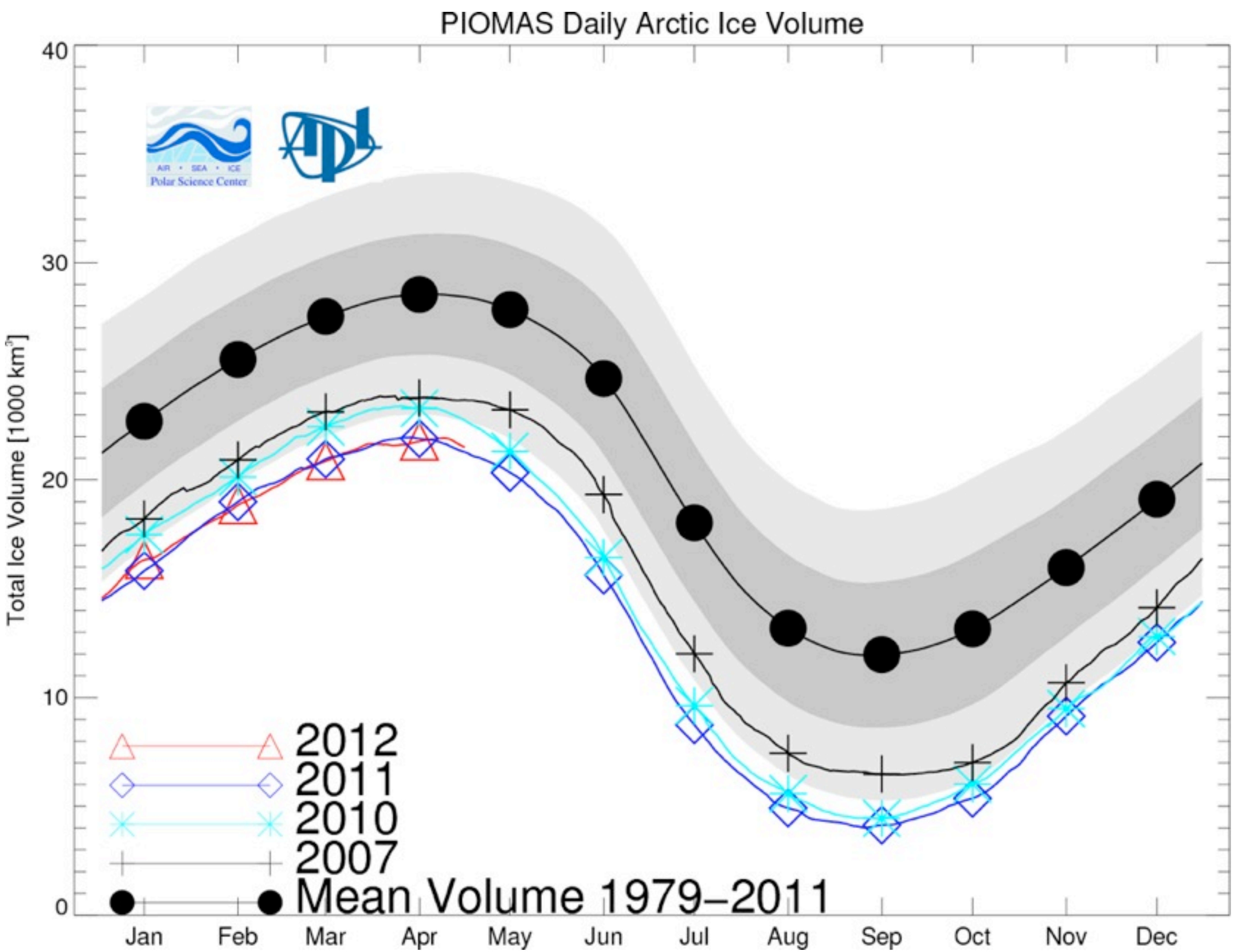
Albedo Feedback



Sea Ice Insulation Feedback

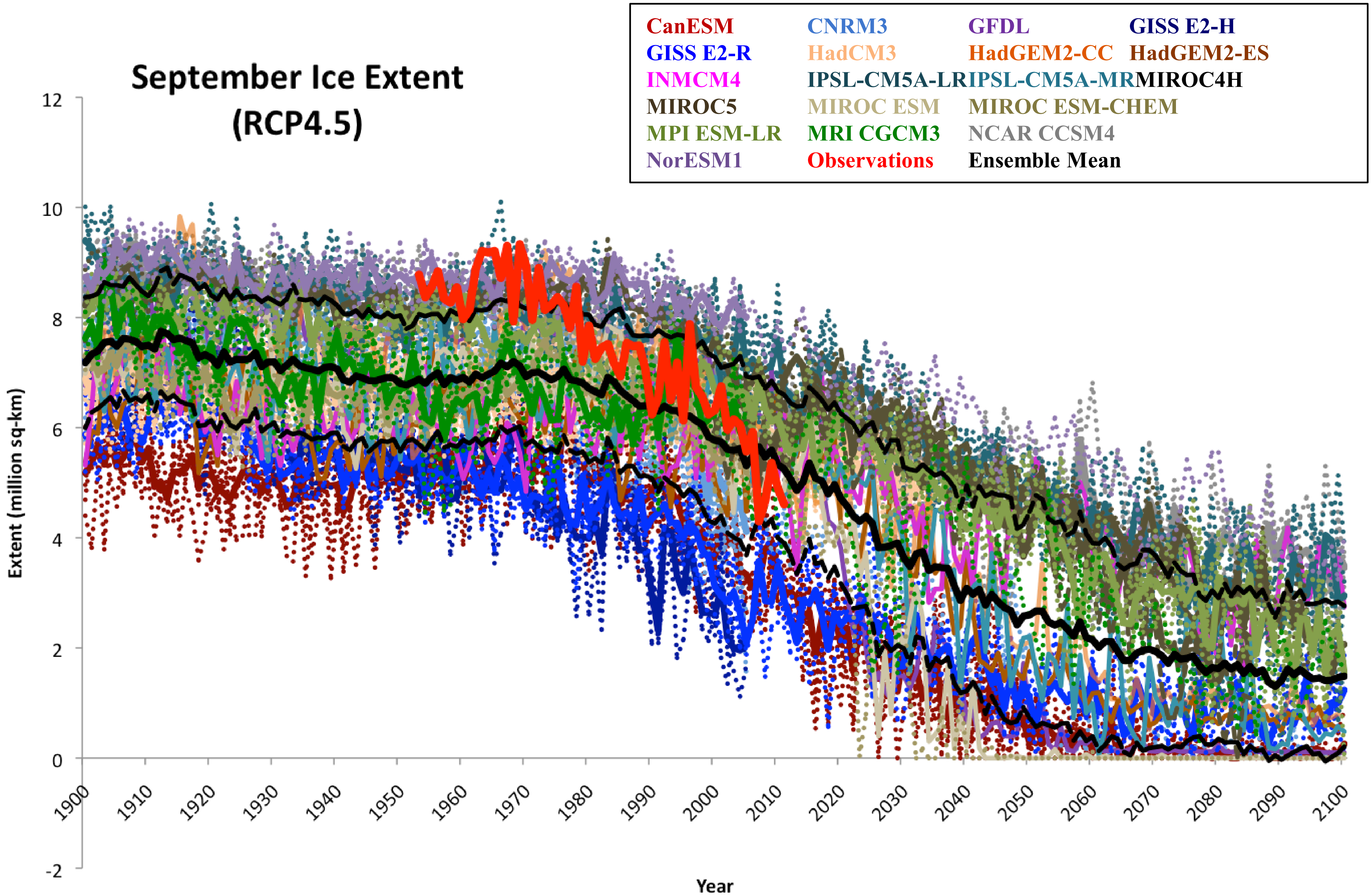



Arctic Sea Ice Extent
2012/05/22
IARC-JAXA
Sea Ice Extent (x10^6 km2)
16
14
12
10
8
6
4
2
1980's Average
1990's Average
2000's Average
2007(1st Lowest)
2011(2nd Lowest)
2008(3rd Lowest)
2012
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec



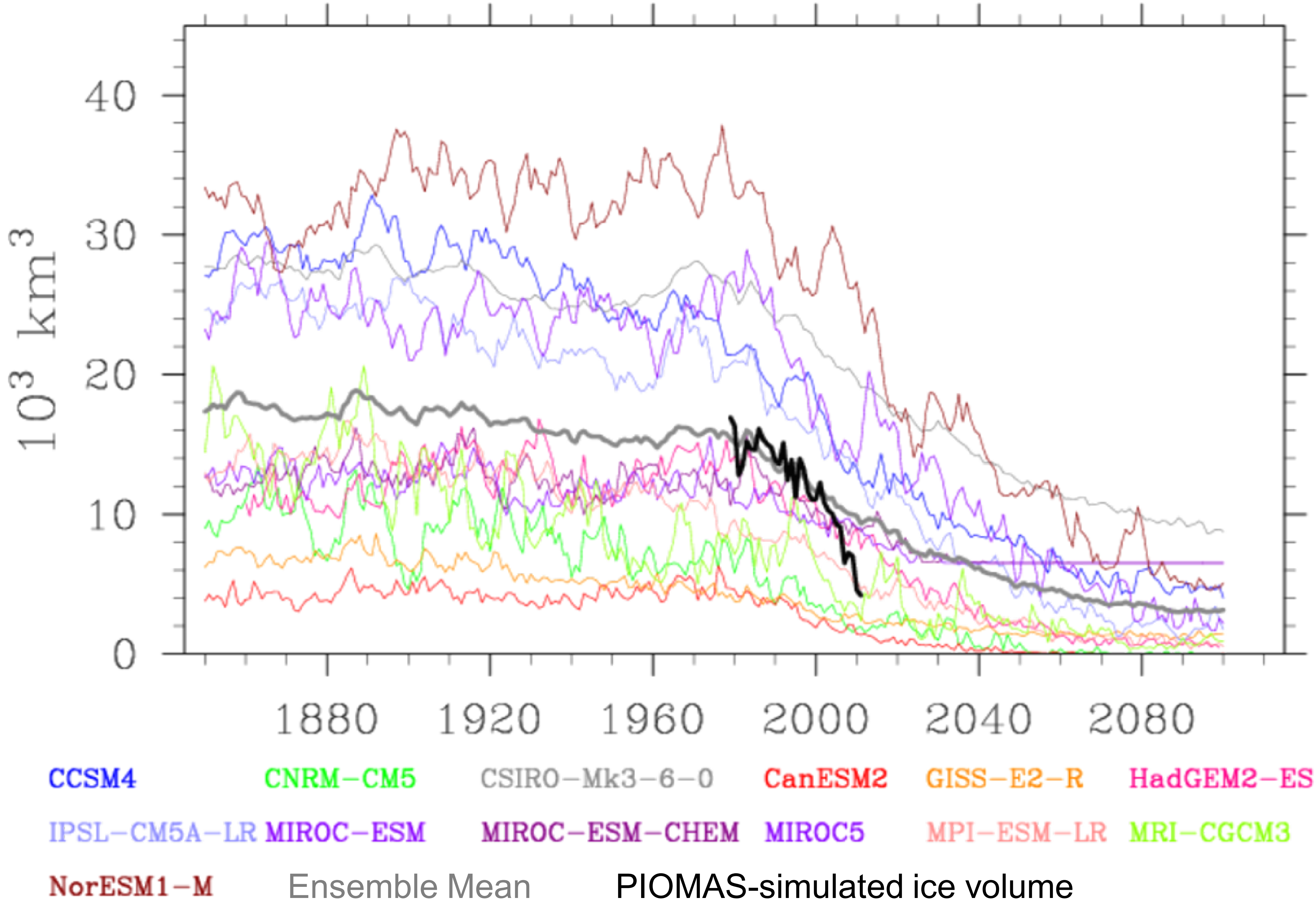
PIOMAS Daily Arctic Ice Volume
Total Ice Volume [1000 km³]
0
10
20
30
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Polar Science Center
2012
2011
2010
2007
Mean Volume 1979–2011

CMIP5 results



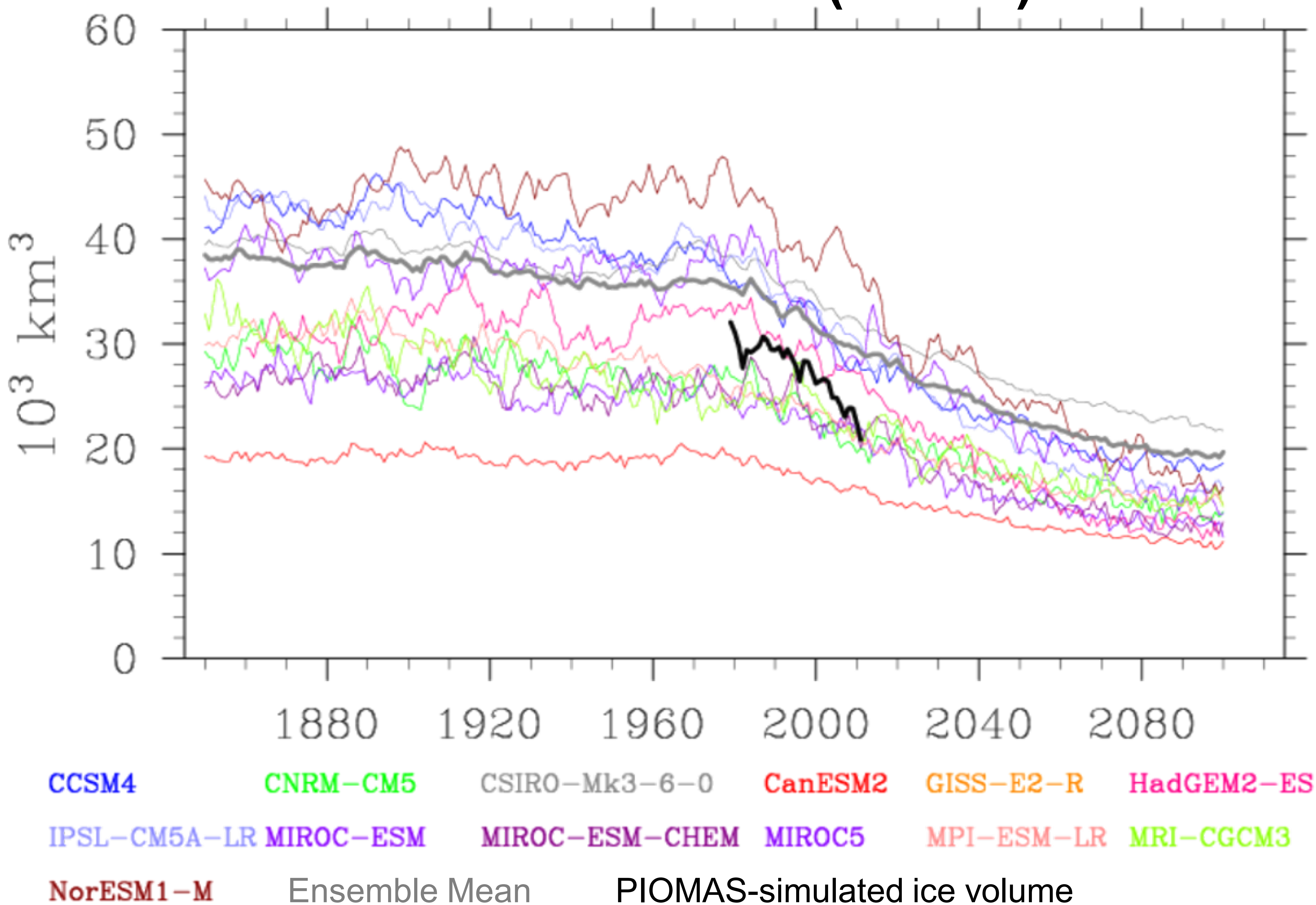
Stroeve et al. (2012)

Summer Minimum (September)



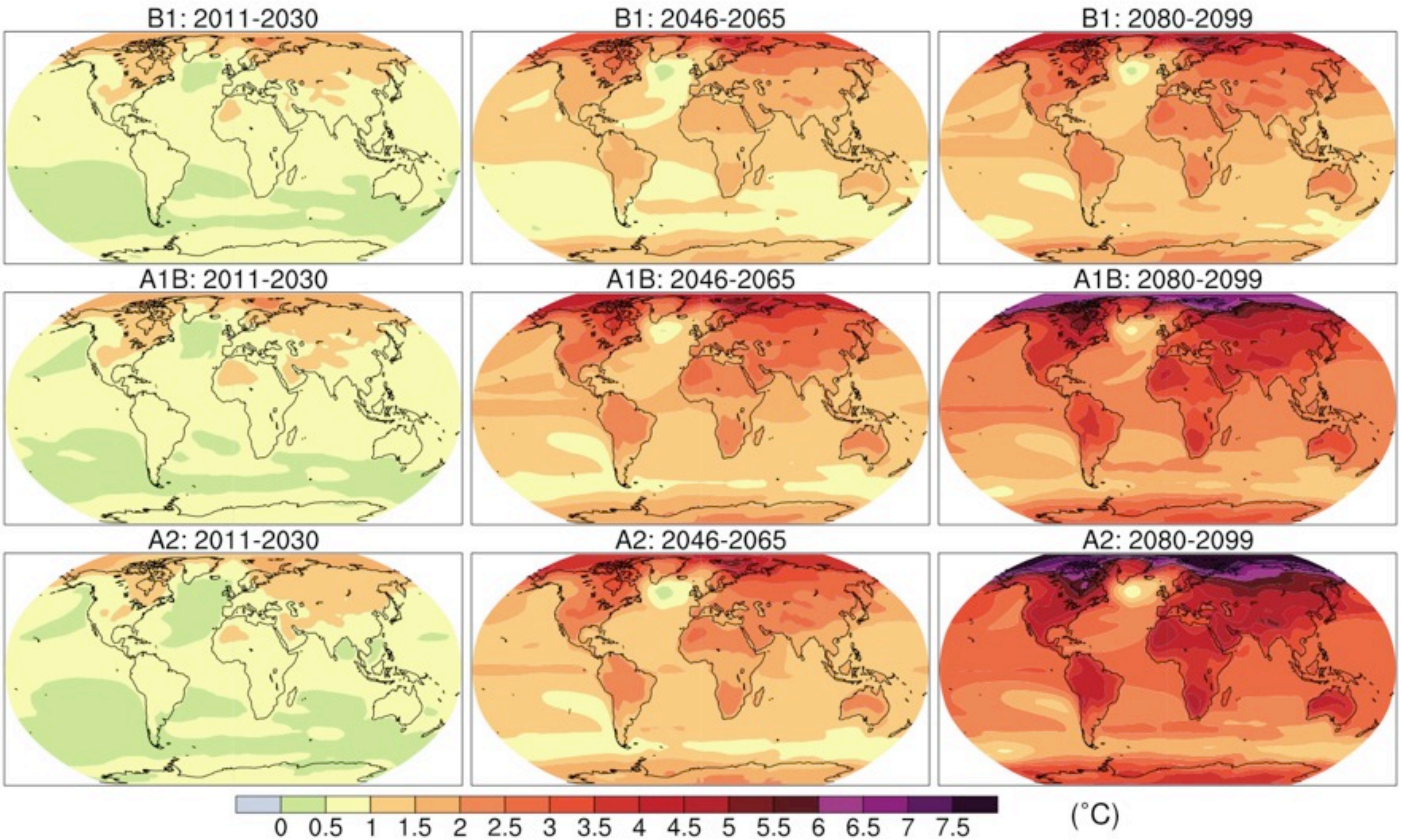
Stroeve et al. (2012)

Winter Maximum (March)

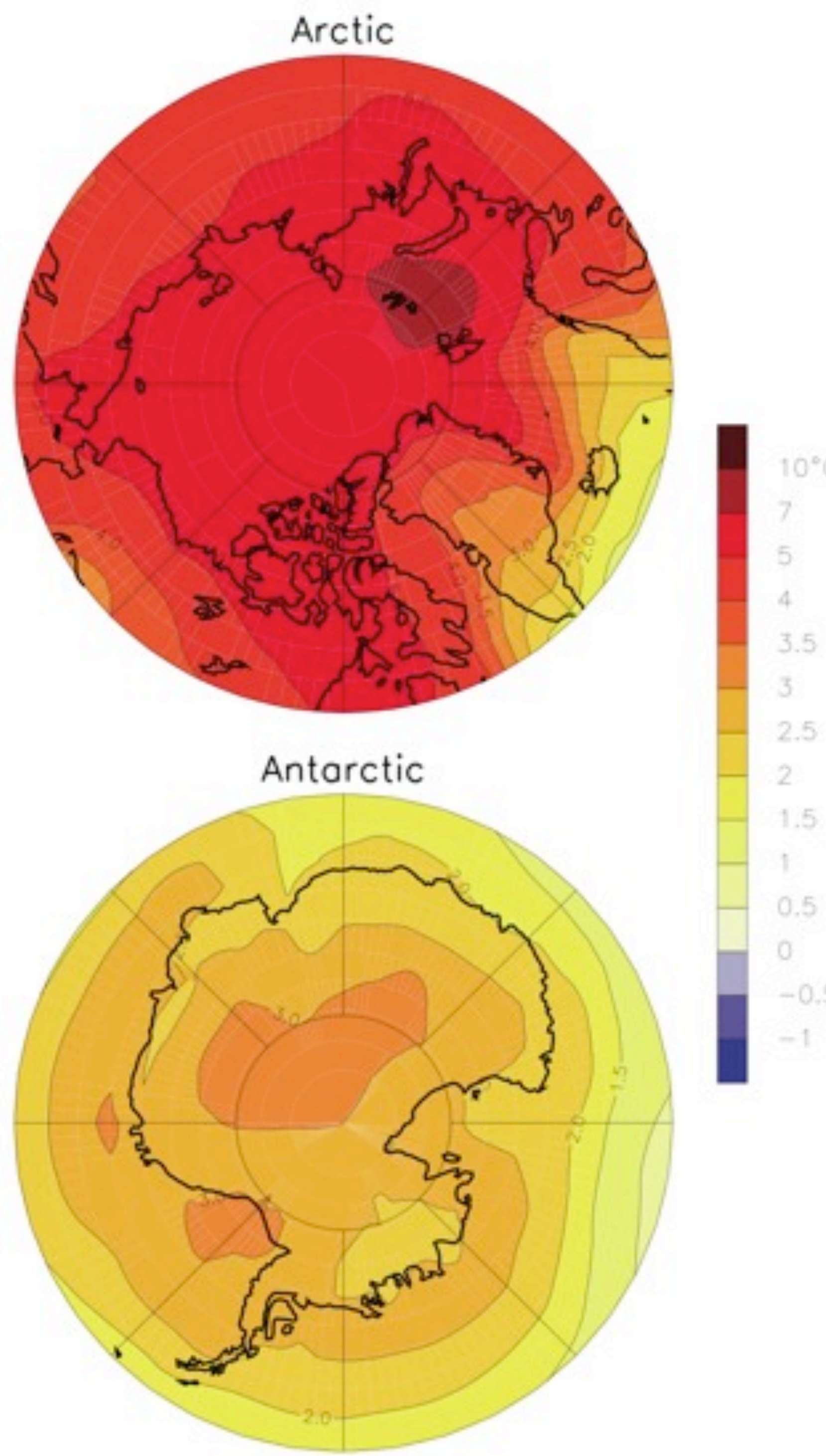


Stroeve et al. (2012)

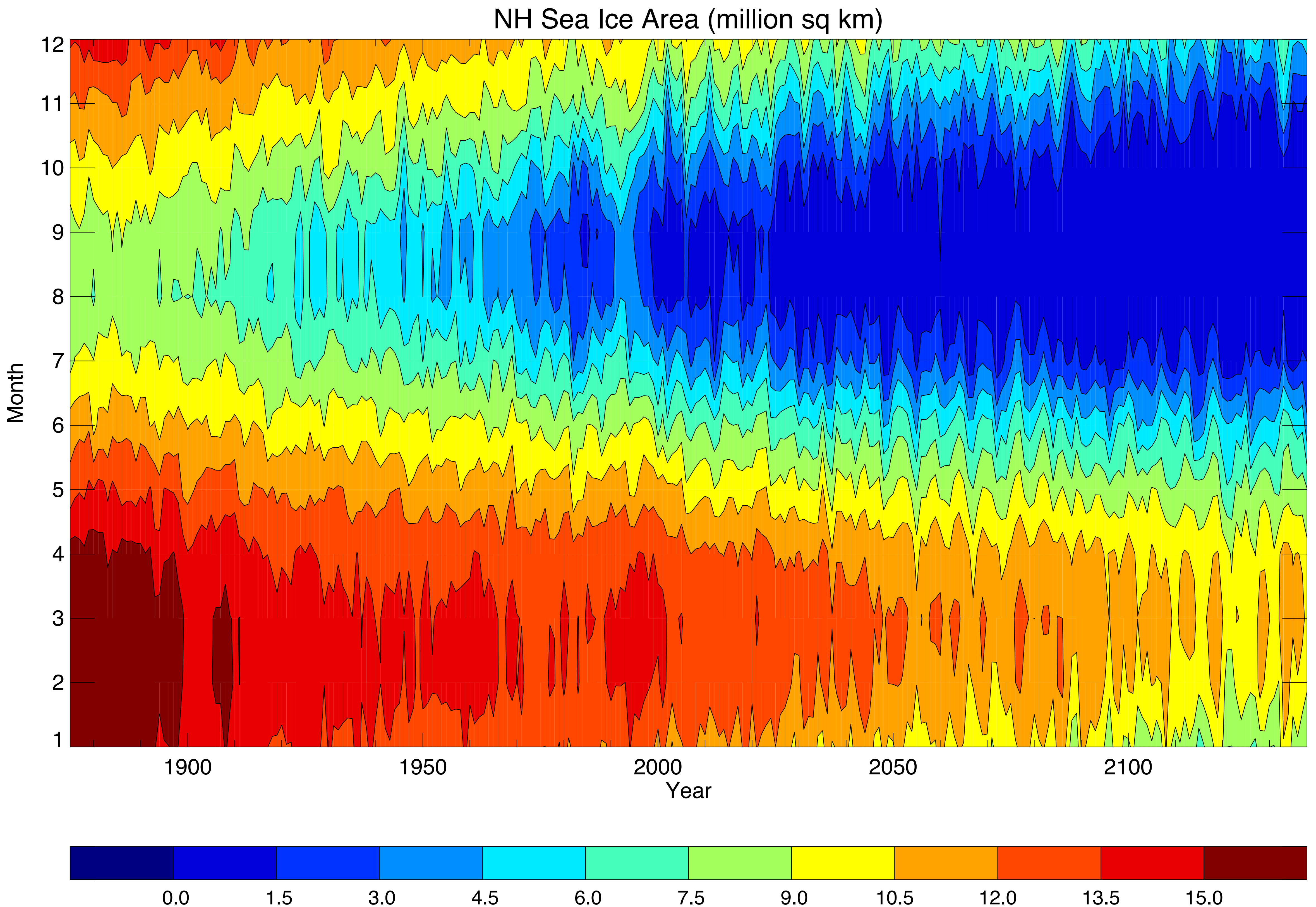
Forecasts for the 21st Century



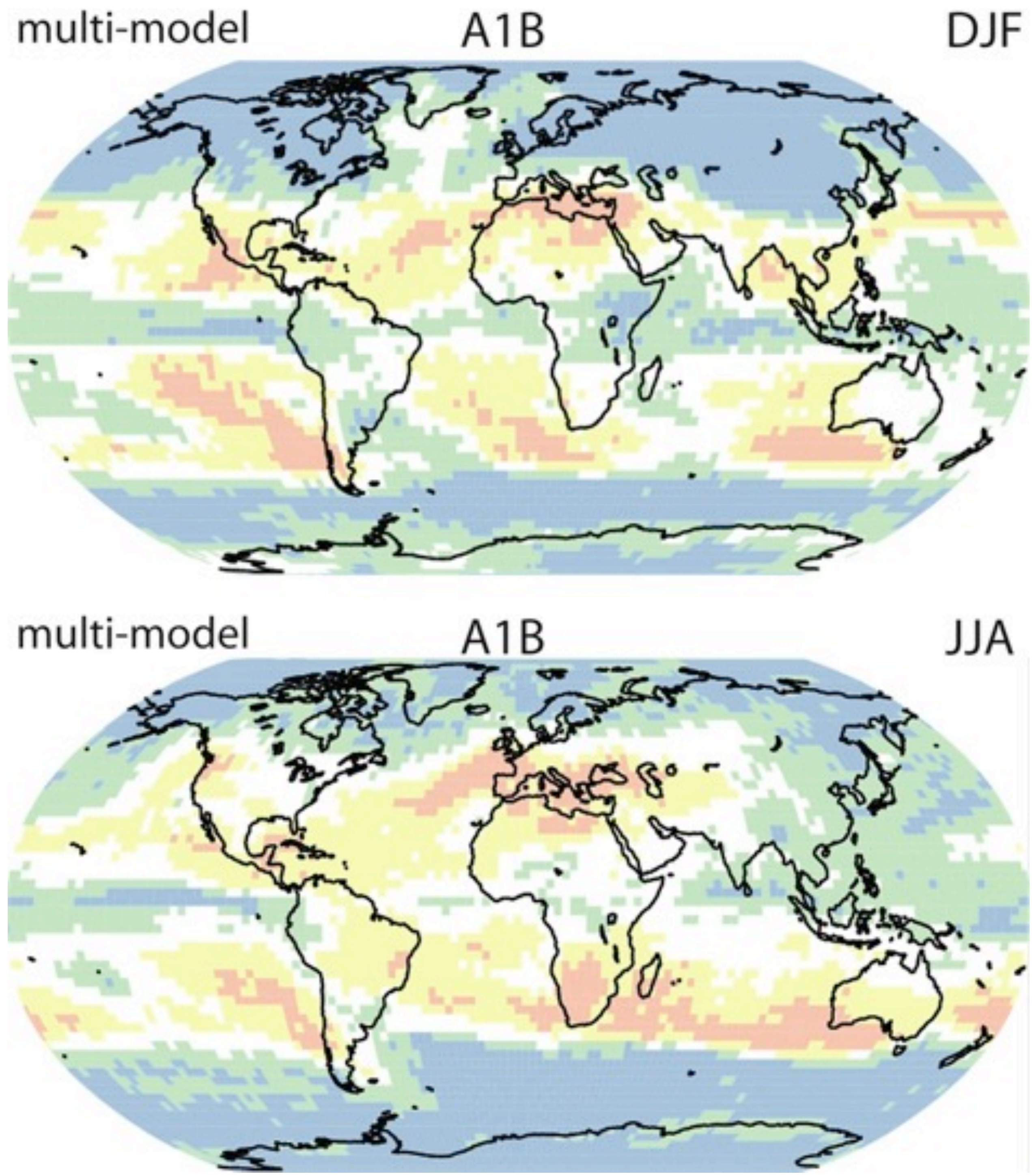
Predicted warming over the 21st century



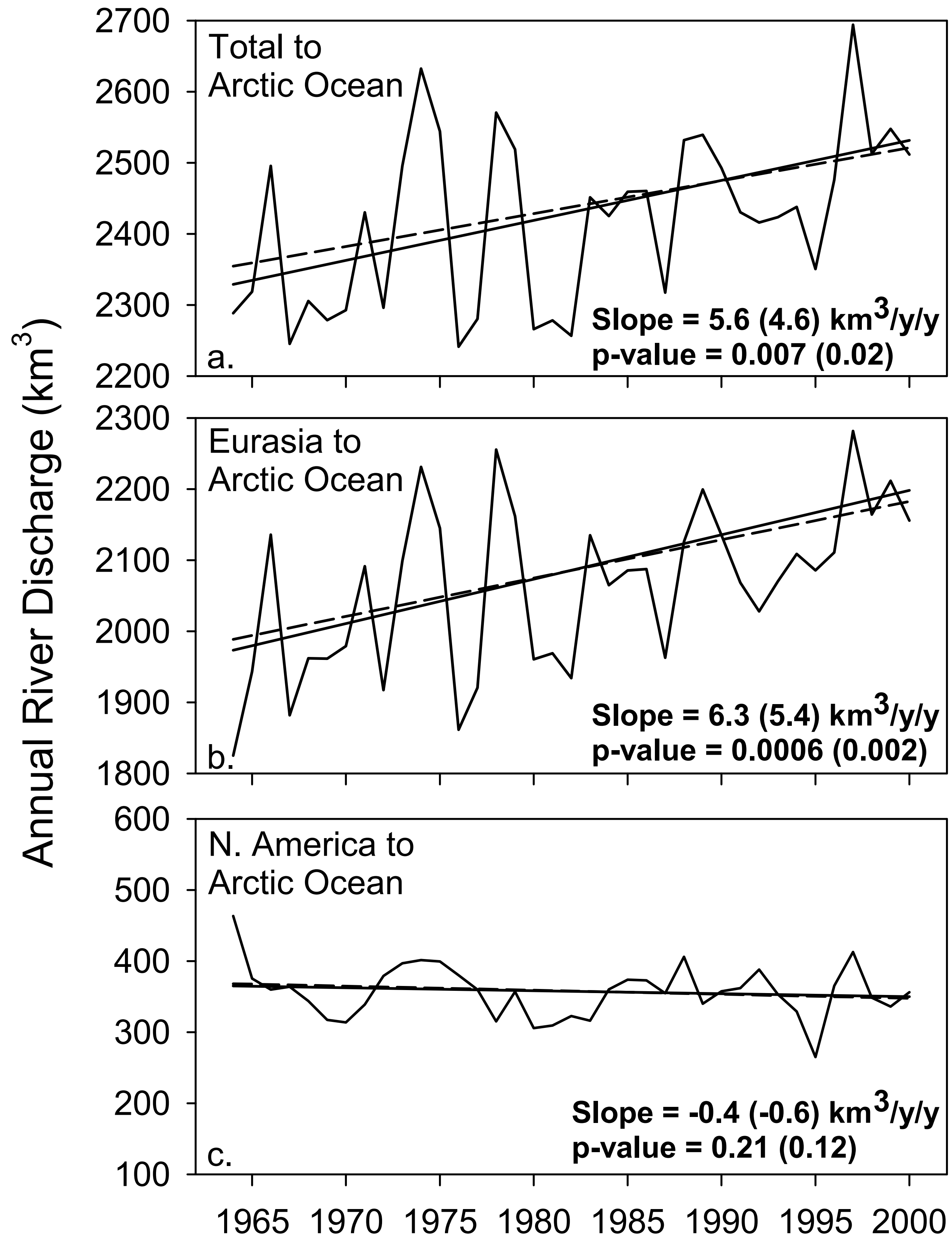
CESM 1% per year



Precipitation:
Late 21st century minus late 20th century

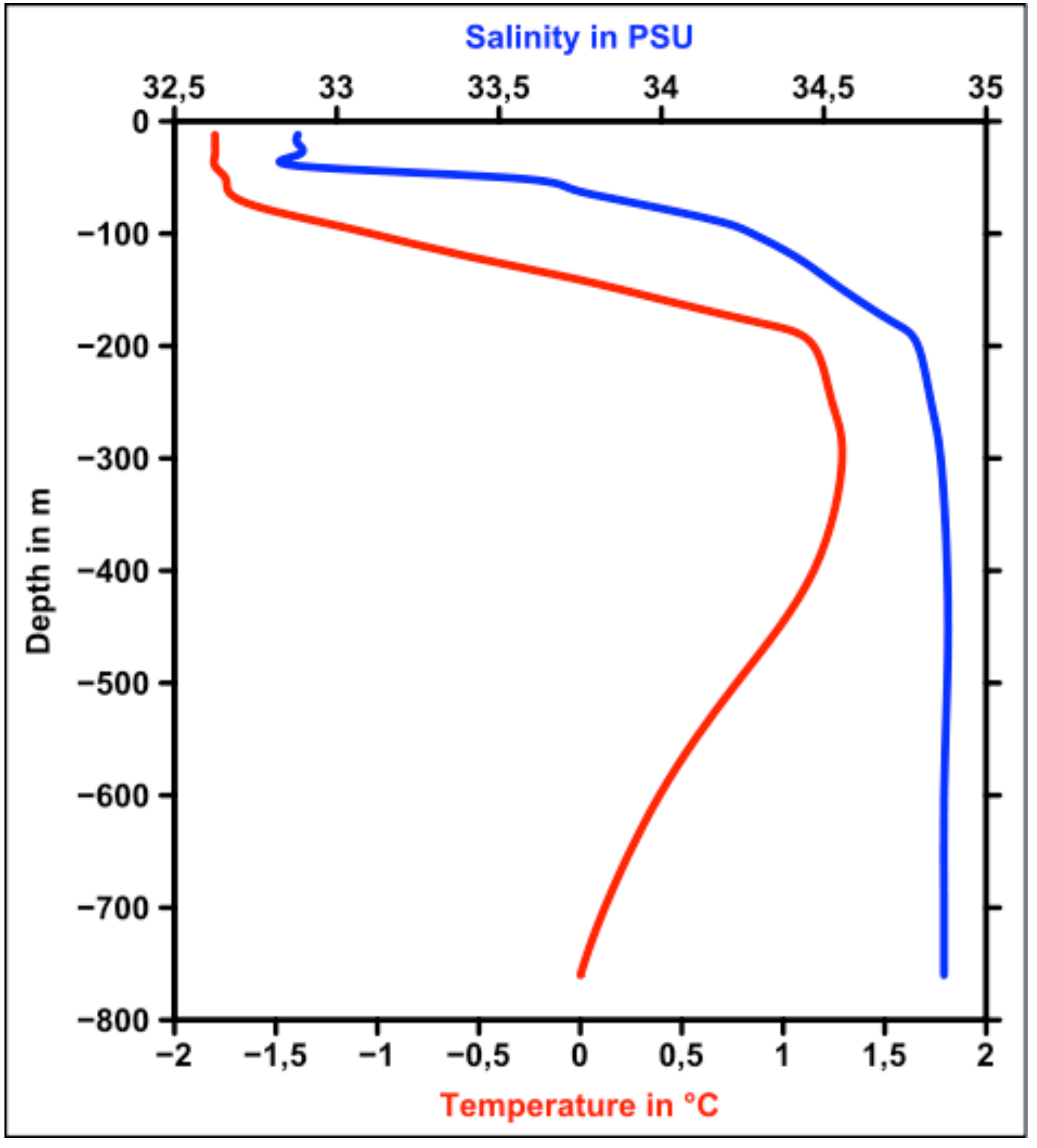


The wet get wetter and the dry get drier.

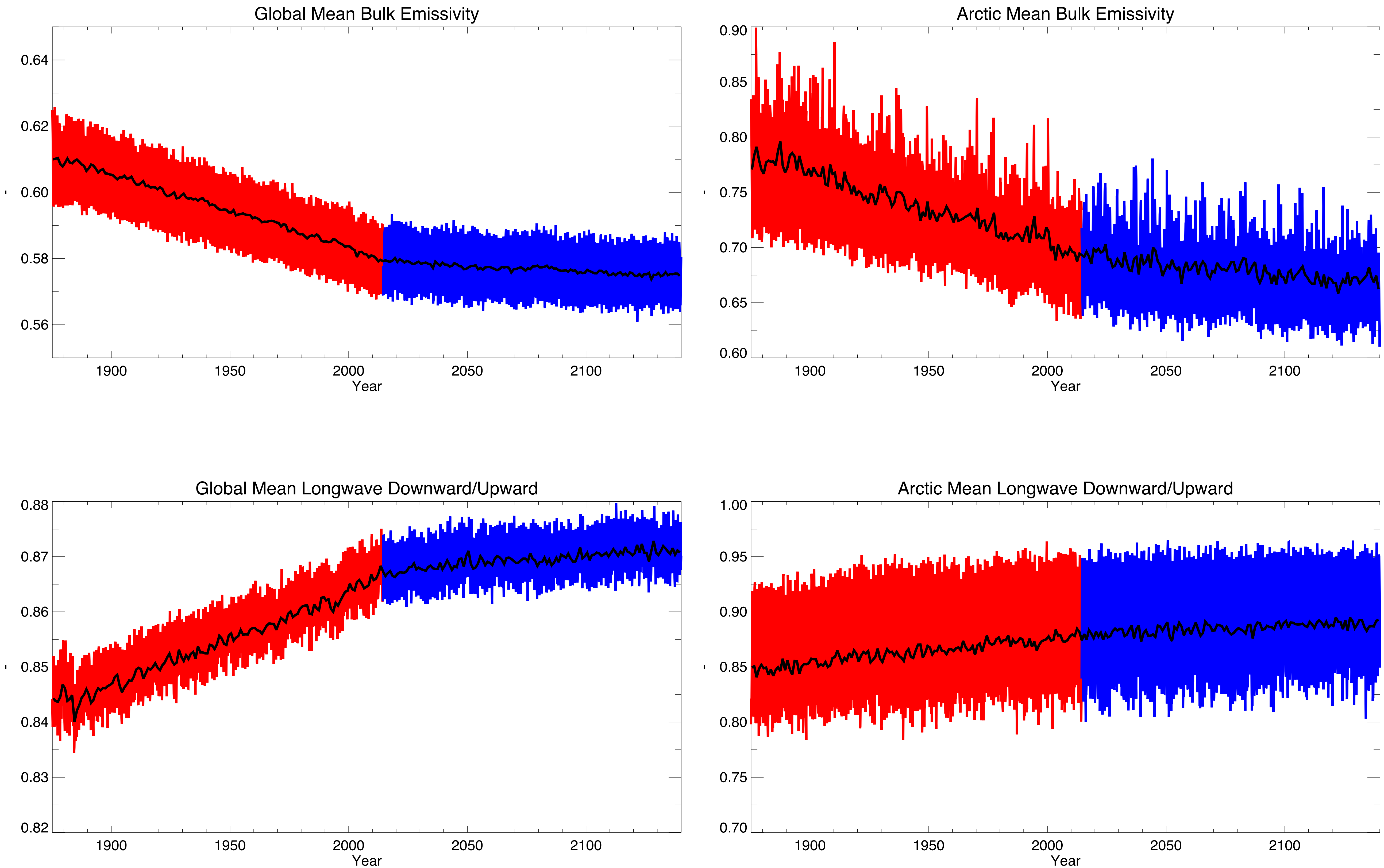


Annual River Discharge (km3)
Total to
Arctic Ocean
Slope = 5.6 (4.6) km3/y/y
p-value = 0.007 (0.02)
a.
2700
2600
2500
2400
2300
2200
Eurasia to
Arctic Ocean
Slope = 6.3 (5.4) km3/y/y
p-value = 0.0006 (0.002)
b.
2300
2200
2100
2000
1900
1800
N. America to
Arctic Ocean
Slope = -0.4 (-0.6) km3/y/y
p-value = 0.21 (0.12)
c.
600
500
400
300
200
100
1965
1970
1975
1980
1985
1990
1995
2000

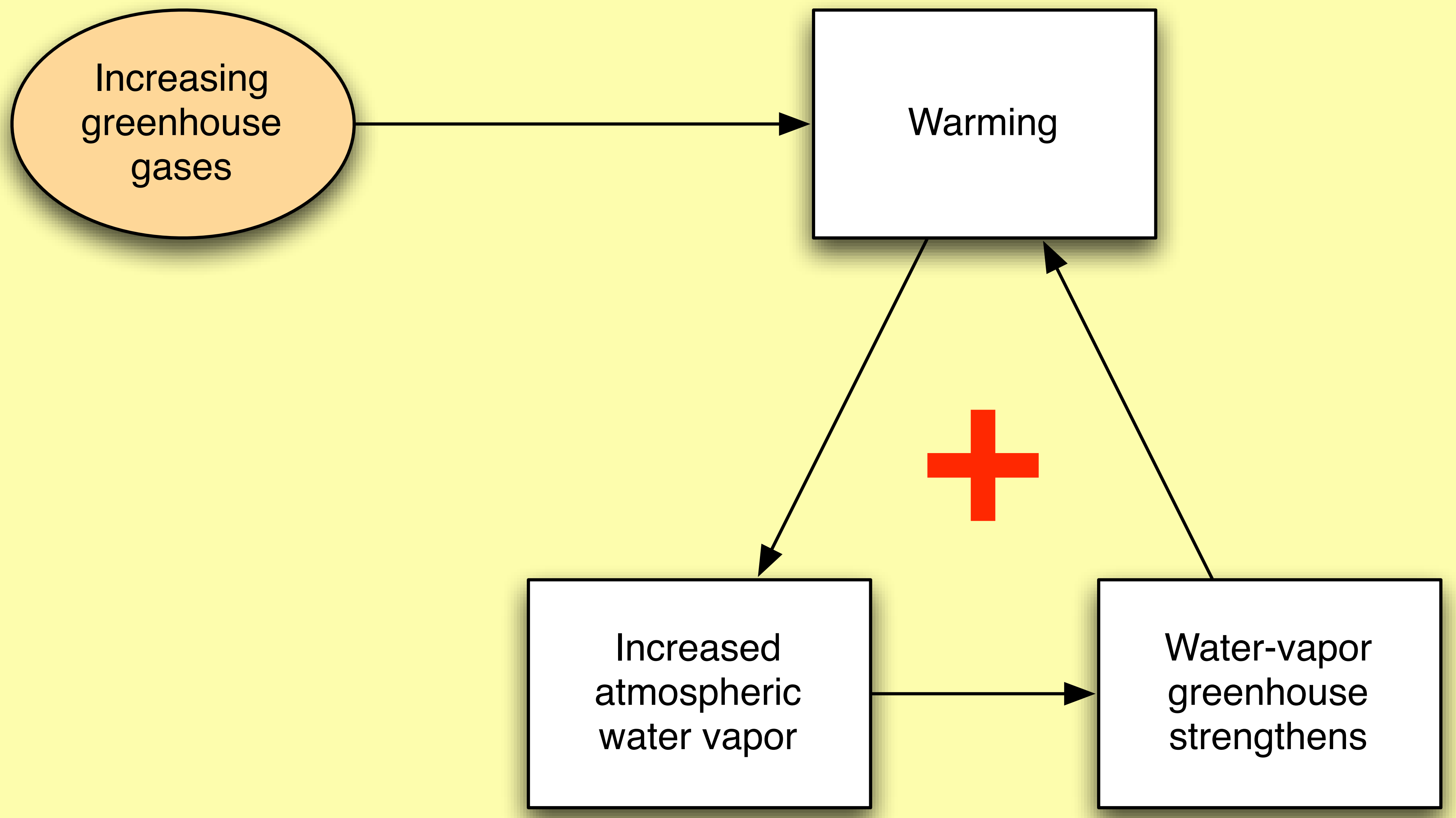
Halocline


Salinity in PSU
32,5
33
33,5
34
34,5
35
0
−100
−200
−300
−400
−500
−600
−700
−800
Depth in m
−2
−1,5
−1
−0,5
0
0,5
1
1,5
2
Temperature in °C

Two Greenhouse Indices

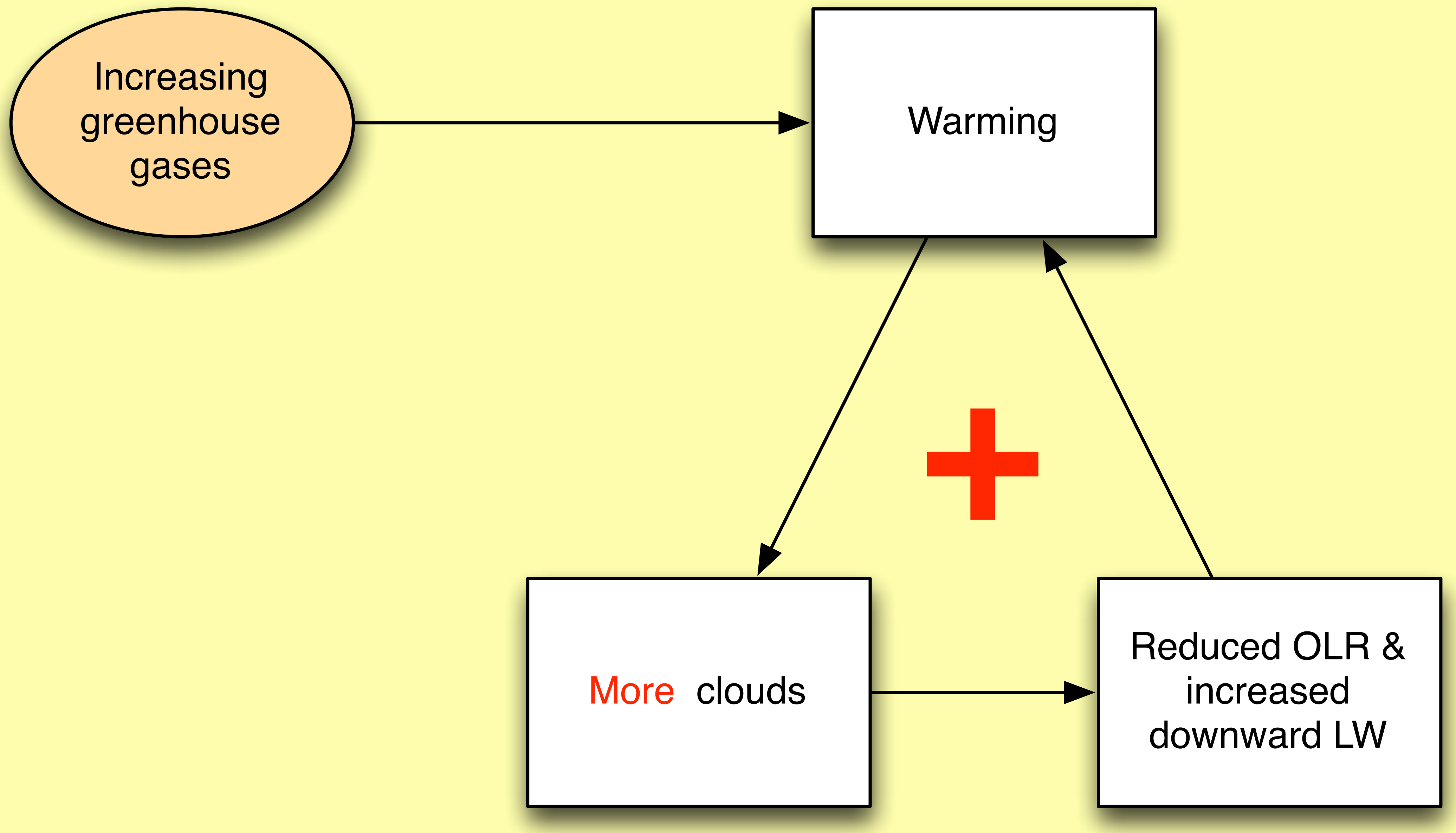


Water Vapor Feedback



As water vapor increases, precipitation and evaporation also increase.

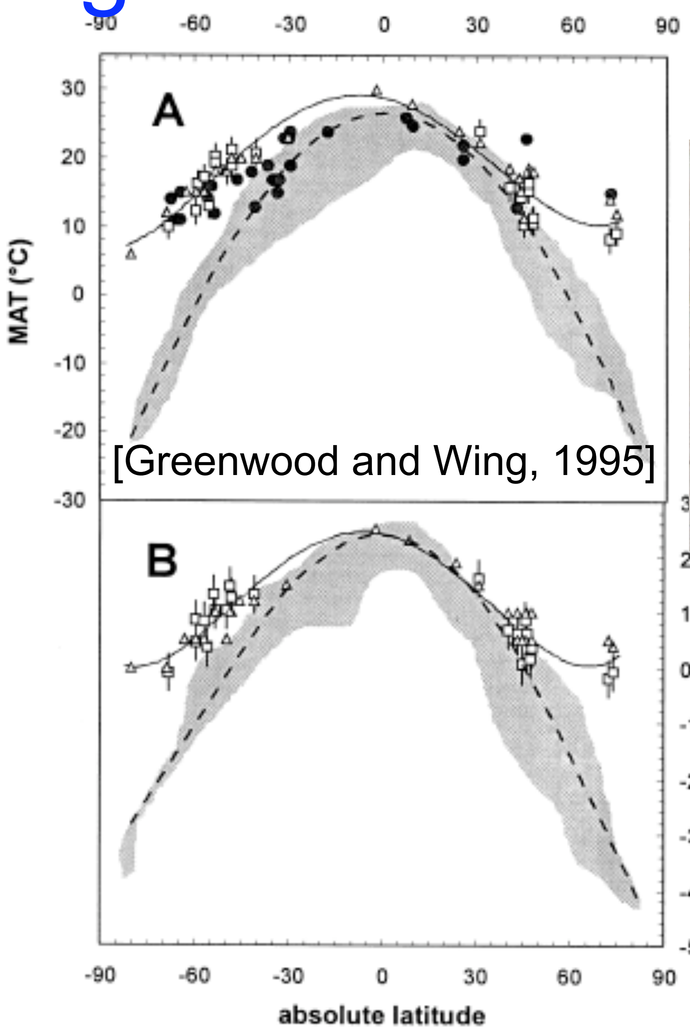
Arctic Winter Cloud Feedback



Ellesmere Island
80 °N
50 MYA
1200 ppmv CO_2

Eocene (50 MYA, ~1200 ppmv)

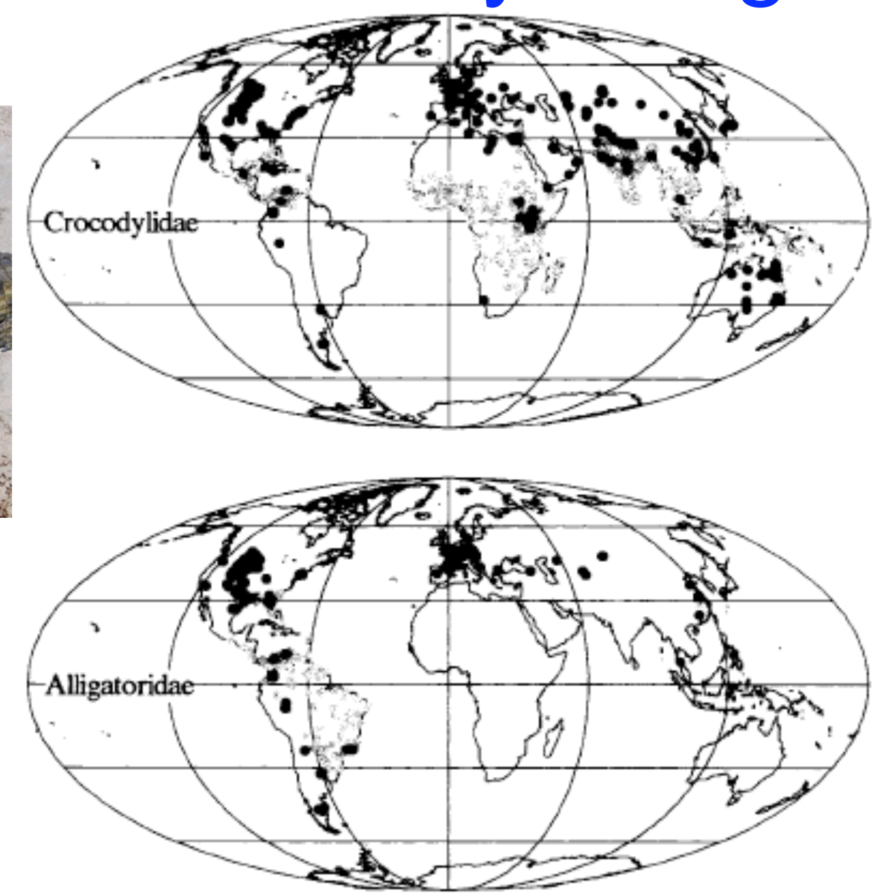
Cool tropics, warm high-latitudes



■ - Modern land temp.

● △ □ - Eocene SST; NLR&LMA, CLAMP

Crocodiles in Greenland, Palm trees in Wyoming!



Crocodiles need: Mean annual T>14.2°C & Cold month mean >5.5°C [Markwick, 1998]

Slide from Eli Tziperman

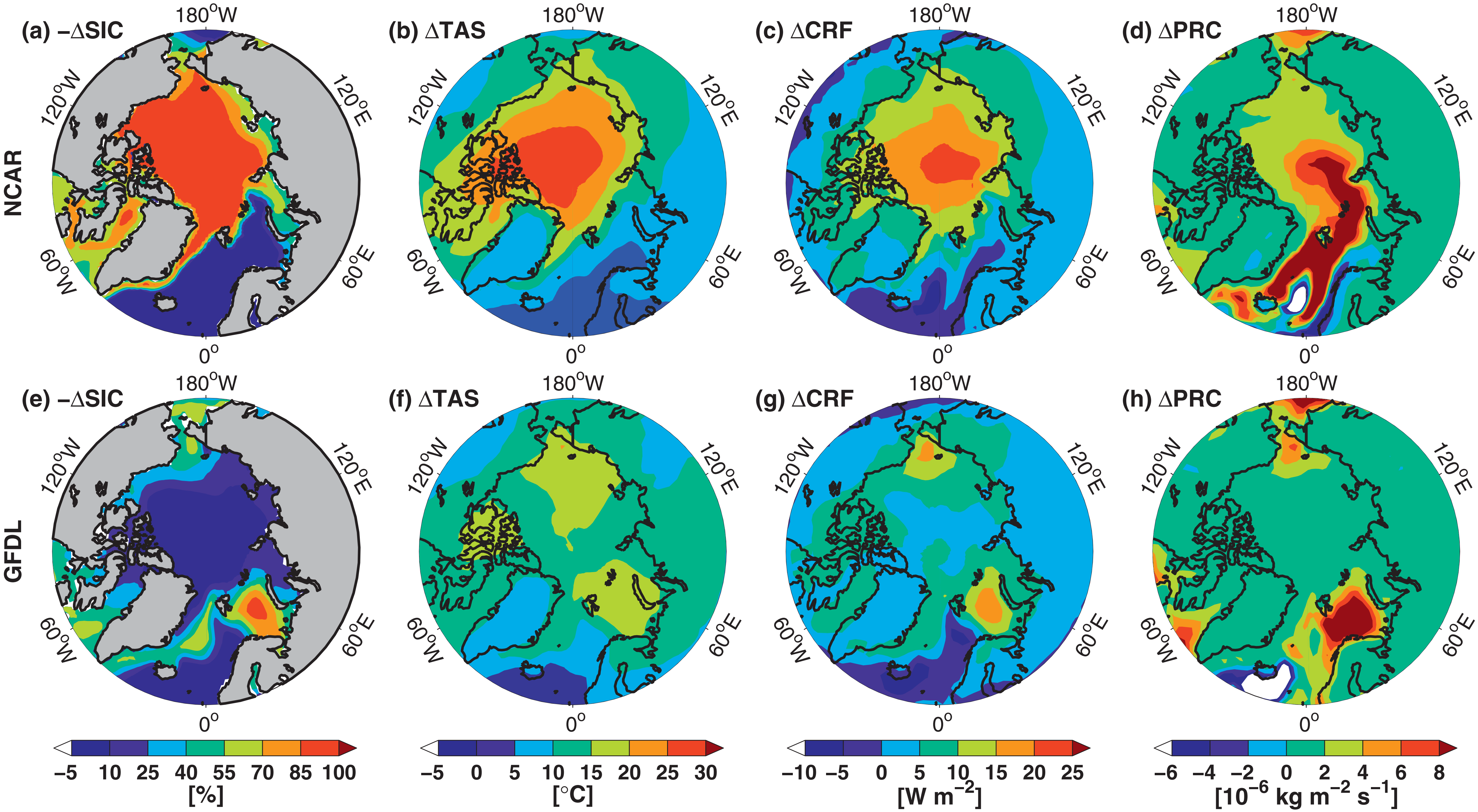
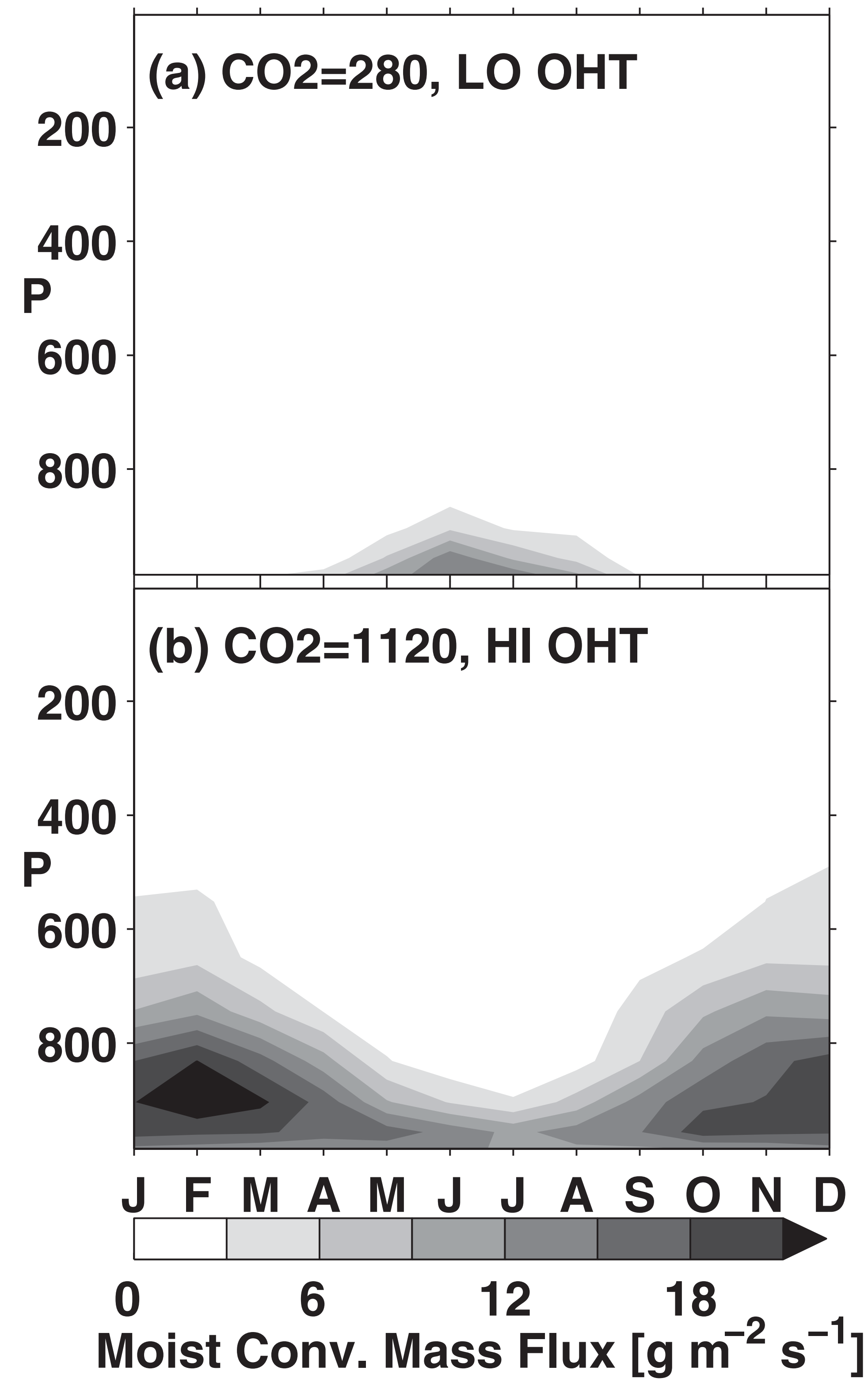


FIG. 1. Change in winter (November–February) Arctic climate over the course of the IPCCAR4 4 × CO_2 experiment. The models are (a)–(d) NCAR CCSM3.0, which loses most Arctic winter sea ice and (e)–(h) GFDL CM2.0, which loses minimal winter Arctic winter sea ice. For each variable, the difference between the mean over the last 10 yr and the mean over the first 10 yr is plotted. (a),(e) −ΔSIC, the negative of the change in sea ice concentration (100% means a complete loss of sea ice); (b),(f) ΔTAS, the change in surface air temperature; (c),(g) ΔCRF, the change in cloud radiative forcing; and (d),(h) ΔPRC, the change in convective precipitation rate.

Abbott et al., J Climate, 2009



"OHT" = ocean heat transport

Abbott et al., J Climate, 2009

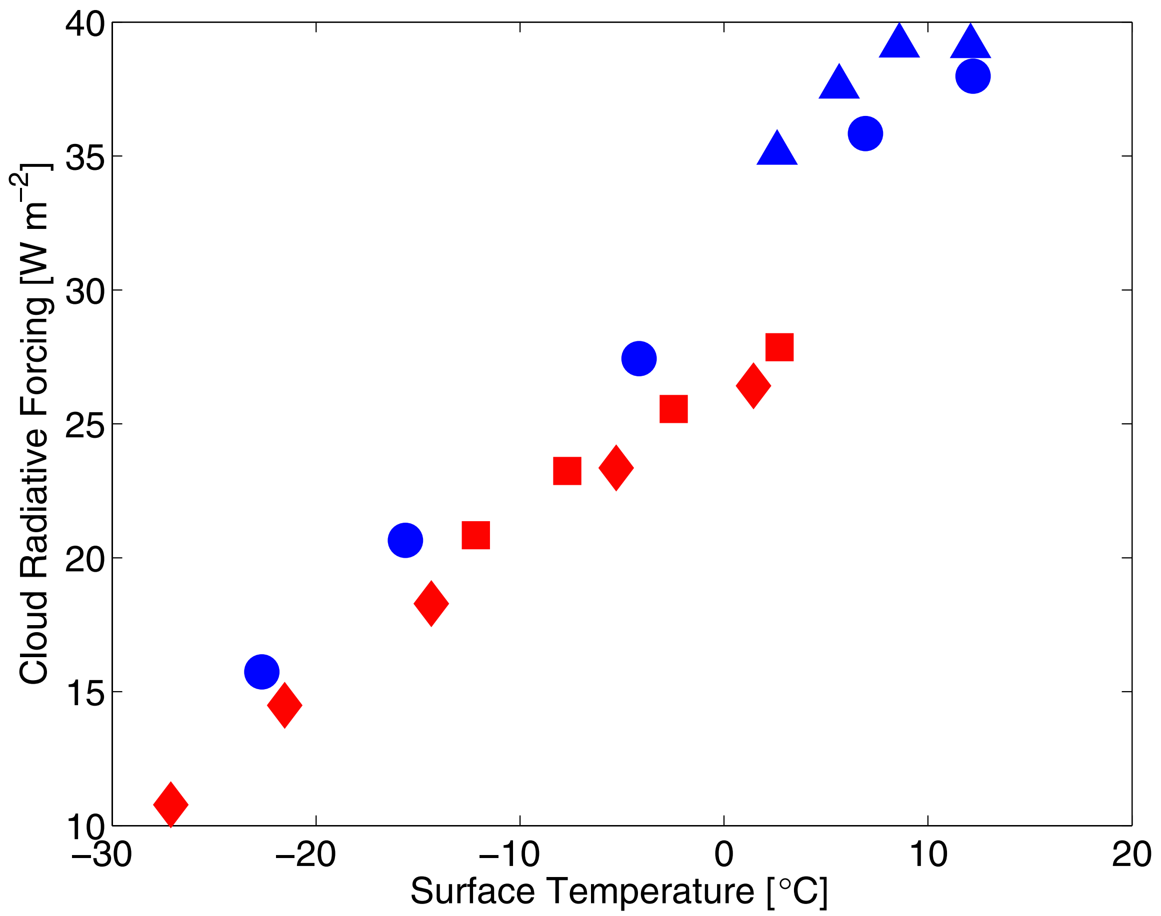
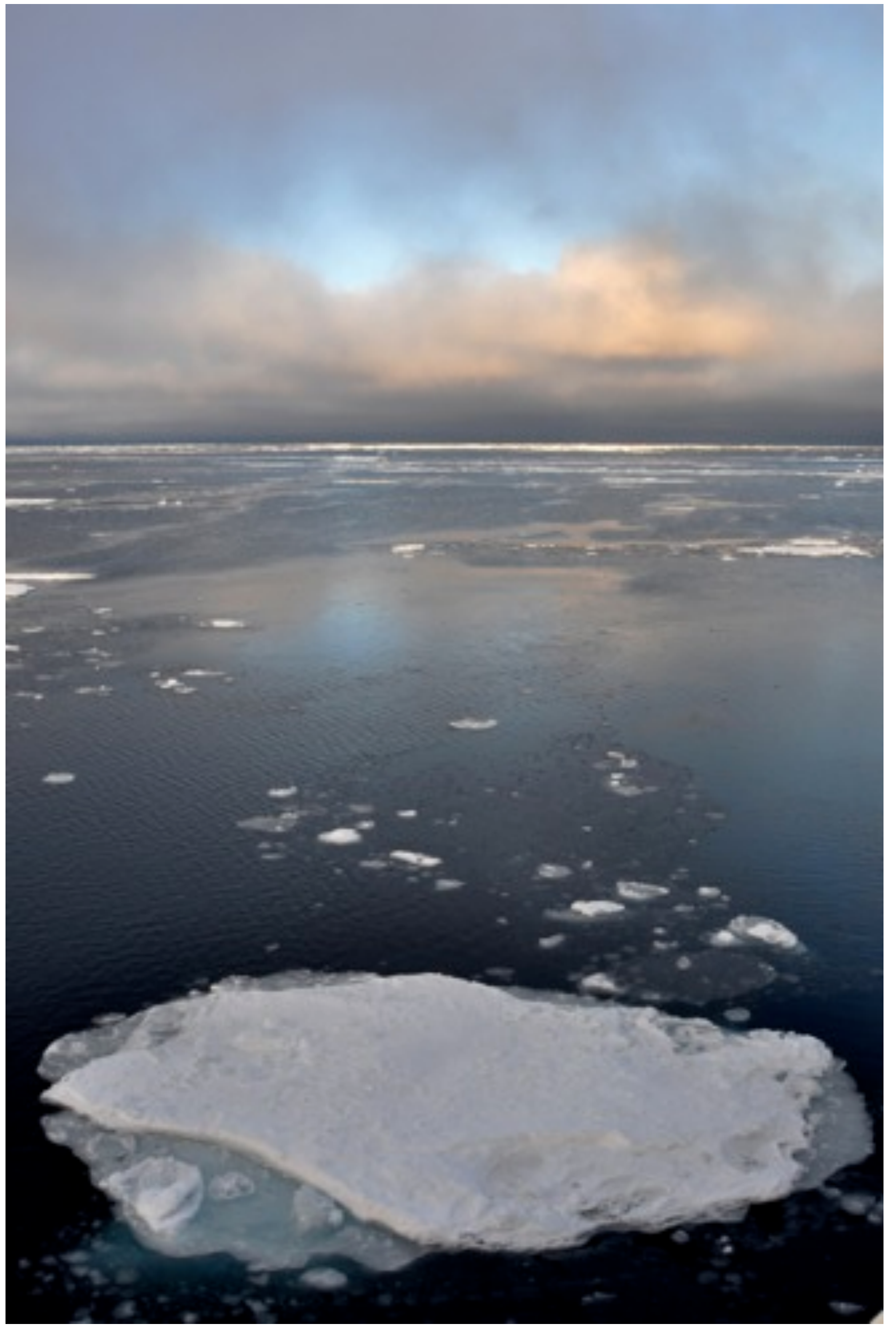


Figure 2. Winter (DJF) cloud radiative forcing averaged north of 60°N as a function of surface temperature averaged north of 60°N, which changes due to either changes in boundary conditions or CO_2. For each of the following cases, one datapoint represents one model run at a different CO_2 concentration: modern configuration land (red diamonds), Eocene configuration land (red squares), modern configuration ocean (blue circles), and Eocene configuration ocean (blue triangles).

Abbott et al., GRL, 2009

Conclusions

- **Current models do not account for the observed rapid melt-back of the Arctic sea ice.**
- **The Arctic shows us climate change in "fast forward."**
- **The positive surface albedo feedback is only one of several contributing factors.**
- **Cloud and water vapor feedbacks may also be very important.**



Schematic of accelerated warming in the Arctic-Boreal zone from effects in the physical climate system.