Interpreting recent Southern Ocean climate trends

John Marshall, MIT

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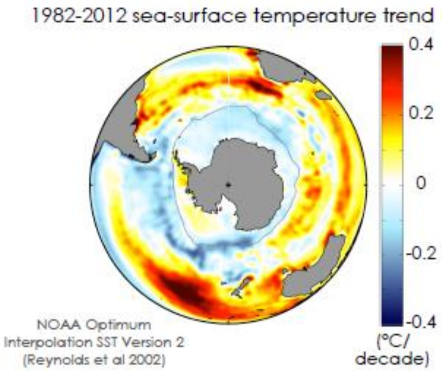

1. Observed trends in SST, sea-ice extent,
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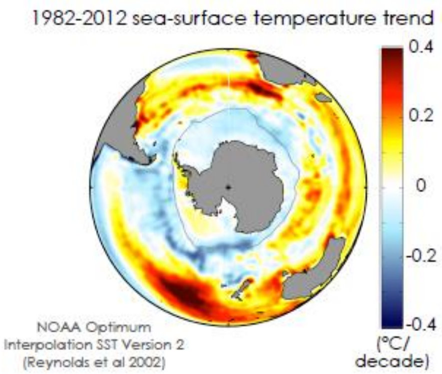

1. Observed trends in SST, sea-ice extent, ocean heat content etc

2. Describe a framework for thinking about the observations

Climate Response Functions (CRFs)

Characteristic patterns and timing of response to step-function perturbations

GHG
Ozone Hole

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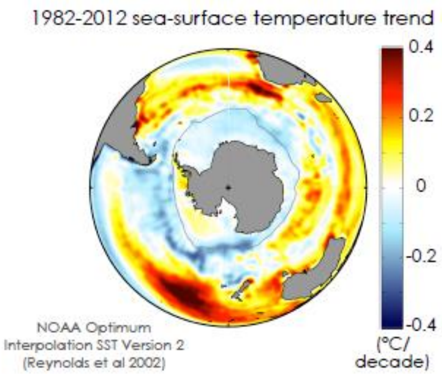

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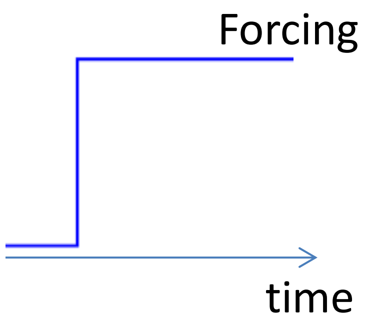

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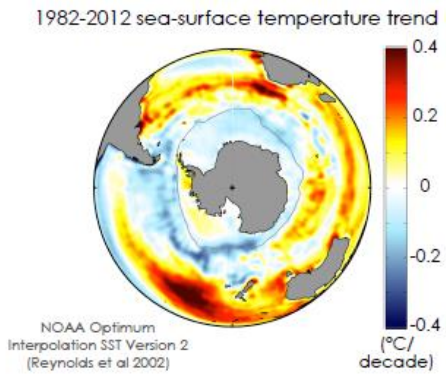

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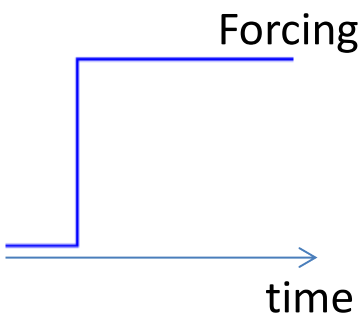

3. Null hypothesis: natural variability

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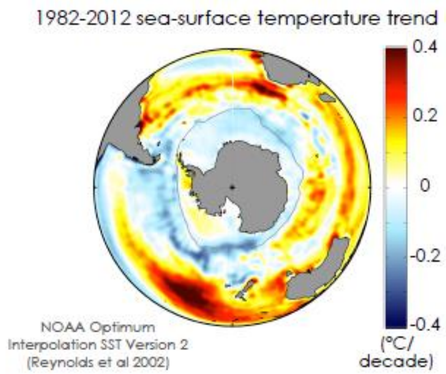

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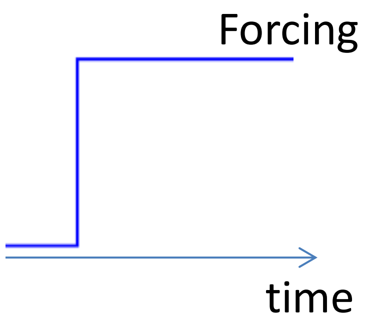

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4. Summary and Conclusions

'Special' dynamics of the SO imprints itself on response

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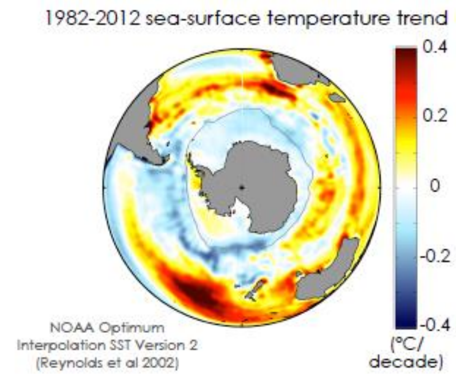

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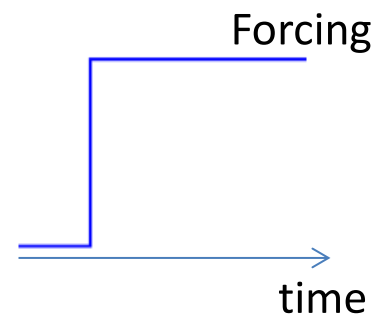

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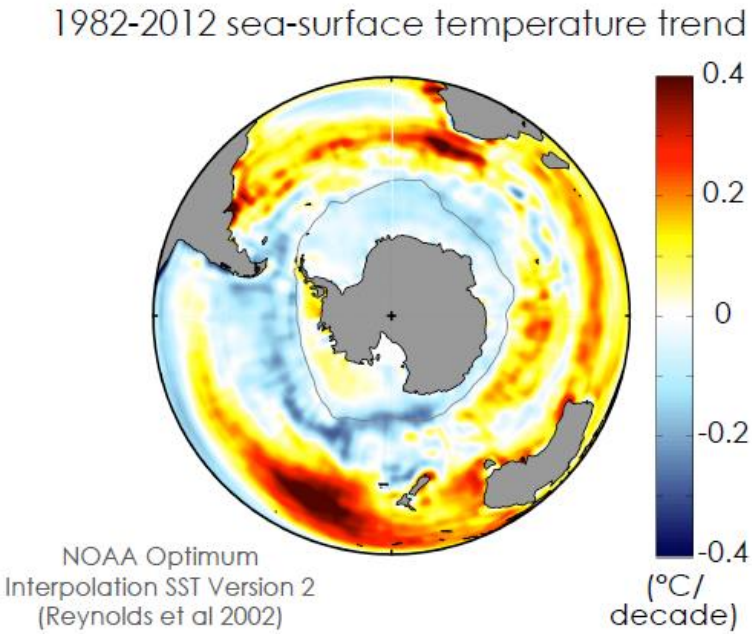
Collaborators:
- Kyle Armour
- Cecelia Bitz
- Ute Hausmann
- Yavor Kostov
- Alan Plumb
- Jeff Scott
- Susan Solomon

Observed Southern Ocean Trends

last 30 years



Observed Southern Ocean Trends

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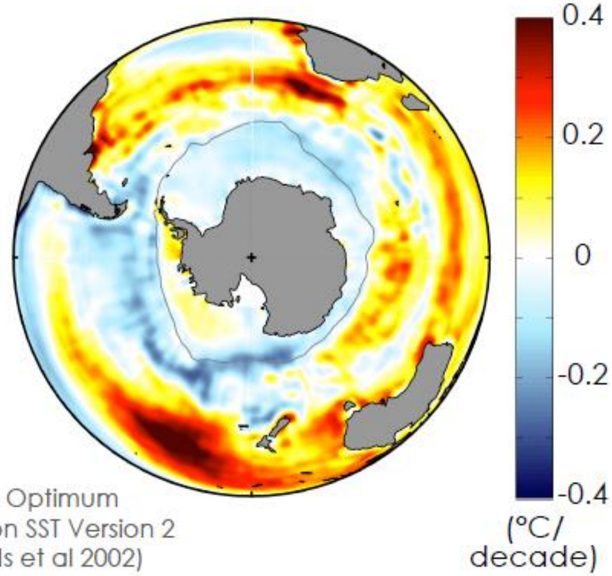
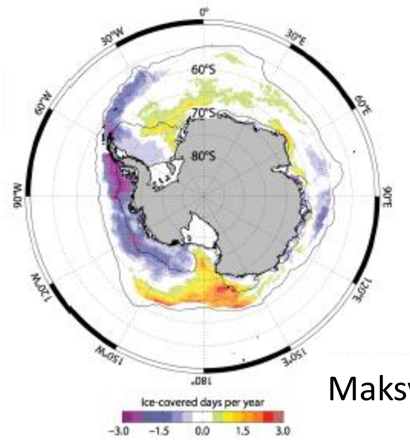
1982-2012 sea-surface temperature trend

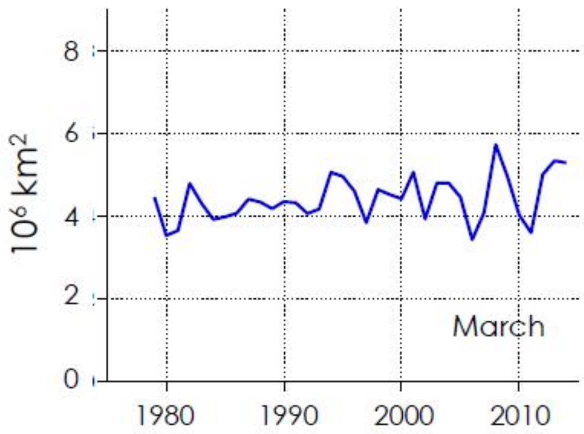


NOAA Optimum
Interpolation SST Version 2
(Reynolds et al 2002)

Antarctic sea-ice extent



Maksym et al (2012)



From National Snow and Ice Data Center
http://nsidc.org/cryosphere/sotc/sea_ice.html

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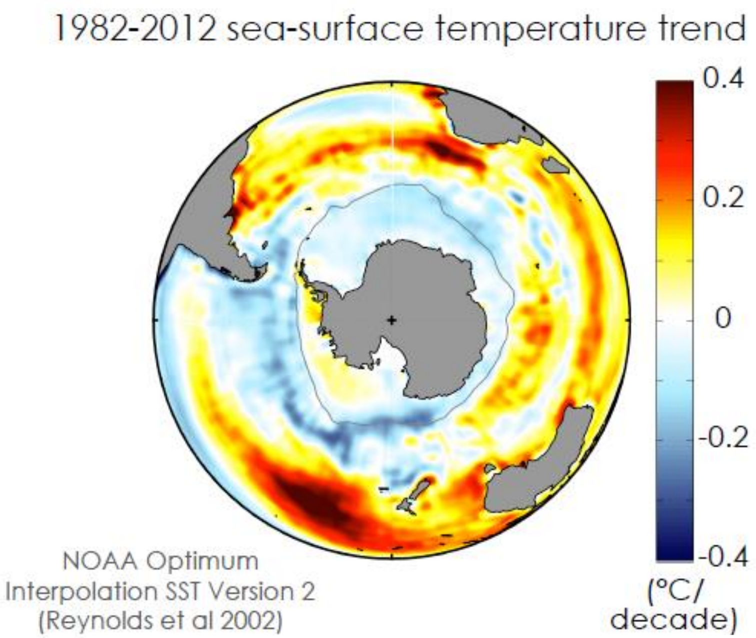

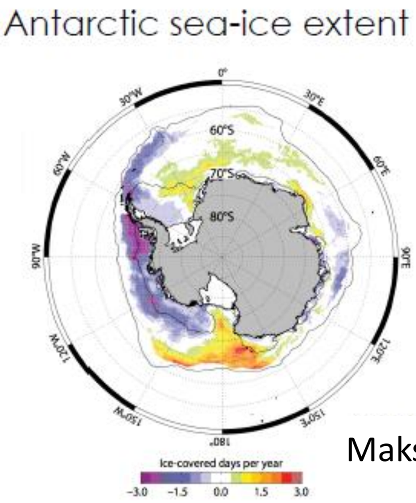

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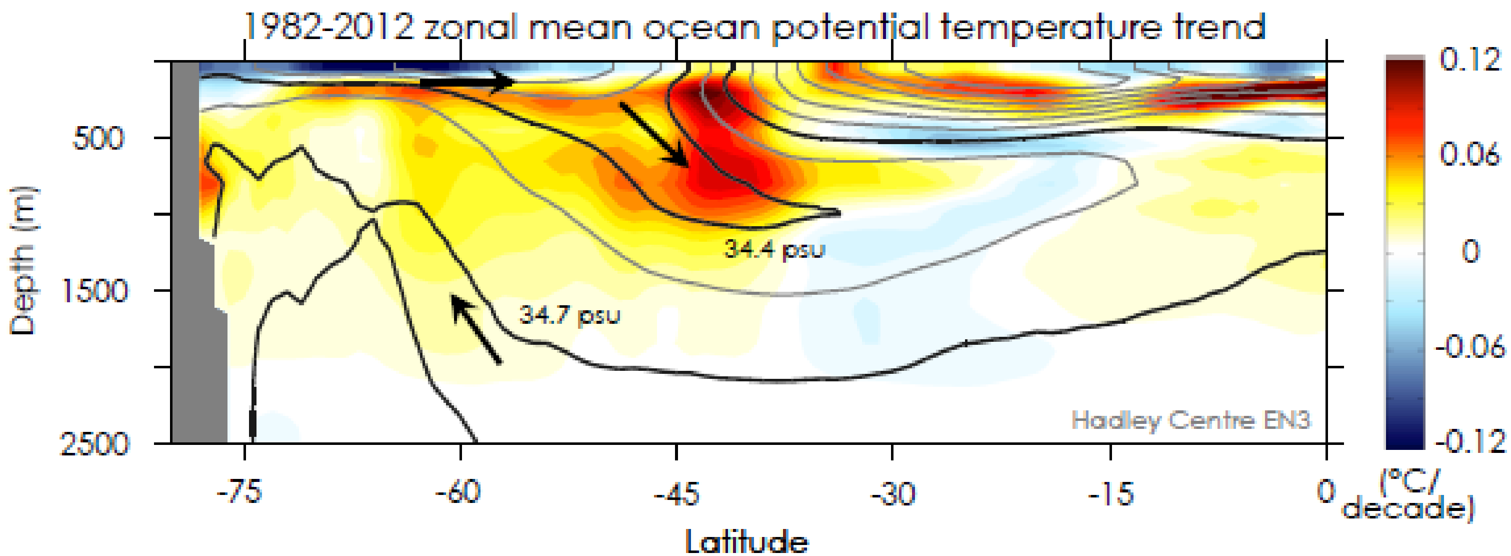
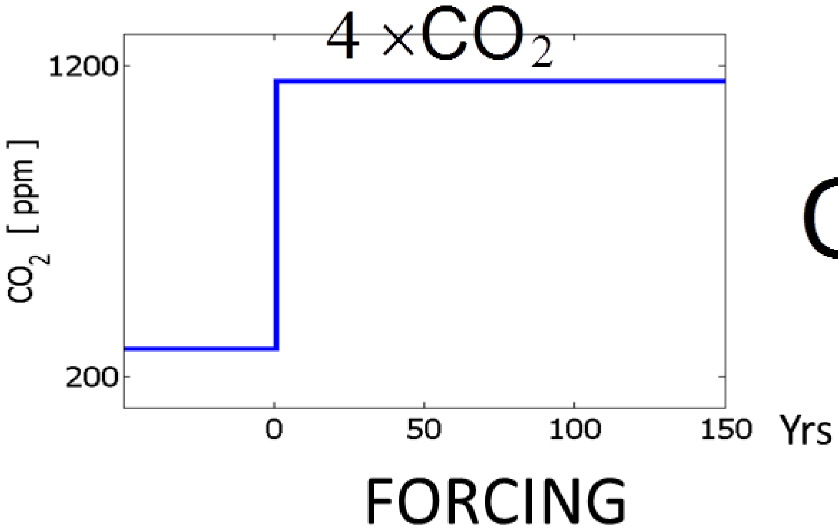
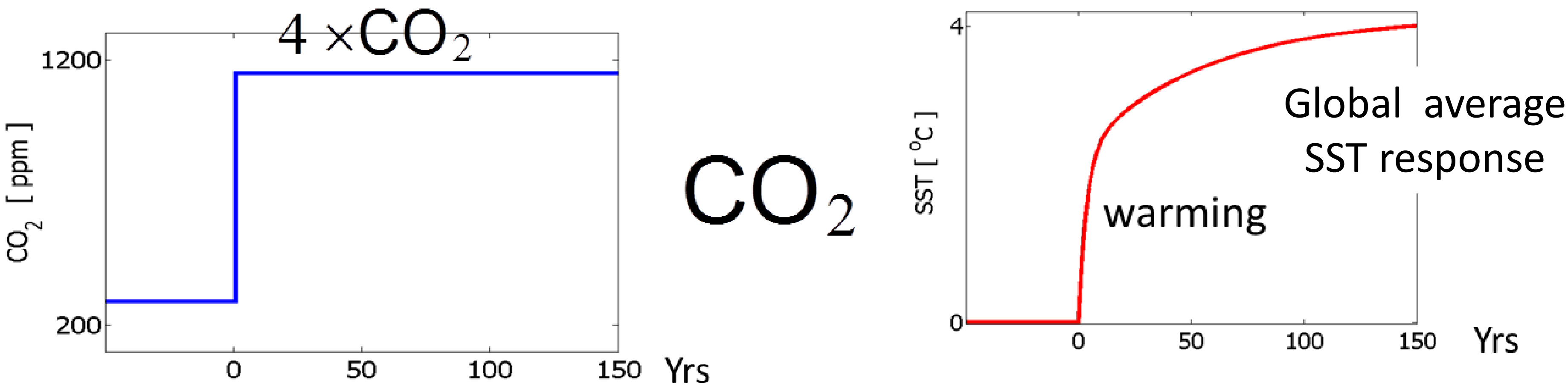


Climate Response Functions



CO_2

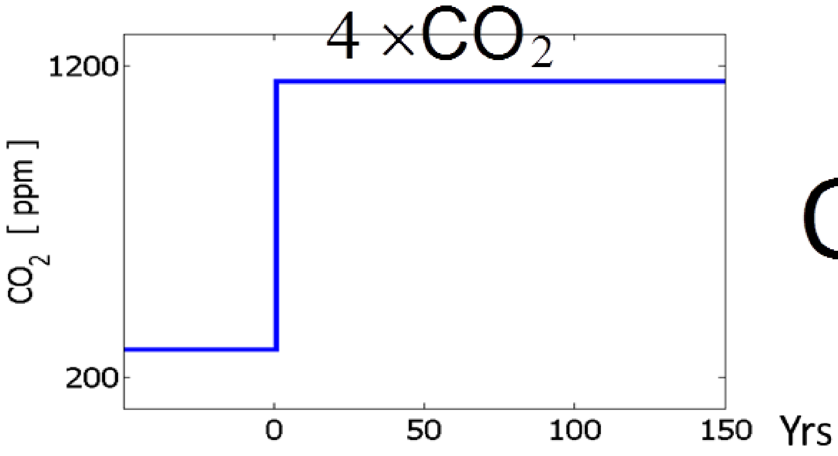
Climate Response Functions



FORCING

RESPONSE

Climate Response Functions



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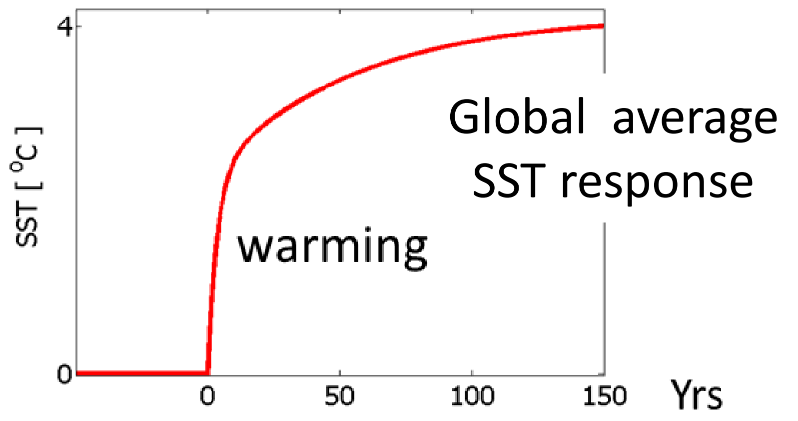

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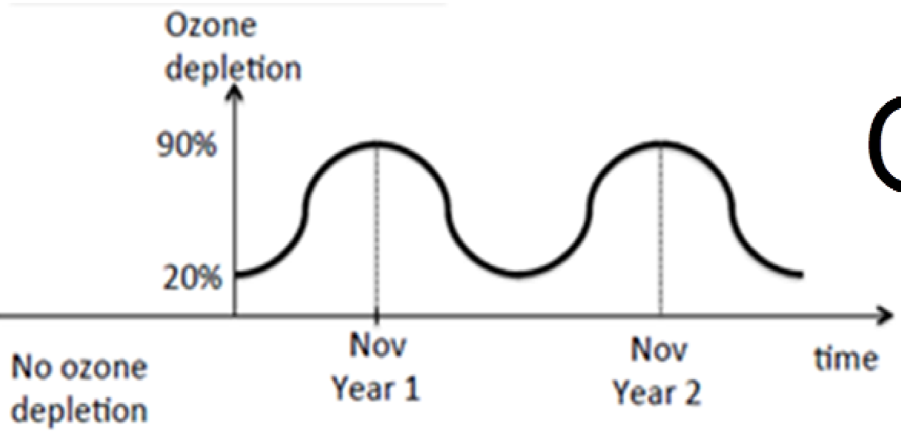
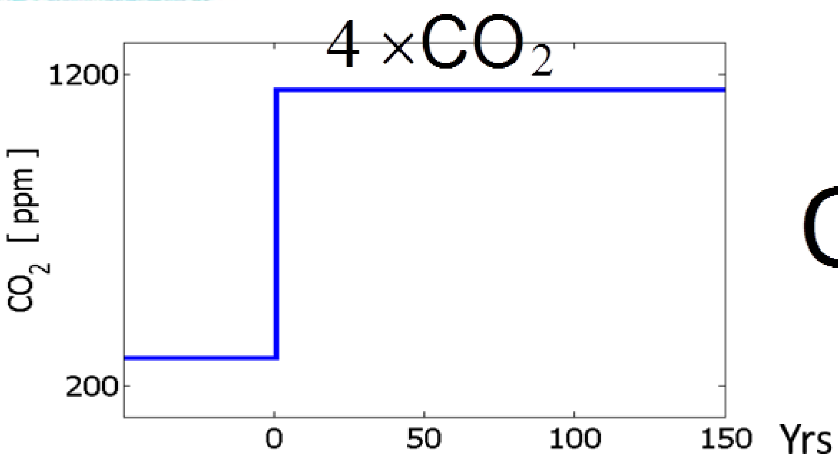


O_3

Climate Response Functions



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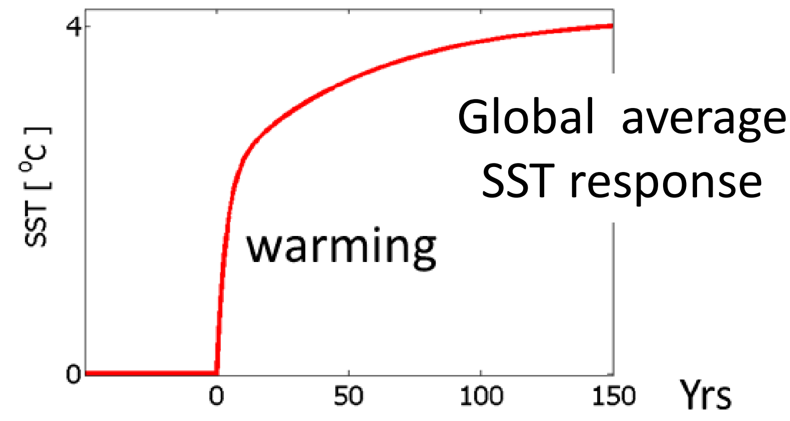

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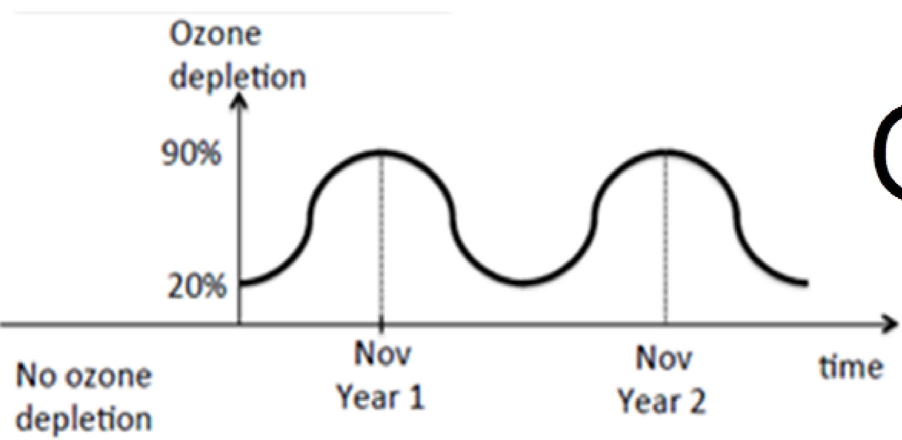

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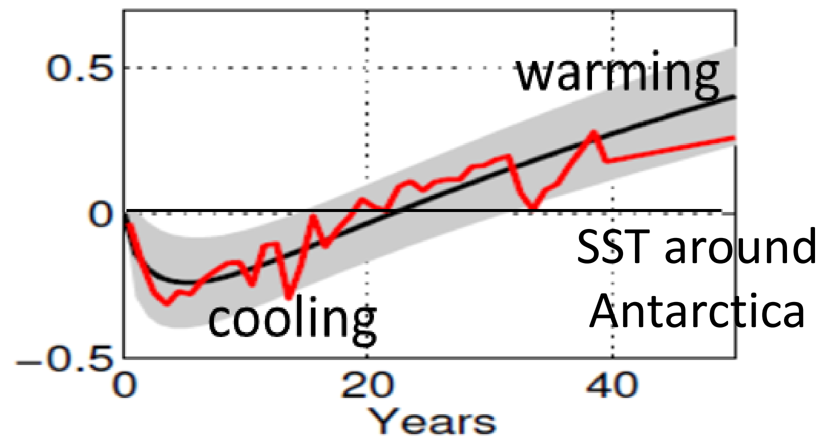
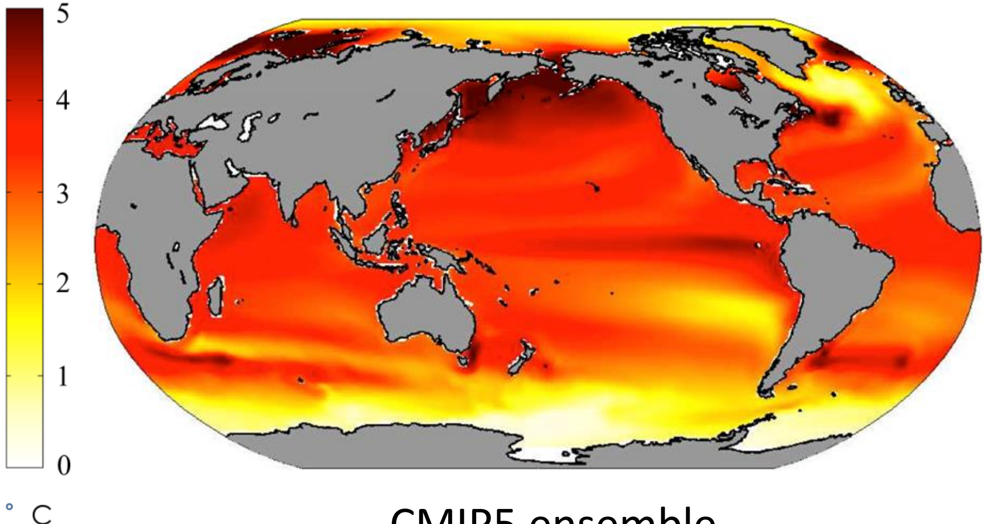


GHG Response Function

Coupled climate models,
Abrupt quadrupling of CO_2



CMIP5 ensemble

Planet warms, but not uniformly

Delayed SO warming

GHG Response Function

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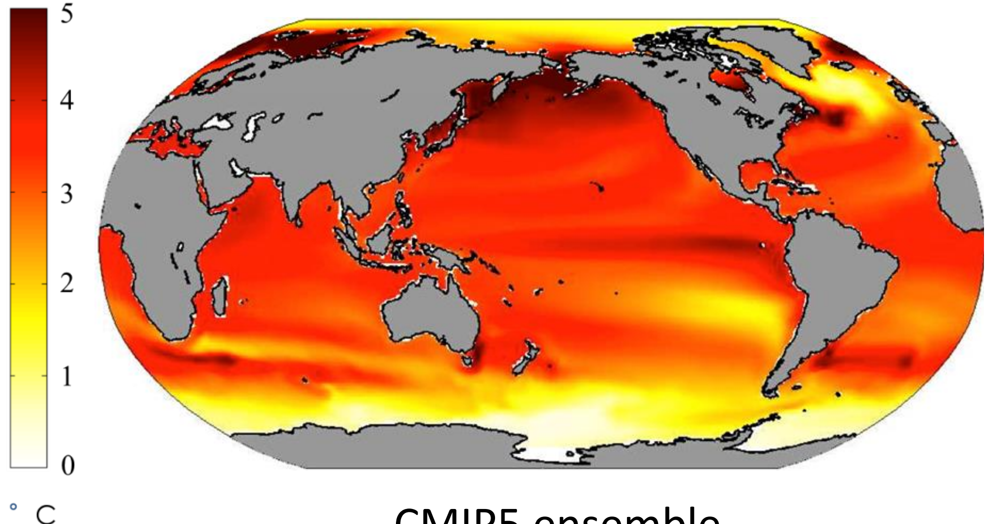

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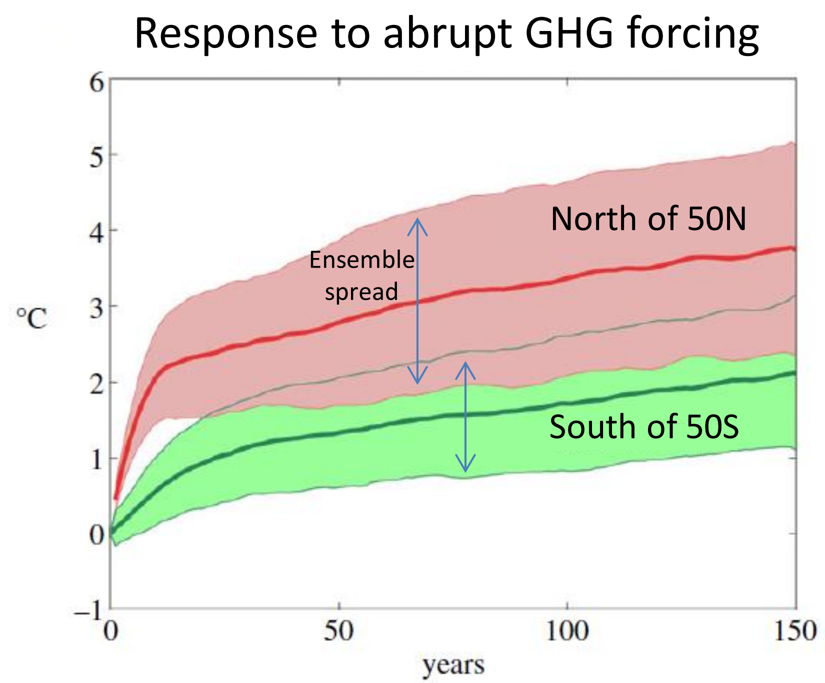

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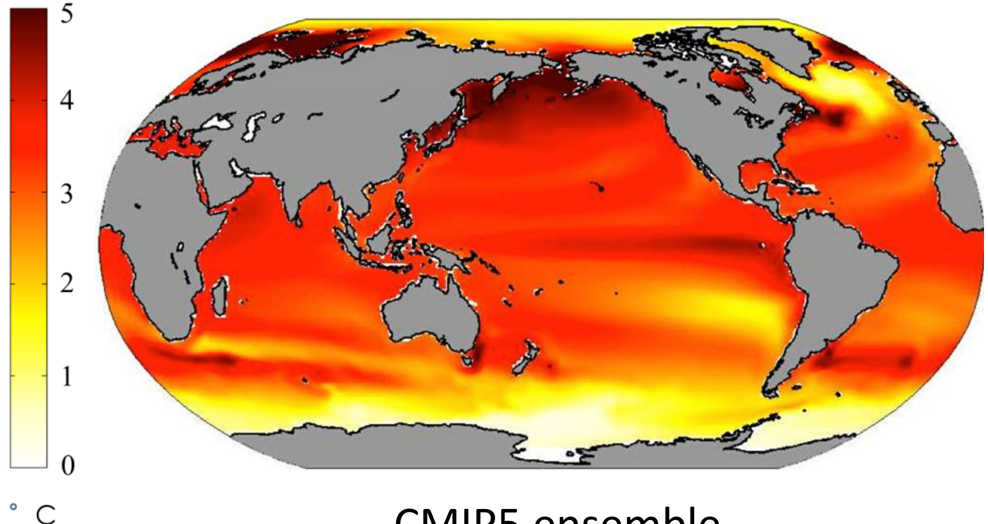

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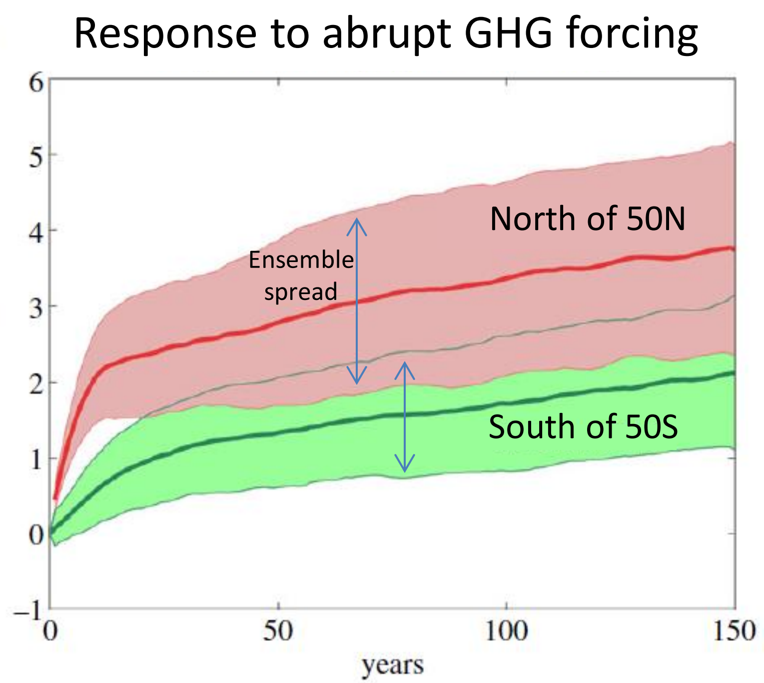

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Delayed SO warming

Previous studies have attribute delayed warming to
- anomalous freshwater fluxes
- local storage of heat in ocean
- changes in winds

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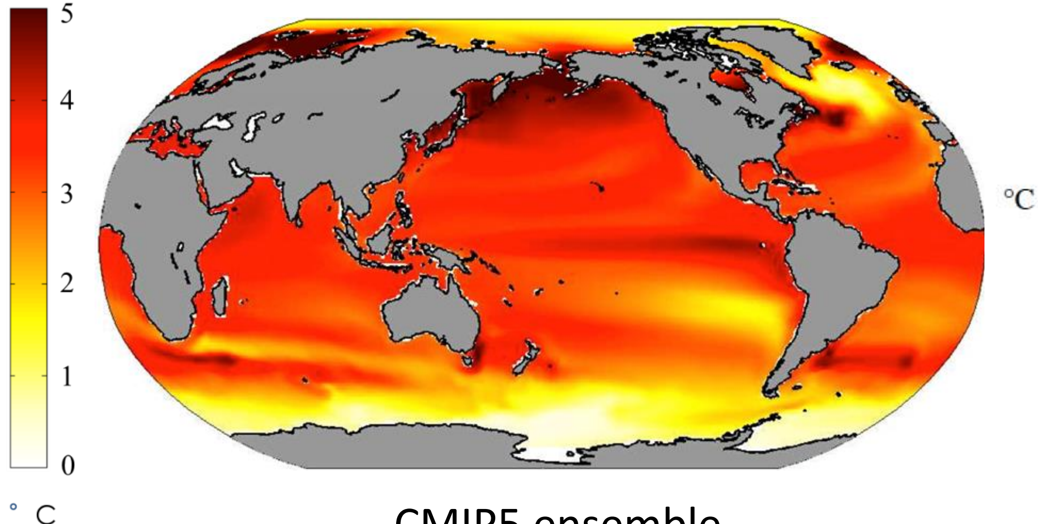

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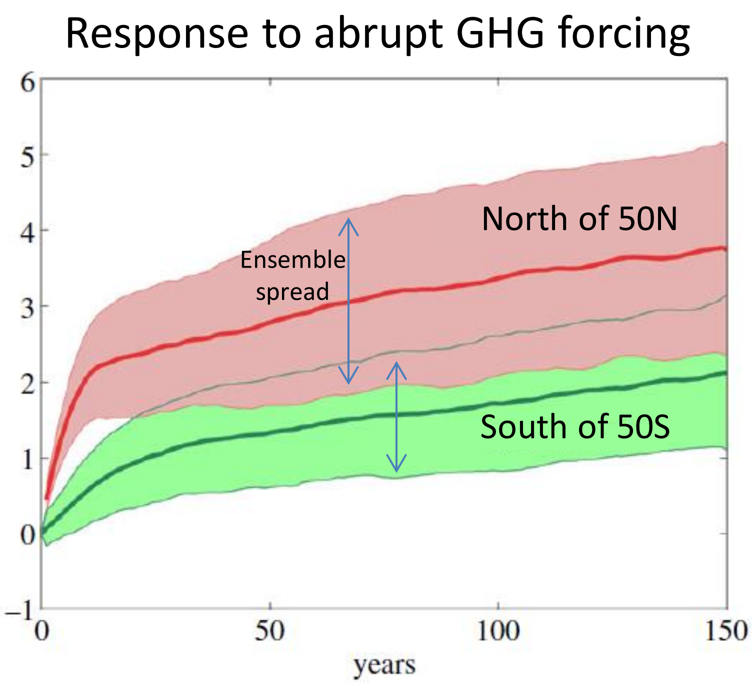

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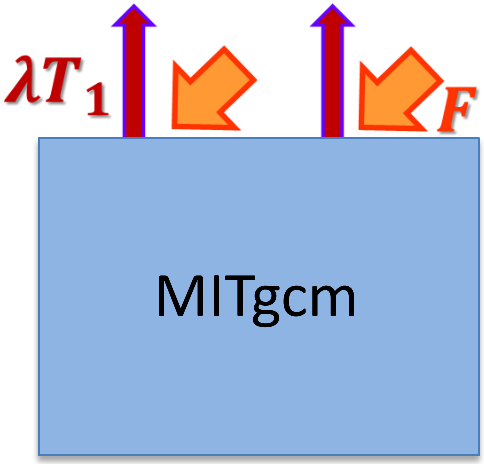
Offer a different explanation

Abrupt warming expt with an ocean model

Take an ocean model run under CORE-1 protocol, run out to equilibrium.

'Step' warming experiment:

- Abrupt, spatially uniform surface forcing of F = 4 W/m^2
- Spatially-invariant climate feedback of $\lambda = 1 \mathrm{W m^{-2} K^{-1}}$



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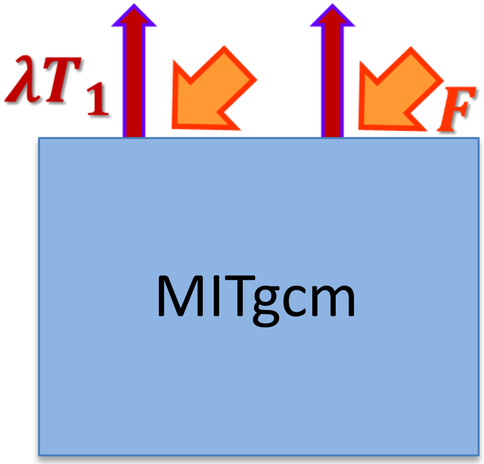

Note:
Only surface heat fluxes are perturbed
No change in winds or E-P

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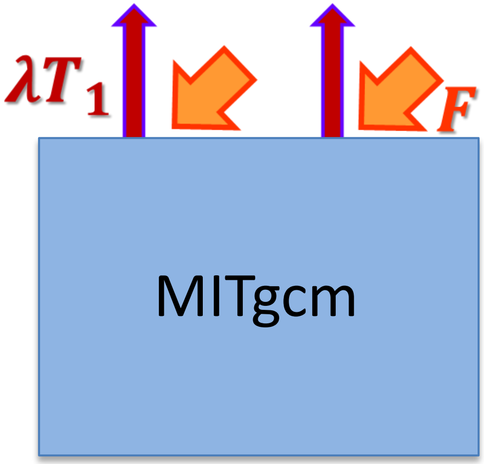

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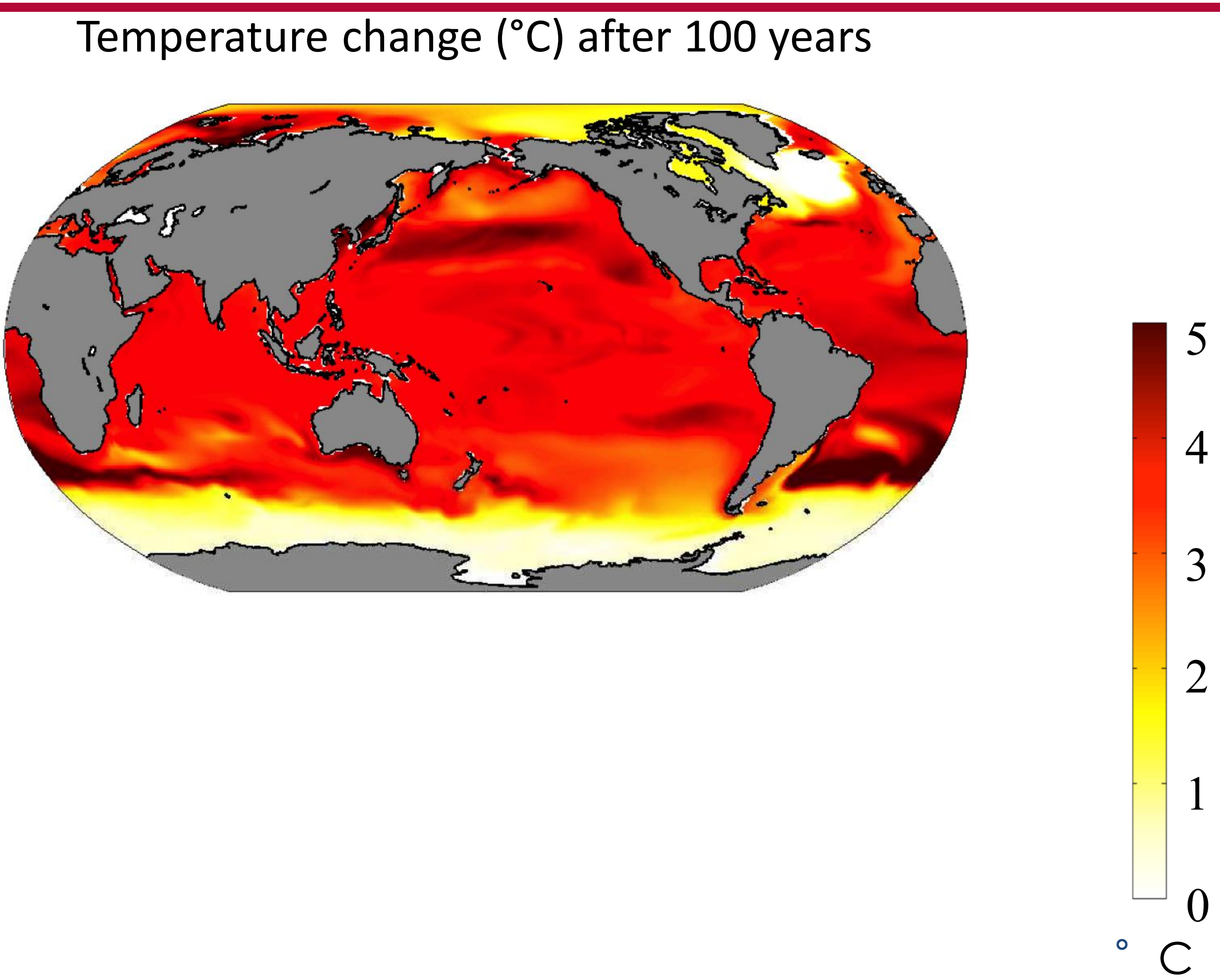
See Marshall et al, 2014: Climate Dynamics for more details

Spatial pattern of warming

Ocean-only
MITgcm



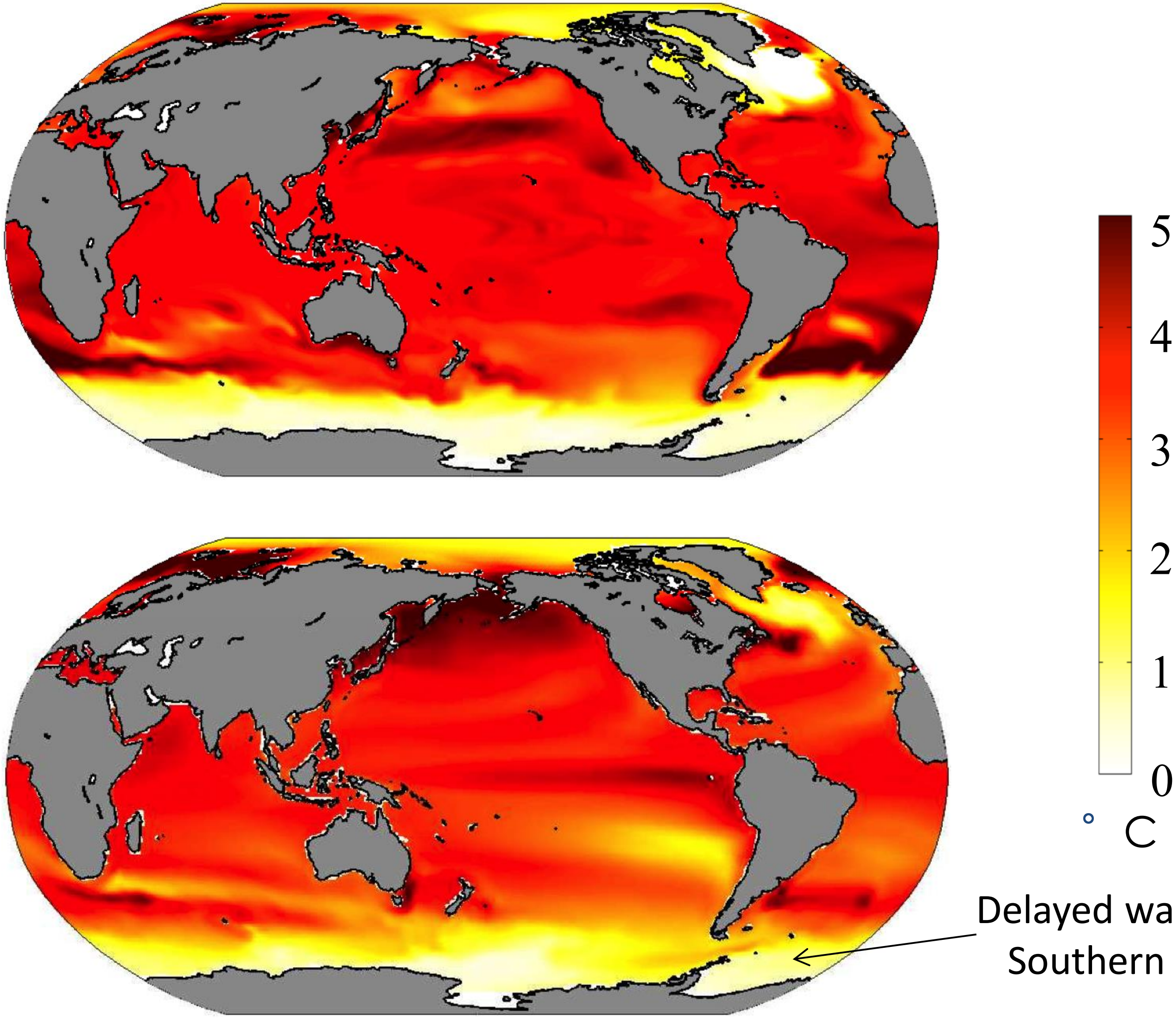
Spatial pattern of warming

Temperature change (°C) after 100 years

Ocean-only MITgcm

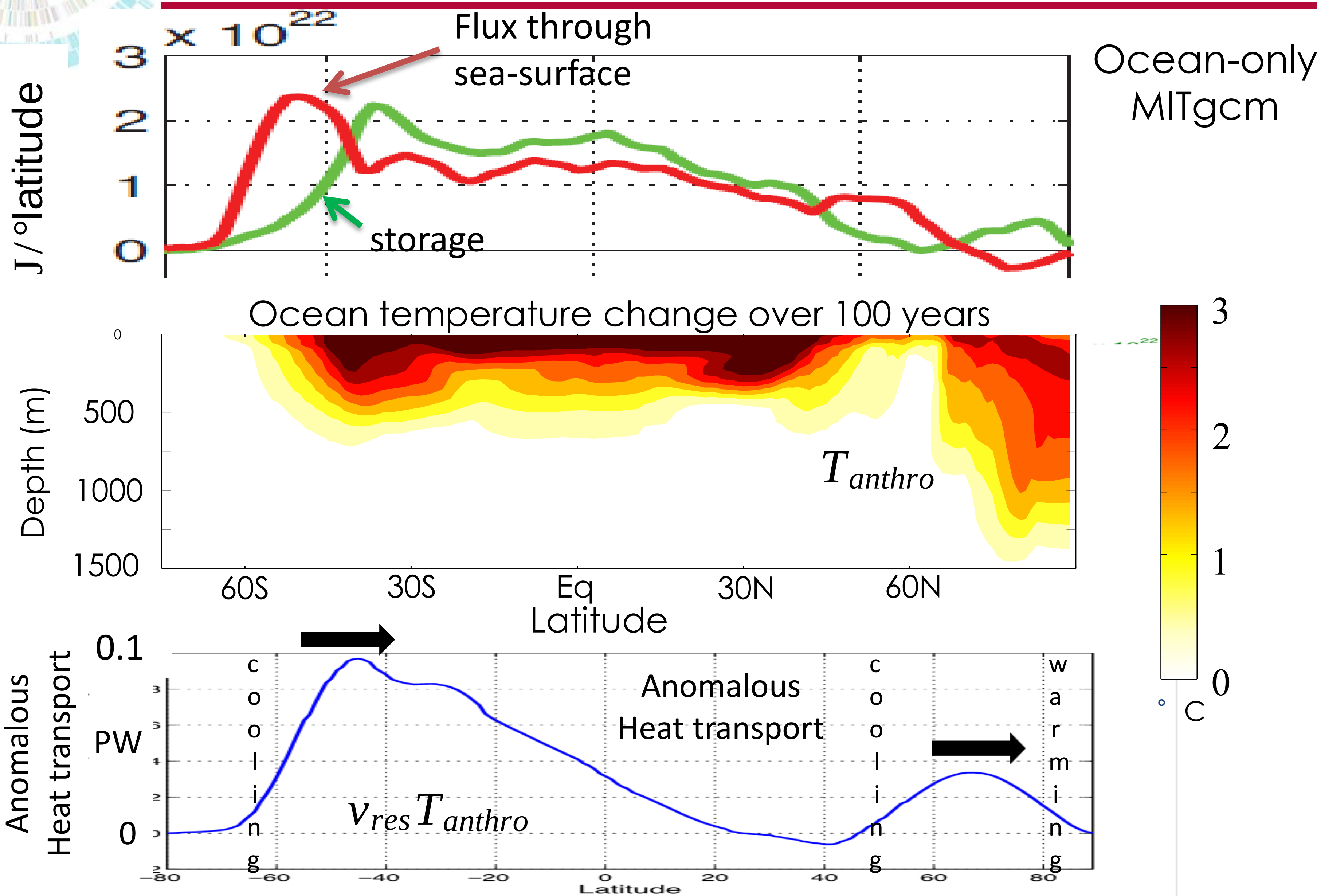
CMIP5 ensemble

(15 models, abrupt 4xCO_2)

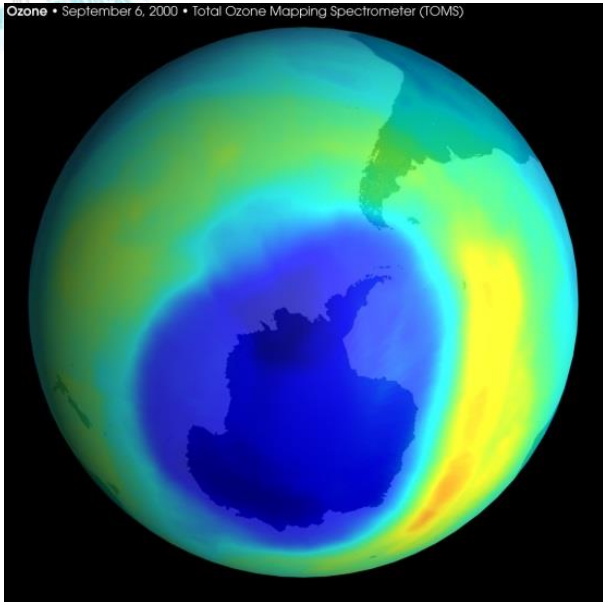


Delayed warming in Southern Ocean

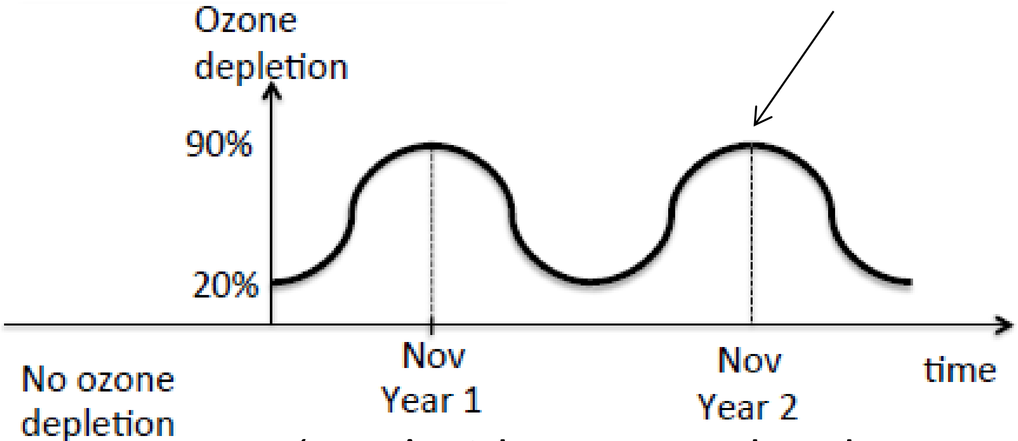
Energy accumulation, storage and transport



Ozone Hole Response Function



Peak depletion at Oct/Nov transition



'Step' with a seasonal cycle

Effect of ozone hole at the surface is mechanical – wind (SAM) change

Expect a seasonal, SAM-like response to ozone depletion

Maximum SAM response in DJF (summertime)

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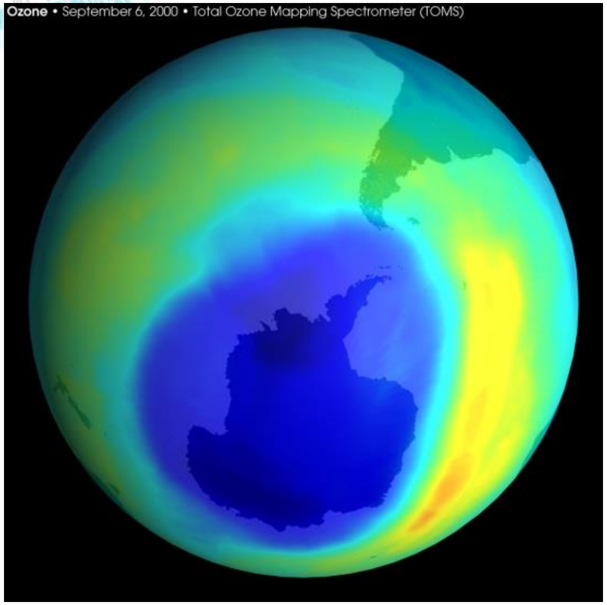

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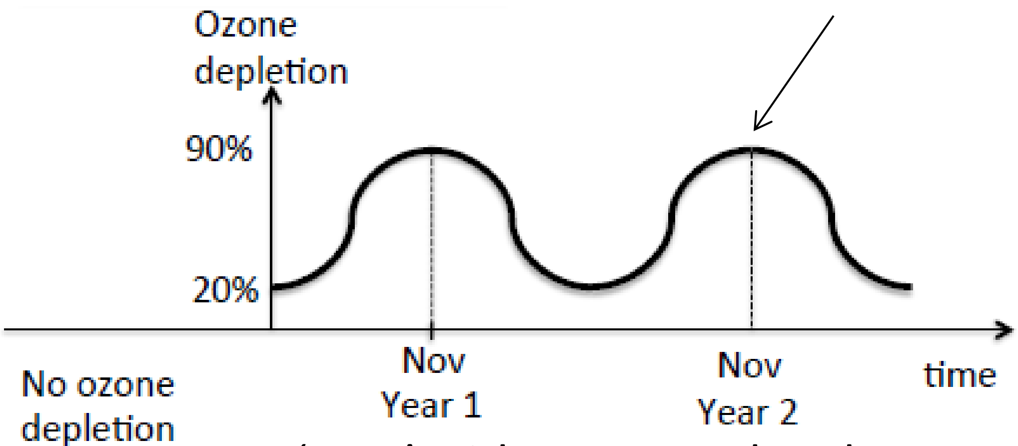

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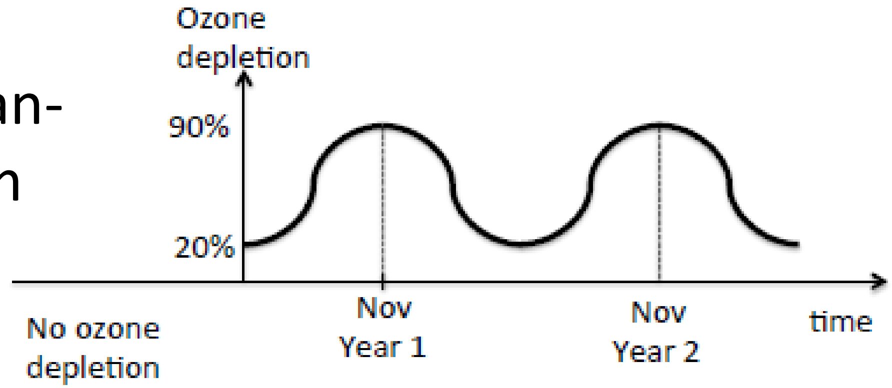
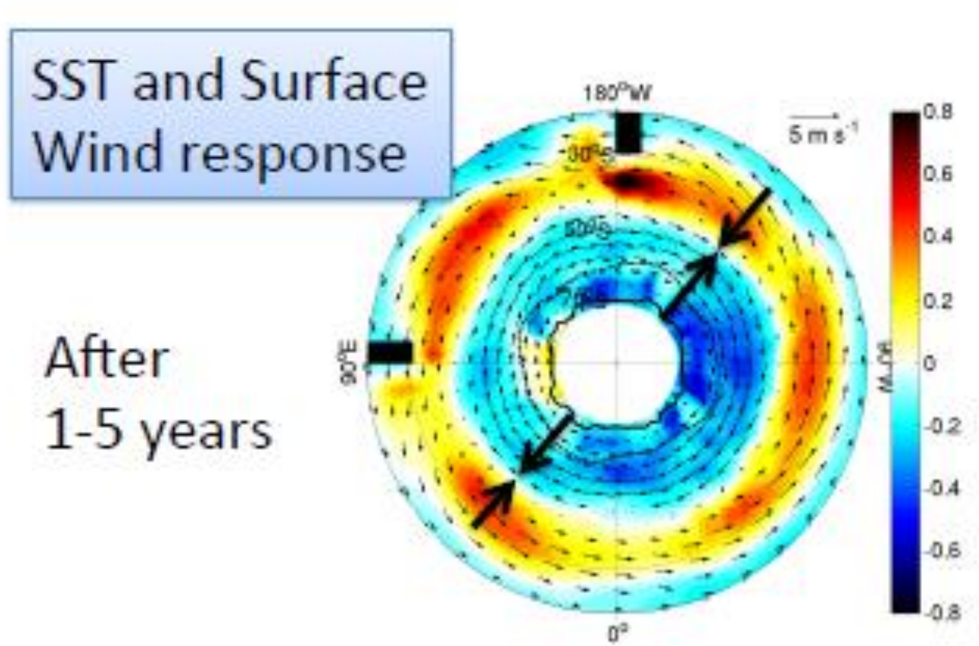
How will SST, sea-ice and interior ocean respond?

Idealized Coupled Model

Simplified coupled Atmosphere-Ocean-Sea-Ice model based on the MITgcm





David Ferreira et al, 2015
J of Climate

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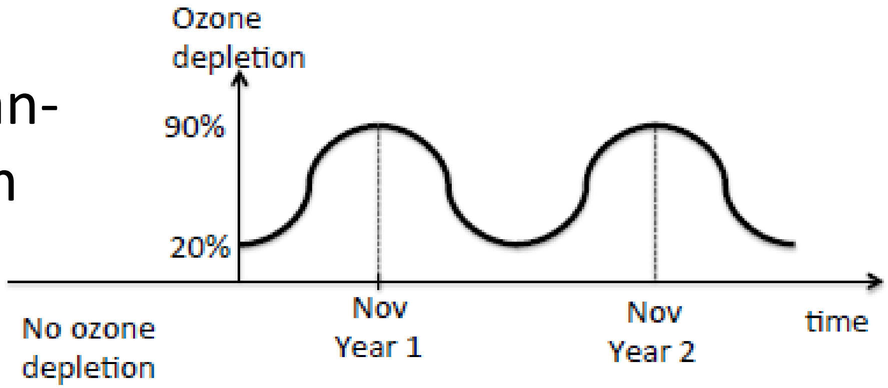
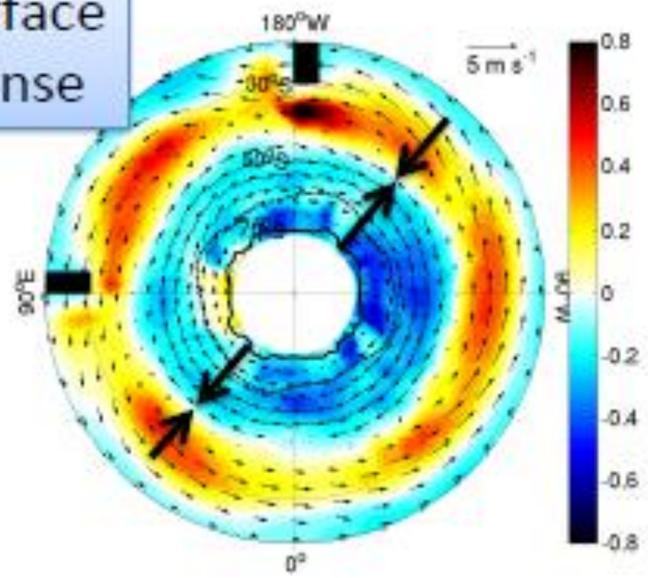
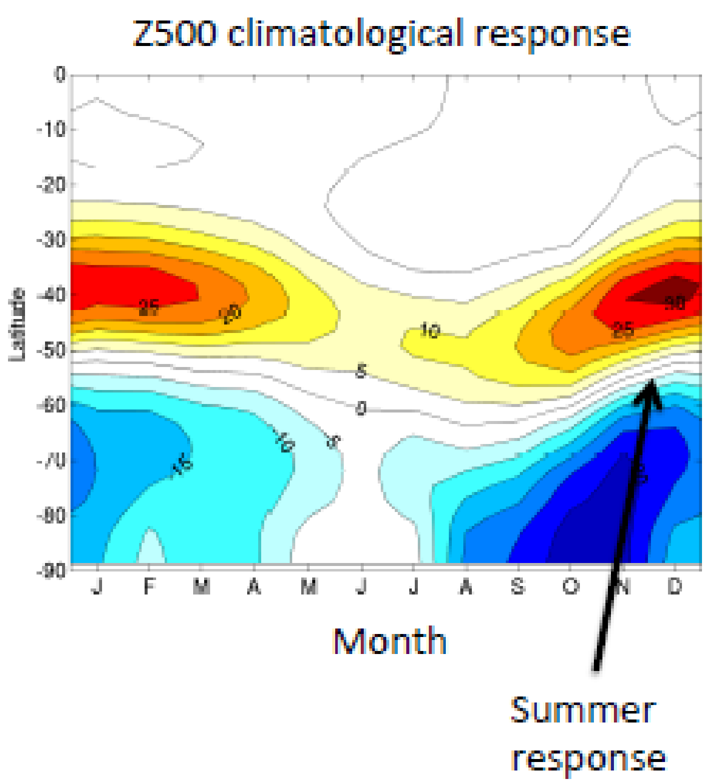


SST and Surface Wind response

After 1-5 years





David Ferreira et al, 2015
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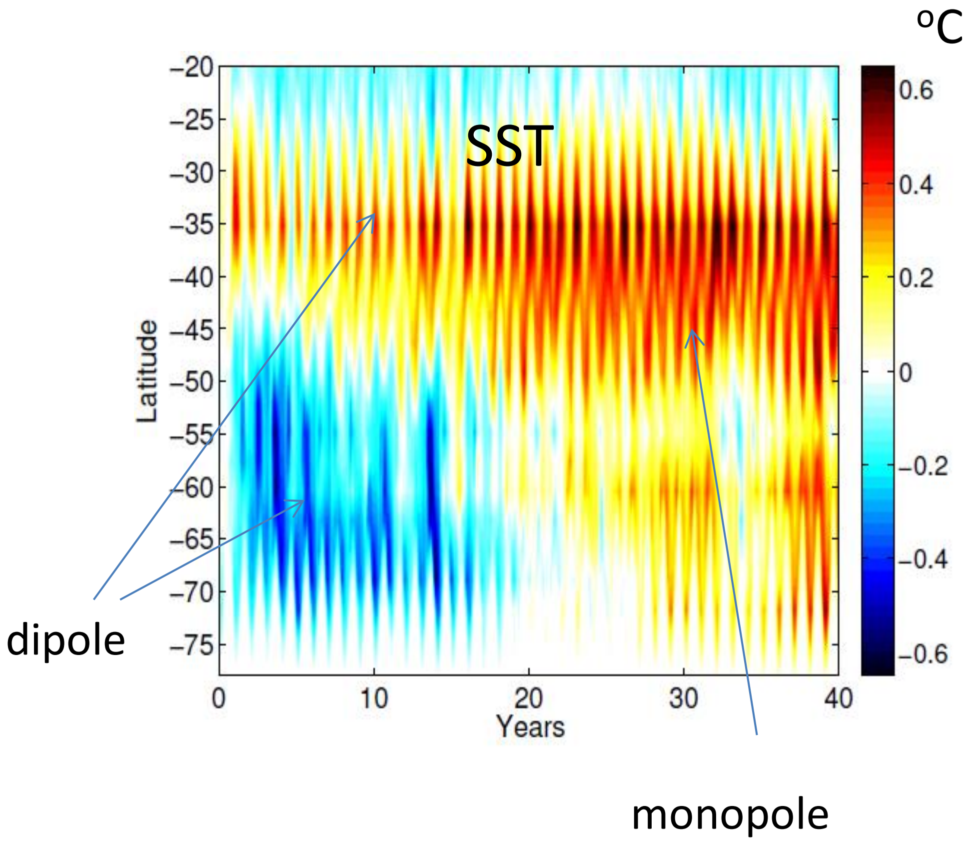
Response to SAM: two-timescale problem



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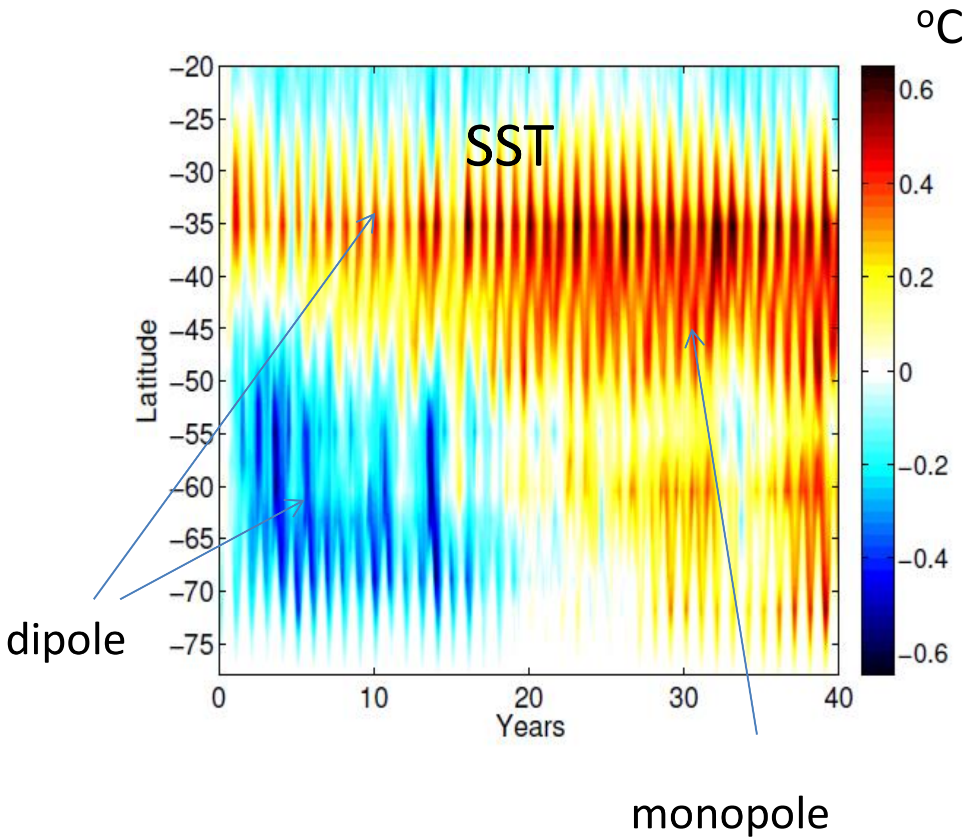

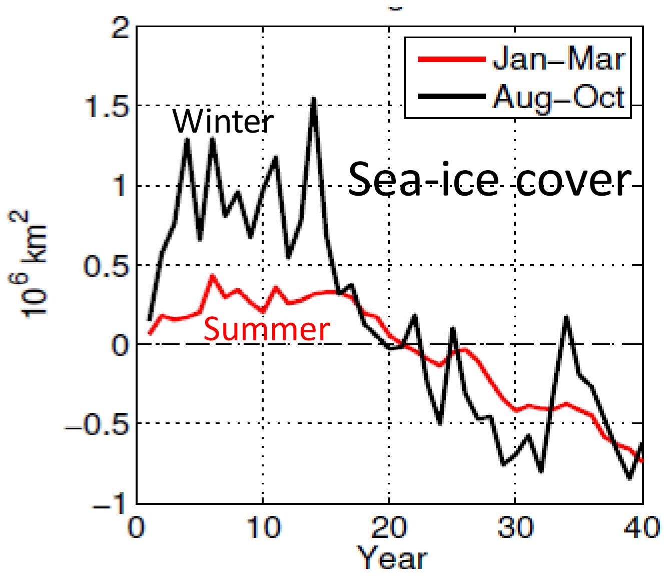

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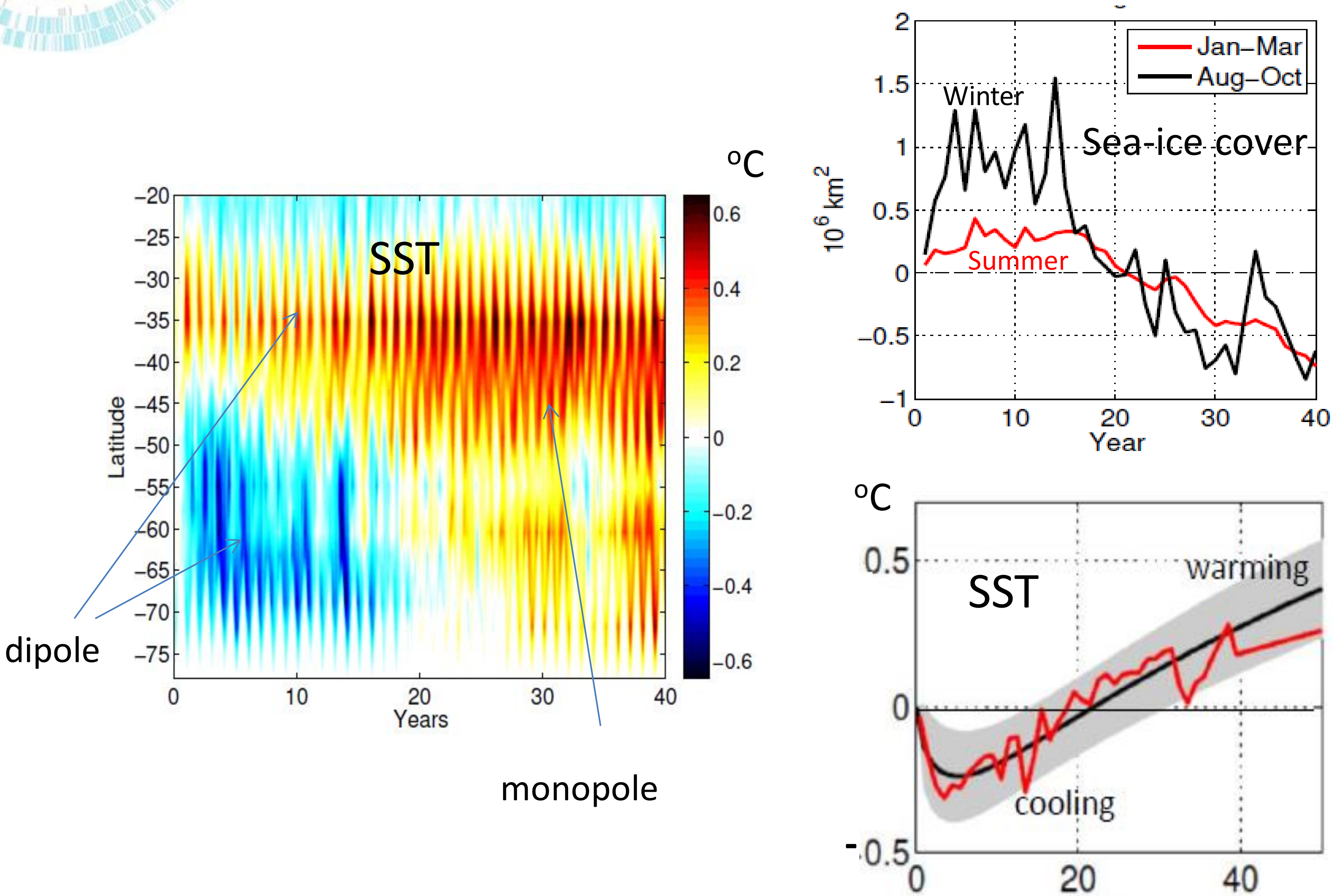
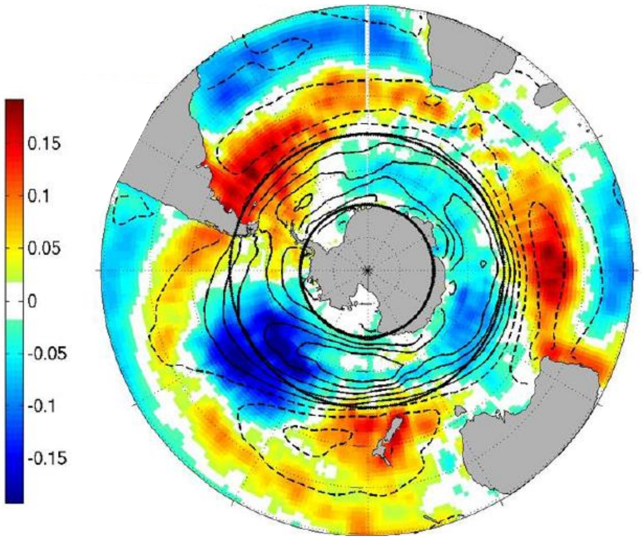


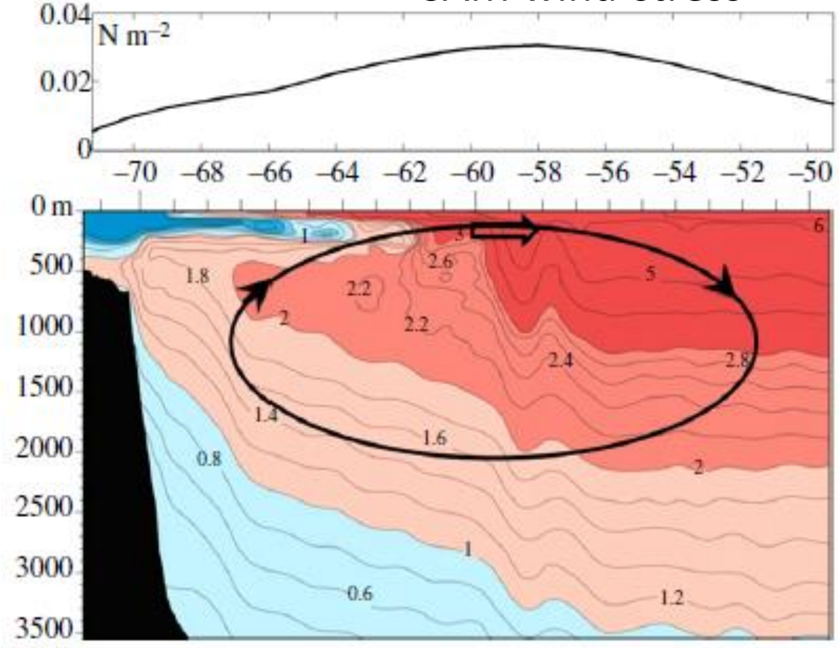
Averaged between 50 & 70S

Mechanisms

SST regressed on to SAM, zero lag



SAM wind-stress



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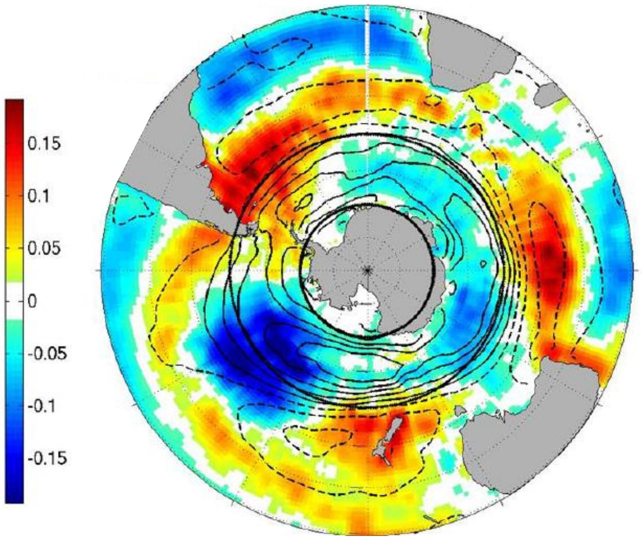

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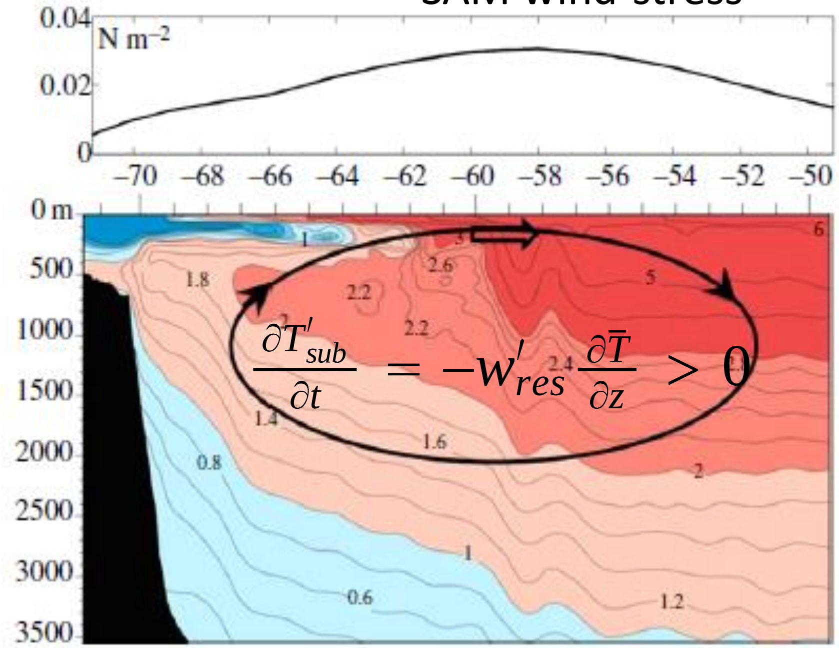

$$\frac{\partial T'}{\partial t} = F' - \lambda T' + \frac{w_{ent}}{h}(T'_{sub} - T')$$

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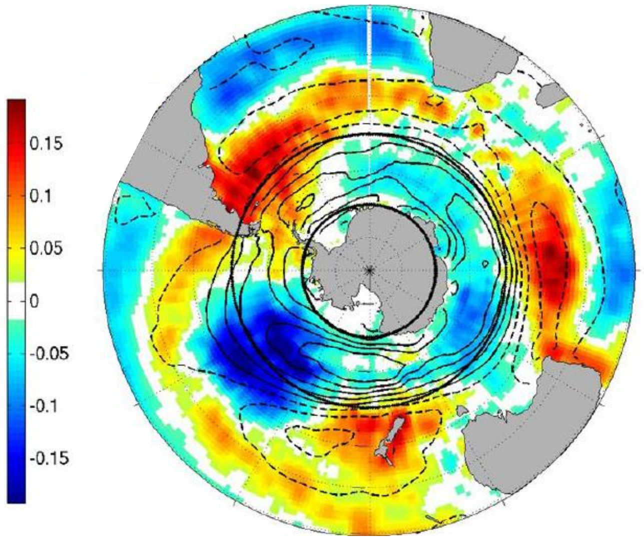

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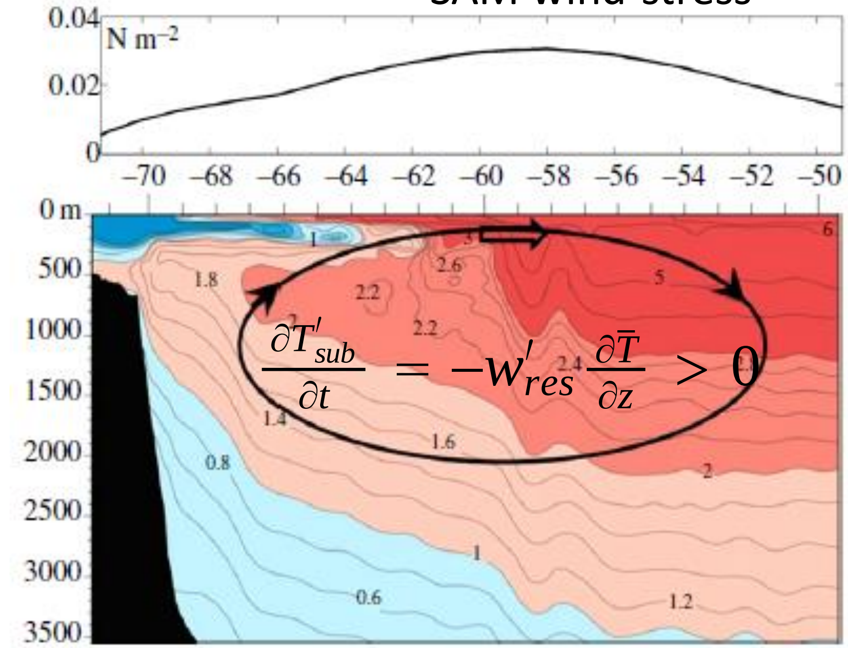

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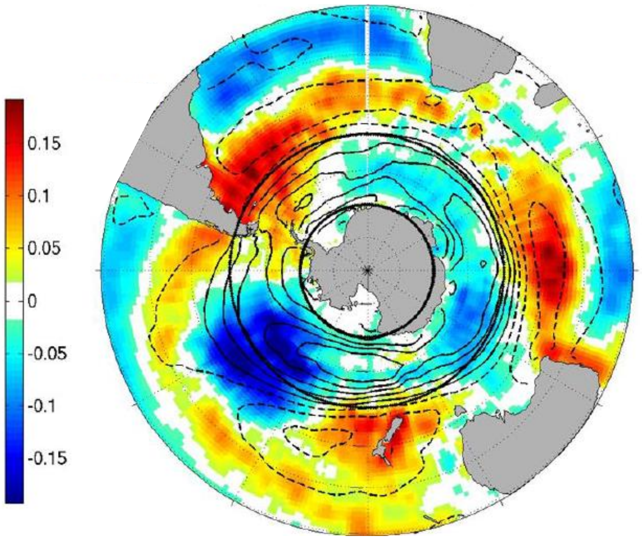
Short time-scale – passive ocean, cooling around Antarctica

Longer time-scale – active ocean, surface ultimately warms

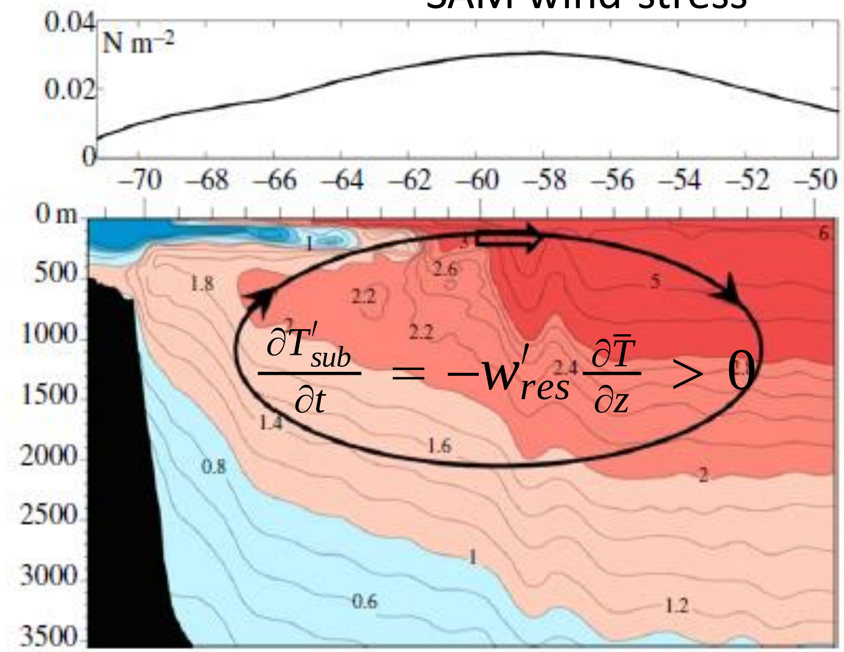
Mechanisms

SST regressed on to SAM, zero lag



See Sigmond and Fyfe, 2010,
Bitz and Polvani, 2012,
Smith et al (2012)
Ferreira et al, 2015
for discussions

SAM wind-stress



$$\frac{\partial T'}{\partial t} = F' - \lambda T' + \frac{w_{ent}}{h}(T'_{sub} - T')$$

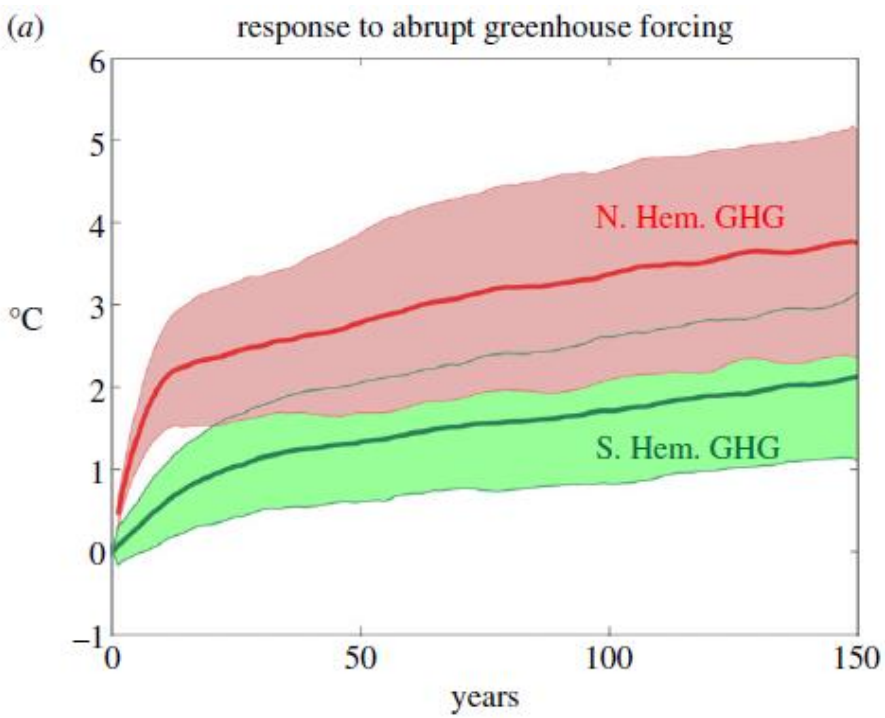
$$\frac{\partial T'_{sub}}{\partial t} = -w'_{res}\frac{\partial \bar{T}}{\partial z} - \lambda_{sub} T'_{sub}$$

Short time-scale – passive ocean, cooling around Antarctica

Longer time-scale – active ocean, surface ultimately warms

GHG and Ozone-Hole Response Functions

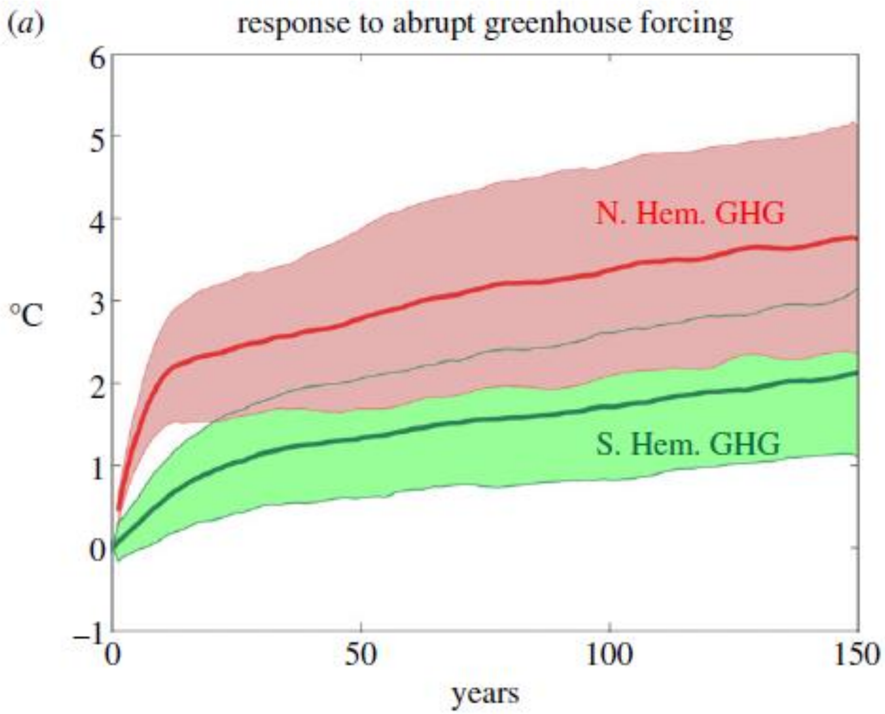
CO_2

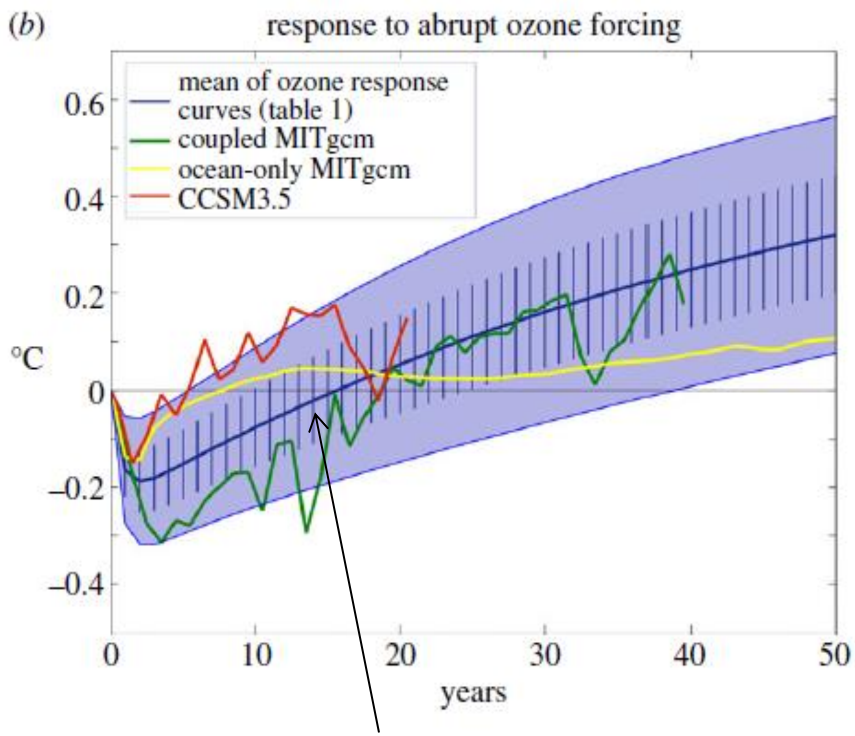


Marshall et al, 2014:
Phil Trans A

GHG and Ozone-Hole Response Functions

CO_2 O_3

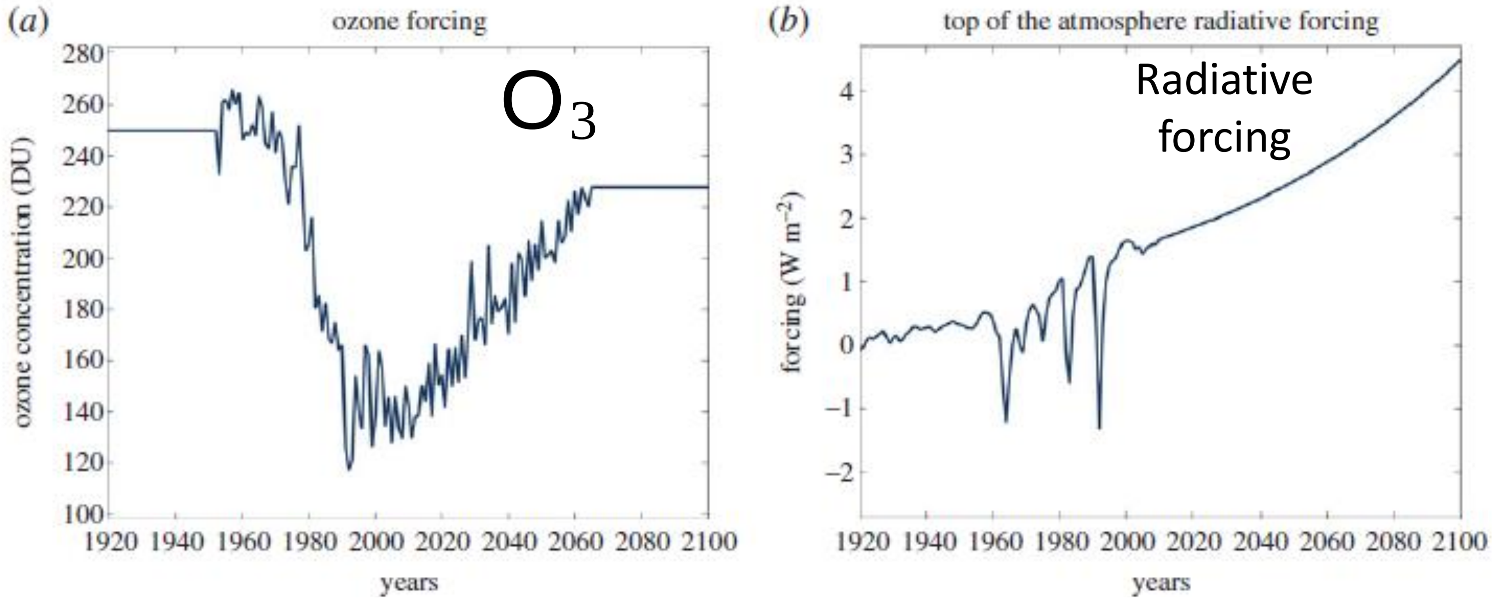




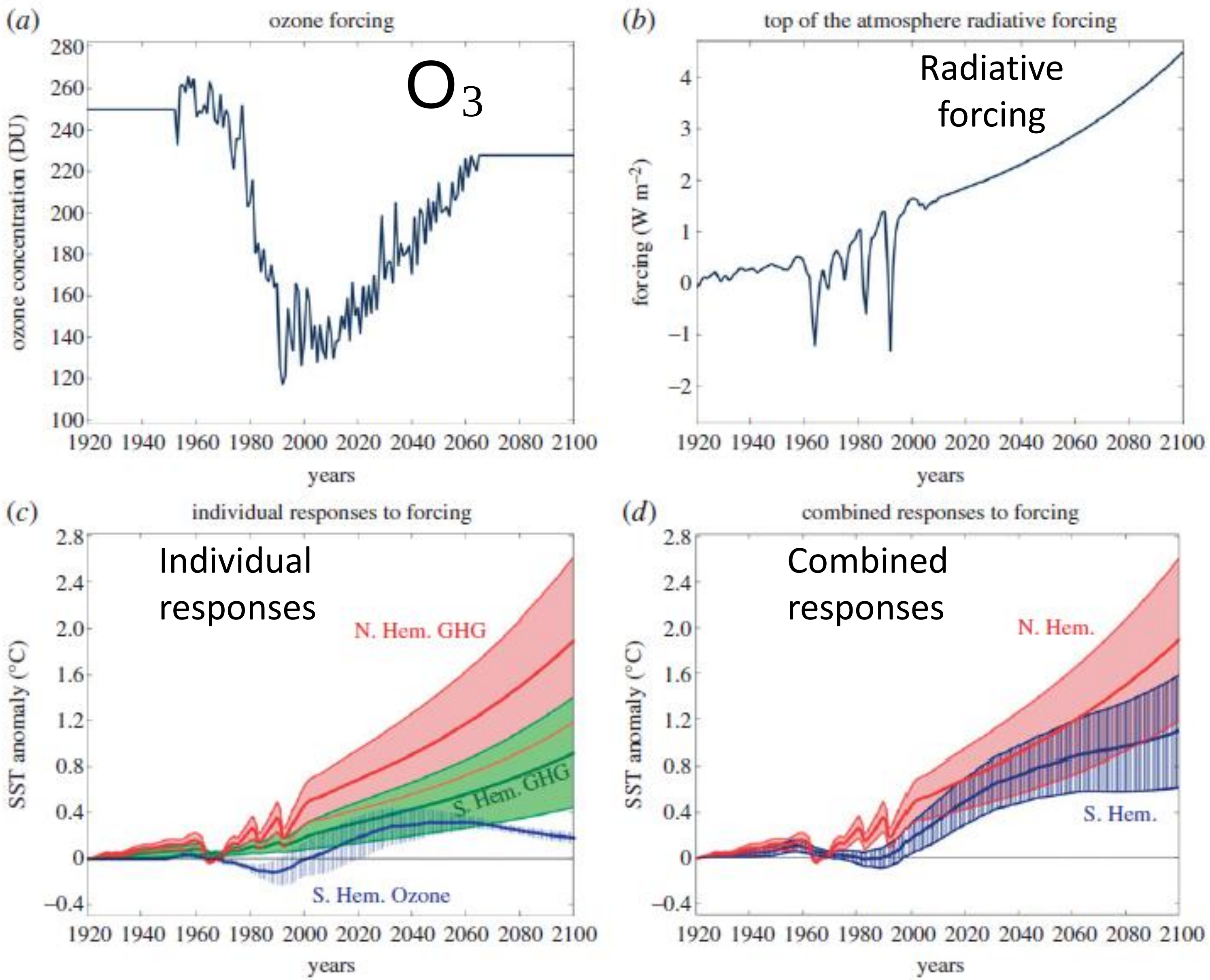
Marshall et al, 2014: Phil Trans A

Time of 'cross-over' from cooling to warming varies widely across models

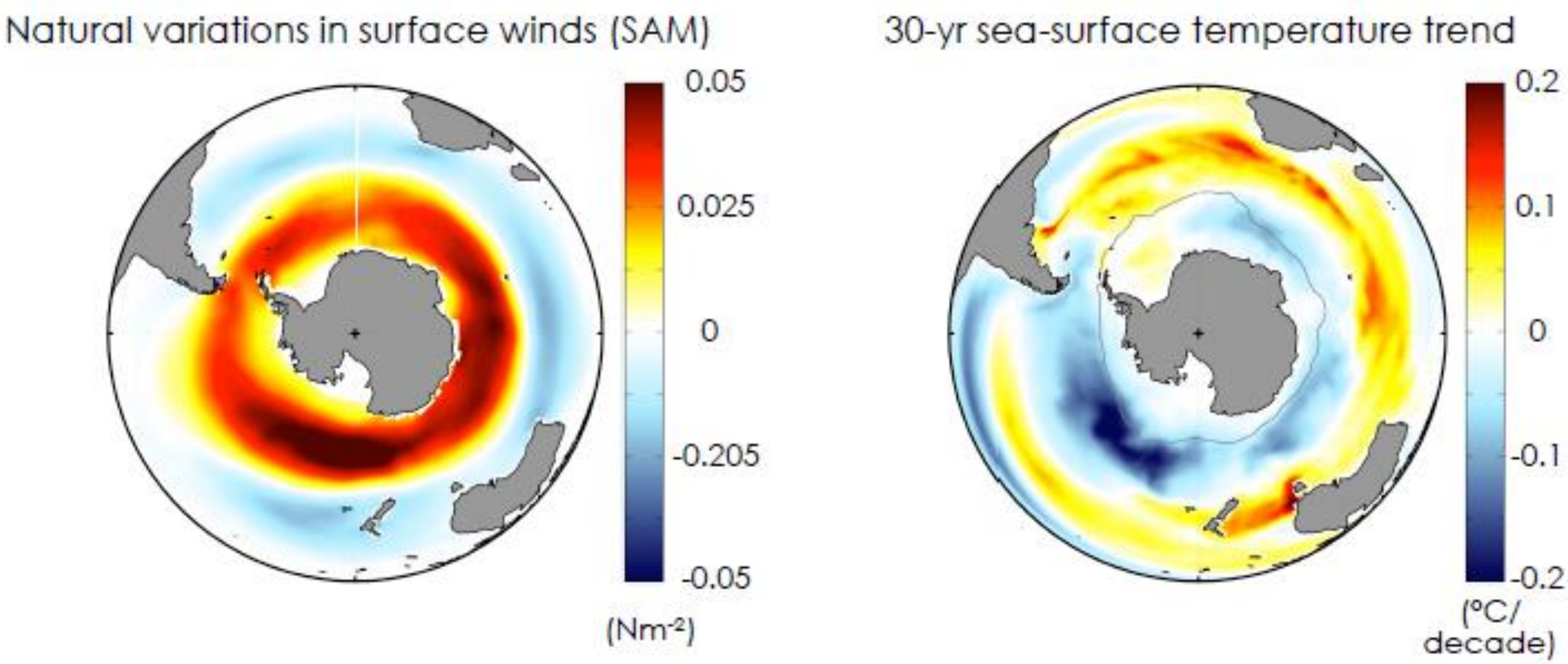
Convolutions with GHG and Ozone Hole forcing



Convolutions with GHG and Ozone Hole forcing



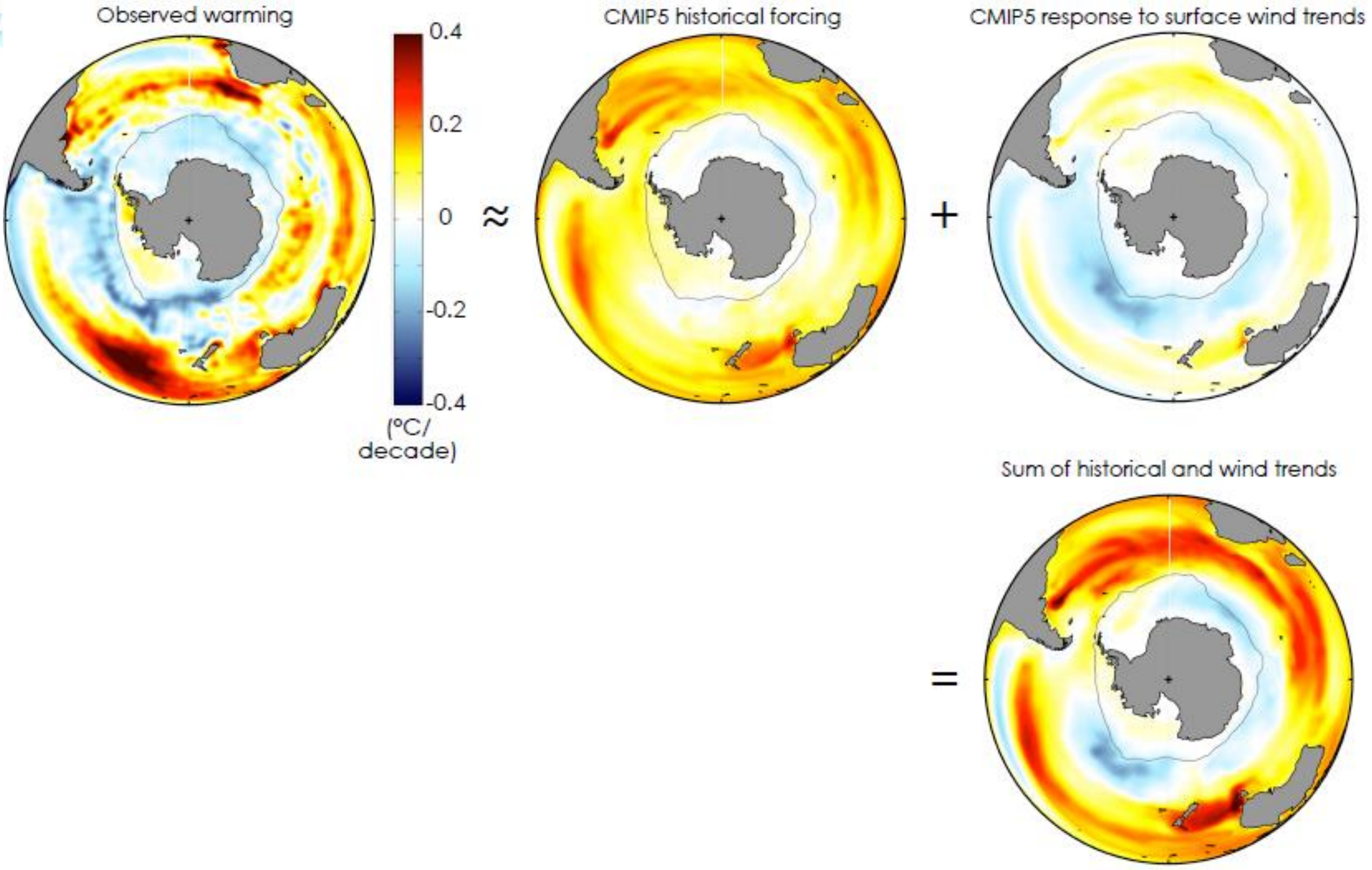
Natural variability (in CMIP5 controls)



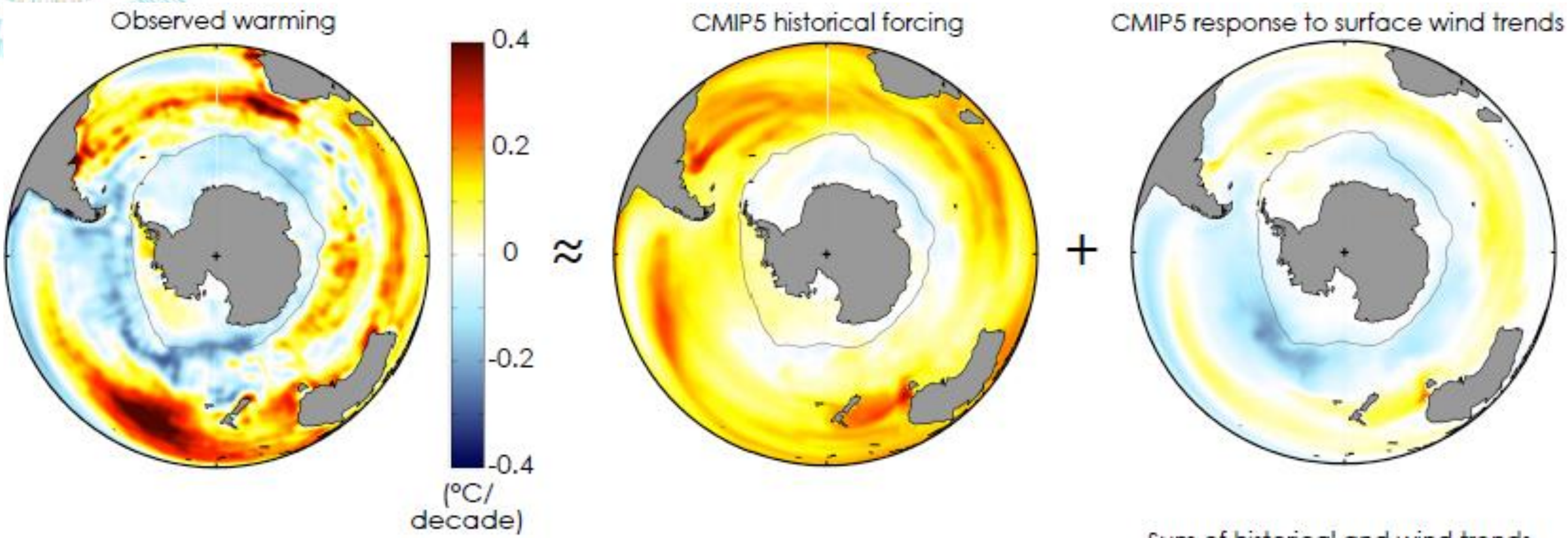
Composite of 30 year SST trends congruent with large 30 year trends in surface winds (internal variability in SAM), normalized to observed wind trend over last 30 years.

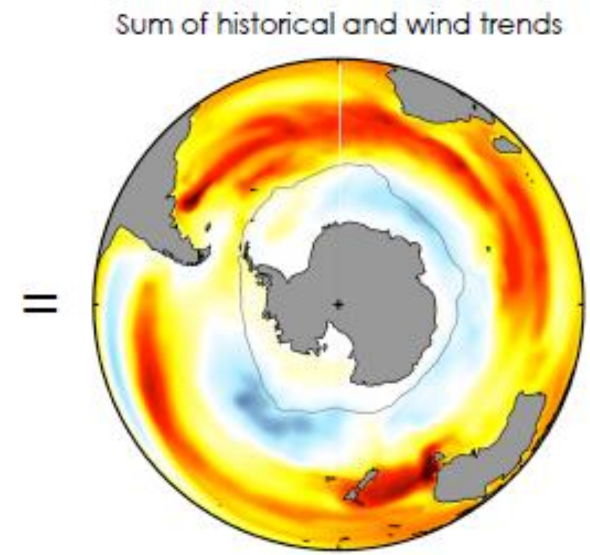
Kostov et al, in prep

Summary


Observed warming
0.4
0.2
0
-0.2
-0.4
(°C/ decade)
≈
CMIP5 historical forcing
+
CMIP5 response to surface wind trends
=
Sum of historical and wind trends

Summary





Several factors likely set Southern Ocean warming/cooling patterns:

- Climatological northward transport damps warming south of the ACC
- Subduction within mode water formation regions enhances warming on the northern flank of the ACC
- Wind-driven changes, due to ozone depletion or natural variability

Linking Glacial-Interglacial cycles to multiple equilibria of climate

David Ferreira and John Marshall
MIT, Cambridge, USA (e-mail: dfer@ocean.mit.edu)

Previous work:
In Ferreira et al. (2011), we show the existence of multiple equilibrium states of the climate system in a complex coupled ocean-atmosphere-sea ice General Circulation Model. In two idealized geometries, two different stable states are found for exactly the same set of parameters and external forcings: a cold state in which a polar sea ice cap extends into the midlatitudes and a warm state, which is ice free (a third, completely sea ice covered, "snowball" state is also possible).

RidgeWorld

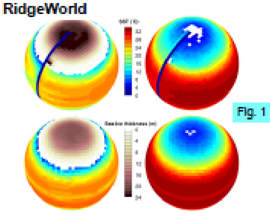


Fig. 1

Aquaplanet

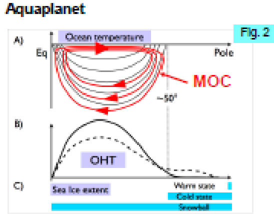


Fig. 2

Mechanism:
The multiple equilibria owe their existence to the presence of meridional structure in ocean heat transport (OHT): namely, a large heat transport out of the tropics and a relatively weak high-latitude transport. The associated large midlatitude convergence of OHT leads to a preferred latitude at which the sea ice edge can rest (see also Rose and Marshall, 2009).

How is carbon stored in the "Glacial" ocean?

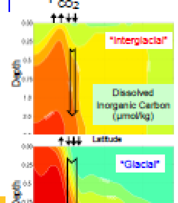
The dynamical model is overlaid with an ocean carbon-cycle model coupled to a well-mixed CO_2 atmospheric box. The inventory of carbon, alkalinity, and phosphate is identical in the two solutions. Note that the atmospheric CO_2 *is not radiatively active.*
The change ("Glacial" minus "Interglacial") in ocean carbon can be split into three reservoirs:

$$\Delta C_{tot} = \Delta C_{sat} + \Delta C_{bio} + \Delta C_{dis}$$

Saturation pump: -83 µmol/kg

Biological pump: -23 µmol/kg

Air-sea desequilibrium pump: +115 µmol/kg



Ocean carbon storage in the "Glacial" state is due to air-sea desequilibrium. Increased sea-ice cover reduces the ventilation of upwelled deep waters: DIC accumulates in the deep ocean (a mechanism

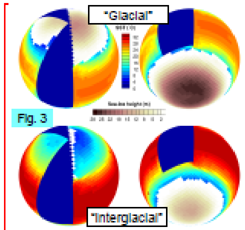


Fig. 3

This study: Multiple equilibrium states with complex geometry
We report that multiple states of the climate system can exist in a geometry with 1) a North-South asymmetry (a blocked northern ocean and a zonally re-entrant southern ocean) and 2) a zonal asymmetry (45° wide continents separating a large and a small basin).

The climate change between the two states is of planetary scale:
•Global SST and SAT decrease by 6.7° C and 13.5° C, respectively,
•the SH sea ice expands by 20° of latitude and the NH sea ice cap grows to ~55° N,
•the atmospheric CO_2 level drops by 118 ppm (from 268 to 150 ppm) in the colder climate (see bottom left box).

The Earth-like continental distribution allows for a direct comparison with paleo observations. In fact, the two states can be thought of as analogs of Interglacial and Glacial (Last Glacial Maximum, LGM) climates.

In the Small Atlantic-like basin, changes from "Interglacial" to "Glacial" match well those inferred from $\delta^{13}C$ measurements (Figs. 4 & 5):

A stronger inflow of bottom water from the Southern Ocean

The AABW-like waters are nutrient rich while the upper ocean is strongly nutrient-depleted

MOC (Sv) and PO4 (mol/m³)

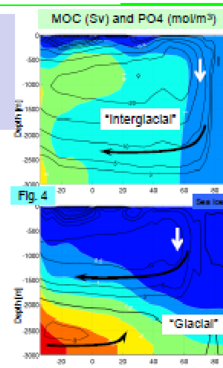


Fig. 4

A 15° southward shift of the site of deep water formation (following the migration of the ice margin) in the "Glacial" state

A weaker and swallower "NADW" cell

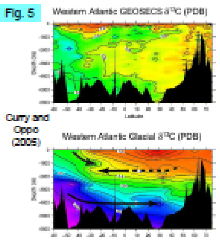


Fig. 5

Curry and Oppo (2005)

Surface winds stress: SH Westerly winds strengthen and shift poleward in the "Interglacial" climate, hence a slightly stronger SO upwelling (contributing to a more northward OHT near 40° S, see Fig.7, top).

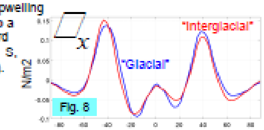


Fig. 8

- In the SH, the growth and equatorward export of sea ice in the "Glacial" climate become large enough to drive, through brine rejection, a large increase of AABW-like bottom water formation (Fig. 9): bottom waters of the Southern Ocean are colder (near freezing) and saltier (+1 psu), closely reproducing estimations for the LGM (Adkins et al. 2002).
- In the NH, the primary effect of sea ice extension is to cap off buoyancy loss over polar water (mainly through reduced latent heat): deep water formation is moved to the ice margin near 55° N.

Global MOC and Temperature

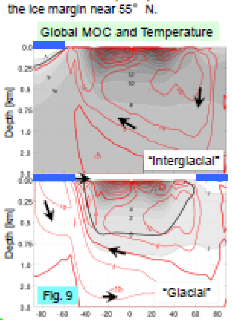


Fig. 9

Energy transports:
•The Small-basin OHT uniformly decreases by ~0.4 PW in the "Glacial" climate. In the subtropics, this effect is largely compensated by an increase of the Large-basin OHT due to a strengthening of the trade winds (Fig. 8).
•The global OHT shows a complex pattern of strengthening and weakening.
•In the atmosphere, compensating decrease/increase in latent/sensible heat transports are seen in the "Glacial" climate. The latent effect dominates in the SH, but not in the NH. This suggests strong (non-linear) effects of the sea edge on the strength and location of mid-latitudes storm-tracks (and Westerly winds).

Ocean Heat Transport

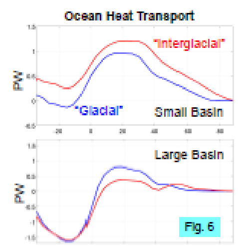


Fig. 6

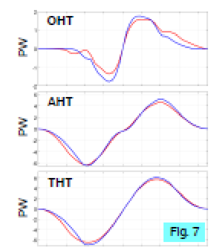
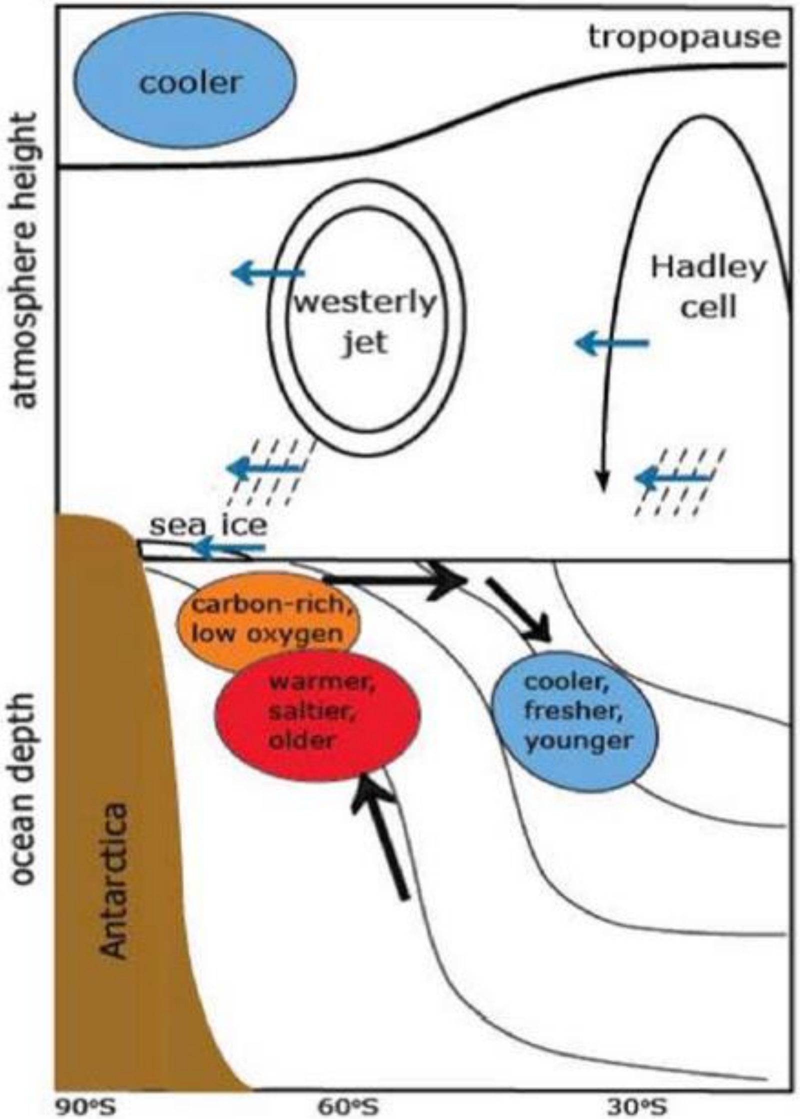


Fig. 7

Summary: Our simulations show that multiple equilibrium states of the coupled climate system can exist in an Earth-like geometry with zonal and meridional asymmetries: (at least) two states are possible – a Warm/Interglacial state and a Cold/Glacial state. The two climate states show many similarities with the climate of the LGM and our present Holocene climate.

Discussion: Our results suggest that Glacial-Interglacial cycles may be related to the existence of multiple states in Earth climate. One can speculate that Milankovitch cycles (and possibly CO_2 feedbacks) provide the modulation for triggering system transitions between states. In this framework, it is noteworthy that two weaknesses of the Milankovitch hypothesis could be addressed:
•*The weakness of the astronomical forcing relative to the magnitude of the climate response:* In a system with an hysteresis, small forcings can result in large responses. The forcing is "only" required to drive the system for one potential well to the other.
•*A straightforward relationship between climate and astronomical forcing is not observed* (see e.g. Yin and Berger, 2010): Phasing between forcing and response are disturbed by critical thresholds and internally-set relaxation time-scales to the equilibrium states (Transitions between states have been explored in the Aqua and Ridge set up, see Rose et al. 2012)

Impact of the Ozone Hole on SH Climate



Courtesy of
Darryn Waugh

Mechanisms underlying observed trends