Interpreting recent Southern Ocean climate trends

John Marshall, MIT
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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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Characteristic patterns and timing of response to step-function perturbations

GHG
Ozone Hole

Forcing
time
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3. Null hypothesis: natural variability
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4. Summary and Conclusions

   ‘Special’ dynamics of the SO imprints itself on response
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‘Special’ dynamics of the SO imprints itself on response

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

1982-2012 sea-surface temperature trend

NOAA Optimum Interpolated SST Version 2
(Reynolds et al. 2002)

(last 30 years)
Observed Southern Ocean Trends

1982-2012 sea-surface temperature trend

Antarctic sea-ice extent

Maksym et al (2012)

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

1982-2012 sea-surface temperature trend

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

Antarctic sea-ice extent

Maksym et al (2012)

1982-2012 zonal mean ocean potential temperature trend

(°C/decade)
Climate Response Functions

\[ 4 \times \text{CO}_2 \]

\[ \text{CO}_2 \text{ [ppm]} \]

\[ \text{Yrs} \]

FORCING

200

1200
Climate Response Functions

**FORCING**

- $4 \times \text{CO}_2$

**RESPONSE**

- Global average SST response
- Warming
Climate Response Functions

**FORCING**

- $4 \times CO_2$

**RESPONSE**

- Global average SST response

**Ozone depletion**

- No ozone depletion
- Nov Year 1
- Nov Year 2
- Time

- 90%
- 20%
Climate Response Functions

FORCING

$4 \times \text{CO}_2$

RESPONSE

Global average SST response

$\text{CO}_2$

warming

$\text{O}_3$

cooling

SST around Antarctica
GHG Response Function

Coupled climate models,
Abrupt quadrupling of CO2

CMIP5 ensemble

Planet warms, but not uniformly

Delayed SO warming
GHG Response Function

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Coupled climate models,
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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
GHG Response Function

Coupled climate models, Abrupt quadrupling of CO2

Planet warms, but not uniformly
Delayed SO warming

Response to abrupt GHG forcing

Previous studies have attribute delayed warming to
- anomalous freshwater fluxes
- local storage of heat in ocean
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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 $F = 4 \text{ W/m}^2$
- Spatially-invariant climate feedback of $\lambda = 1 \text{ W/m}^{-2} \text{ K}^{-1}$

MITgcm
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 \( F = 4 \text{ W/m}^2 \)
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Note:
Only surface heat fluxes are perturbed
No change in winds or E-P
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See Marshall et al, 2014: Climate Dynamics for more details
Spatial pattern of warming

Temperature change (°C) after 100 years

Ocean-only MITgcm

Temperature change (°C) after 100 years

The map illustrates the spatial pattern of warming, showing temperature changes in degrees Celsius (°C) after 100 years. The data is modeled using an ocean-only MITgcm simulation.
Spatial pattern of warming

Temperature change (°C) after 100 years

Ocean-only MITgcm

CMIP5 ensemble
(15 models, abrupt 4xCO₂)

Delayed warming in Southern Ocean
Energy accumulation, storage and transport

Flux through sea-surface

Ocean-only MITgcm

Ocean temperature change over 100 years

Depth (m)

Energy accumulation, storage and transport

J/°latitude

0

1

2

x 10^22

Flux through sea-surface

storage

Ocean temperature change over 100 years

T_{anthro}

Depth (m)

0

500

1000

1500

60S 30S

Eq

30N 60N

Latitude

Anomalous Heat transport

Anomalous

Heat transport

v_{res} T_{anthro}

Latitud
Ozone Hole Response Function

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)
Ozone Hole Response Function

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)

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

Peak depletion at Oct/Nov transition

‘Step’ with a seasonal cycle
Idealized Coupled Model

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

David Ferreira et al, 2015
J of Climate
Idealized Coupled Model

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

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

- SST dipole
- monopole
Response to SAM: two-timescale problem

Sea-ice cover

SST

°C

dipole

monopole

Winter

Summer
Response to SAM: two-timescale problem

Sea-ice cover

Averaged between 50 & 70S

SST

Winter

Summer

dipole

monopole
Mechanisms

SST regressed on to SAM, zero lag

SAM wind-stress
Mechanisms

SST regressed on to SAM, zero lag

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

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

SST regressed on to SAM, zero lag

Short time-scale – passive ocean, cooling around Antarctica
Longer time-scale – active ocean, surface ultimately warms

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

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\]
Marshall et al, 2014:
Phil Trans A
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

(a) Ozone forcing

(b) Radiative forcing

\[ \text{O}_3 \]
Convolutions with GHG and Ozone Hole forcing

\[ O_3 \]

Radiative forcing

Individual responses

Combined responses
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
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
Several factors likely set Southern Ocean warming/cooling patterns:

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• Subduction within mode water formation regions enhances warming on the northern flank of the ACC
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Linking Glacial-Interglacial cycles to multiple equilibria of climate

David Ferreira and John Marshall
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Previous work:
In Ferreira et al. (2011), we show the existence of multiple equilibrium states of the climate system in a coupled ocean-sea ice-carbon cycle model. In two idealized geometries, two different stable states are found, which differ in the sea ice extent. The two states are separated by a hysteresis loop, where the system remains in the same state even when the forcing is varied. This hysteresis loop indicates the presence of multiple distinct climate states, each with its own set of characteristics.

Mechanism:
The multiple equilibria owe their existence to the presence of a positive feedback loop involving the Ocean-Atmosphere system. As the ocean absorbs more heat, it warms up, leading to more evaporation and hence more rainfall. This additional rainfall leads to a larger oceanic heat transport, which further warms the ocean, creating a positive feedback that drives the system towards one of the stable states.

A weaker and shallower "NAADW" cell

Surface wind stress: On present day winds strengthen and shift back in the "Interglacial" climate, hence a slightly stronger northern "NAADW" cell as depicted in Toggweiler et al. (2001) and Fig. 5.1.

Energy transports:
The small basin of the Northern Pacific, which is characterized by a relatively strong "NAADW" cell, is unlikely to be affected by the changes in the ocean circulation. However, the changes in the ocean circulation in the Southern Ocean may have a significant impact on the energy transport and thus on the climate in that region.

Summary:
Our simulations show that multiple equilibrium states of the coupled climate system can exist in an Earth-like geometry with continental and thermal asymmetries. At least two states are possible - a Warm Interglacial state and a Cold Glacial state. These two climate states show many similarities with the climate of the present-day and our present Holocene climate.

Discussion:
Our results suggest that Glacial-Interglacial cycles may be related to the existence of multiple stable states in Earth climate. One can speculate that similar feedbacks and hysteresis loops drive the switch between states. In this scenario, it is noteworthy that two weaknesses of the Milankovitch hypothesis could be addressed:

- The weakness of the atmospheric response to the magnitude of the temperature response. In a system with hysteresis, small forcings can result in large responses. The forcing is "frozen" to drive the system for one potential well to the other.

- The large-scale occurrence of the Dansgaard-Oeschger events in the LGM climate after the collapse of the Laurentide and Fennoscandian ice sheets (see e.g. Mix and Ziegler, 2001). The collapse between forcing and response are driven by critical thresholds and thermodynamic variation time-scales of the system.
Impact of the Ozone Hole on SH Climate

Courtesy of Darryn Waugh
Mechanisms underlying observed trends

Anthropogenic temperature