On the Origin of Antarctic Warming Events: A Modeling Study of Causes and Effects

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variability in the Southern Hemisphere?

⭐ What are the primary forcing factors?

❖ *How important are remote, local forcing and feedbacks?*

❖ *Can tropical oceans affect Antarctic climate?*

⭐ What terminates A-events?

⭐ Can Antarctic warming events trigger an Antarctic cold reversal?
What are the “patterns” of millennial-scale climate variability in the Southern Hemisphere?

Signatures of non-uniform warming pattern

Oxygen/Deuterium Isotopes from Antarctic ice cores

Timmermann et al. QSR, accepted, 2009
Signatures of non-uniform warming pattern in “waterhosing” model simulations

Wind and SST anomalies during shutdown of the Atlantic Meridional Overturning Circulation

Timmermann et al. QSR, accepted, 2009

SST anomaly [K]
What are the primary forcing factors?

Negative SST anomalies in tropical Atlantic and tropical Pacific lead to SH circulation anomalies

Atmosphere only experiments:
SST anomalies from preindustrial waterhosing experiments

green (orange) contours: positive (negative) rainfall anomalies (interval 1mm/day)
contours: sea level pressure anomaly

surface temp. anomalies [K]

Tropical Atlantic forcing only

Timmermann et al. QSR, accepted, 2009
What are the primary forcing factors today?

Tropical forcing projects onto Pacific South America (PSA) pattern

contours: sea level pressure anomaly associated with second EOF

Timmermann et al. QSR, accepted, 2009
Heinrich event

northern hemisphere cooling

atmospheric connection via tropics

non-uniform warming pattern

+ albedo feedback

southern hemisphere warming

reduced sea-ice

bi-polar seesaw
Causes of Antarctic Warming:
Oceanic seesaw accompanied by atmospheric CO$_2$ increase

Figure 1 from Jinho Ahn and Edward Brook, Science, 322, 83-85, 2008
Causes of Antarctic Warming:

Model* experiments show importance of CO$_2$ increase for warming

Atmospheric CO$_2$ increase can account for 25-30% of Antarctic warming during A-events

Source of atm. CO$_2$ increase in this model: Northern Hemisphere terrestrial vegetation

*Model LOVECLIM forced with ice core reconstructed CO$_2$ time series
What are the primary forcing factors?
Remote freshwater input into North Atlantic Ocean

Freshwater flux in the North Atlantic starting from a pre-industrial and a glacial climate state
Causes of Antarctic Warming:
Sources and sinks of atmospheric CO₂

Terrestrial carbon release outweighs ocean carbon uptake

Menviel et al., Paleoceanography (2007)
Enhanced southern hemispheric warming due to CO$_2$ increase during Heinrich events

Air temperature anomalies during AMOC collapse

CO$_2$ = 300 ppmv

($CO_2$ = 300 ppmv) – ($CO_2$ = 280 ppmv)

CO$_2$ contributes to an additional warming of $\sim$1°C at high southern latitudes
Causes of Antarctic Warming:
relative contribution of 20ppmv CO$_2$ during Heinrich event to Antarctic warming:

Timmermann et al. QSR, accepted, 2009
Heinrich I impacts: summary for Antarctic Warming

Center of action

Atlantic seesaw

ENSO +

Vegetation -

ITCZ

PSA

C.0
Conceptual model:
**ocean seesaw and atmospheric bridge and CO\(_2\)**

- **Heinrich event**
  - reduced terrestrial vegetation
  - reduced sea-ice
  - atmospheric connection via tropics
  - + albedo feedback
- **northern hemisphere cooling**
- **southern hemisphere warming**
  - bi-polar seesaw
- **marine carbon cycle**
- **atmospheric CO\(_2\)**
  - increase
  - reduction (in LOVECLIM model)
Revisiting the Antarctic Cold Reversal

During the last deglaciation South Atlantic IRD peak SA0 (14.2 to 13.5 ka) coincides with the Antarctic Cold Reversal and global meltwater pulse 1a and may point to an influx of icebergs from the AIS as the cause of these events.

Anderson et al. 2009, Science

Kanfoush et al. 2000, Science
Causes of Antarctic Cold Reversal:
Meltwater pulse from West Antarctic Ice Sheet
Freshening of the Southern Ocean

“Waterhosing” model simulation with LOVECLIM:
Meltwater pulse in Ross Sea area (158°E-60°W, 70°S-80°S)

Maximum overturning circulation in the Southern Ocean (Sv)
Ocean Climate Response of Freshening of the Southern Ocean

Time series of meltwater pulse (black), strength of the AABW (blue), and transport through Drake passage (green) in Sv.

ACC slowdown due to reduction in meridional density gradient
Climate response to Meltdown of the West Antarctic Ice-sheet

- Cooling of Southern Ocean
- Annual mean sea-ice area doubles
- Ekman transport intensifies
- Westerly winds intensify by 50%
- Export production in SO decreases by 30%
- Global opal production decrease by 10%
Antarctic Ice-sheet instability ⇒ Meltwater pulse

Cooling of ACC area ⇒ Sea ice increases ⇒ Westerlies increase

Increased Stratification

Productivity decreases

AABW formation decreases

Reduced light

Reduced opal flux

Reduced CO₂ flux

Alternative explanation to Anderson et al. (Science, 2009)
Antarctic Subsurface Warming: Further Destabilization of West Antarctic Ice Sheet?

Ocean Layer depth

20-50m
Antarctic Subsurface Warming: Further Destabilization of West Antarctic Ice Sheet?

Ocean Layer depth

50-100m
Antarctic Subsurface Warming: Further Destabilization of West Antarctic Ice Sheet?

Ocean Layer depth

100-140m
Antarctic Subsurface Warming: Further Destabilization of West Antarctic Ice Sheet?

Ocean Layer depth

140-250m
Antarctic Subsurface Warming: Further Destabilization of West Antarctic Ice Sheet?

Ocean Layer depth

250-500m
Antarctic Subsurface Warming: Further Destabilization of West Antarctic Ice Sheet?

Ocean Layer depth

500-1000m
Antarctic Subsurface Warming:
Further Destabilization of West Antarctic Ice Sheet?
Antarctic Subsurface Warming: Further Destabilization of West Antarctic Ice Sheet?

- Freshwater forcing
- Reduction of AABW formation
- Destabilization of marine-based ice-sheets
- Subsurface warming
Conceptual model for Heinrich 1, A(0)-event and Antarctic Cold Reversal:

- Reduced terrestrial vegetation
- Reduced sea-ice
- Atmospheric CO₂ increase
- Meltwater pulse into Southern Ocean
- Cooler SST Southern Ocean (Antarctic Cold Reversal)
- Marine carbon cycle
- Bi-polar seesaw
- Albedo feedback
- Delayed trigger?
- Increase/reduction (?)
Conceptual model for Heinrich 1, A(0)-event and Antarctic Cold Reversal:

- Heinrich event
  - reduced terrestrial vegetation
  - atmospheric CO₂ increase
  - sea level rise

- northem hemisphere cooling
  - reduced sea-ice
  - albedo feedback
  - atmospheric connection via tropics
  - Meltwater pulse into Southern Ocean
  - Subsurface warming
  - trigger ?

- southern hemisphere warming
  - + albedo feedback
  - Cooler SST Southern Ocean (Antarctic Cold Reversal)
  - feedback

- marine carbon cycle
  - - feedback
  - bi-polar seesaw