Periodic Fluctuations in Deep Water Formation Due to Sea Ice

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Past Climate

100,000 year cycles

Abrupt warming, gradual cooling

Possibly due to large scale fluctuations in global oceanic circulation

Zachos et al. 2001
Past Climate

100,000 year cycles
Abrupt warming, gradual cooling
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Zachos et al. 2001
Past Climate

100,000 year cycles

Abrupt warming, gradual cooling

Possibly due to large scale fluctuations in global oceanic circulation

Zachos et al. 2001
Past Climate

\[
\delta^{18}O (\%) \text{ NGRIP}
\]

Kilo Years Before Present

NGRIP
Past Climate

1,500 year cycles

Dansgaard-Oeschger (D-O) Events
Past Climate

1,500 year cycles
Abrupt warming, gradual cooling

Dansgaard-Oeschger (D-O) Events
Past Climate

1,500 year cycles
Abrupt warming, gradual cooling
Fluctuations most pronounced in the North Atlantic

Dansgaard-Oeschger (D-O) Events
Past Climate

![Graph showing past climate data with δ¹⁸O (%) over Kilo Years Before Present.](image)
Past Climate

Quasi-periodic ice-sheet disintegration

Heinrich Events

$^{18}$O (‰) NGRIP

Kilo Years Before Present
Past Climate

Quasi-periodic ice-sheet disintegration

Large amounts of freshwater dumped into the North Atlantic
Past Climate

Quasi-periodic ice-sheet disintegration

Large amounts of freshwater dumped into the North Atlantic

Heinrich Events
Past Climate

Quasi-periodic ice-sheet disintegration

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Heinrich Events
Past Climate

Quasi-periodic ice-sheet disintegration

Large amounts of freshwater dumped into the North Atlantic

Probable cause for abrupt shifts in ocean circulation?

Heinrich Events
Past Climate

\[ \Delta^{18}O \text{‰ NGRIP} \]

Kilo Years Before Present
Past Climate

Origin of the 1,500 year cycles? (external or internal?)
Past Climate

Origin of the 1,500 year cycles? (external or internal?)

Pattern of fluctuations between 50 kyr and 30 kyr before present - How / Why?
The Freshwater Hypothesis

Freshwater from ‘purged’ ice sheets destabilize circulation

Leads to disruption in heat transport to northern latitudes

*Ganopolski and Rahmstorf (2001)*
Other Proposed Mechanisms

Solar Influence?

Combination of two known solar cycles of 87 and 210 years
\( (Braun \text{ et al.}, 2005) \)

However, comparison of proxy records for the climate and solar influence do not reveal a correlation
\( (Muscheler \text{ and Beer, } 2006) \)

Oceanic Tidal Cycle?

1,800 year periodic variations in oceanic tides caused by resonances in the orbits of Earth and Moon
\( (Keeling \text{ and Whorf, } 2000) \)

However, there is a period mismatch

Internal Oceanic Mechanisms?

Several models produce fluctuations in the circulation due to anomalies in polar sea surface salinity
\( (Winton \text{ and Sarachik, } 1993; \text{ Sakai and Peltier, } 1995; \text{ Haarsma et al. } 2001; \text{ de Verdière et al. } 2006) \)

However, the period of fluctuations are heavily dependent on polar sea surface conditions
Questions

Origin of the 1,500 year cycles, pattern
Driven by external (astronomical) or internal (oceanic) mechanisms?
How are the D-O events connected to Heinrich events?
A Simple Dynamical Model

Goal:
A Simple Dynamical Model

Goal:

To examine the interaction between circulation (deep water formation) and sea ice
A Simple Dynamical Model

Spatial Layout
A Simple Dynamical Model

Spatial Layout
A Simple Dynamical Model

Spatial Layout

Subtropical
A Simple Dynamical Model

Spatial Layout
A Simple Dynamical Model

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Spatial Layout
A Simple Dynamical Model

Spatial Layout

Gildor and Tziperman (2001)
de Verdière et. al. (2005)
A Simple Dynamical Model

Forcing

Applied Atmospheric Temperatures

Applied Surface Salinities

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A Simple Dynamical Model

Physical Processes

\[ \psi_1 > 0 \quad \rightarrow \quad \text{Surface pole-bound flow (Thermal)} \]

\[ \psi_1 < 0 \quad \rightarrow \quad \text{Surface equator-bound flow (Haline)} \]
# A Simple Dynamical Model

## Physical Processes

Pressure driven circulation

\[ \psi_1 > 0 \quad \rightarrow \quad \text{Surface pole-bound flow (Thermal)} \]

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\[ \psi'_1 \]

\[ \psi'_2 \]

\[ \psi'_3 \]

\[ \psi'_4 \]

Sea Ice

\[ \text{TH} \]

\[ \text{SA} \]

\[ \text{TH} \]

\[ \text{SA} \]

\[ \text{TH} \]

\[ \text{SA} \]
A Simple Dynamical Model

Physical Processes

Pressure driven circulation

$\psi_1 > 0 \implies \text{Surface pole-bound flow (Thermal)}$

$\psi_1 < 0 \implies \text{Surface equator-bound flow (Haline)}$

Sea ice grows on the polar box
A Simple Dynamical Model

Governing Equations

\[ m_i C_p T_i = \dot{Q}_i + \rho_0 C_p \psi_{i,j} T_j + \rho_0 C_p D_{i,j} T_j + C_0(T_i) + \dot{Q}_{ice} \]

\[ m_i \dot{S}_i = \xi_i + \rho_0 \psi_{i,j} S_j + \rho_0 D_{i,j} S_j + C_0(S_i) + S_0 \dot{B} \]
A Simple Dynamical Model

Governing Equations

Heat exchange with atmosphere

\[ m_i C_p T_i = \dot{Q}_i + \rho_0 C_p \psi_{i,j} T_j + \rho_0 C_p D_{i,j} T_j + Co(T_i) + \dot{Q}_{\text{ice}} \]

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A Simple Dynamical Model

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\[
m_i \dot{S}_i = [\xi_i + \rho_0 \psi_{i,j} S_j + \rho_0 D_{i,j} S_j + Co(S_i) + S_0 \dot{B}]
\]

Evaporation/Precipitation (salinity forcing)
A Simple Dynamical Model

Governing Equations

\[ m_i C_p T_i = \dot{Q}_i + \rho_0 C_p \psi_{i,j} T_j + \rho_0 C_p D_{i,j} T_j + Co(T_i) + \dot{Q}_{ice} \]

Advective transport of heat and salt

\[ m_i \dot{S}_i = \xi_i + \rho_0 \psi_{i,j} S_j + \rho_0 D_{i,j} S_j + Co(S_i) + S_0 \dot{B} \]
A Simple Dynamical Model

Governing Equations

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*Diffusive transport of heat and salt*

\[ m_i \dot{S}_i = \xi_i + \rho_0 \psi_{i,j} S_j + \rho_0 D_{i,j} S_j + C_0(S_i) + S_0 \dot{B} \]
A Simple Dynamical Model

Governing Equations

\[ m_i C_p T_i = \dot{Q}_i + \rho_0 C_p \psi_{i,j} T_j + \rho_0 C_p D_{i,j} T_j + \boxed{Co(T_i)} + \dot{Q}_{\text{ice}} \]

where \( Co(T_i) \) corresponds to convection.

\[ m_i \dot{S}_i = \xi_i + \rho_0 \psi_{i,j} S_j + \rho_0 D_{i,j} S_j + \boxed{Co(S_i)} + S_0 \dot{B} \]
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Brine rejection
A Simple Dynamical Model

Governing Equations

\[ m_i C_p T_i = \dot{Q}_i + \rho_0 C_p \psi_{i,j} T_j + \rho_0 C_p D_{i,j} T_j + \text{Co}(T_i) + \dot{Q}_{\text{ice}} \]

\[ m_i \dot{S}_i = \dot{\xi}_i + \rho_0 \psi_{i,j} S_j + \rho_0 D_{i,j} S_j + \text{Co}(S_i) + S_0 \dot{B} \]
Solutions

Circulation States

Haline

Oscillatory

Thermal

Adective Flux (\(\dot{\psi}\)) [\(\times 10^8\) m³/s]

Model Years

Model Years

Model Years

Solutions Circulation States
Solutions

Domain of States

Oscillations

3D plot showing the relationship between Tropical E–P (ε) [mm/day], Thermal Gradient (η) [K/° lat], and Adveective Flux ($ψ_1$) [$×10^{11}$ kg/s]. The plot highlights the domain of states with specific markers indicating SA and TH.
Solutions

Domain of States

No Sea Ice

Graph showing:
- Tropical E–P ($\epsilon$) [mm/day]
- Thermal Gradient ($\eta$) [K/°lat]
- Advective Flux ($\psi_1$) [$\times 10^{11}$ kg/s]
Phase-space Trajectories of Advective Fluxes
Phase-space Trajectories of Advective Fluxes
Phase-space Trajectories of Advective Fluxes (several initial states)
Phase-space Trajectories of Advective Fluxes (several initial states)

With Sea ice: $\psi_{\text{min}}$

No Sea Ice
Solutions

Oscillation Periods: Relative Strength of Thermal to Salinity Forcing

Periods between 200 and 4,000 years

Scale with $\varepsilon/\eta$

Depends on the rate of build up and eradication of instabilities
**Solutions**

**Oscillation Periods: Geometry**

Larger polar volume increases effective heat capacity of the system

Periods get longer with volume (heat capacity)

Since geometry is invariant, it can produce a persistent period

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**Graphs**

- Left graph: Period (years) vs. Number of Instances (Frequency) with a peak at 480 years and $V^*_8 = 0.5 V_8$
- Right graph: Period (years) vs. Number of Instances (Frequency) with a peak at 780 years and $V^*_8 = 3.5 V_8$
Solutions

Animation
Mechanism of Oscillations

- Insulating effect
- Brine rejection
- Heat exchanges from formation / melting
Mechanism of Oscillations

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<tr>
<th></th>
<th>( \gamma )</th>
<th>( \dot{B} )</th>
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Insulating effect

Brine rejection

Heat exchanges from formation / melting

**Insulating effect is key to oscillations in this system**
Mechanism of Oscillations

Insulating effect is key to oscillations in this system
Mechanism of Oscillations

Advective Flux

Diagram showing the mechanism of oscillations with a graph and illustrations of fluid flow.
Mechanism of Oscillations

Advective Flux
Mechanism of Oscillations

Advective Flux
Heat Loss to Atmosphere

Advective Flux

Mechanism of Oscillations
Mechanism of Oscillations

Advective Flux

Vertical Instability
Mechanism of Oscillations
Large heat loss from the polar surface ocean during sea ice retreats cool the water, making it more dense and creating conditions for convection.
Glacial Freshwater Scenario

Ice sheet growth and decay

Increased tropical (global) evaporation

Increased freshwater anomalies at high North Atlantic latitudes due to ice sheet runoffs
Glacial Freshwater Scenario: Ice Sheet Growth / Disintegration

Ice sheet growth and decay

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Observation and Model

\[ \delta^{18}O \text{ NGRIP} \]

Kilo Years Before Present

¡ Model !
Observation and Model

$\delta^{18}O$ (%o) NGRIP

65° N Summer Insolation

Kilo Years Before Present
A *Cartoon* of the Ice Sheet Cycles and D-O events

Ice sheet growth phase
Sea ice **max**
**A Cartoon of the Ice Sheet Cycles and D-O events**

Ice sheet growth phase
Sea ice *min*
A Cartoon of the Ice Sheet Cycles and D-O events

Ice sheet growth phase
Sea ice / AMOC oscillations
A *Cartoon* of the Ice Sheet Cycles and D-O events

Ice sheet growth phase

*Sea ice / AMOC oscillations*
A *Cartoon* of the Ice Sheet Cycles and D-O events

- Ice sheet growth phase
- *Sea ice / AMOC oscillations*
- Summer melting
A Cartoon of the Ice Sheet Cycles and D-O events

Ice sheet growth phase
Sea ice / AMOC oscillations
Summer melting
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A Cartoon of the Ice Sheet Cycles and D-O events

Sea ice / AMOC oscillations
Heinrich Event
Animated Cartoon
Conclusion
Conclusion
Conclusion

Sea Ice initiates oscillations of the circulation
Conclusion

Sea Ice initiates oscillations of the circulation

Period of oscillations tied to geometry of the system, hence robust
Conclusion

Sea Ice initiates oscillations of the circulation

Period of oscillations tied to geometry of the system, hence robust

Ice sheet growth/decay cycles produced observed D-O patterns
Conclusion

Sea Ice initiates oscillations of the circulation

Period of oscillations tied to geometry of the system, hence robust

Ice sheet growth/decay cycles produced observed D-O patterns

Weak (and therefore unstable) overturning circulation during glacial periods

Freshwater anomalies could have triggered state changes

In addition to freshwater, insolation variations can also trigger abrupt state changes in the overturning circulation, especially during early glacial periods

Sea ice may also serve as a similar trigger for glacial-interglacial cycles (Gildor and Tziperman, 2001)
Future Work
Carbon Storage in the Ocean: Dr. Irina Marinov, UPenn

Glacial - Interglacial Cycles

Interglacial Circulation

CO₂

Unstable stratification

Small Sea Ice Extent

AABW

NADW

Gildor, Tziperman, Toggweiler (2002)
Carbon Storage in the Ocean: Dr. Irina Marinov, UPenn

Glacial - Interglacial Cycles

Glacial Circulation

Gildor, Tziperman, Toggweiler (2002)
Reduction to Stommel: Andrew Roberts, UNC-Chapel Hill

Adding deep boxes and Sea ice to Stommel’s 2 box model
Acknowledgements

Chris Jones
John Bane
Pam Martin
Mary Lou Zeeman
Dorian Abbot
Ray Pierrehumbert
Mary Silber
Richard McGehee
Val Tenyotkin
Hassan Hatam
Thank You
Questions?