Periodic Fluctuations in Deep Water Formation Due to Sea Ice

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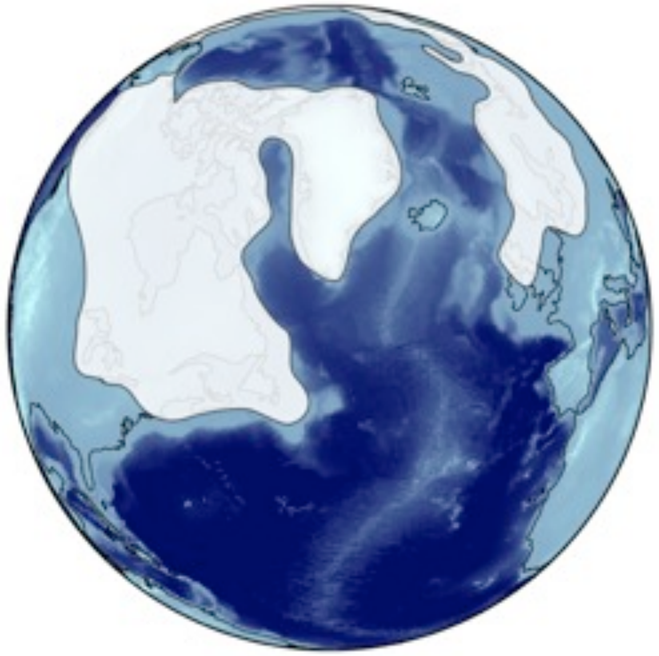
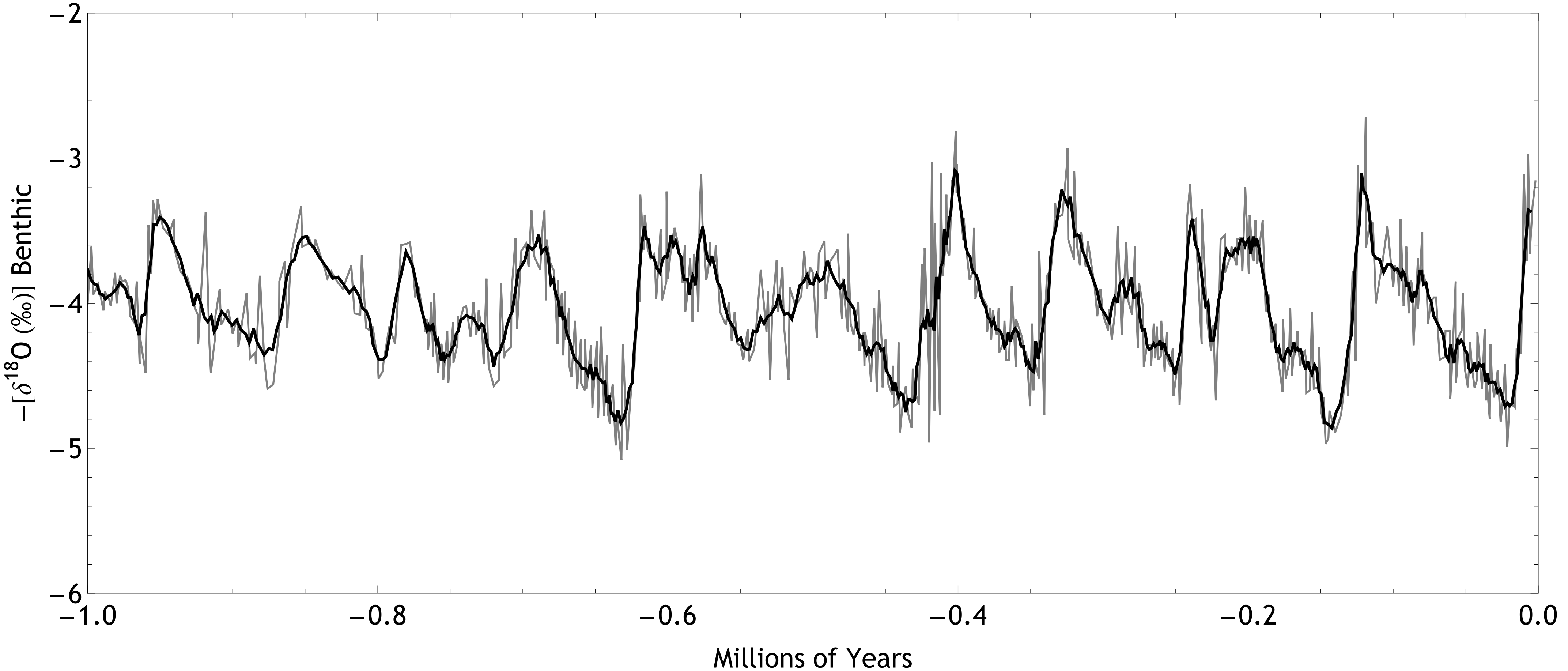
Past Climate

100,000 year cycles

Abrupt warming, gradual cooling

Possibly due to large scale fluctuations in global oceanic circulation





Zachos et al. 2001

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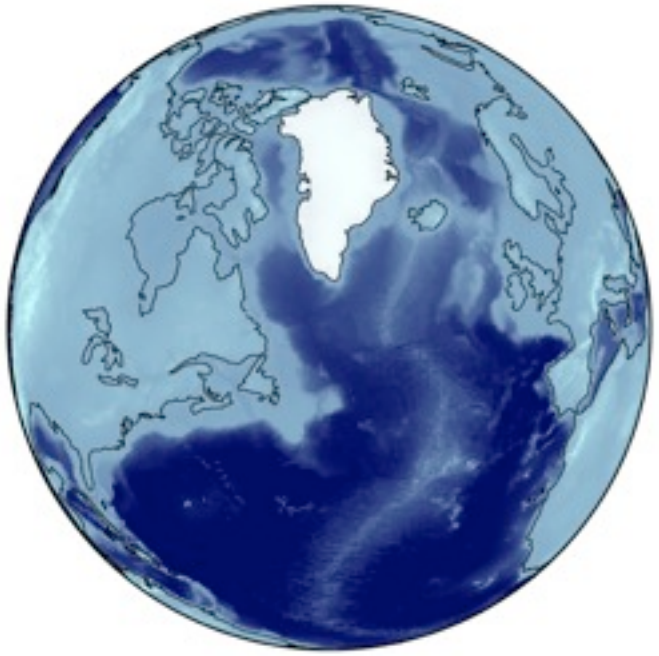

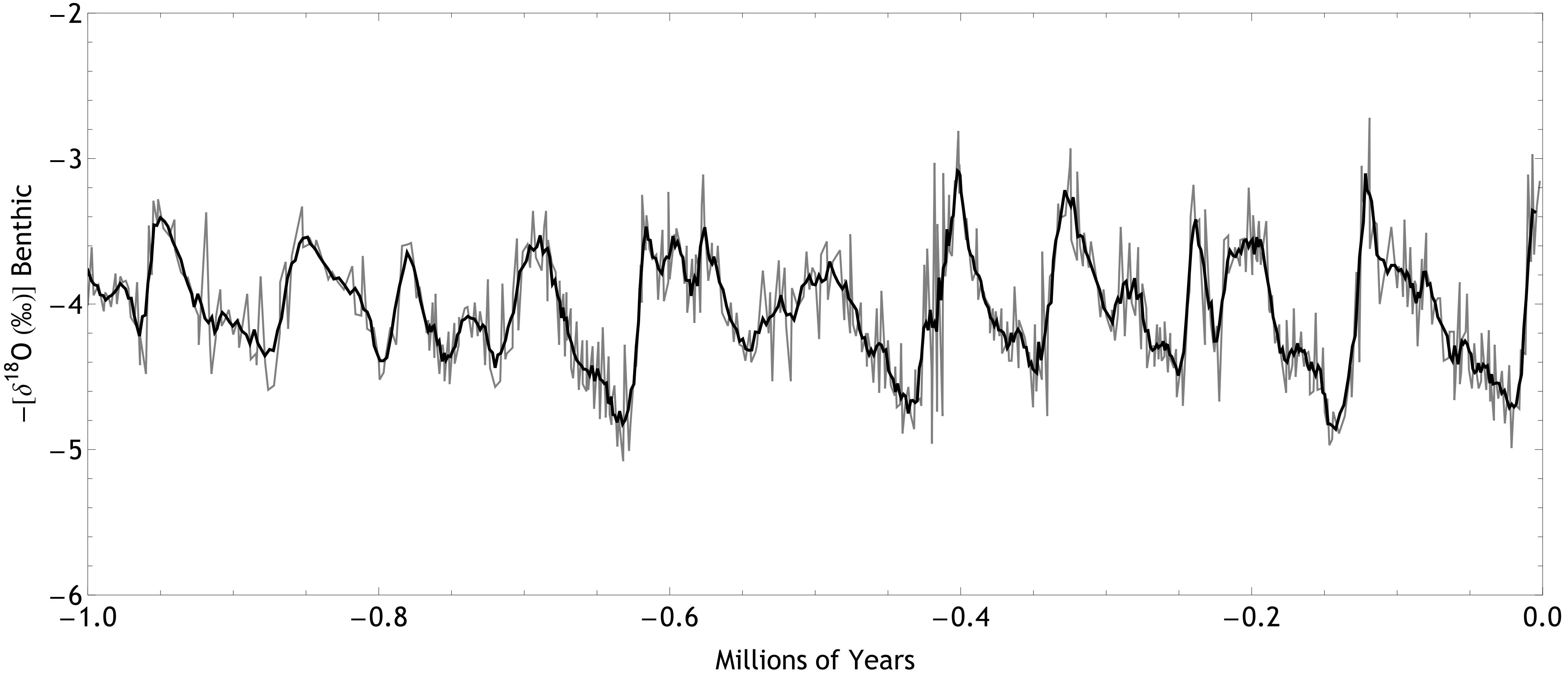

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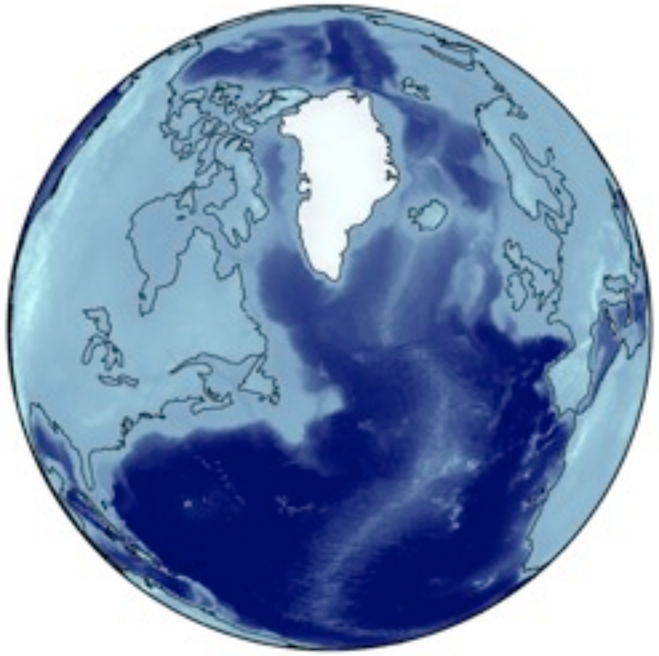

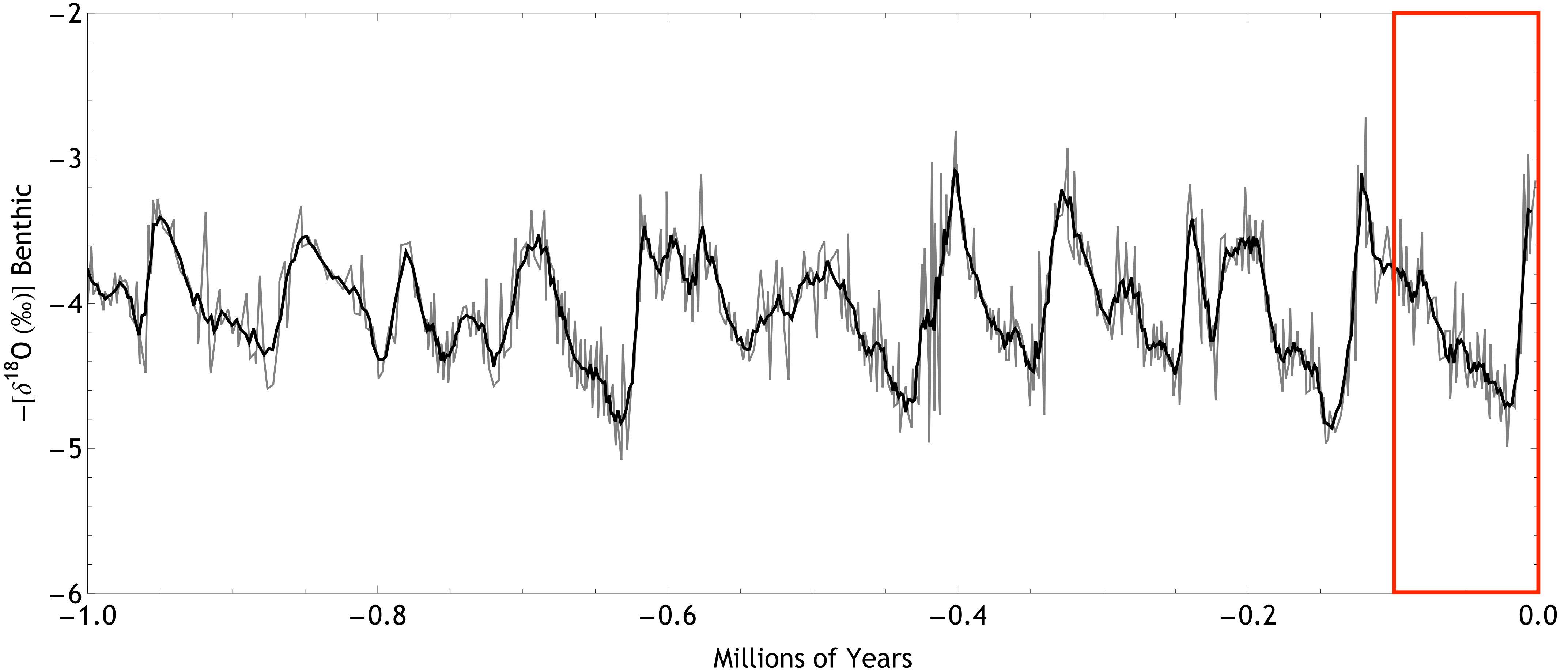

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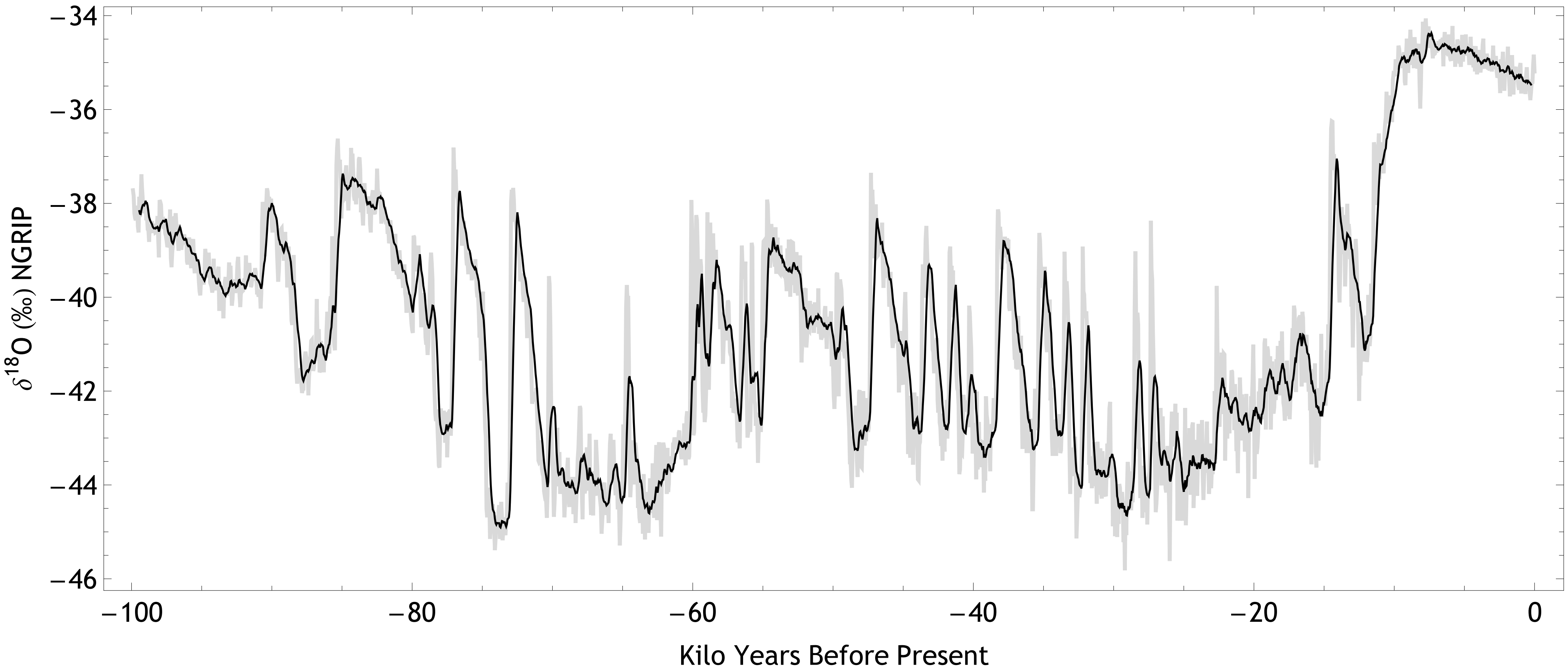
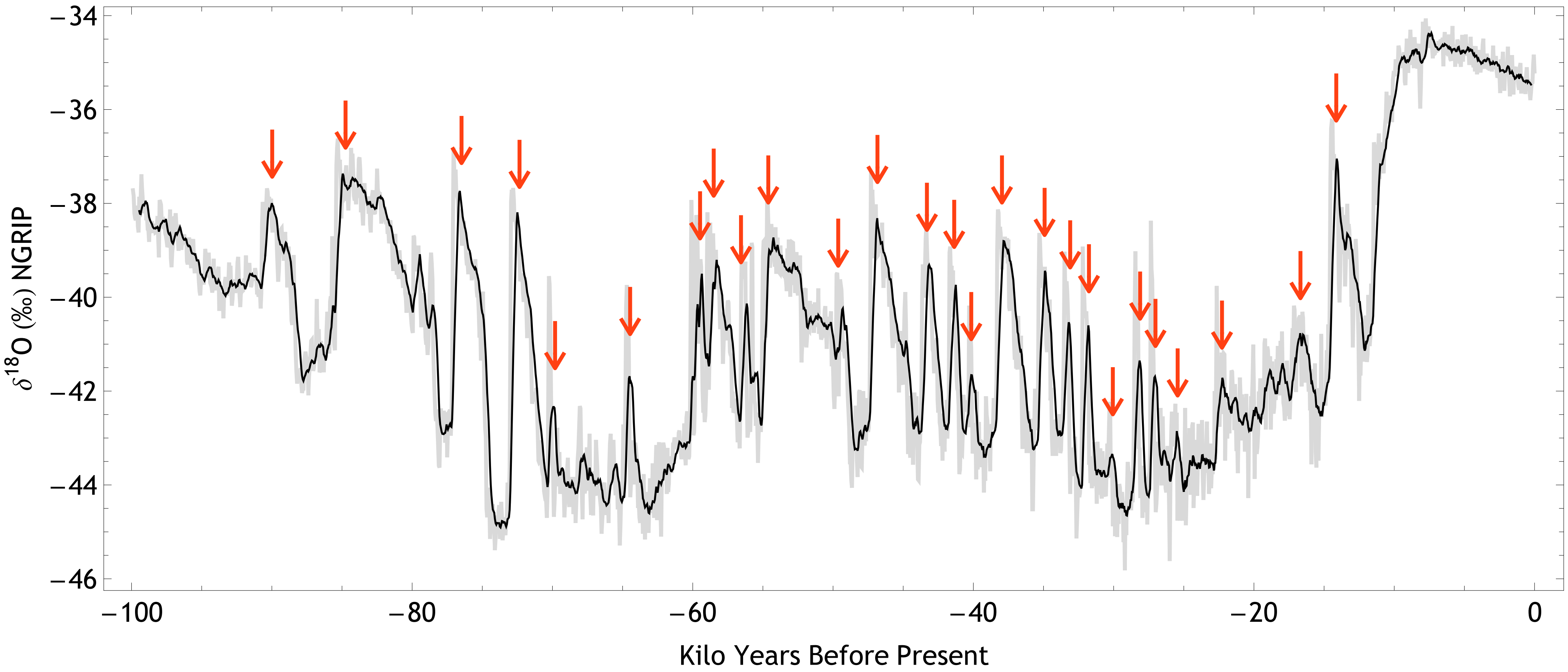


NGRIP

Past Climate

1,500 year cycles

Dansgaard-Oeschger (D-O) Events



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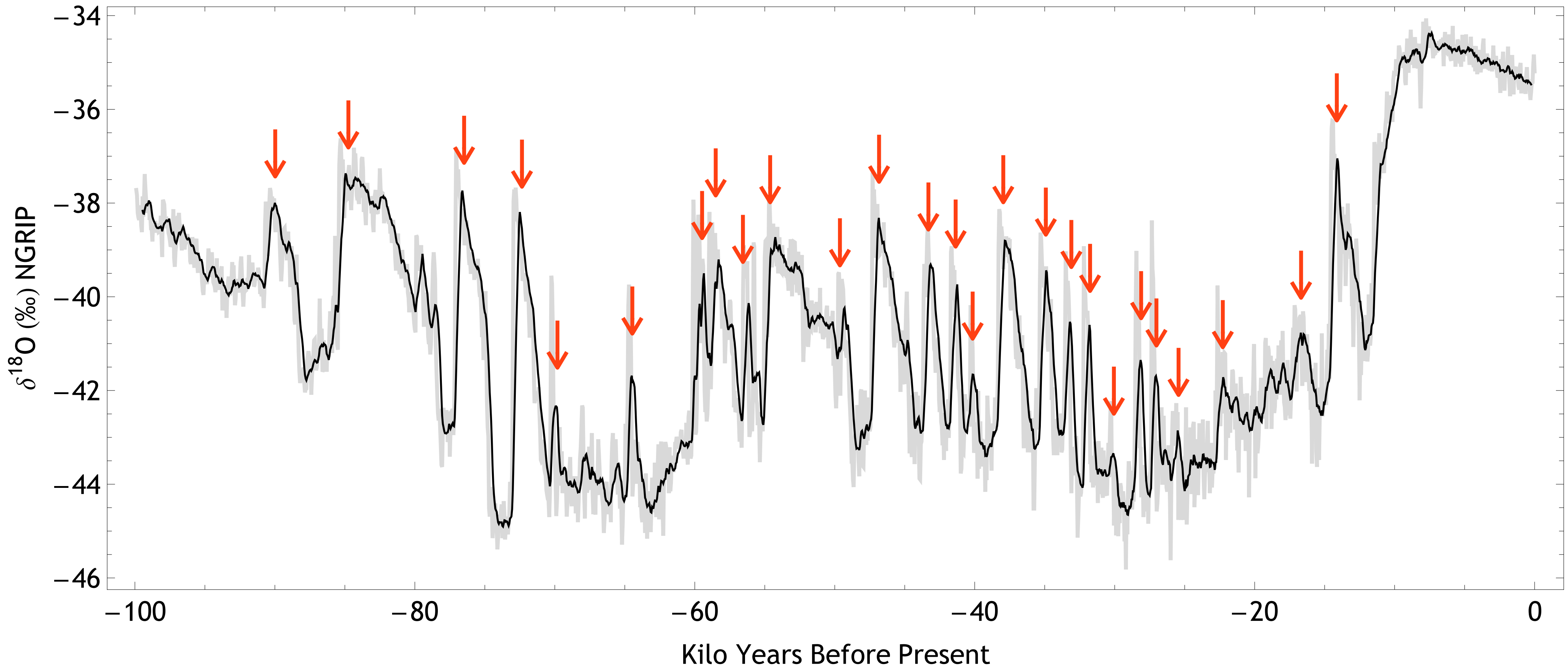

NGRIP

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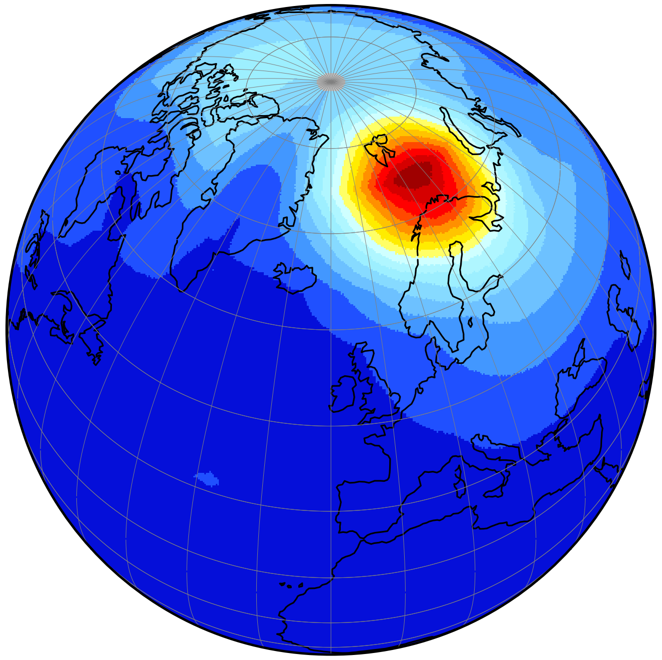
Abrupt warming, gradual cooling

Fluctuations most pronounced in the North Atlantic



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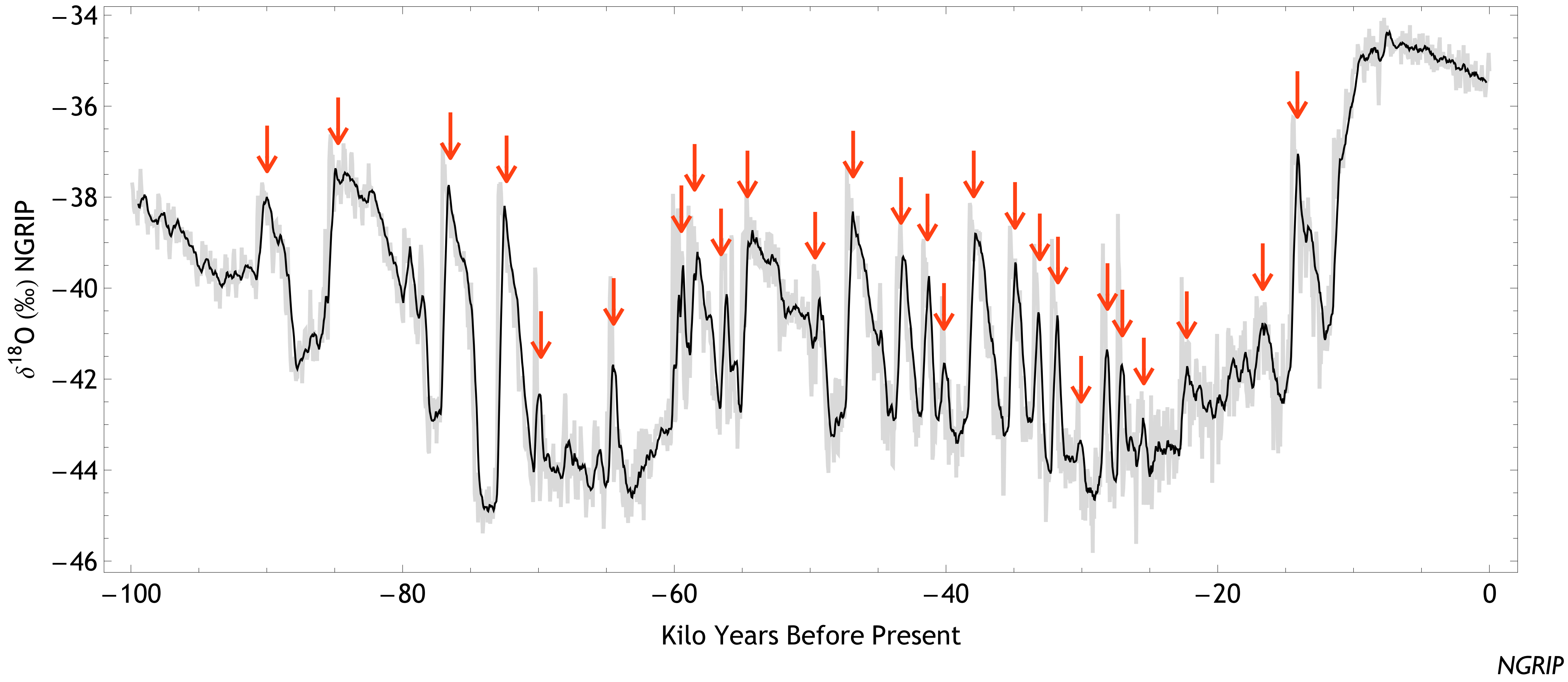

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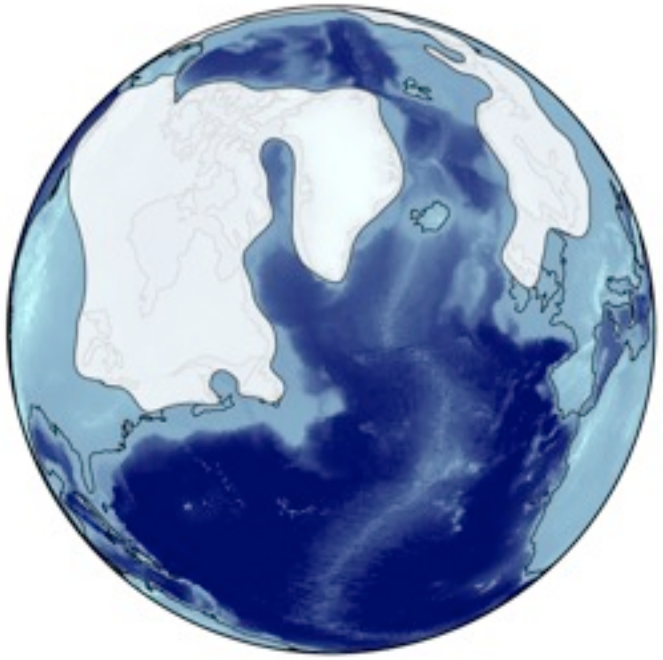
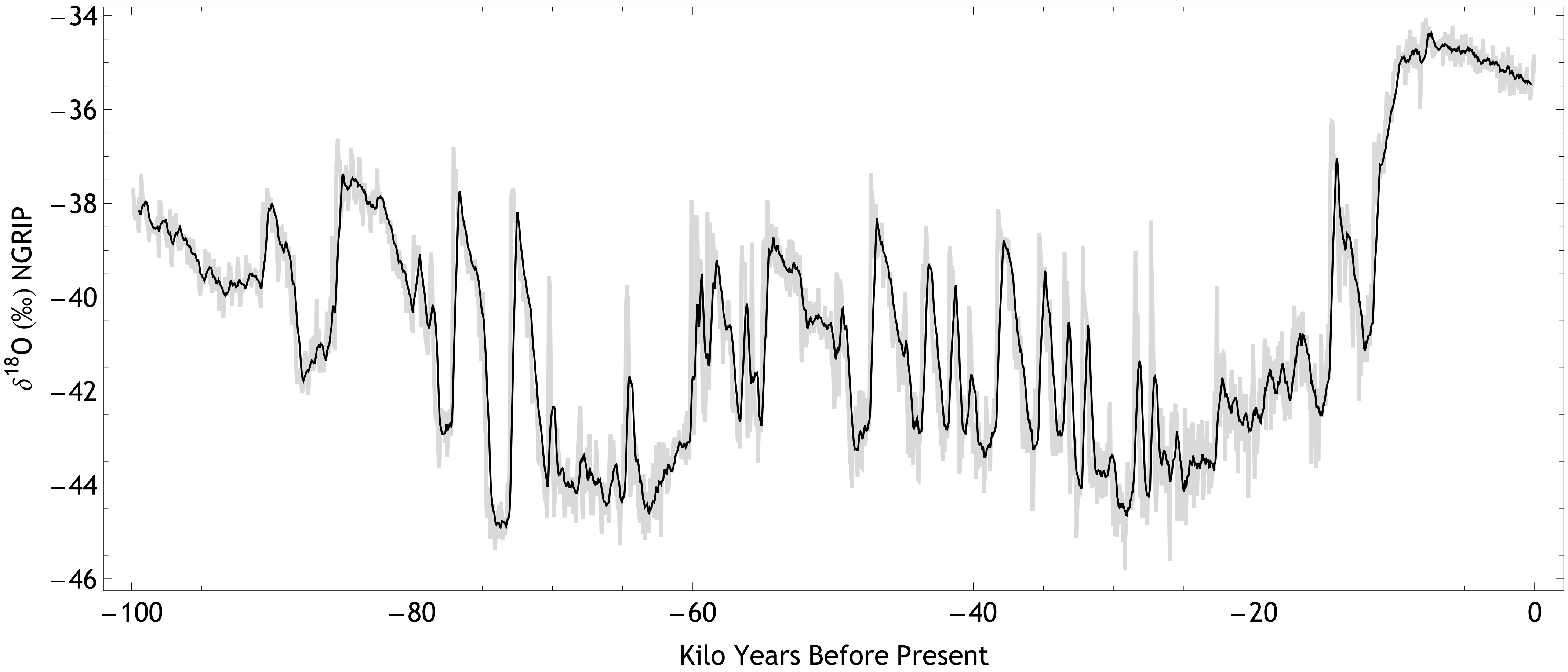
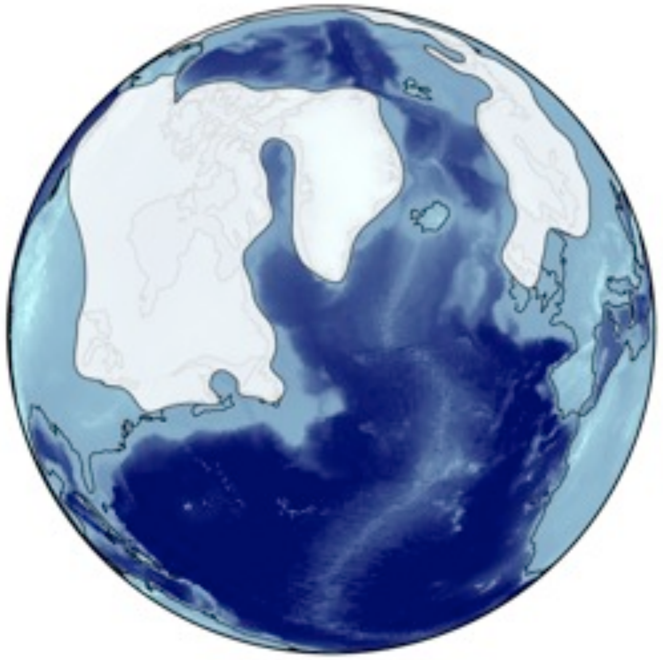
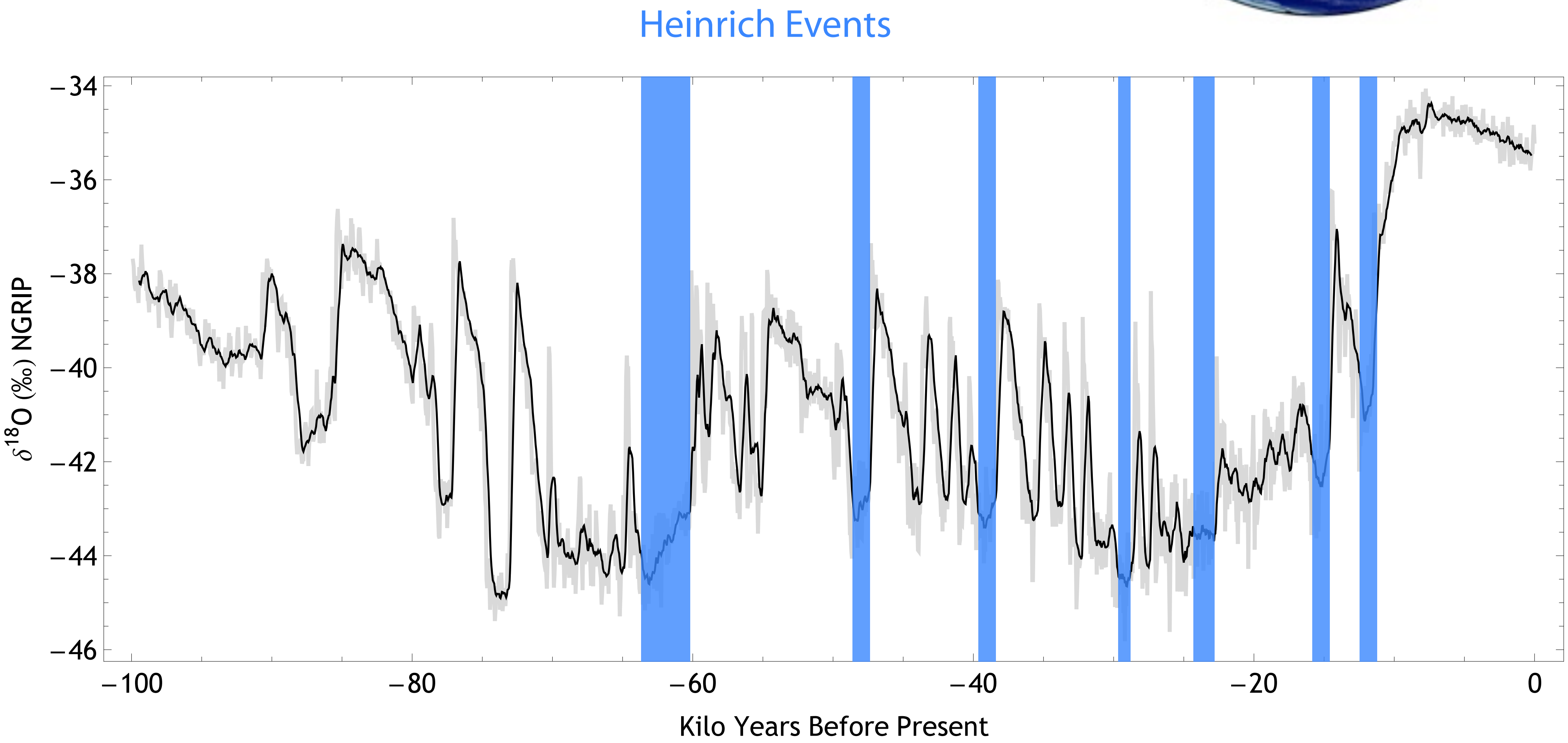




Past Climate

Quasi-periodic ice-sheet disintegration

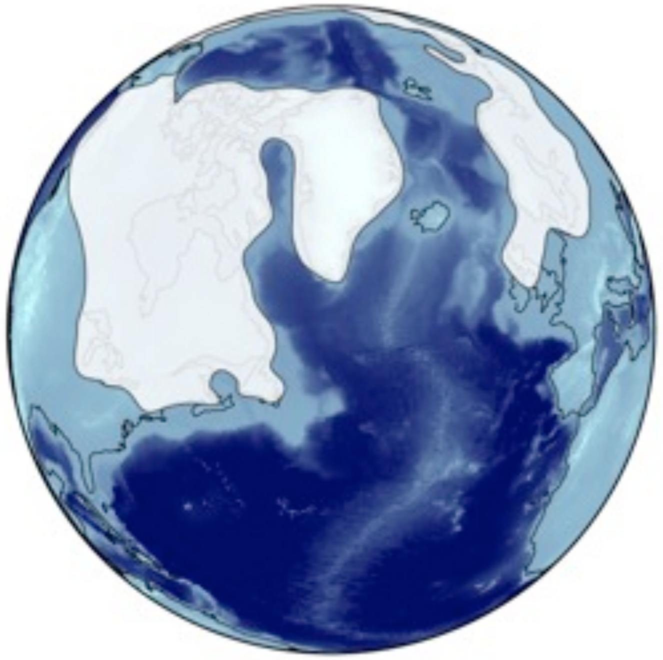


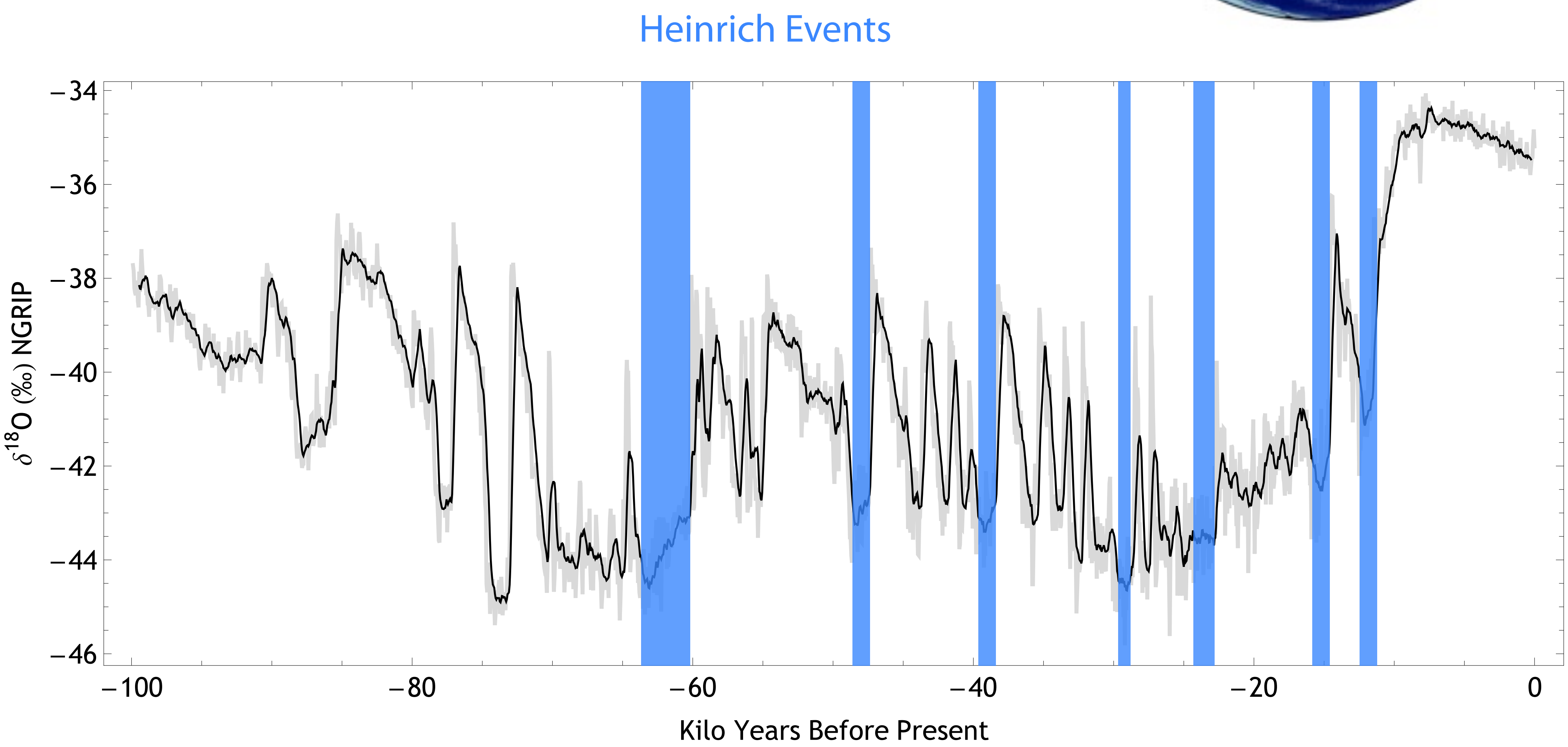


Past Climate

Quasi-periodic ice-sheet disintegration

Large amounts of freshwater dumped into the North Atlantic





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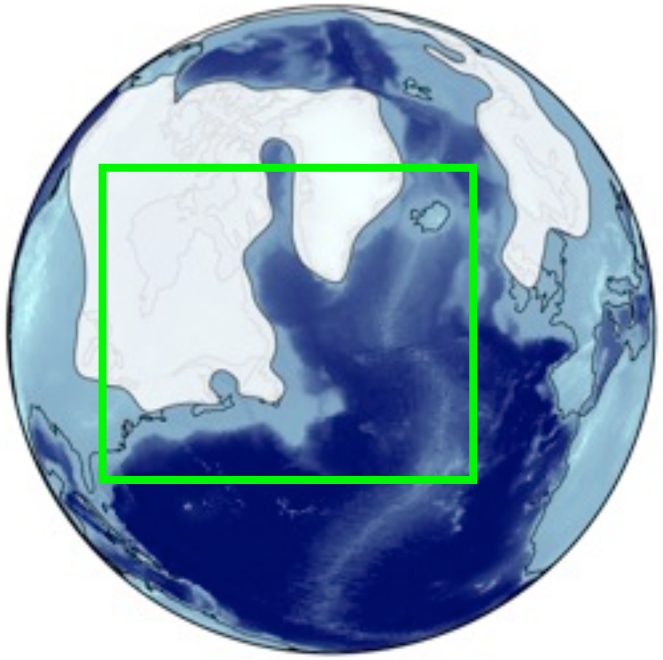

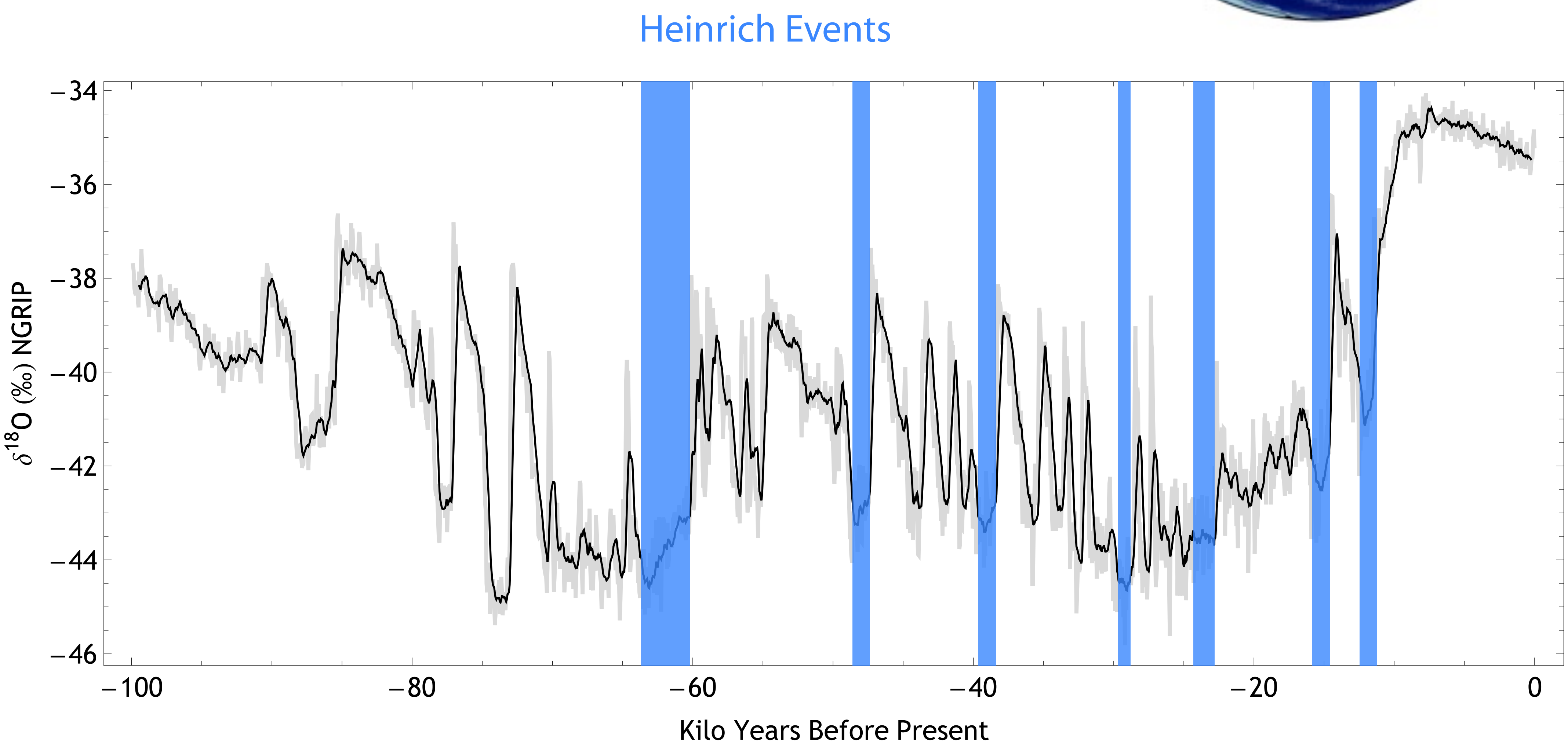

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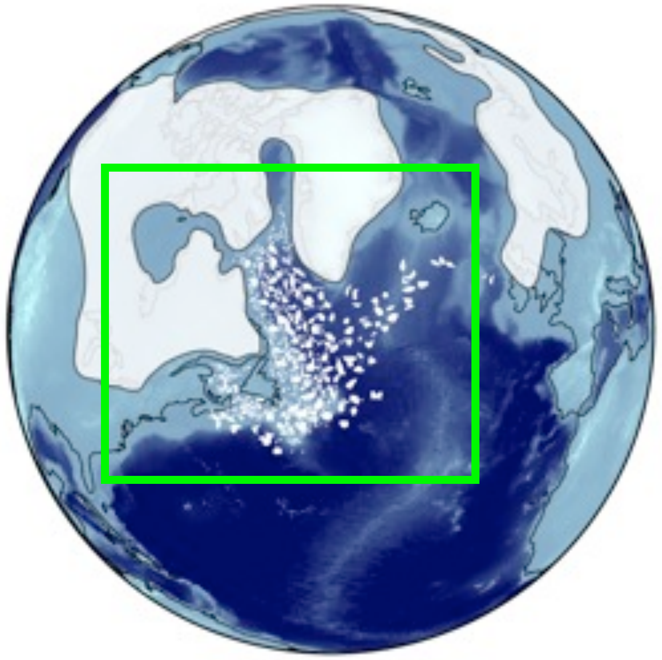
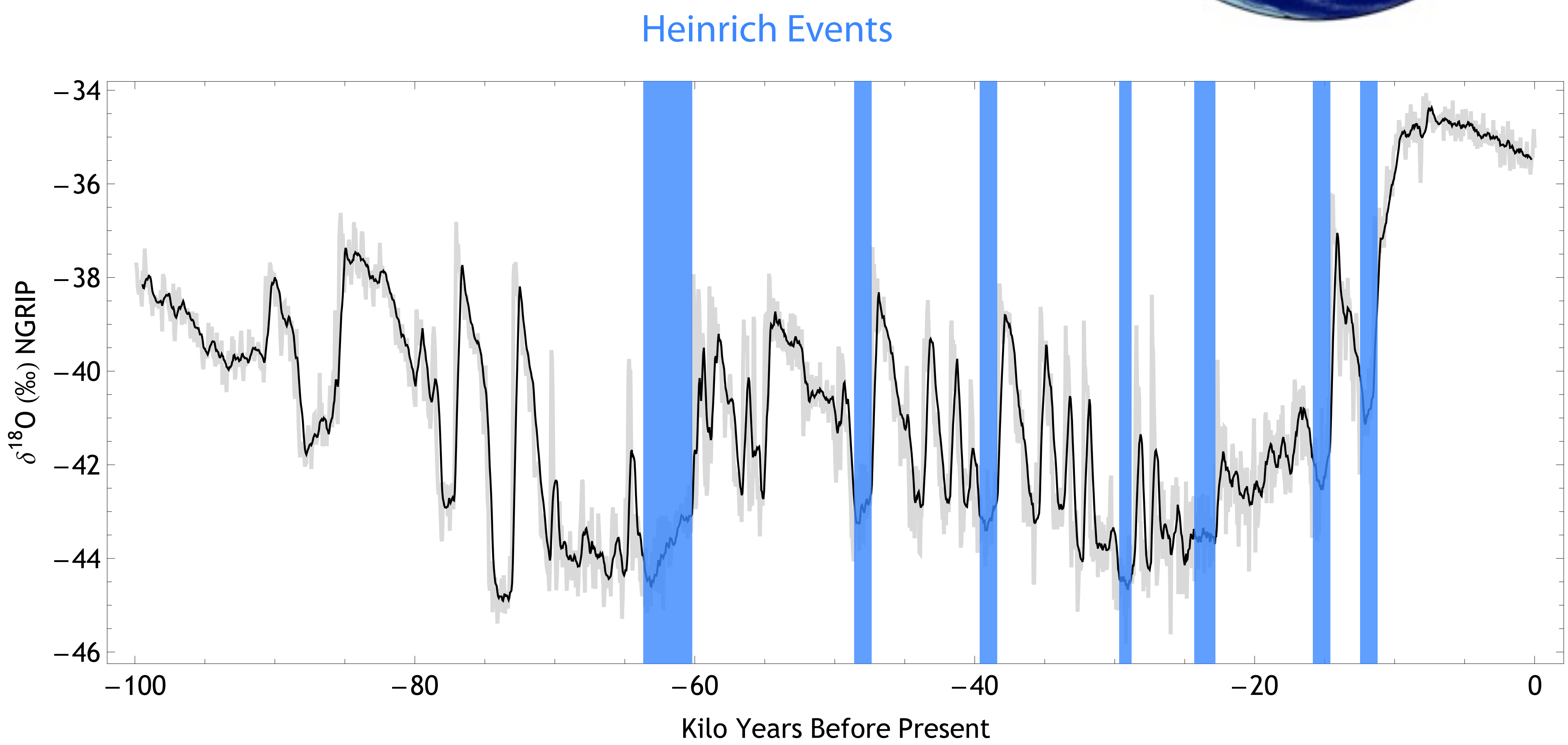


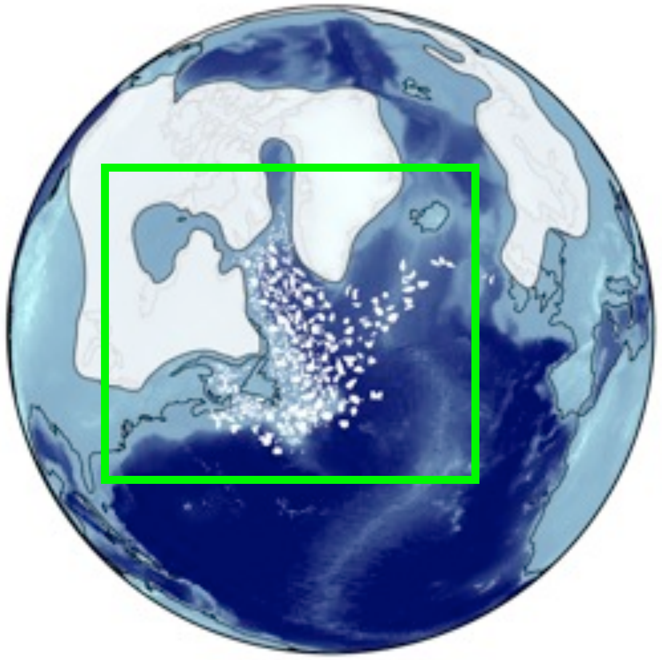


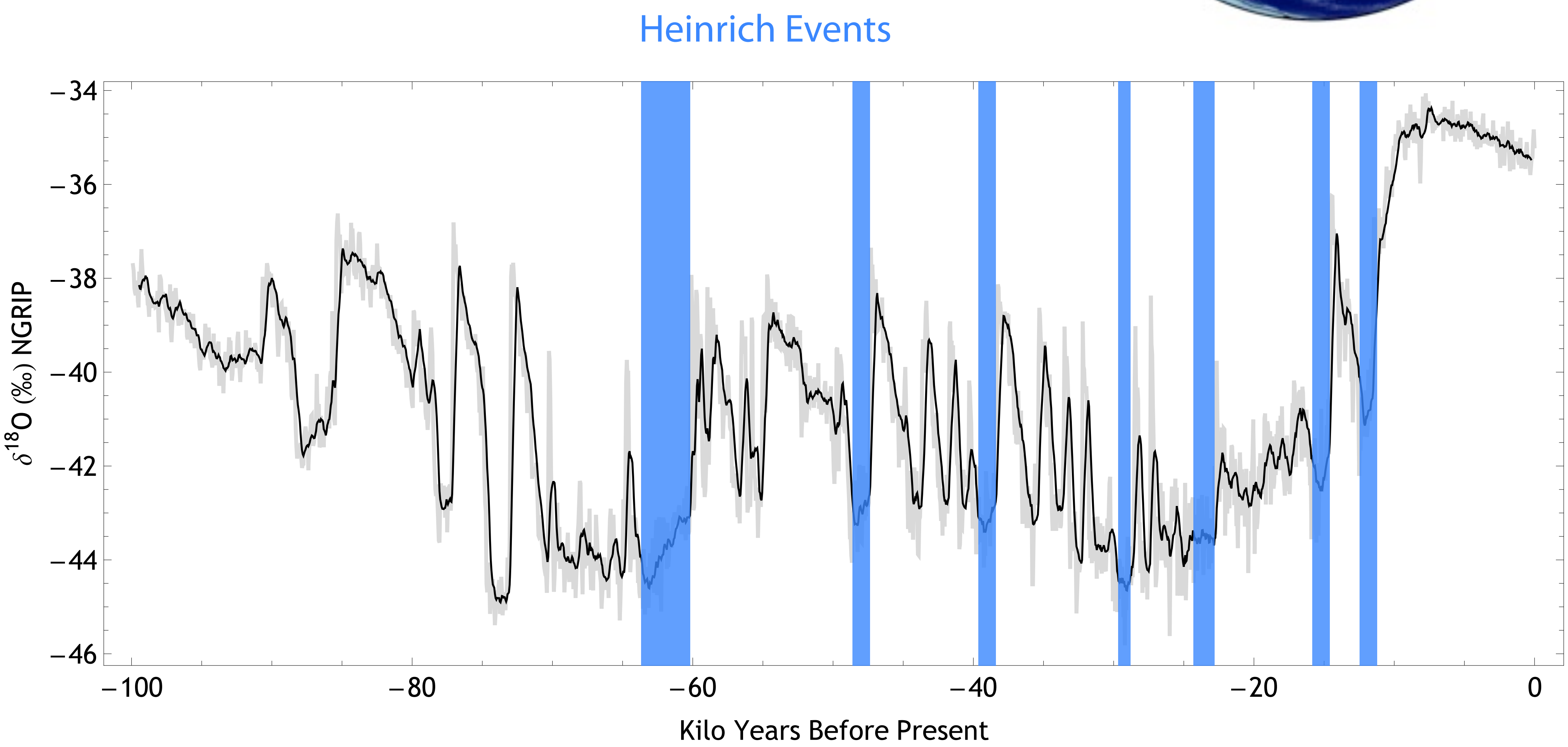
Past Climate

Quasi-periodic ice-sheet disintegration

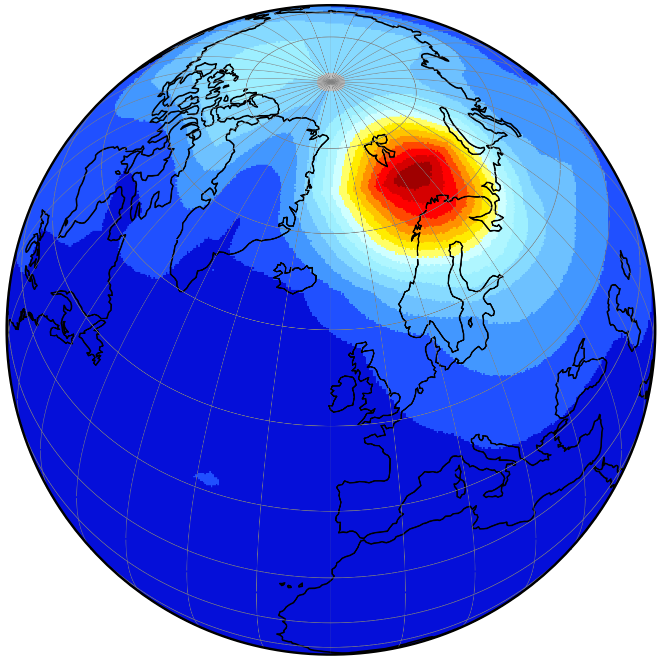
Large amounts of freshwater dumped into the North Atlantic

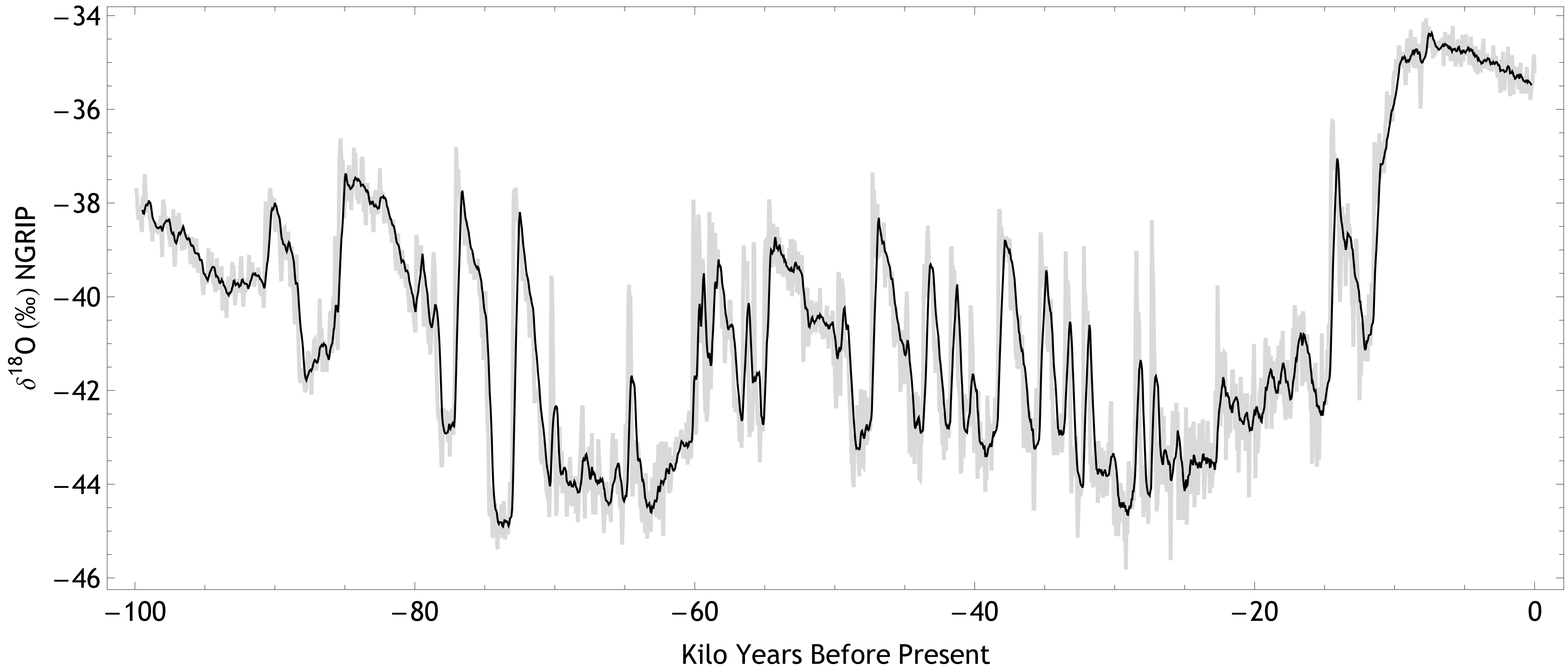
Probable cause for abrupt shifts in ocean circulation?





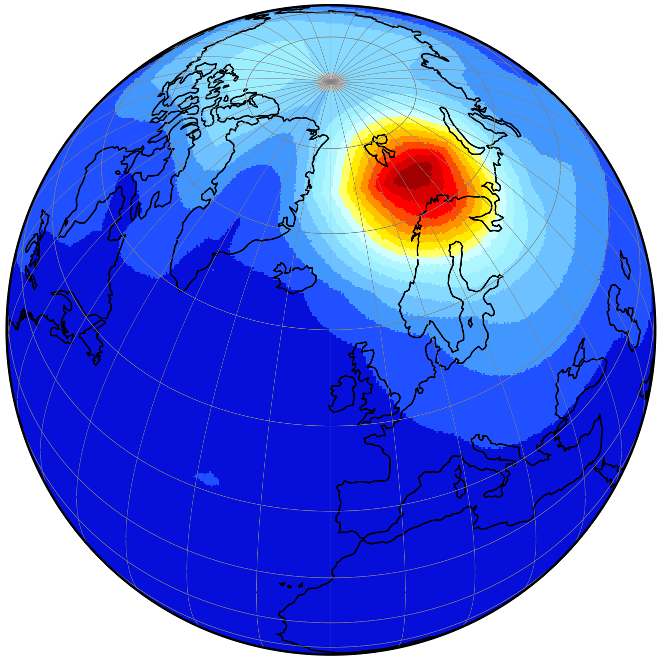
Past Climate

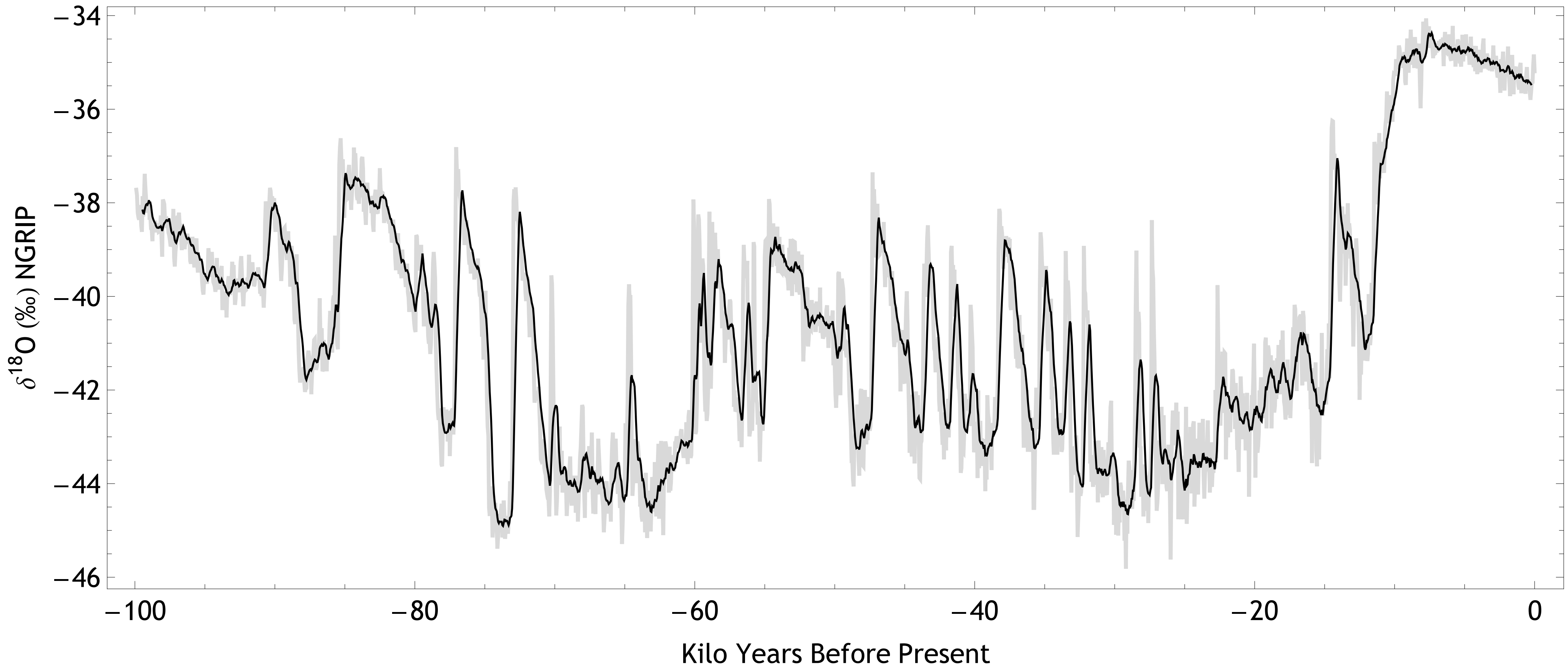




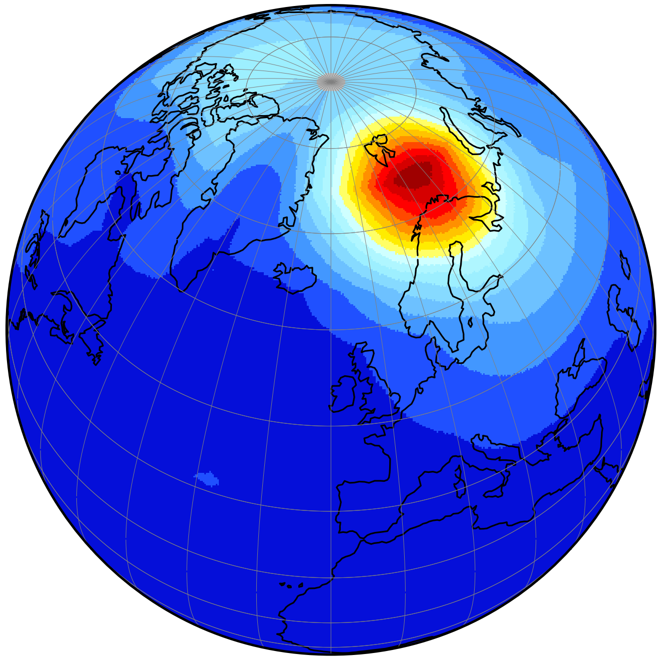
Past Climate

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



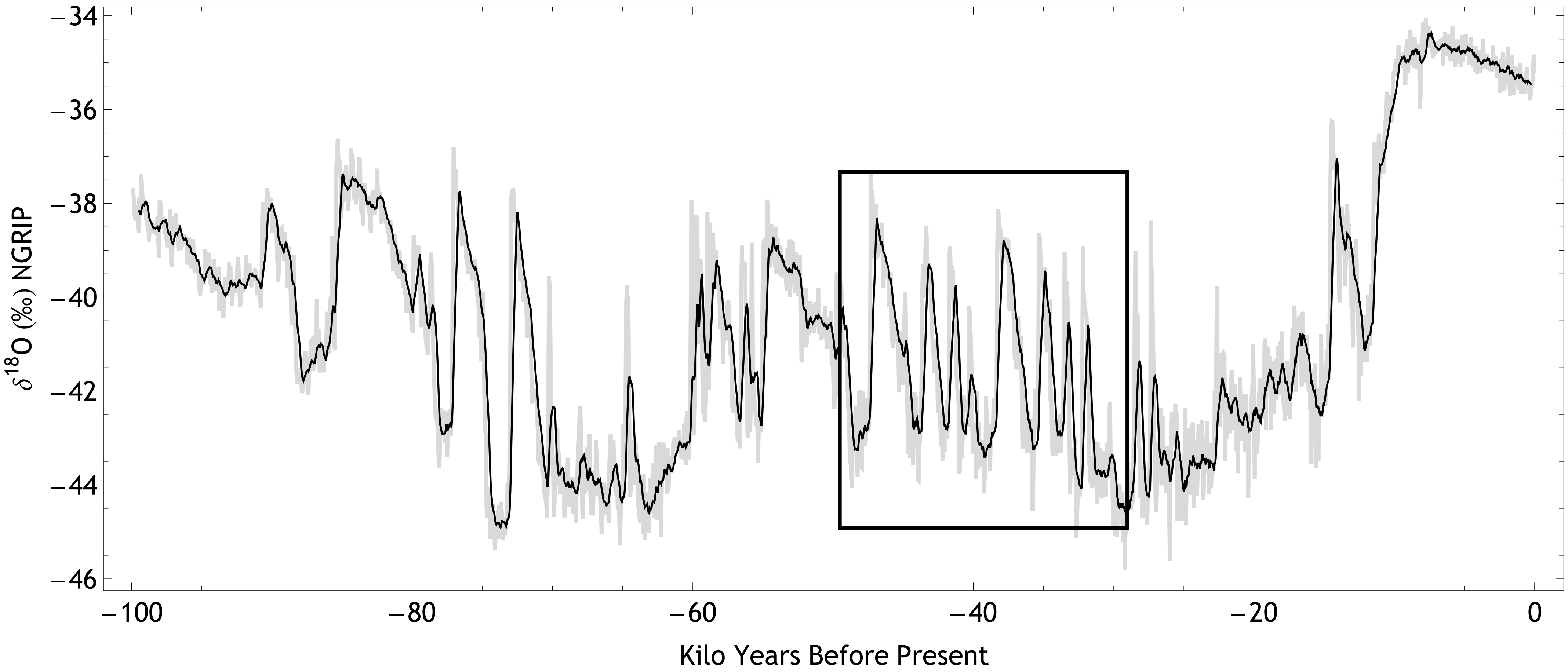


Past Climate



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

Pattern of fluctuations between 50 kyr and 30 kyr before present - **How / Why?**

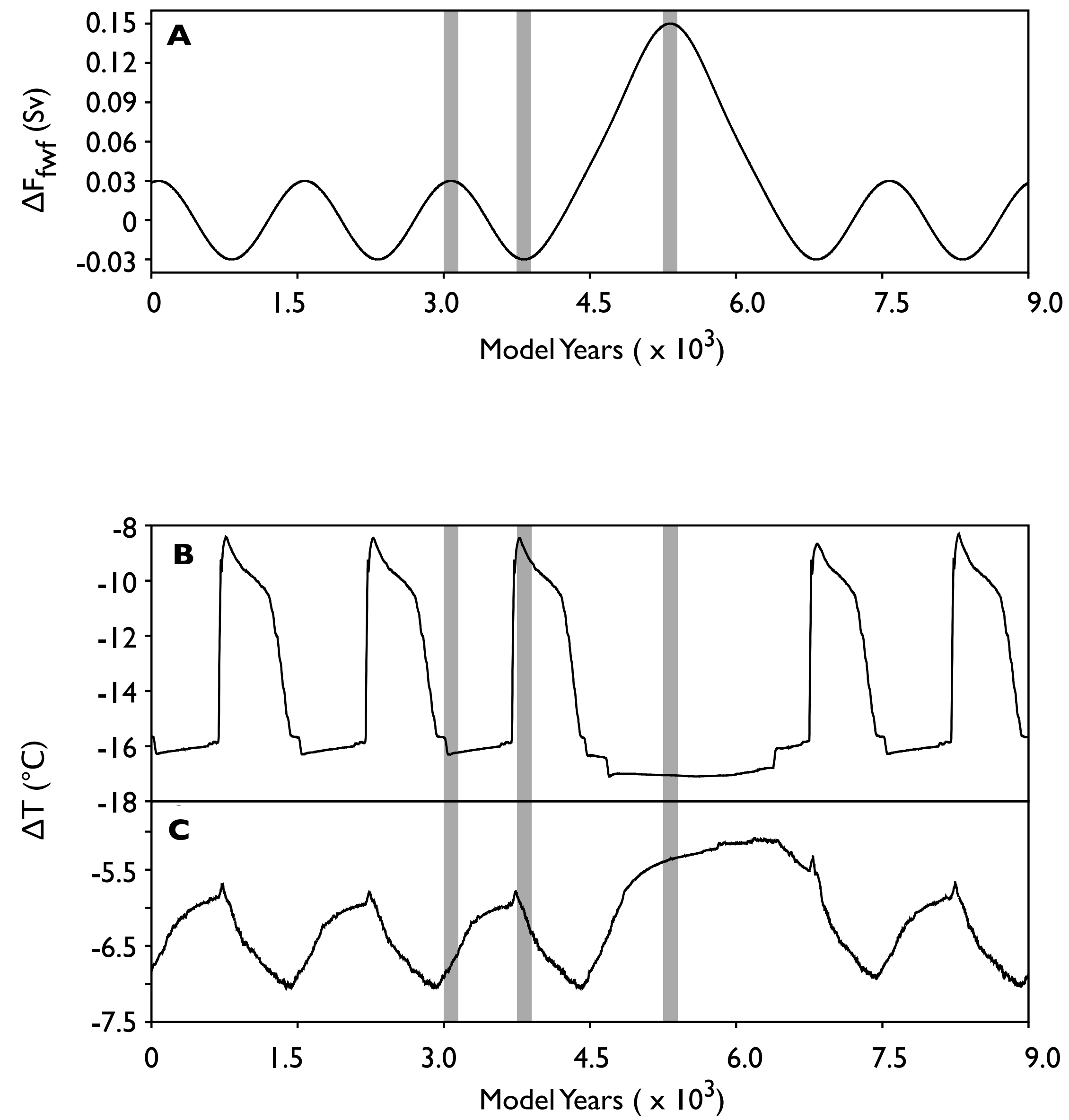


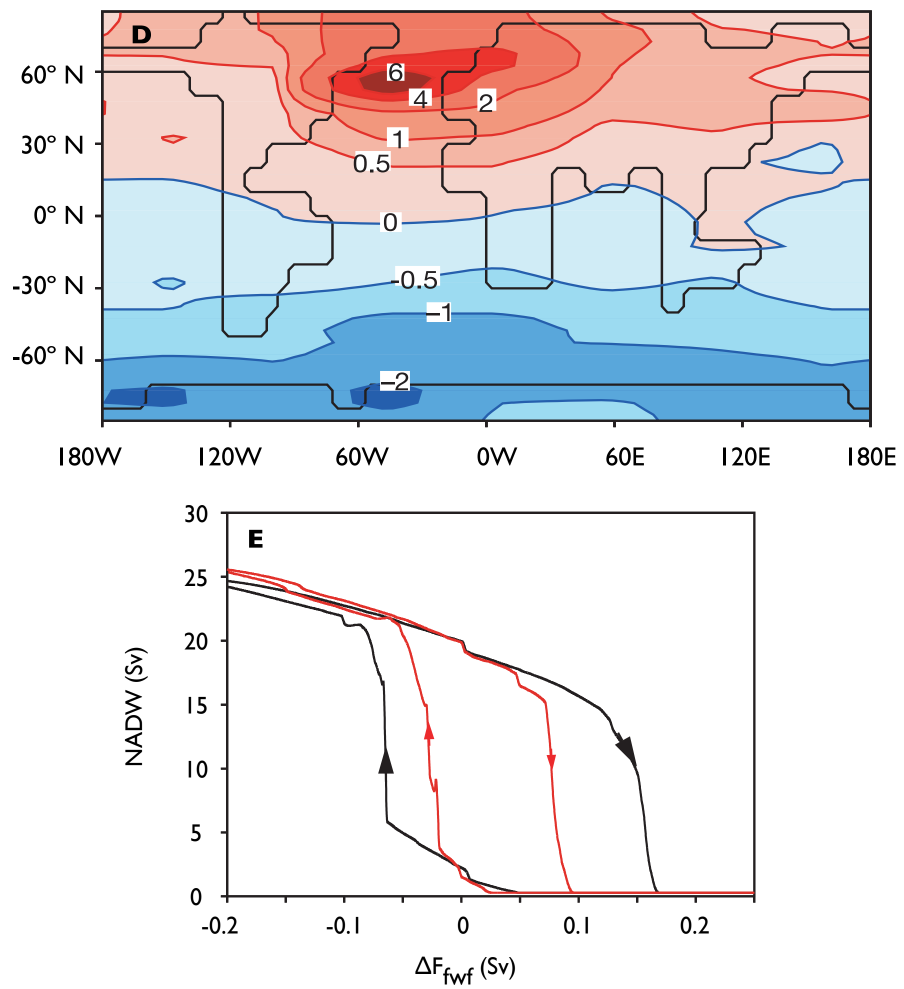
The Freshwater Hypothesis

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 et al., 2005)

However, comparison of proxy records for the climate and solar influence do not reveal a correlation
(Muscheler 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 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 and Sarachik, 1993; Sakai and Peltier, 1995; Haarsma et al. 2001; de Verdiére et al. 2006)

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

Questions

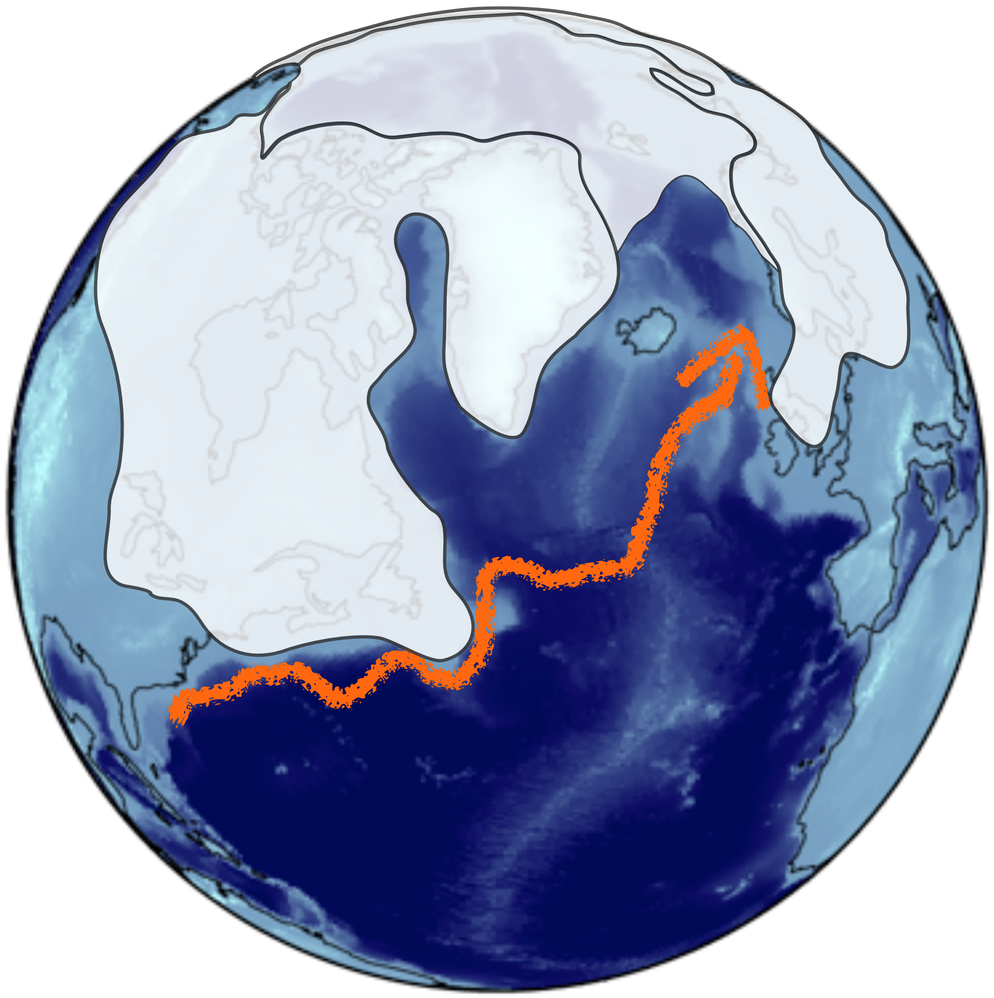
Origin of the 1,500 year cycles, pattern

Driven by external (astronomical) or internal (oceanic) mechanisms?

How are the D-O events connected to Heinrich events?

A Simple Dynamical Model

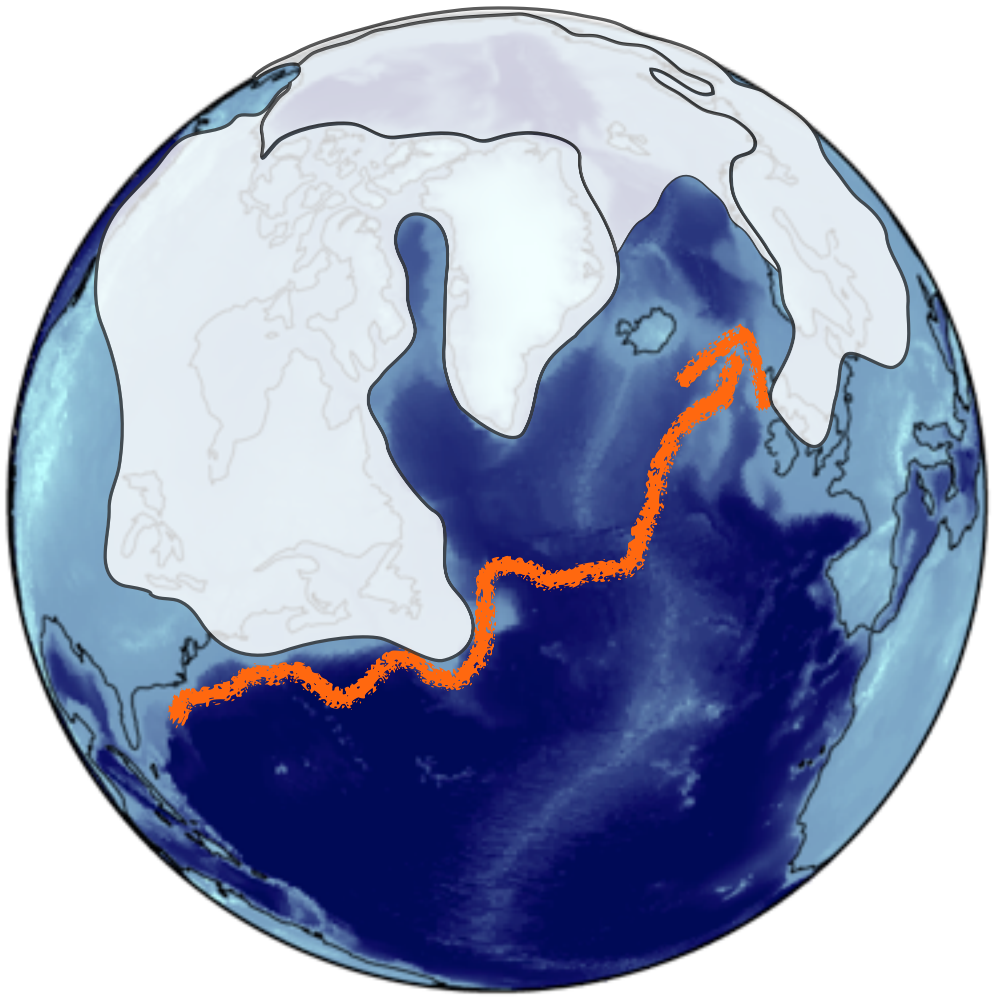
Goal:



A Simple Dynamical Model

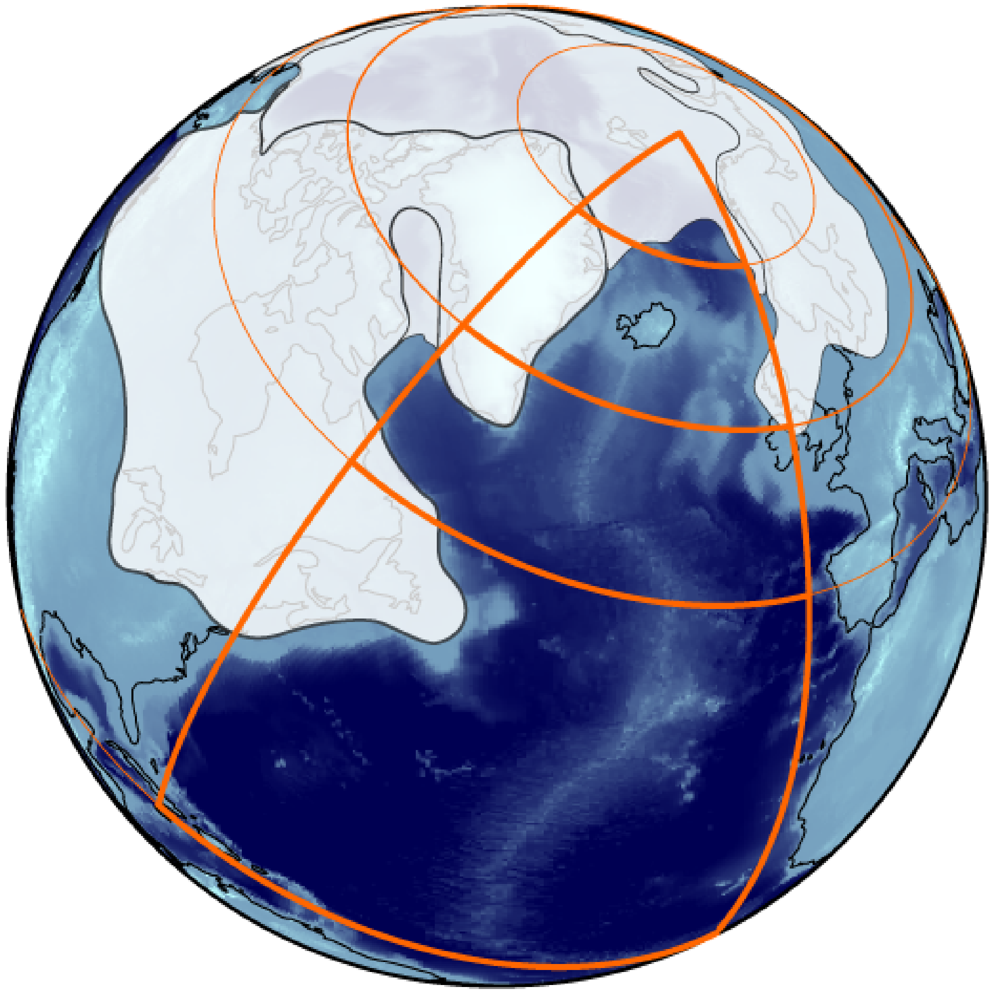
Goal:

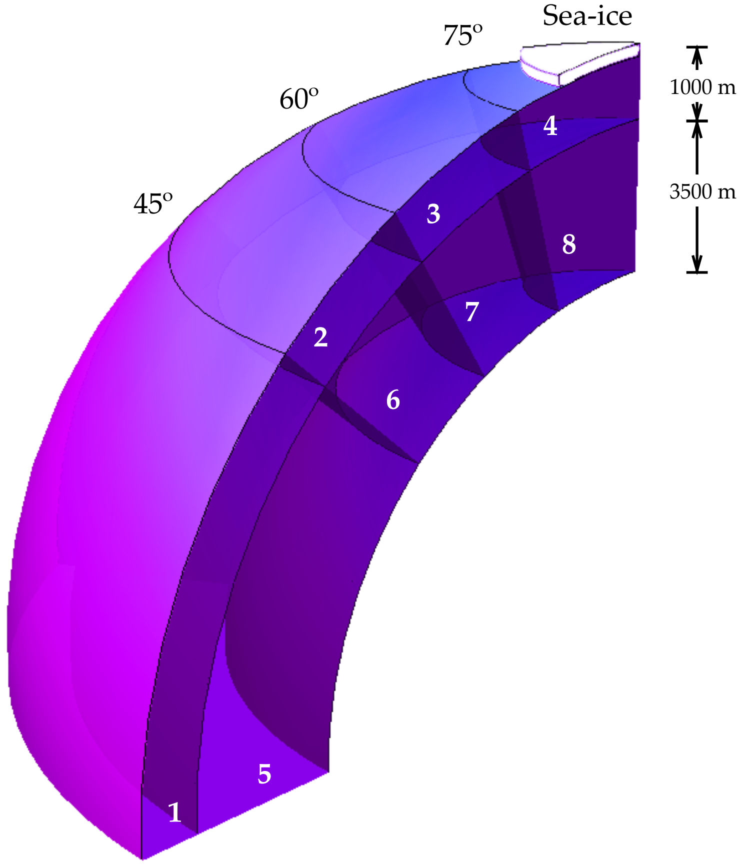
To examine the interaction between **circulation** (deep water formation) and **sea ice**



A Simple Dynamical Model

Spatial Layout





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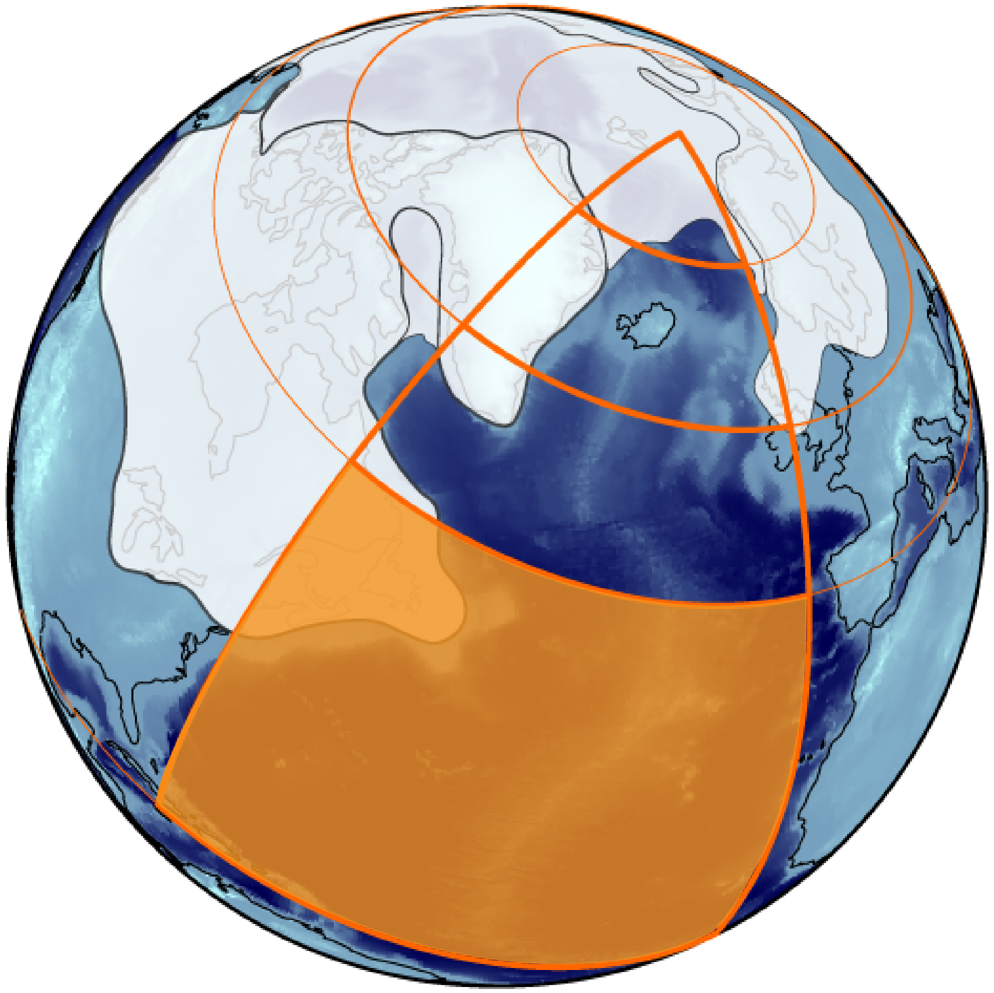
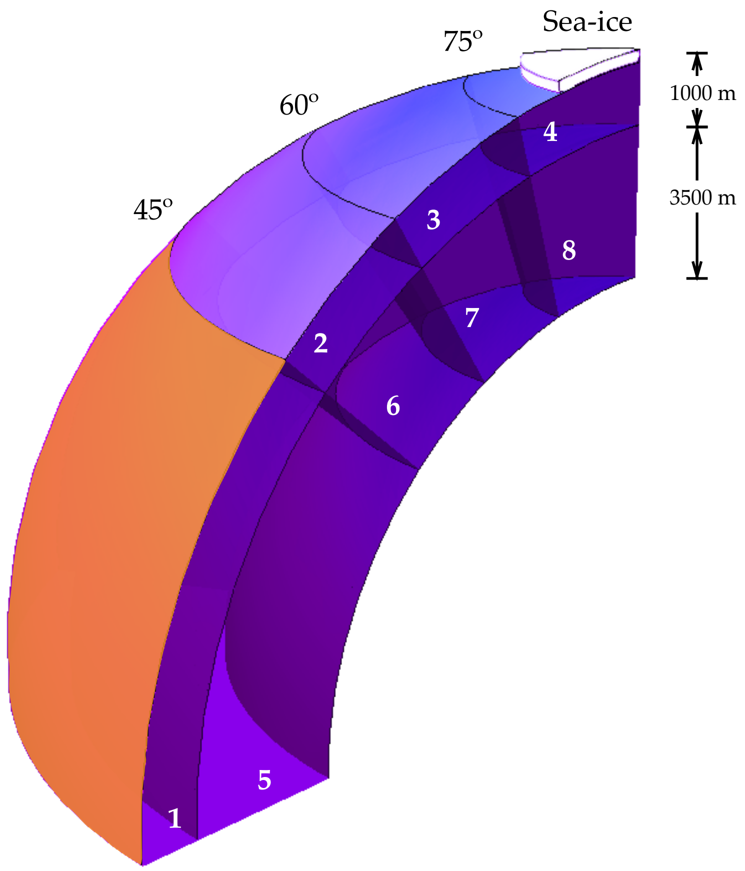


Tropical



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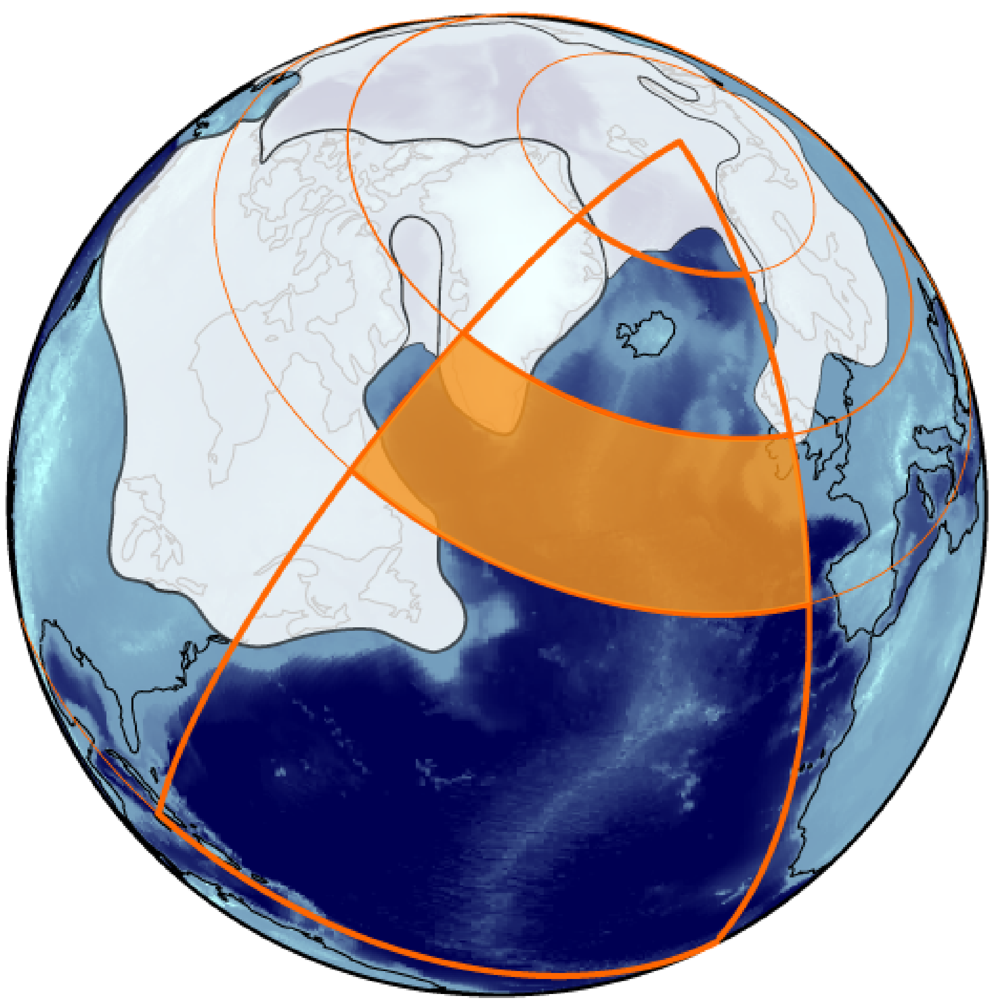
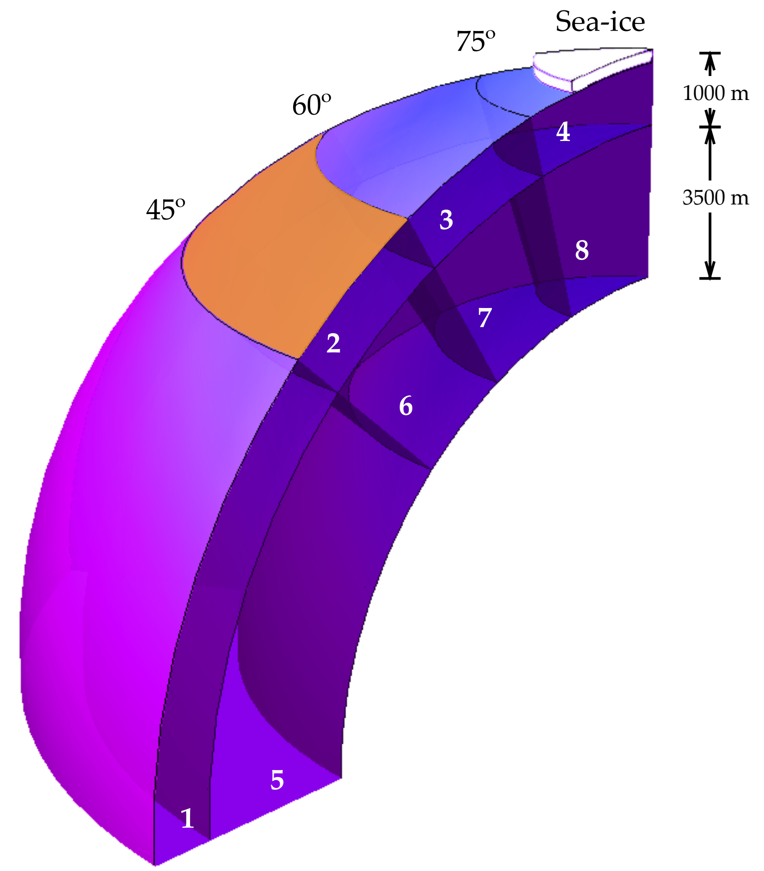


Subtropical



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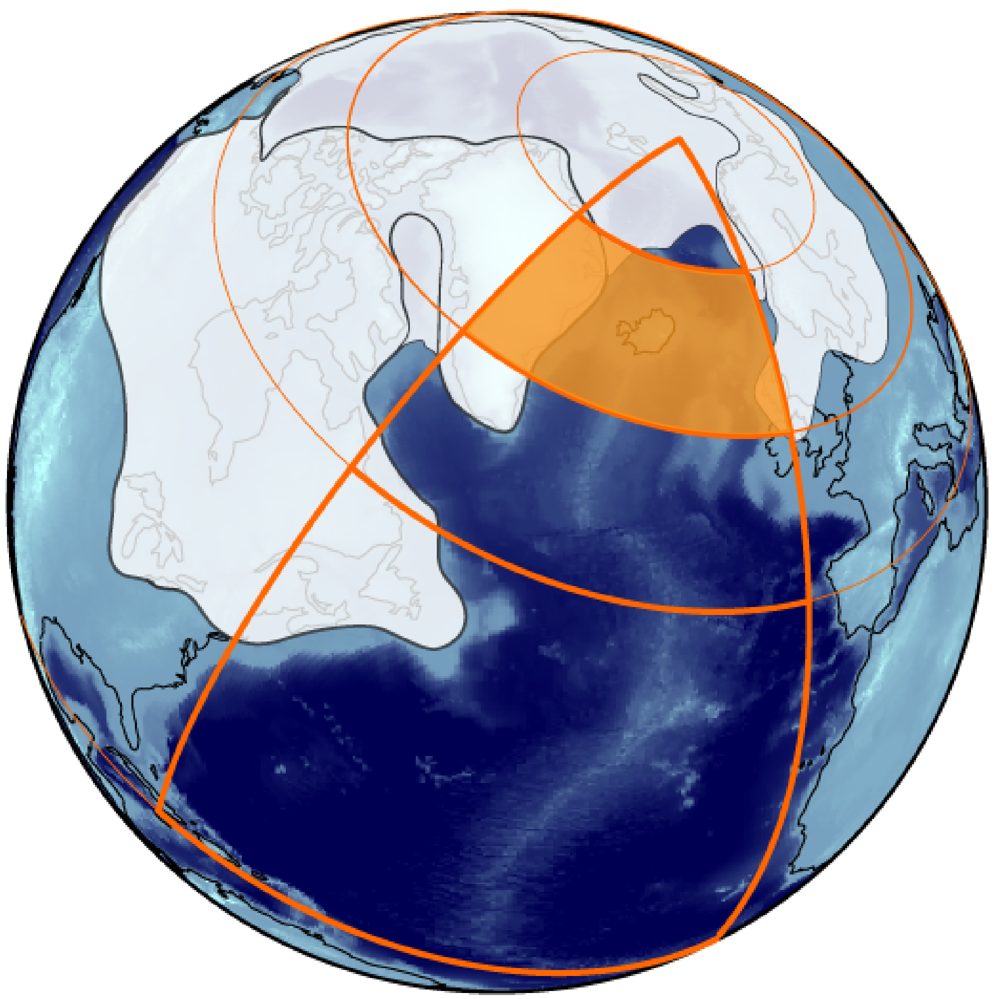
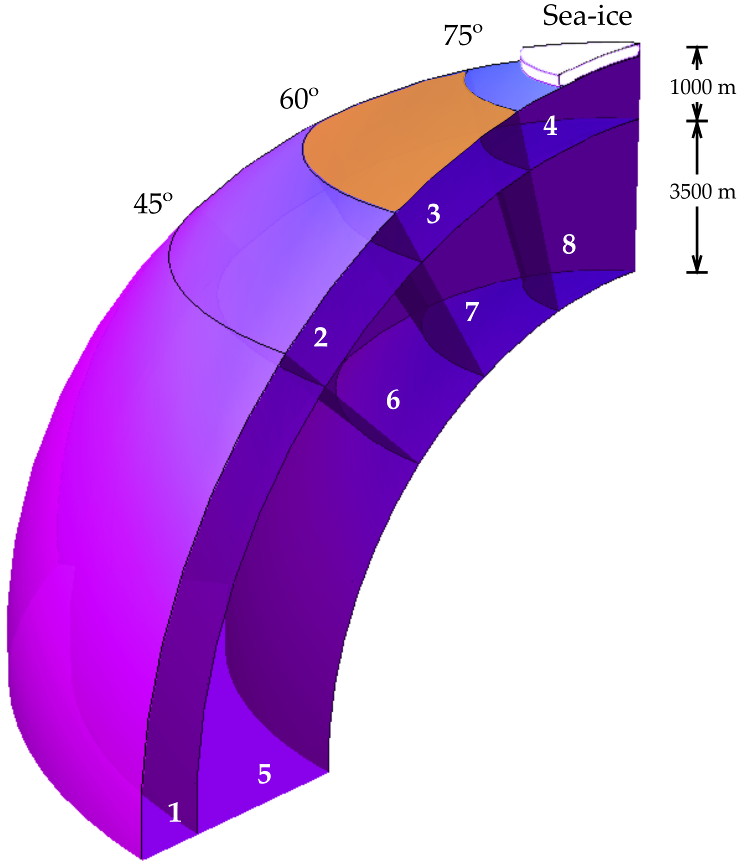


Subpolar



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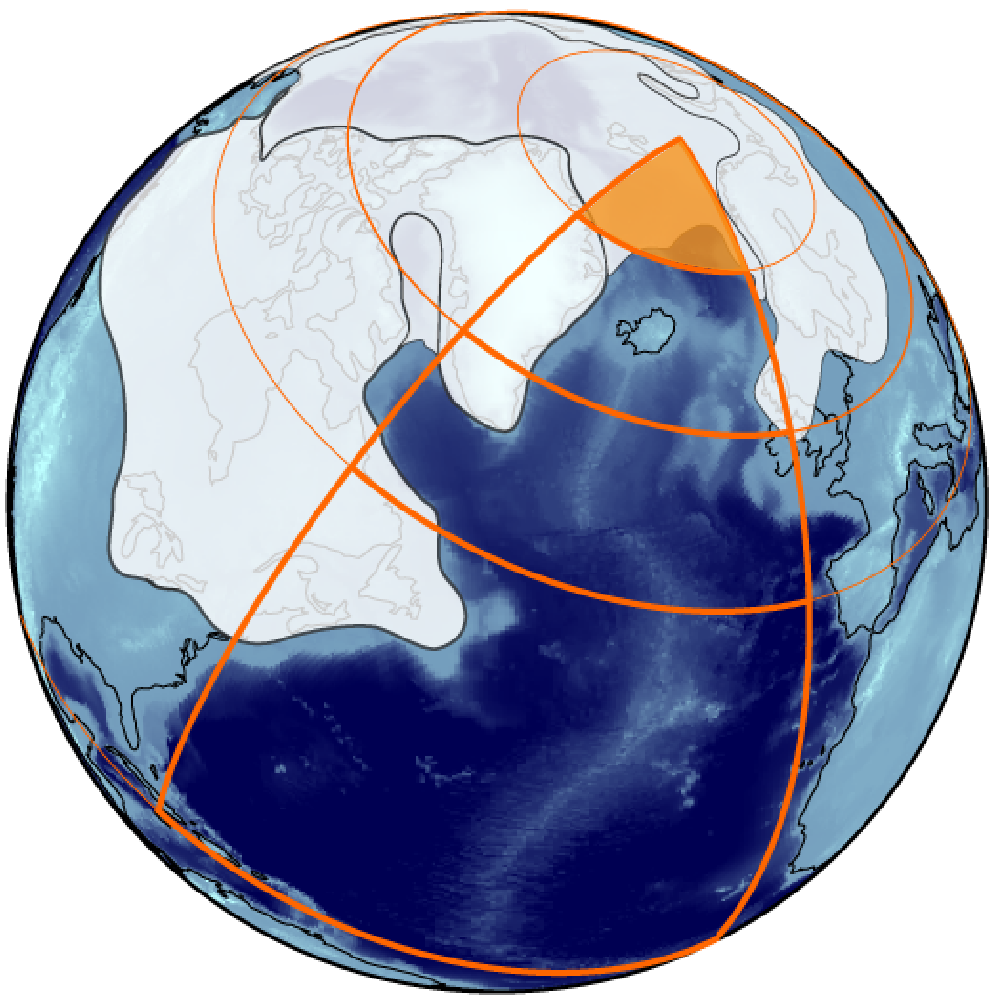
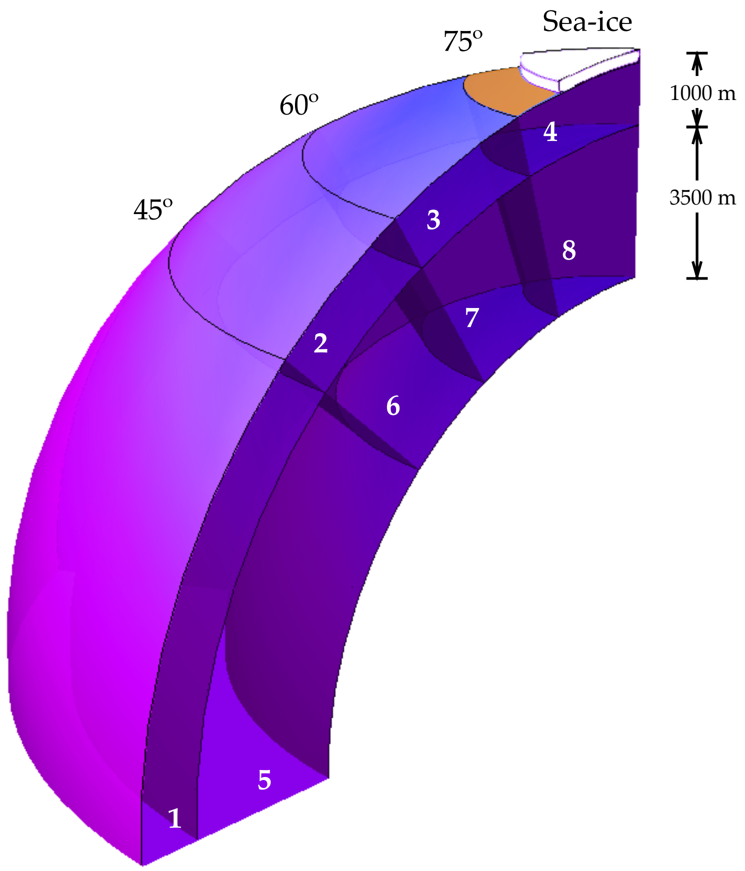


Polar



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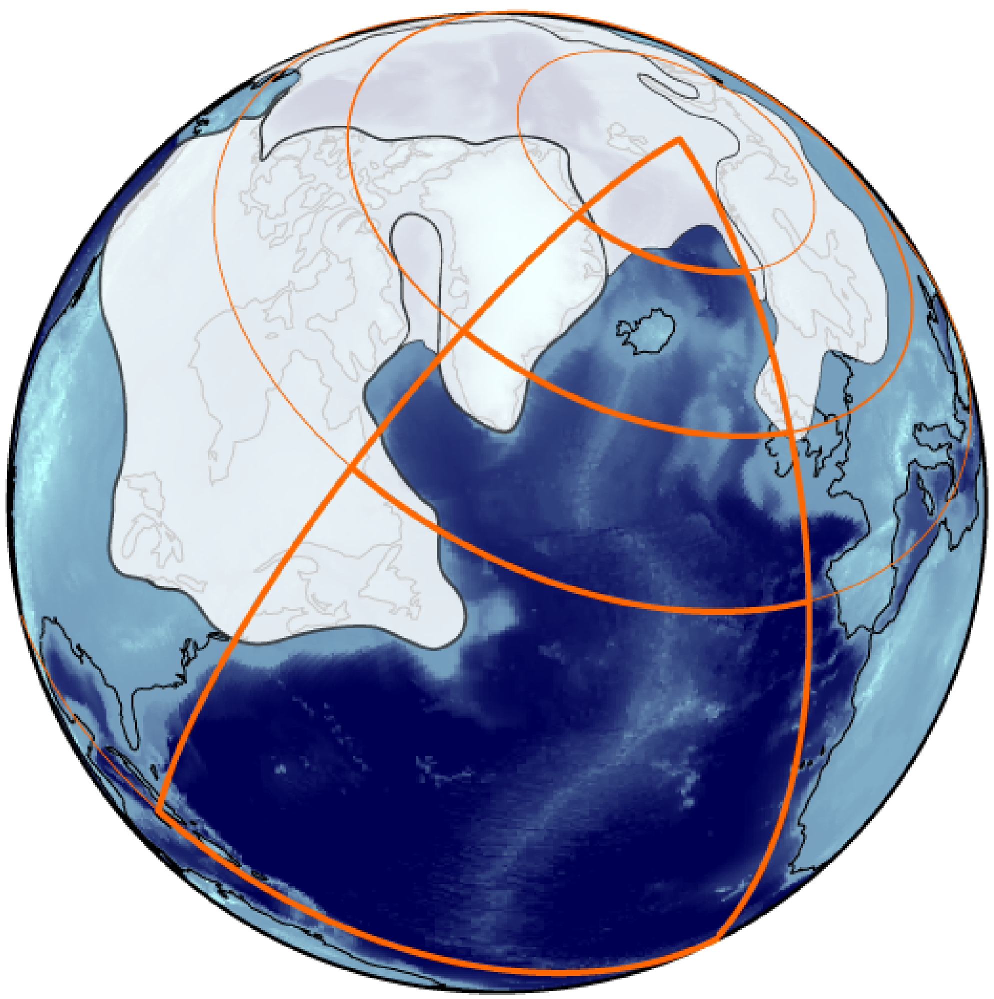
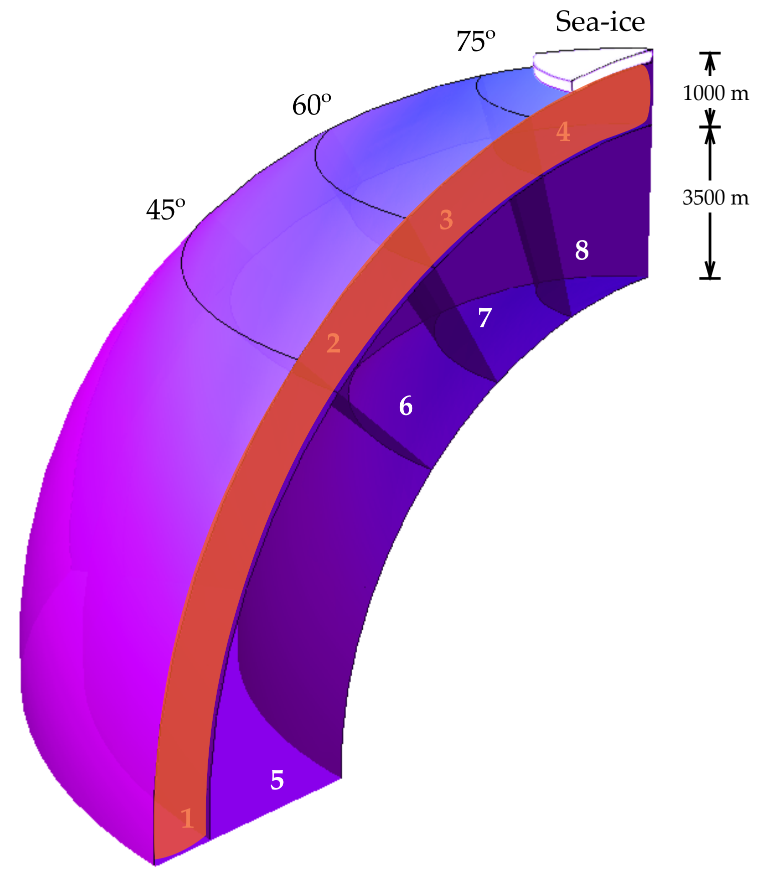
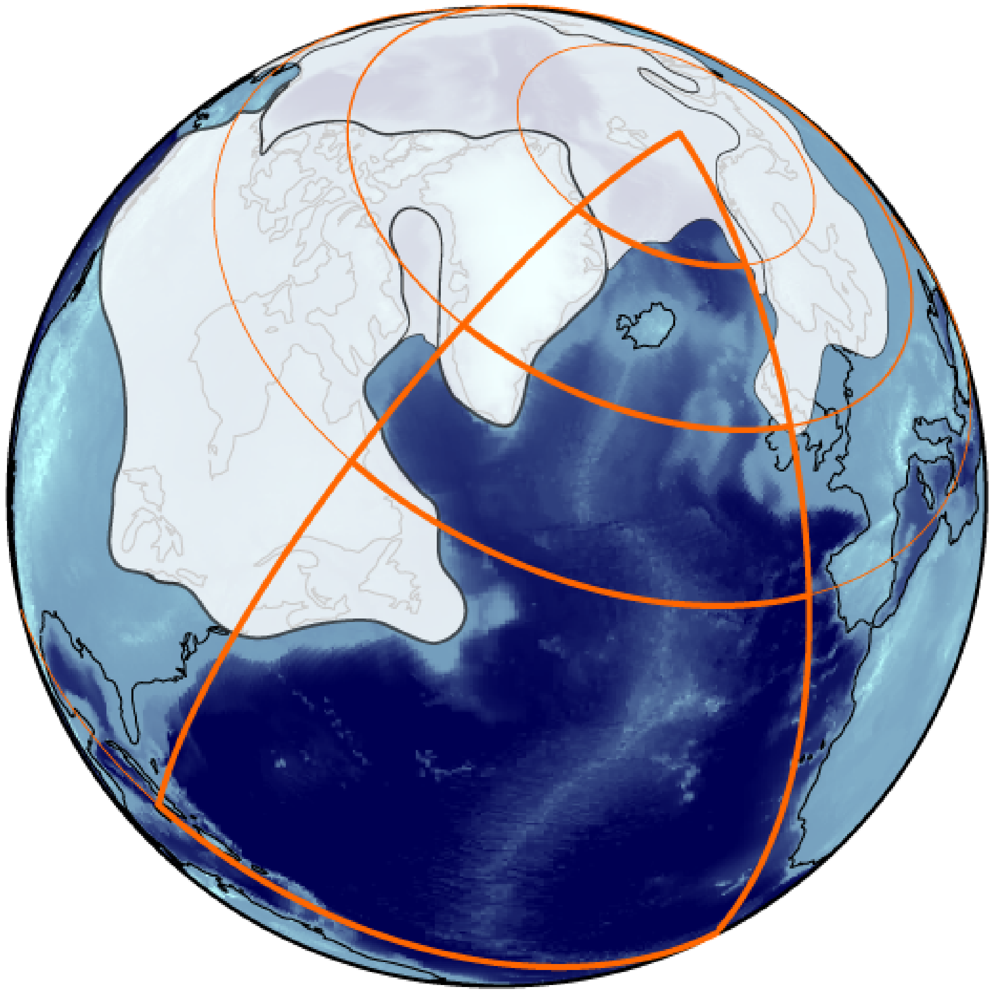


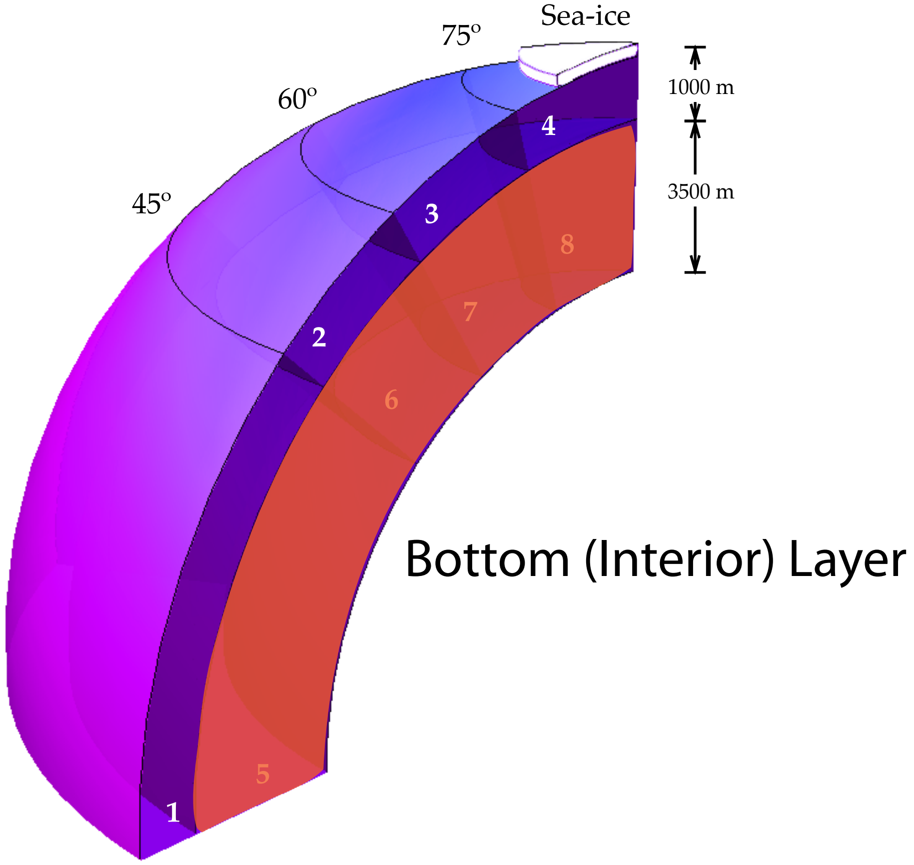


Top Mixed Layer

A Simple Dynamical Model

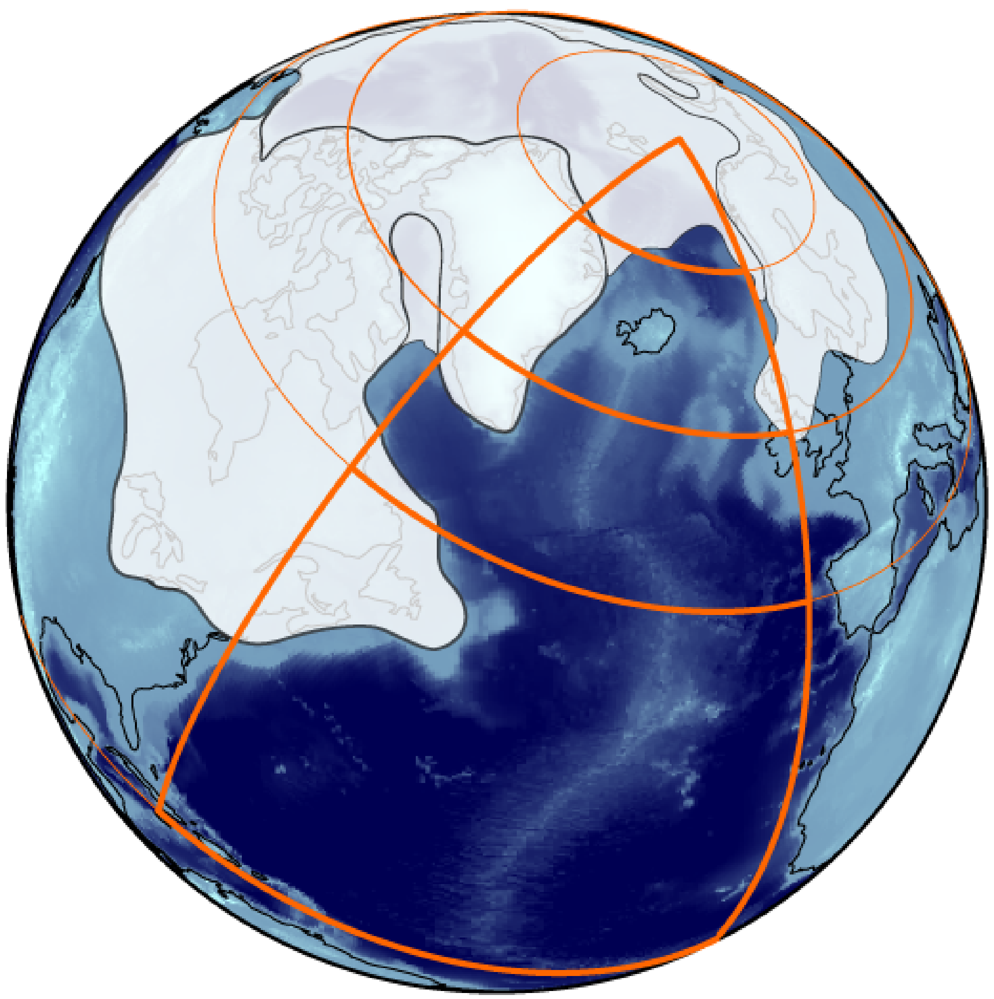
Spatial Layout



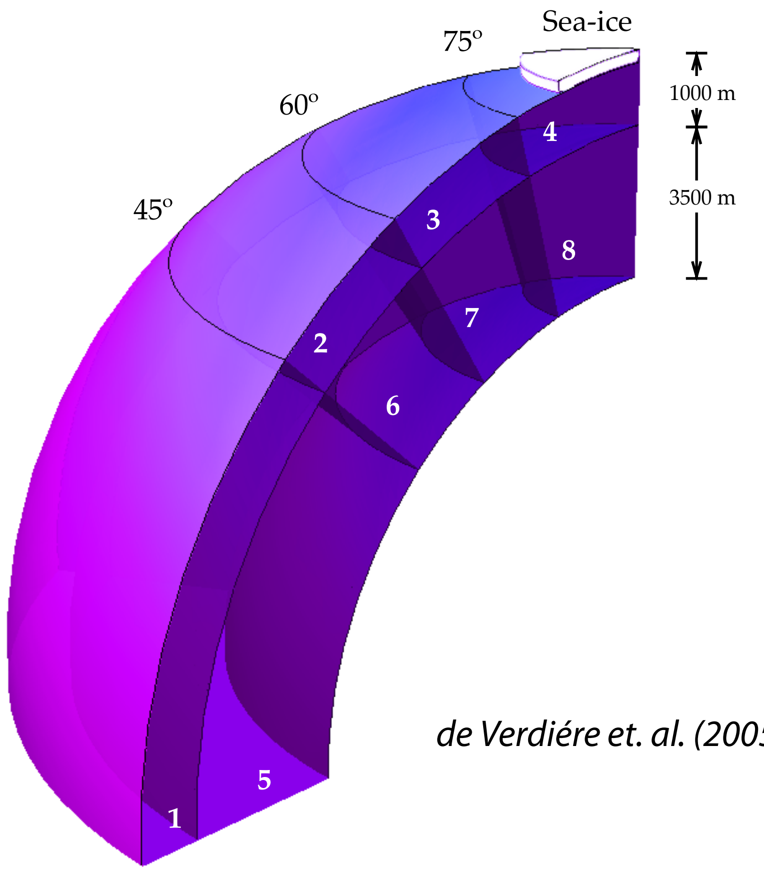


A Simple Dynamical Model

Spatial Layout



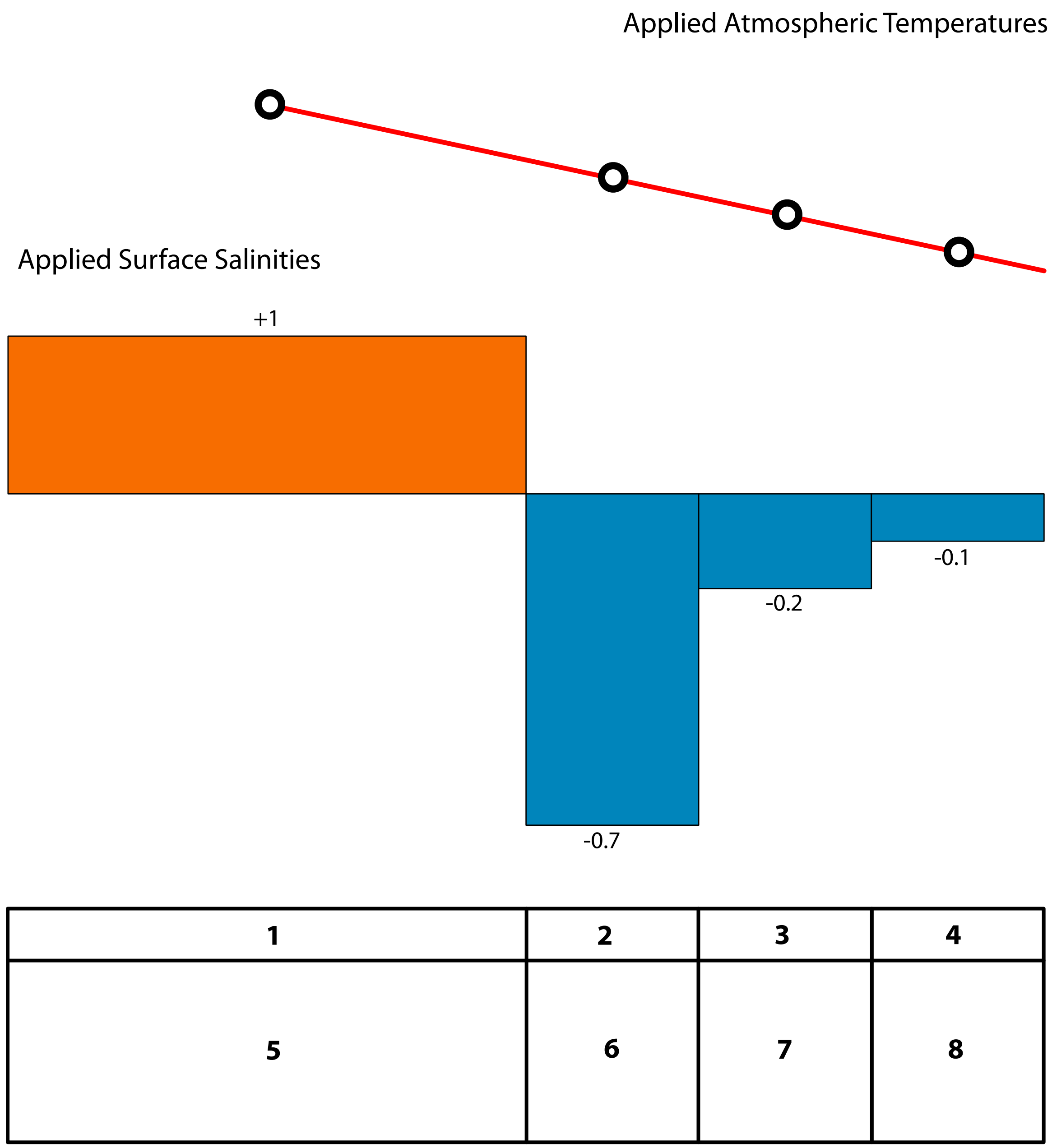
Gildor and Tziperman (2001)

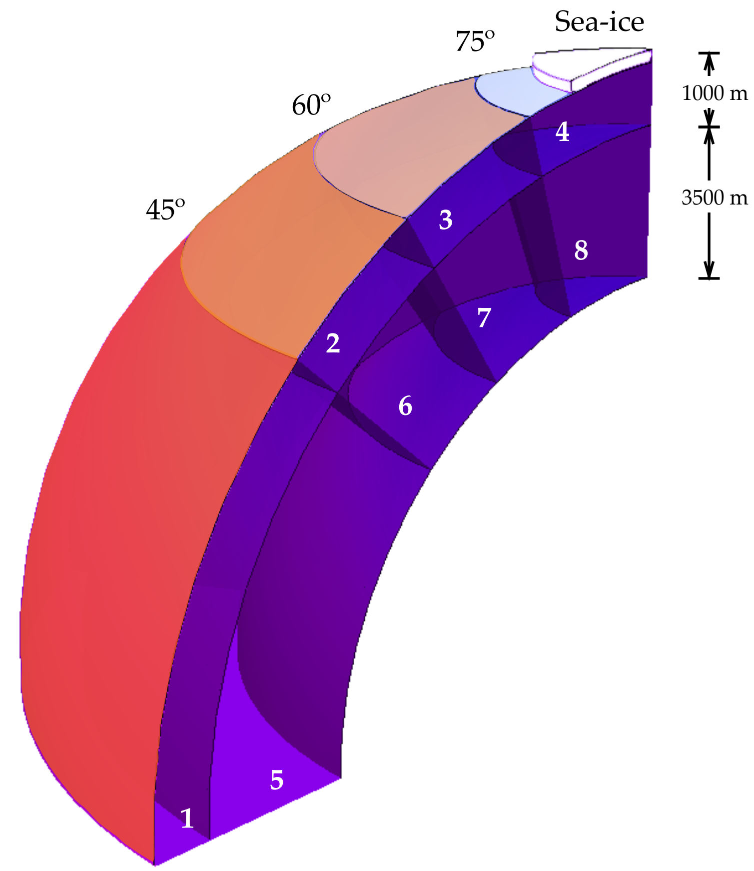


de Verdiére et. al. (2005)

A Simple Dynamical Model

Forcing

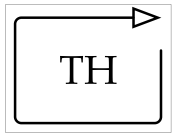




A Simple Dynamical Model

Physical Processes

$\psi_1 > 0$ —» Surface pole-bound flow (Thermal)



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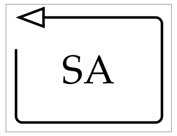

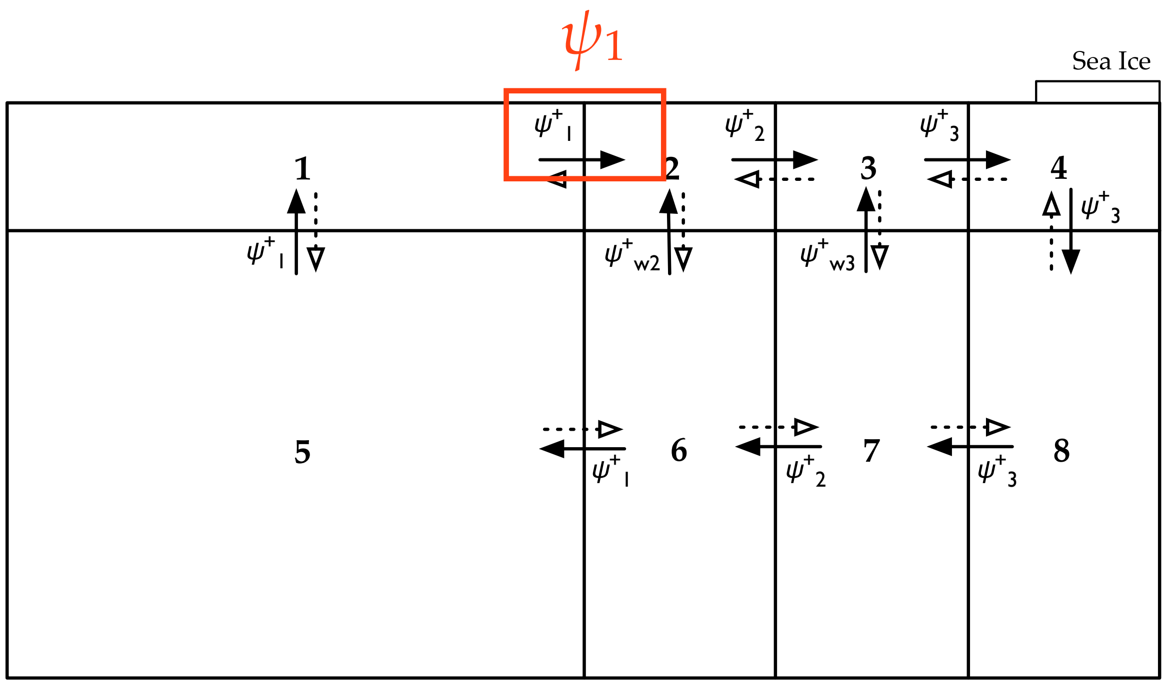

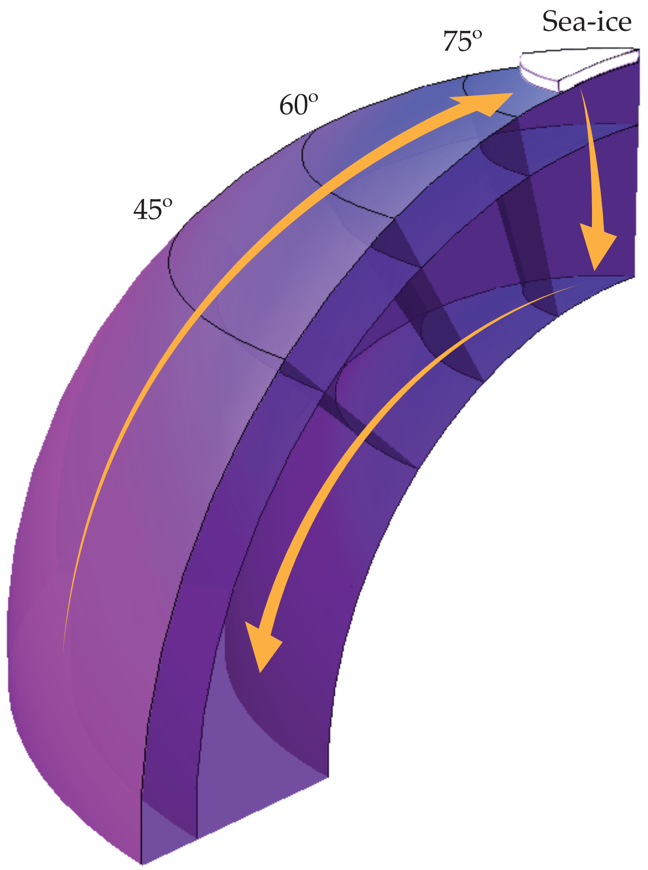

A Simple Dynamical Model

Physical Processes

Pressure driven circulation

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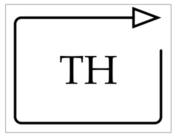

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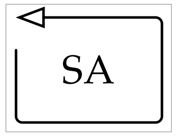

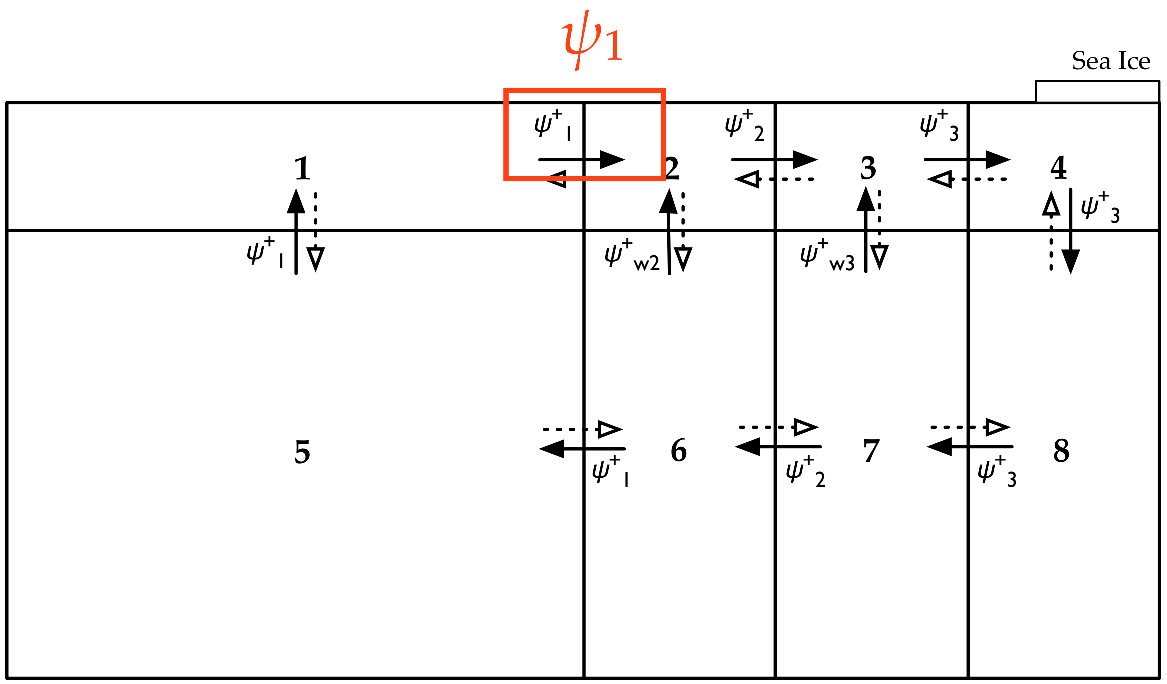

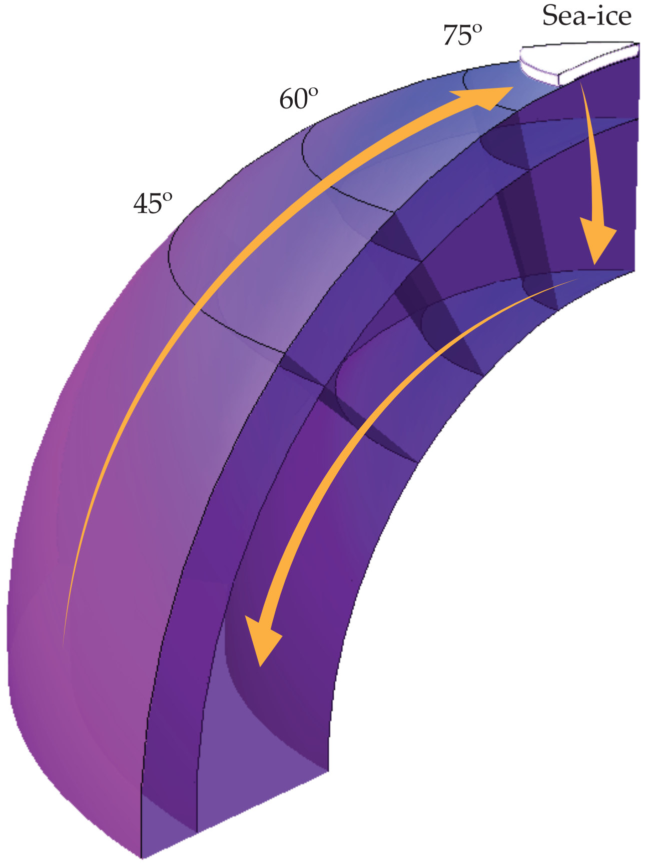

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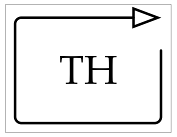

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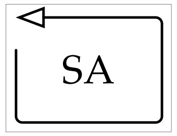
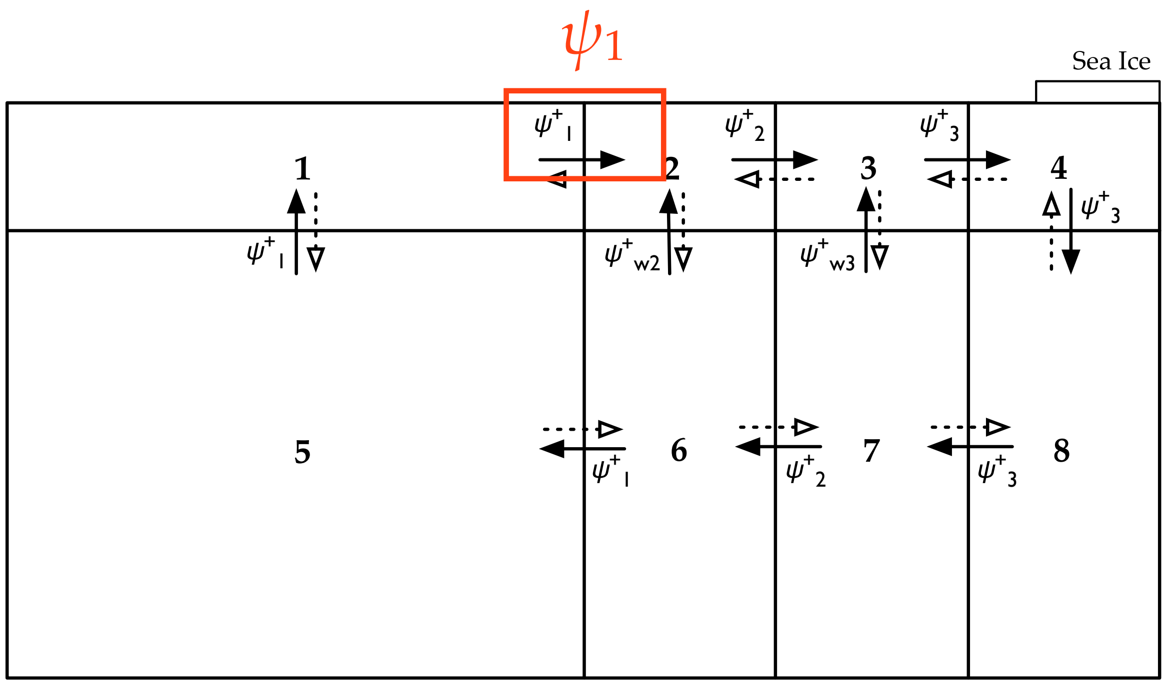
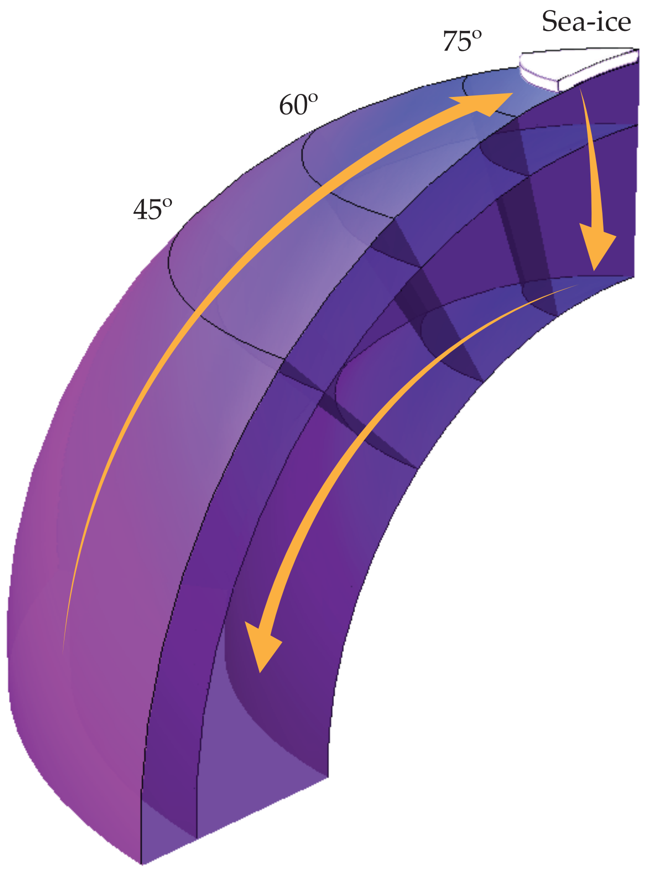


Sea ice grows on the polar box





A Simple Dynamical Model

Governing Equations

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

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

A Simple Dynamical Model

Governing Equations

Heat exchange with atmosphere

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

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

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Governing Equations

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

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

Evaporation/Precipitation (salinity forcing)

A Simple Dynamical Model

Governing Equations

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

Advective transport of heat and salt

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

A Simple Dynamical Model

Governing Equations

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

Diffusive transport of heat and salt

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

A Simple Dynamical Model

Governing Equations

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

Convection

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

A Simple Dynamical Model

Governing Equations

Enthalpy of formation/melting

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

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

A Simple Dynamical Model

Governing Equations

$$
\begin{aligned}
m_i C_p \dot{T}_i &= \dot{Q}_i + \rho_0 C_p \psi_{i,j} T_j + \rho_0 C_p D_{i,j} T_j + Co(T_i) + \dot{Q}_{\text{ice}} \\
m_i \dot{S}_i &= \xi_i + \rho_0 \psi_{i,j} S_j + \rho_0 D_{i,j} S_j + Co(S_i) + \underbrace{\boxed{S_0 \dot{B}}}_{\text{Brine rejection}}
\end{aligned}
$$

A Simple Dynamical Model

Governing Equations

$$
\begin{aligned}
m_i C_p \dot{T}_i &= \dot{Q}_i + \rho_0 C_p \psi_{i,j} T_j + \rho_0 C_p D_{i,j} T_j + Co(T_i) + \dot{Q}_{\mathrm{ice}} \\
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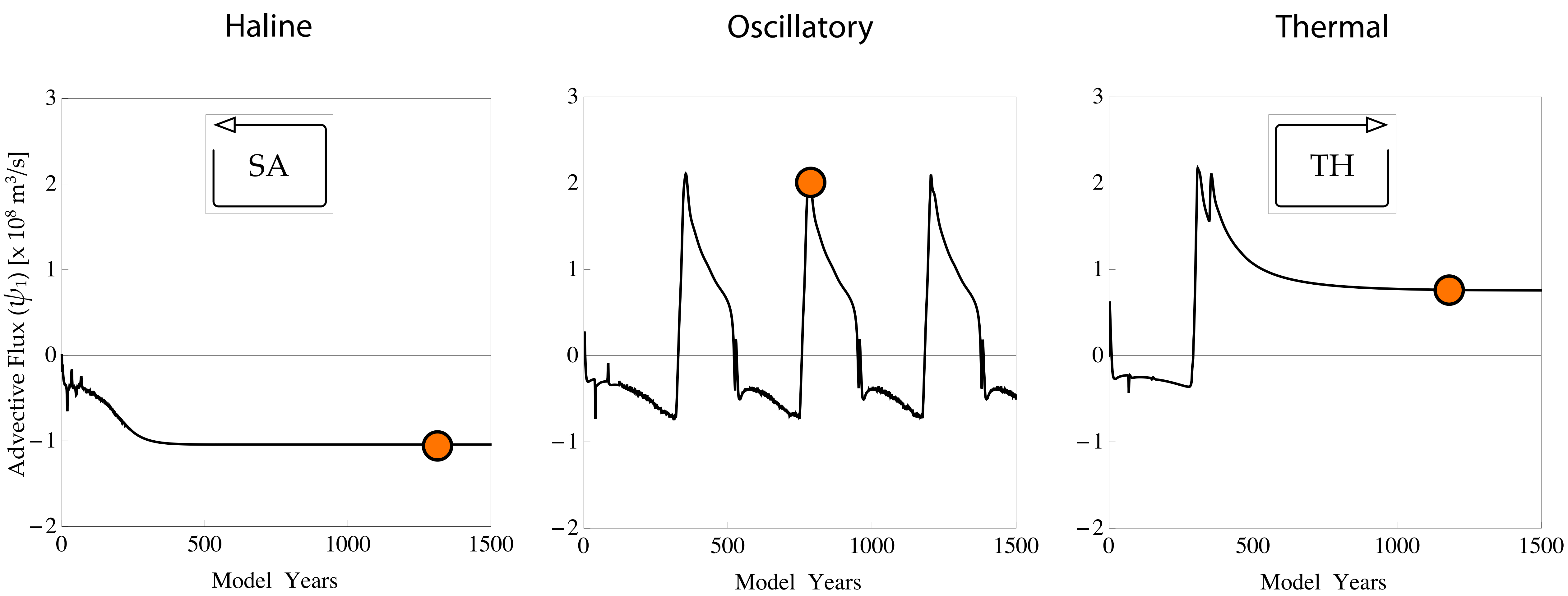
\end{aligned}
$$

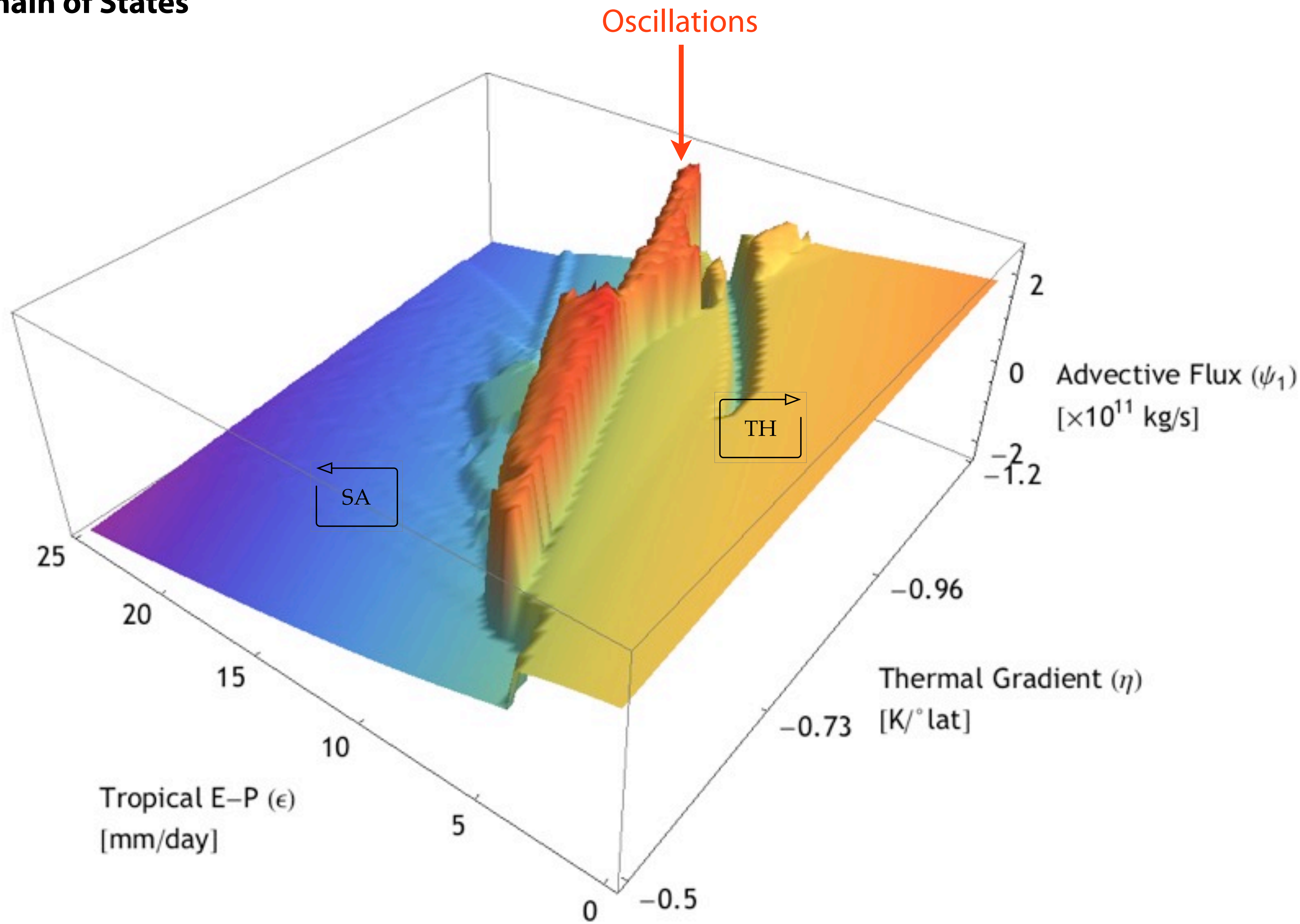
Solutions

Circulation States



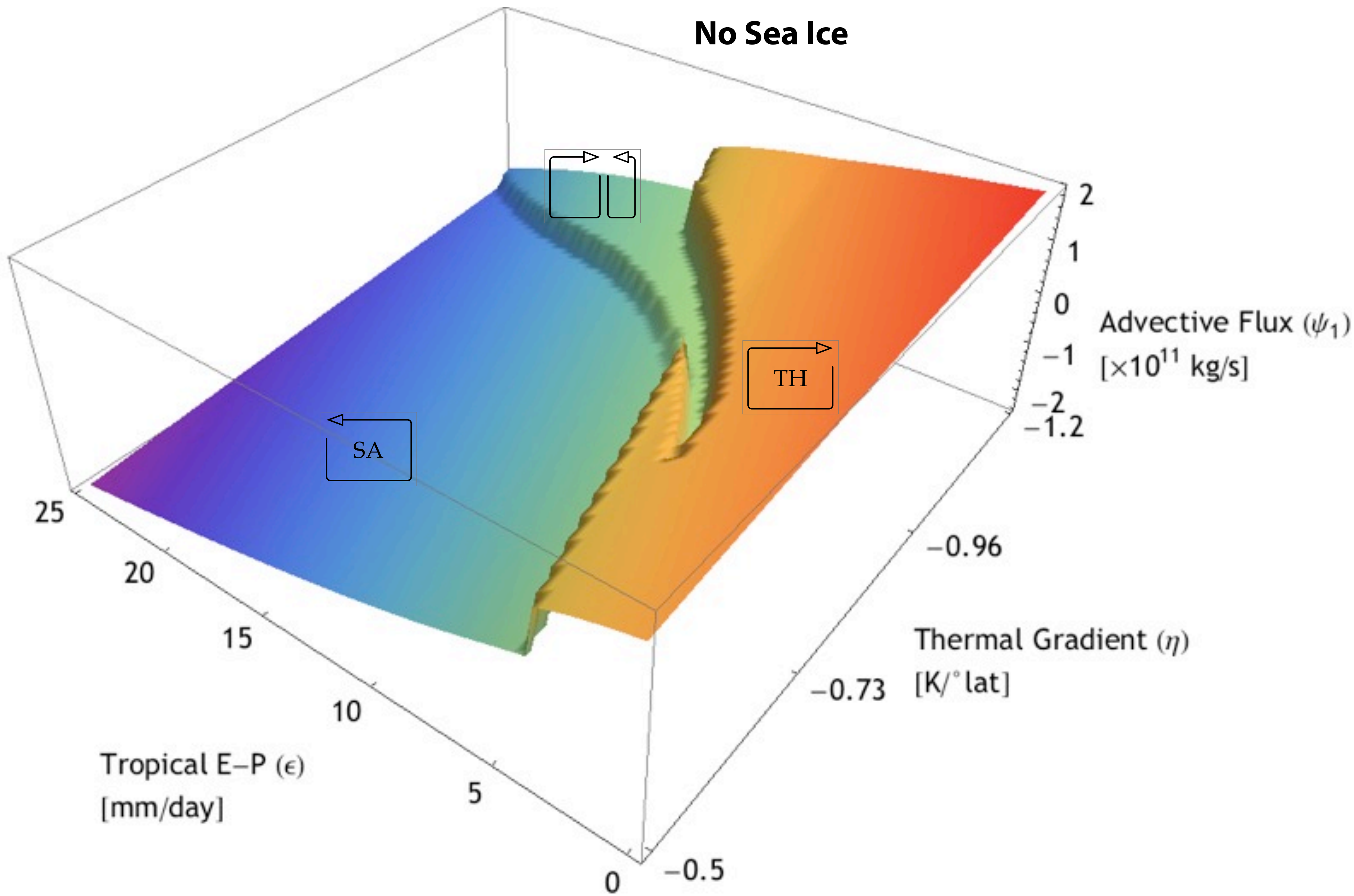
Solutions

Domain of States

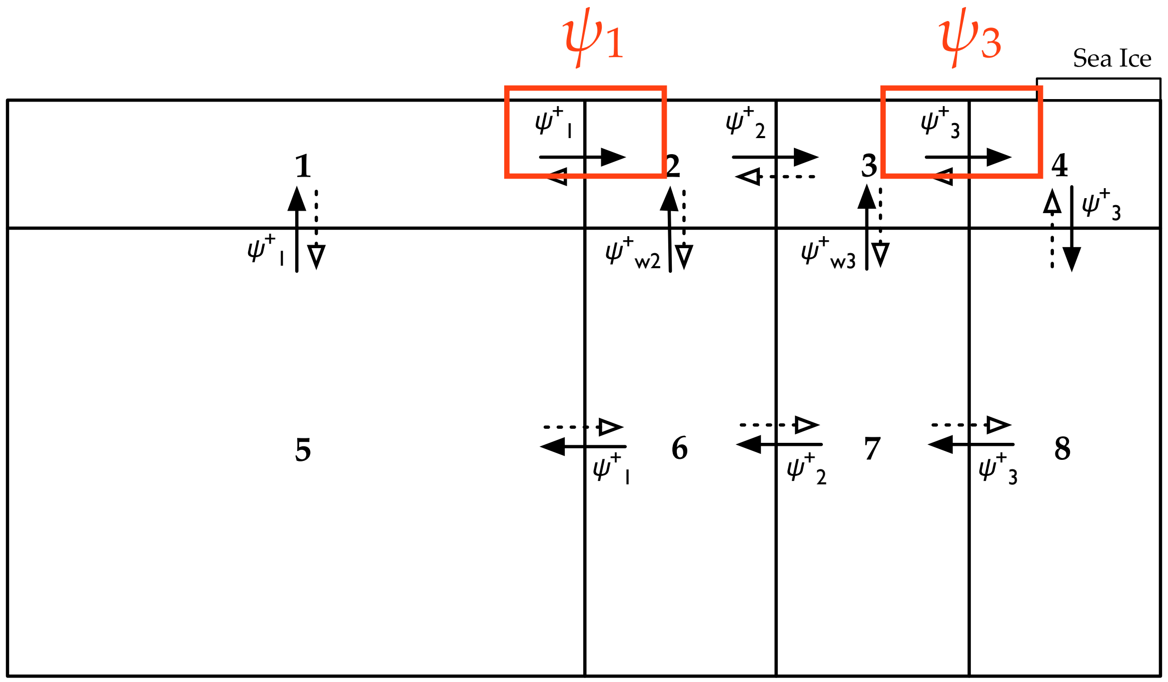


Solutions

Domain of States



Phase-space Trajectories of Advective Fluxes



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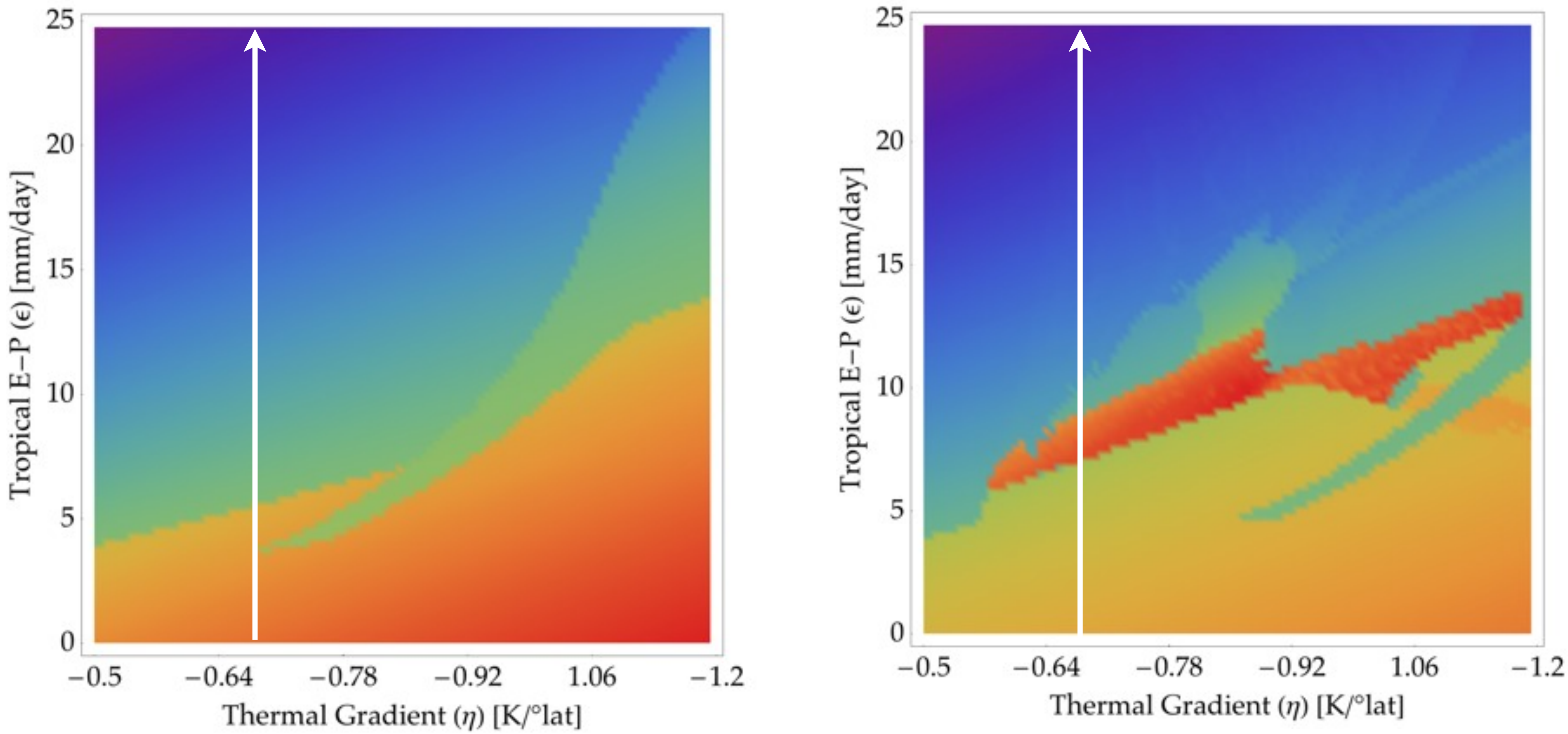
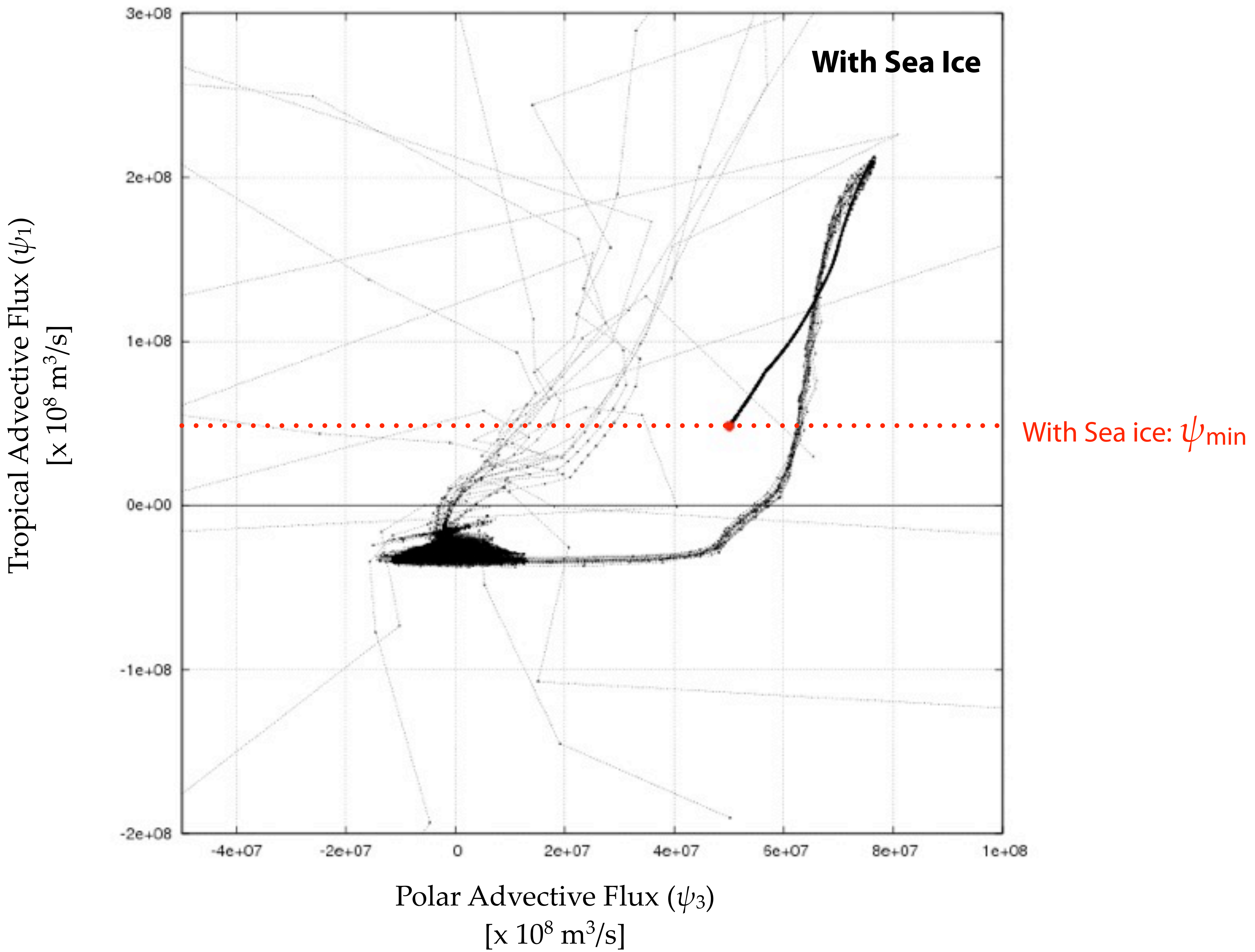
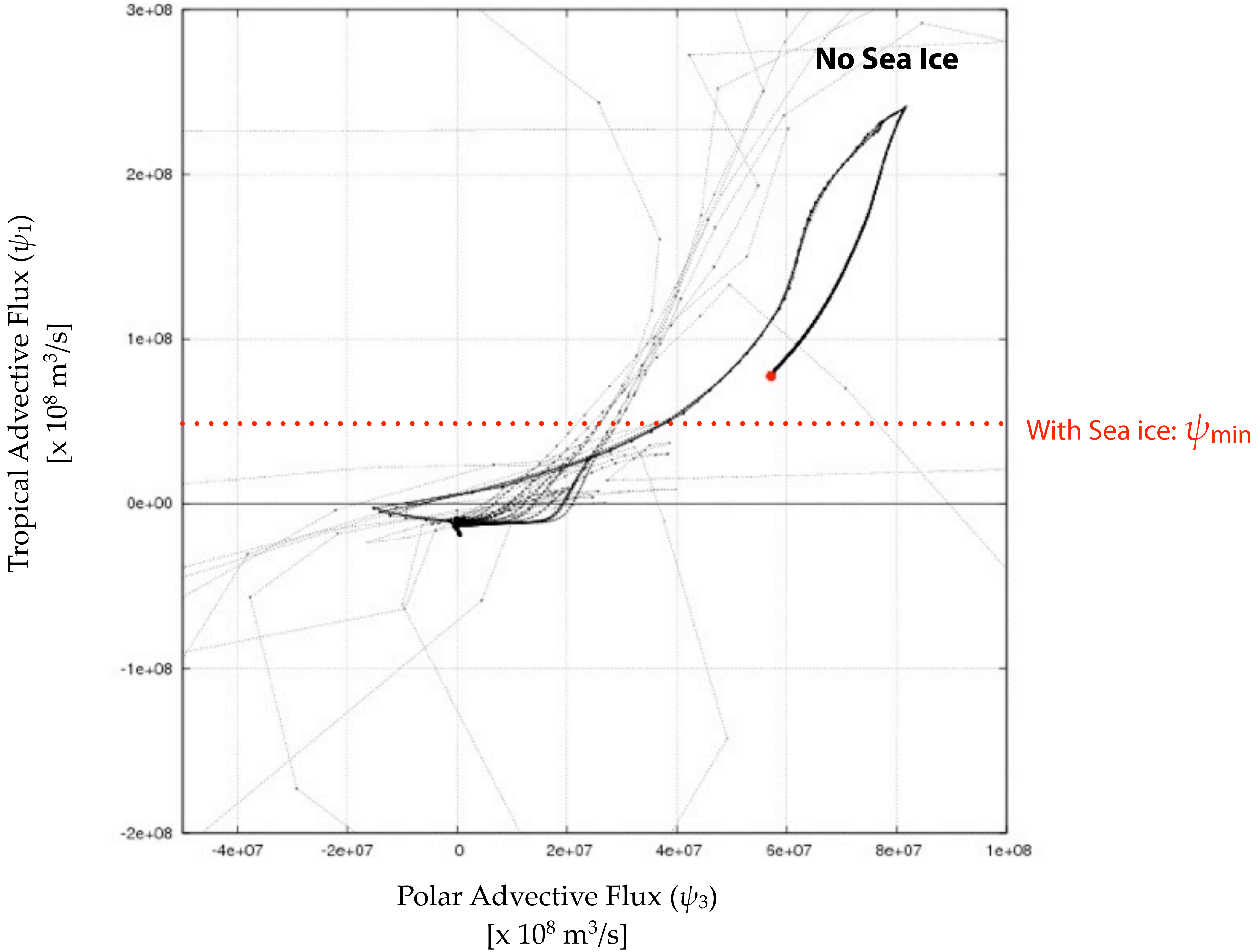


Phase-space Trajectories of Advective Fluxes (several initial states)



Phase-space Trajectories of Advective Fluxes (several initial states)



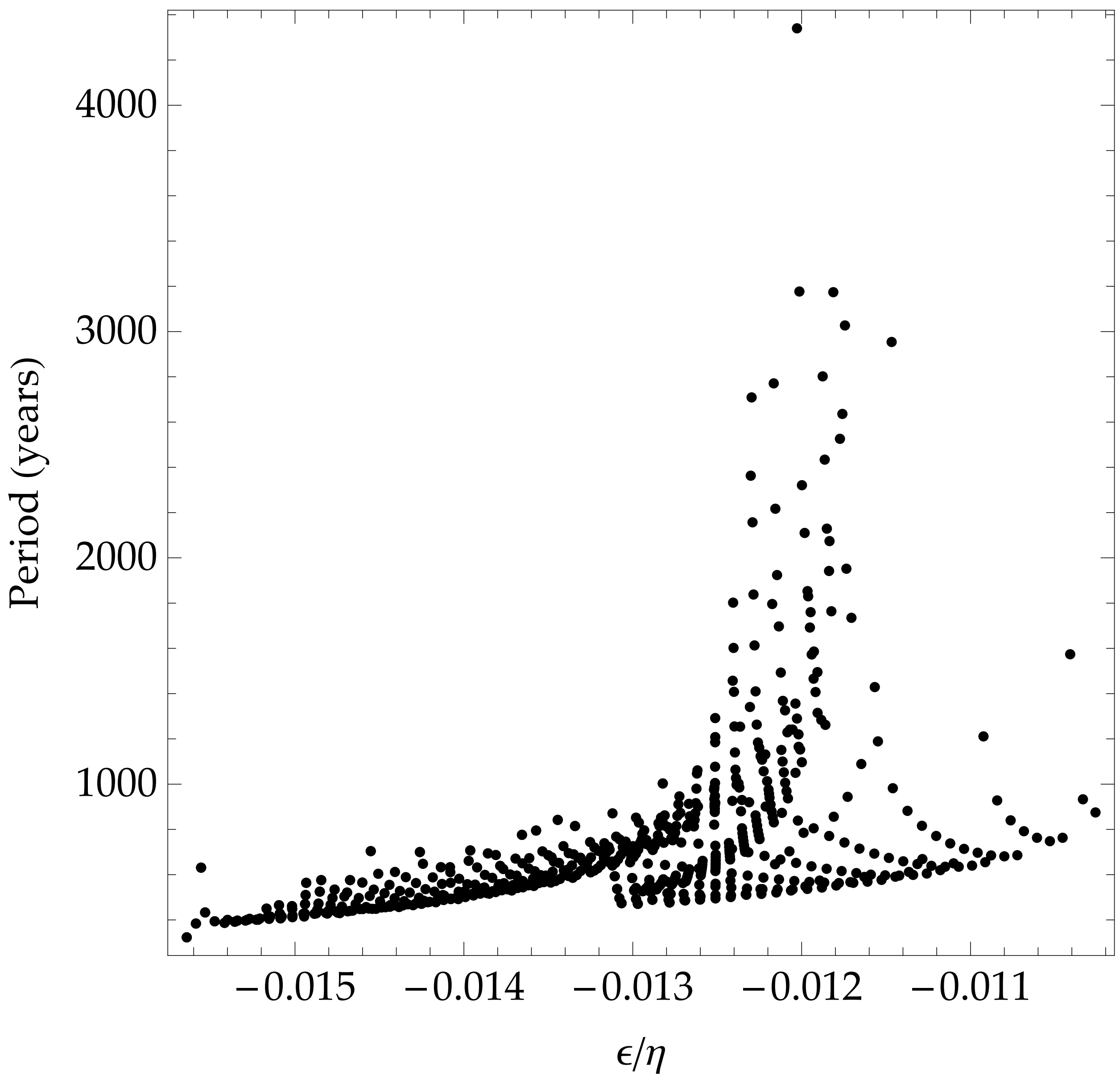
Solutions

Oscillation Periods: Relative Strength of Thermal to Salinity Forcing

Periods between 200 and 4,000 years

Scale with ε/η

Depends on the rate of build up
and eradication of instabilities



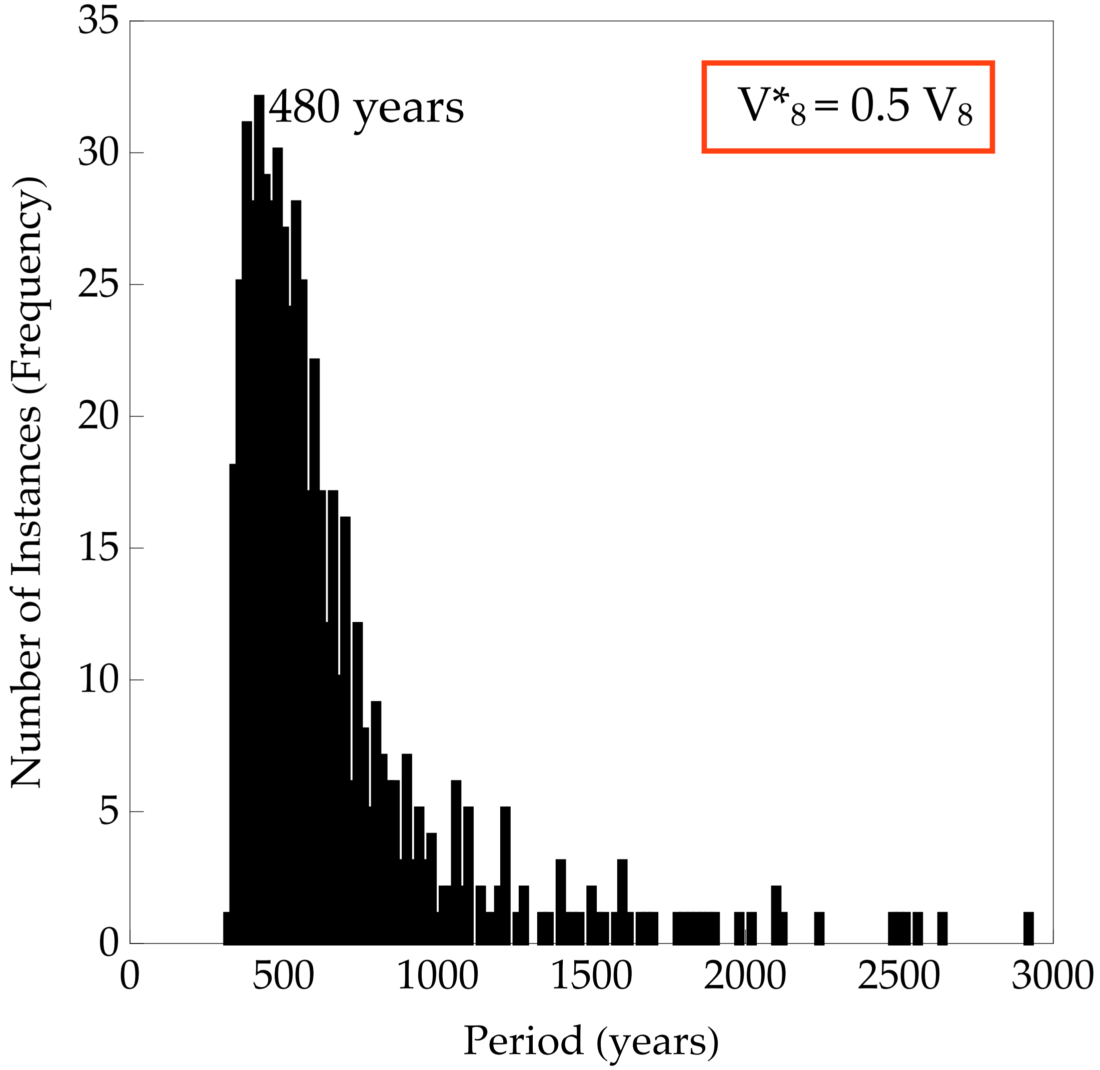
Solutions

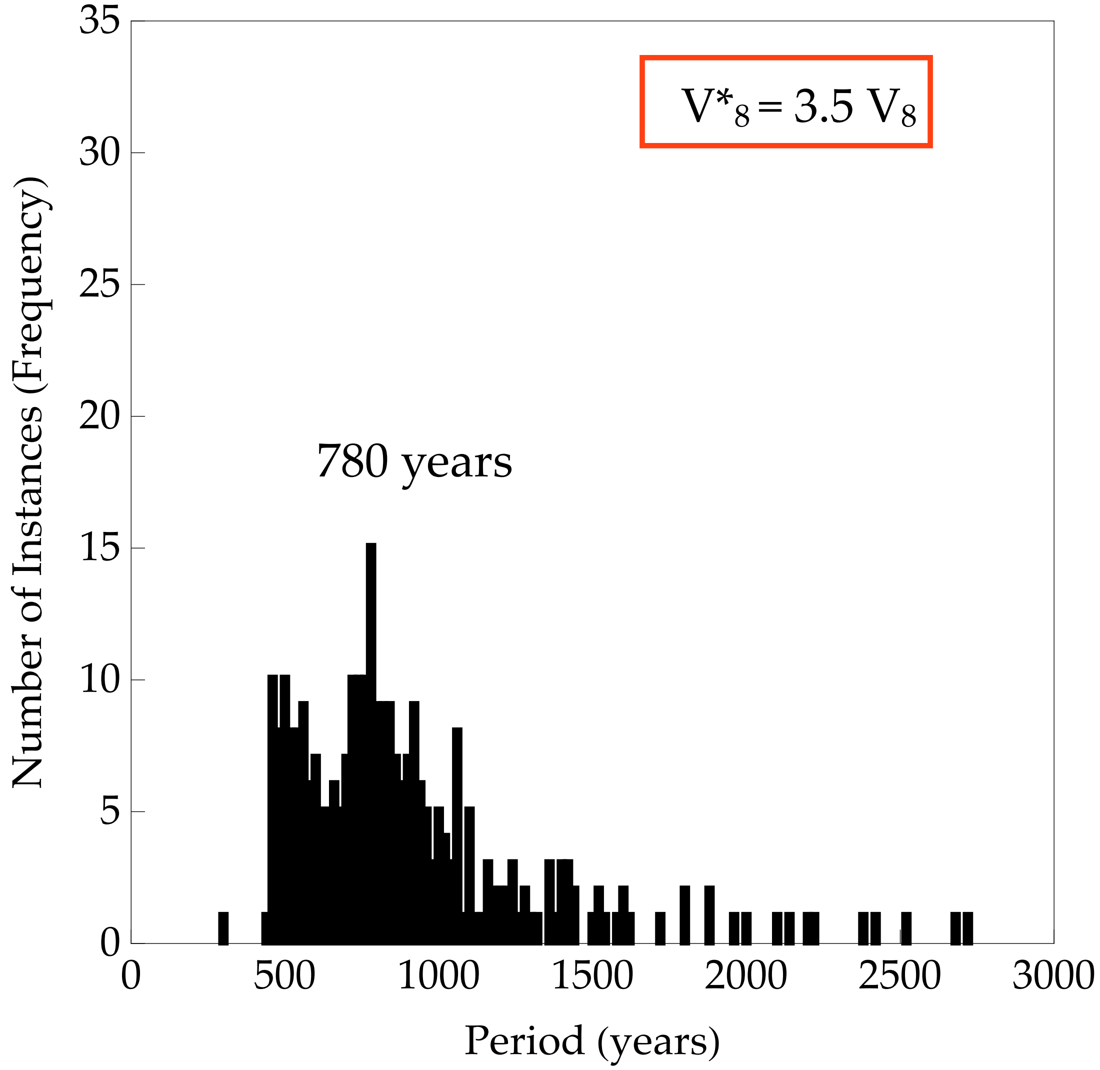
Oscillation Periods: Geometry

Larger polar volume increases effective heat capacity of the system

Periods get longer with volume (heat capacity)

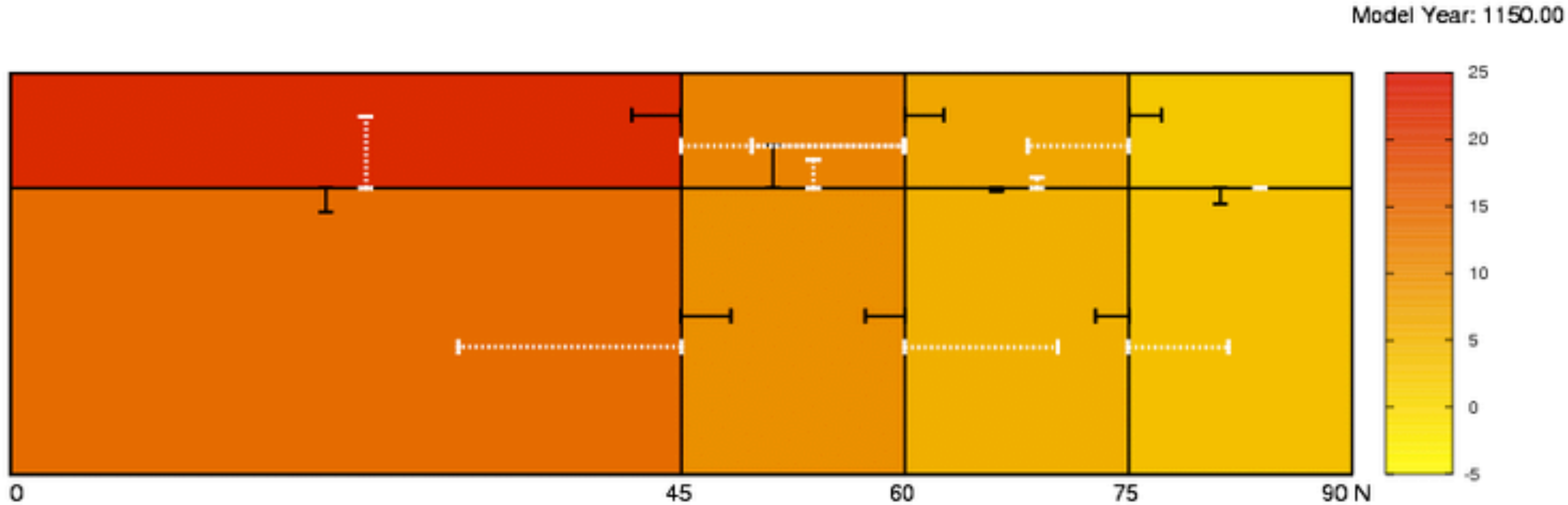
Since geometry is invariant, it can produce a persistent period

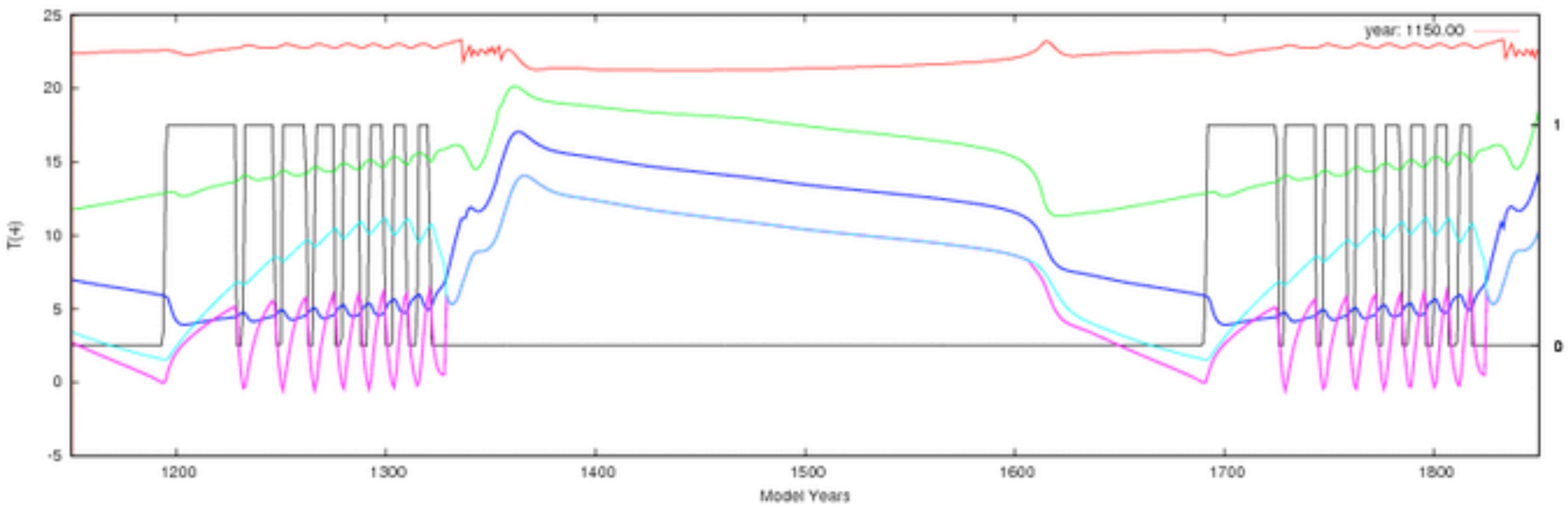




Solutions

Animation



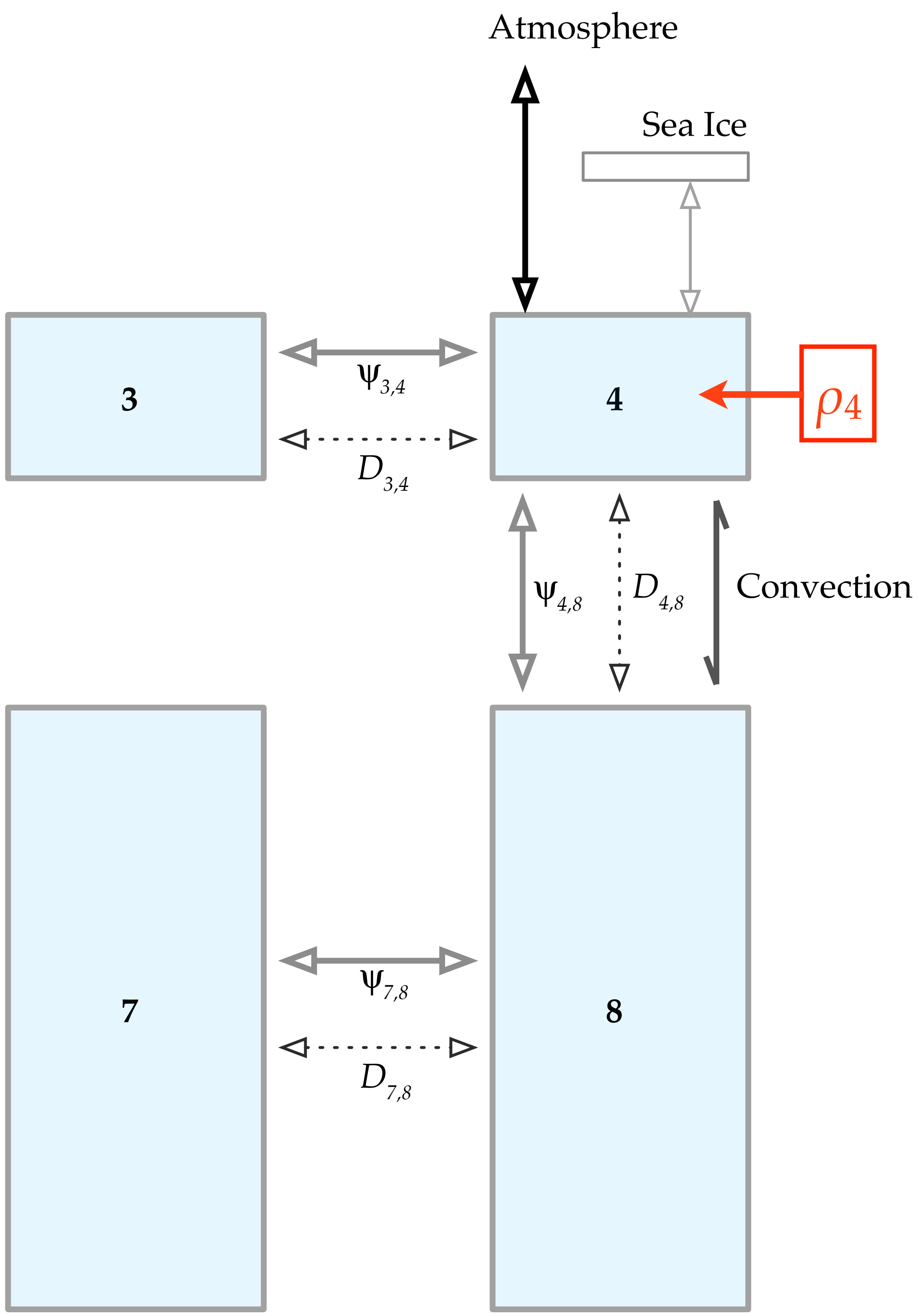


Mechanism of Oscillations

Insulating effect

Brine rejection

Heat exchanges from formation / melting



Mechanism of Oscillations

Insulating effect

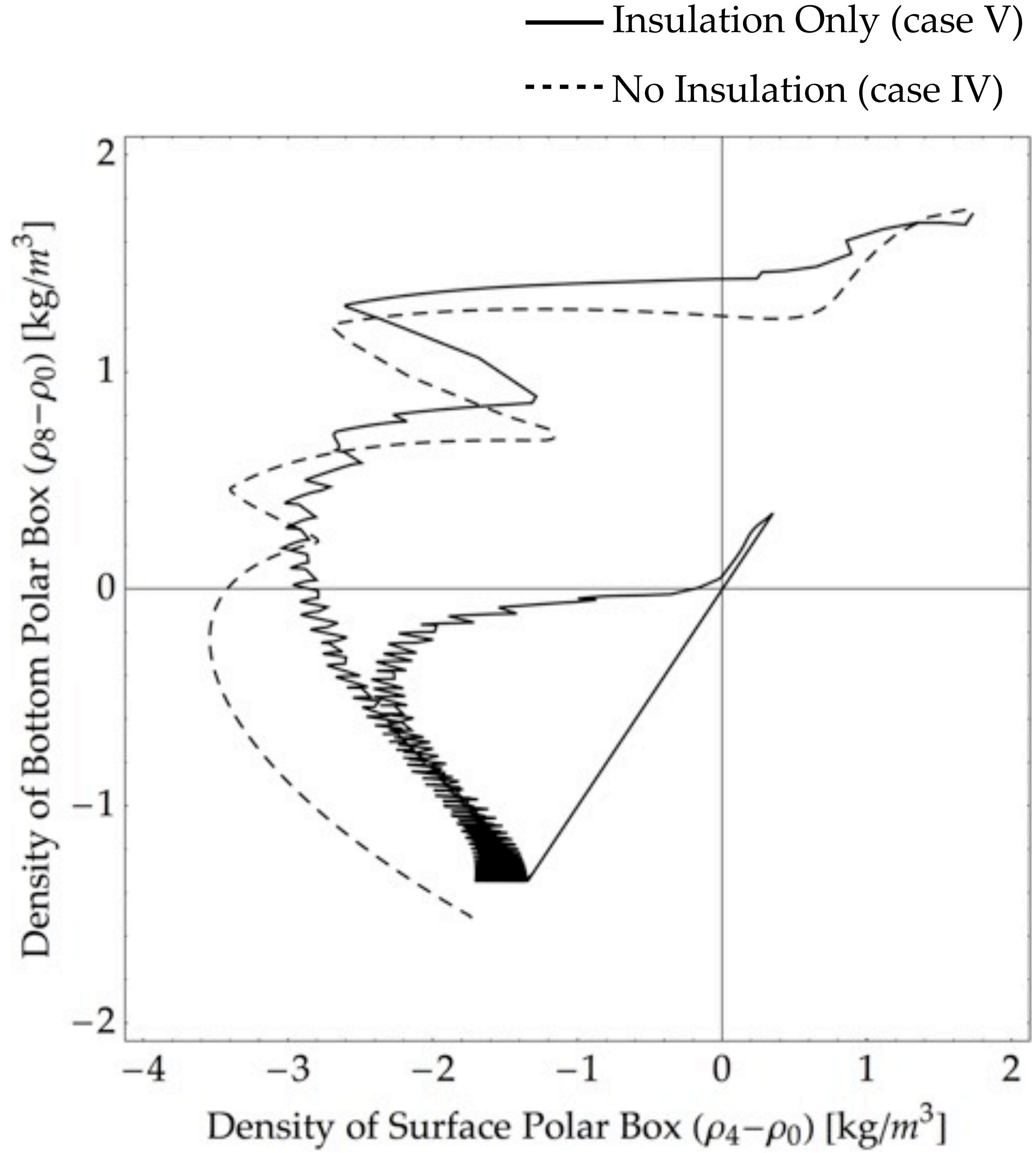
Brine rejection

Heat exchanges from formation / melting

Insulating effect is key to oscillations in this system

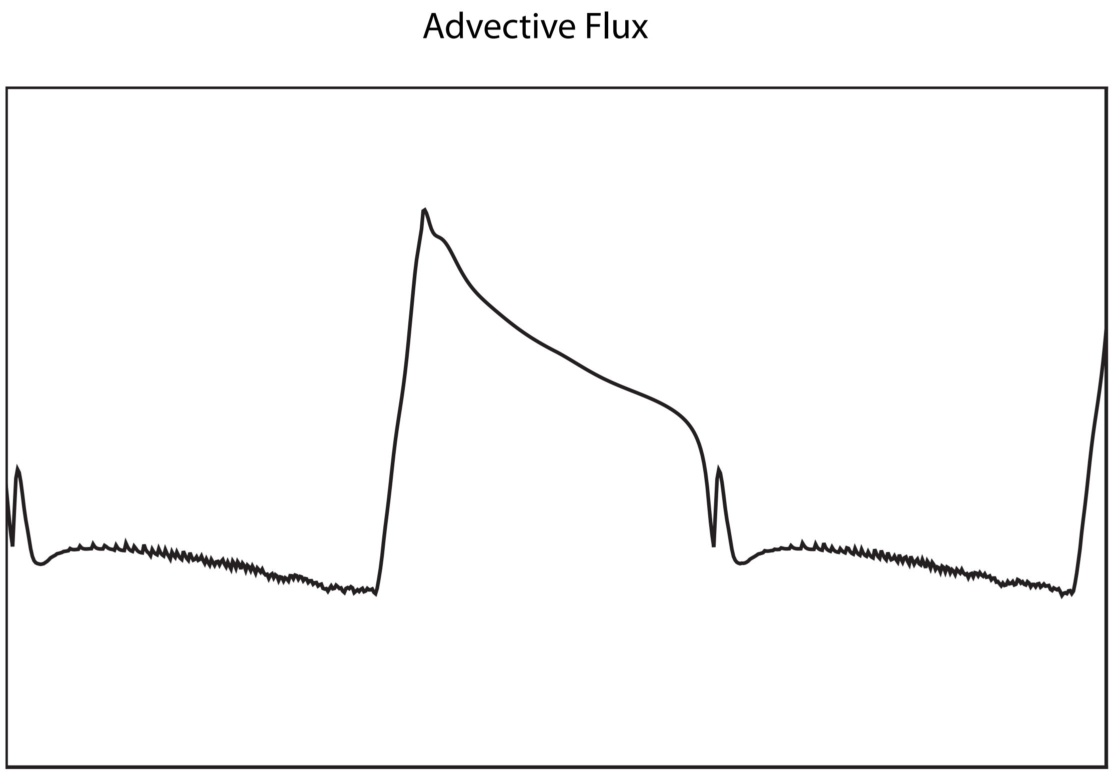
	γ	$\dot{B}$	$\dot{Q}_{\mathrm{ice}}$	Oscillations
I	0	0	0	**0**
II	0	0	1	**0**
III	0	1	0	**0**
IV	0	1	1	**0**
V	1	0	0	**1**
VI	1	0	1	**1**
VII	1	1	0	**1**
VIII	1	1	1	**1**

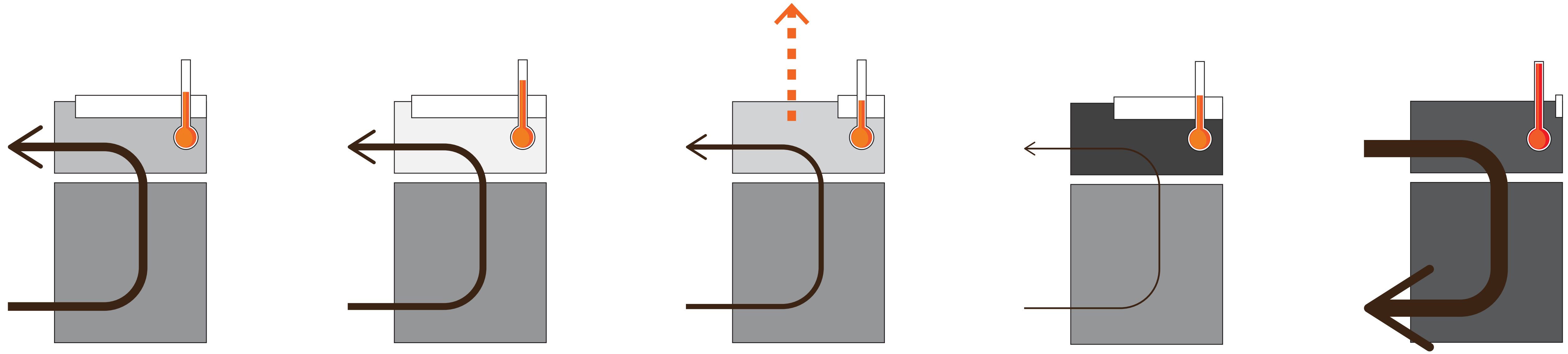
Mechanism of Oscillations



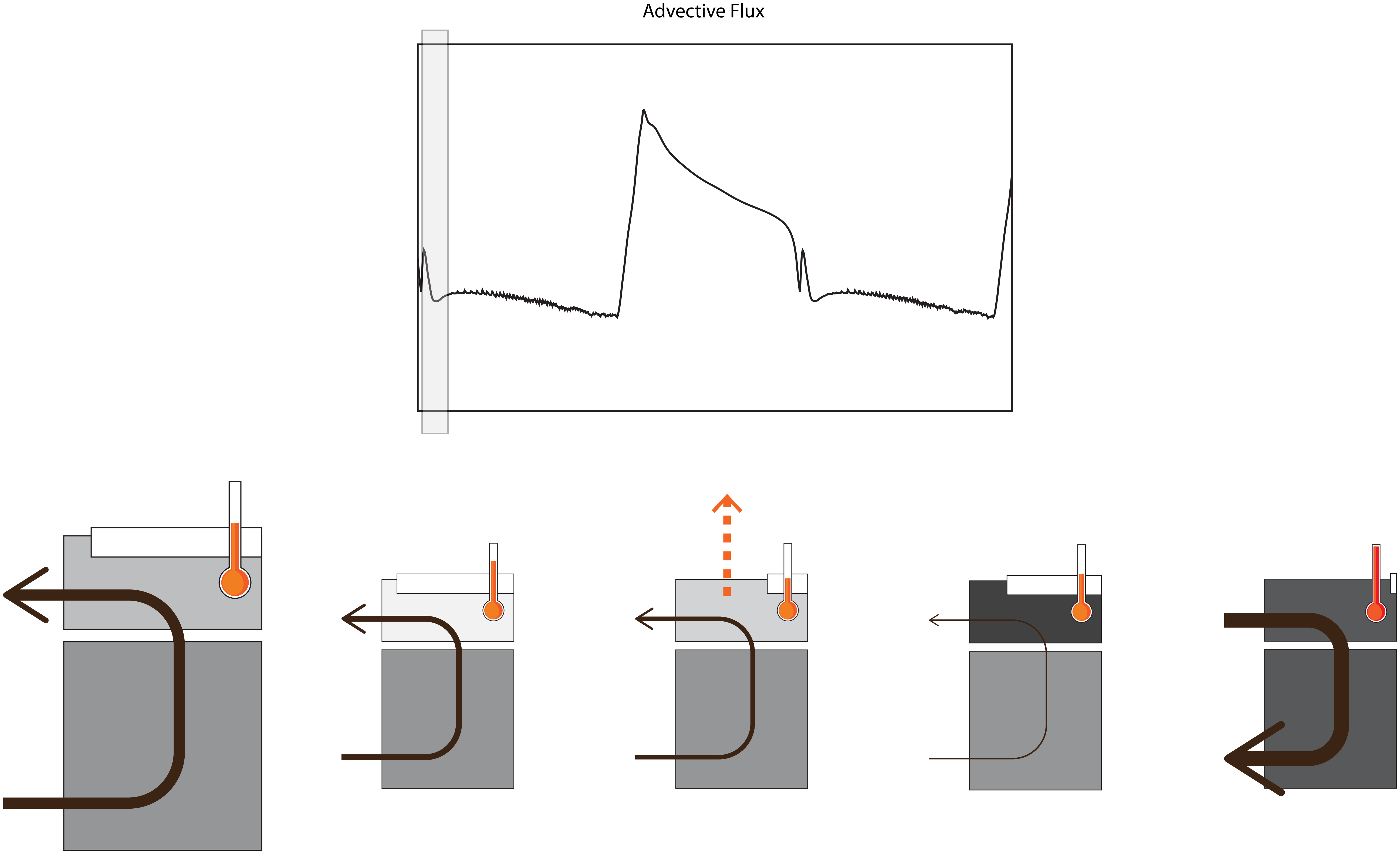
Insulating effect is key to oscillations in this system

Mechanism of Oscillations

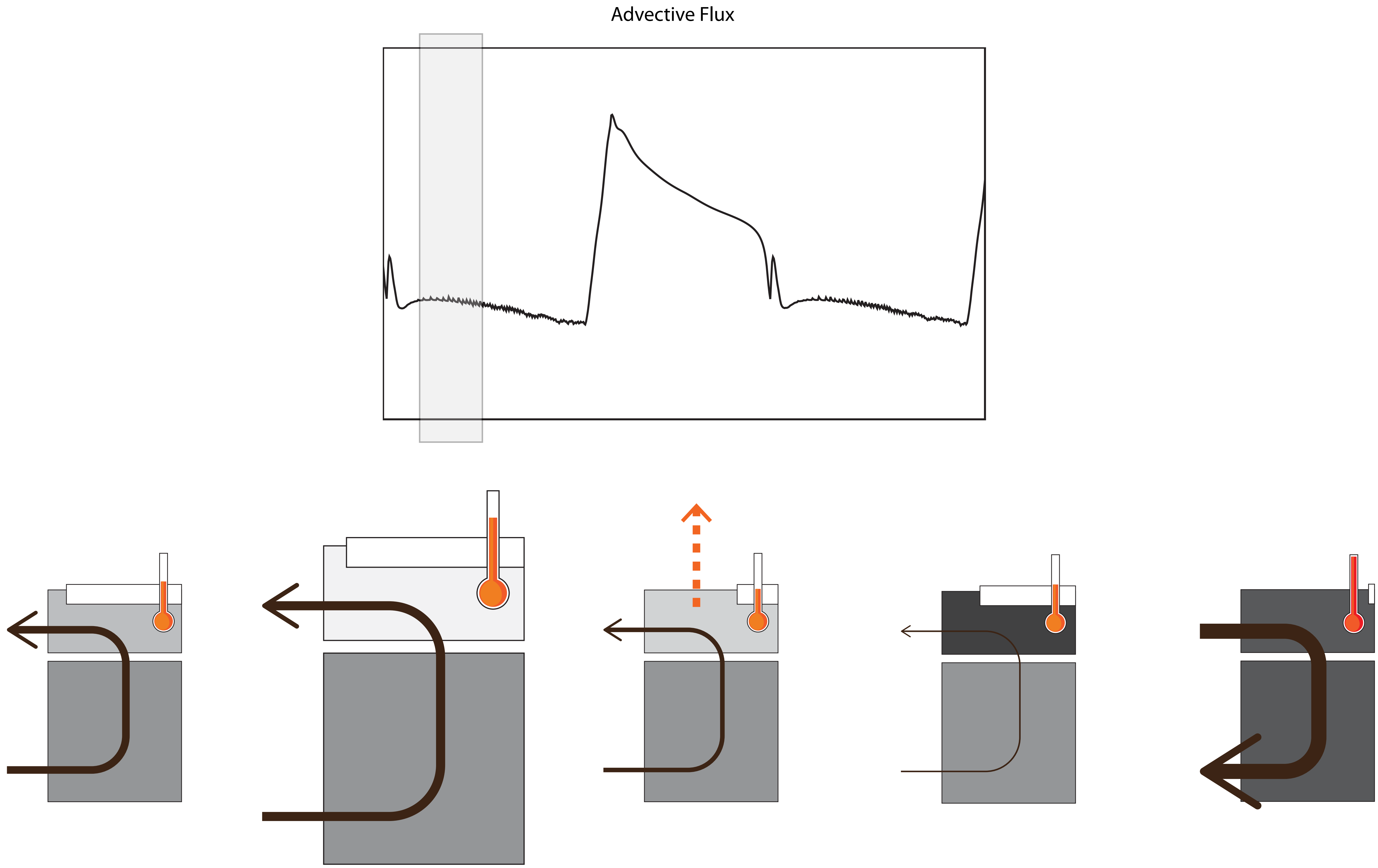




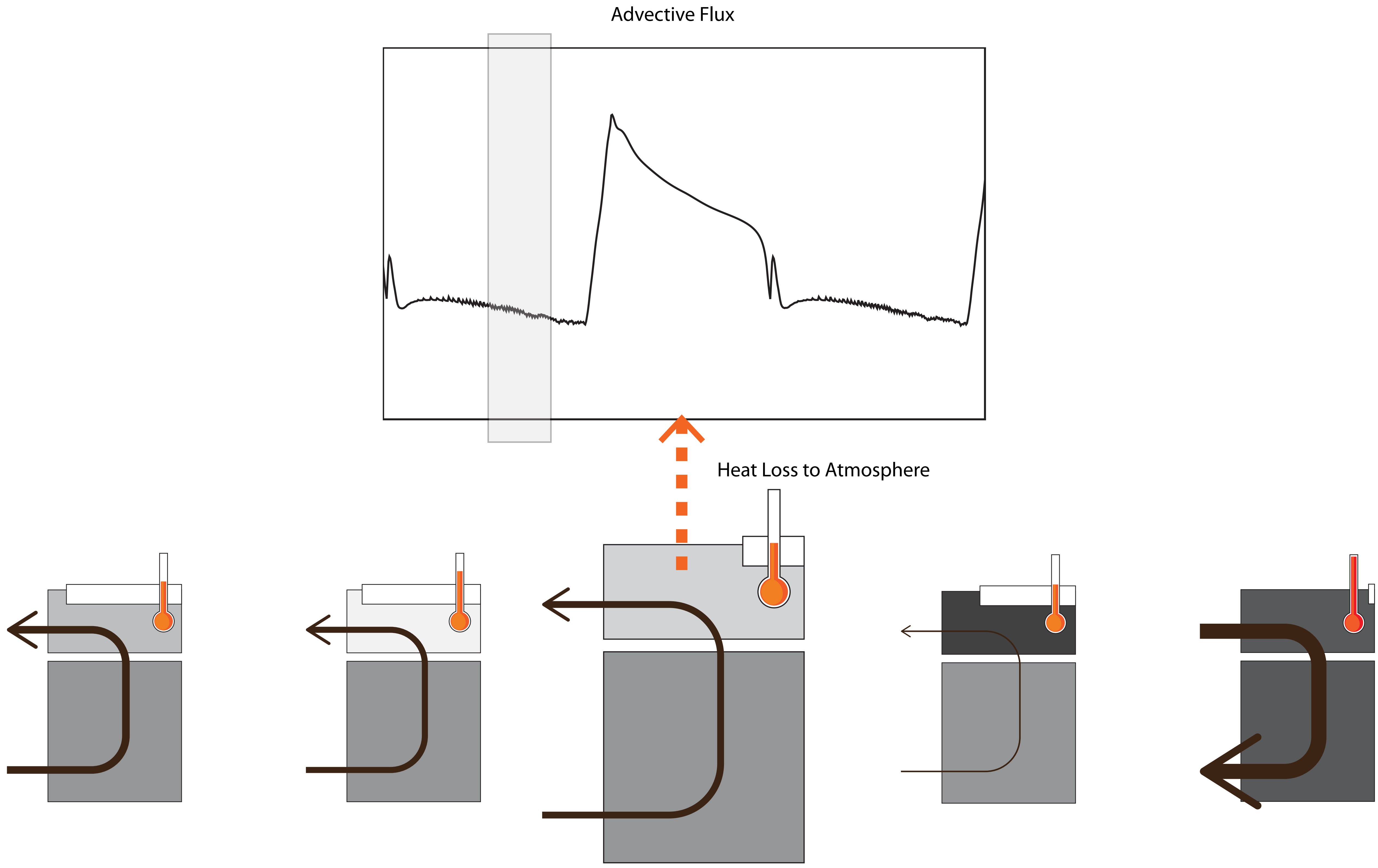
Mechanism of Oscillations



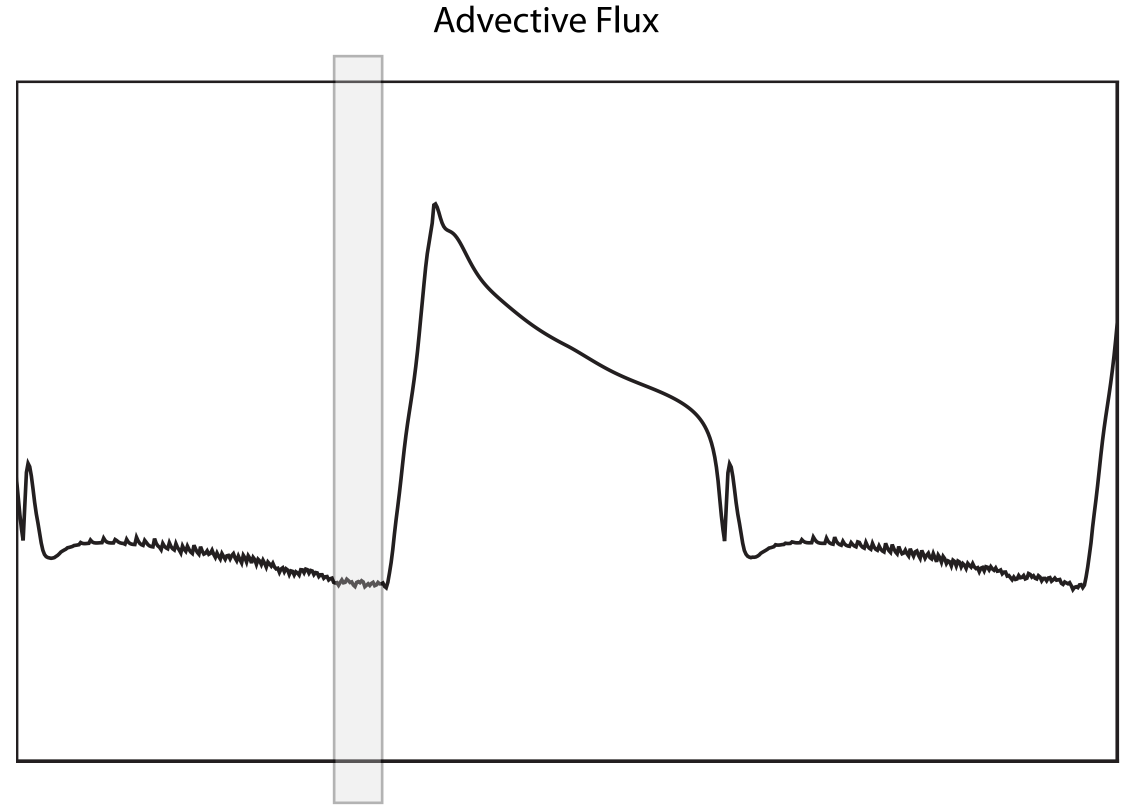
Mechanism of Oscillations

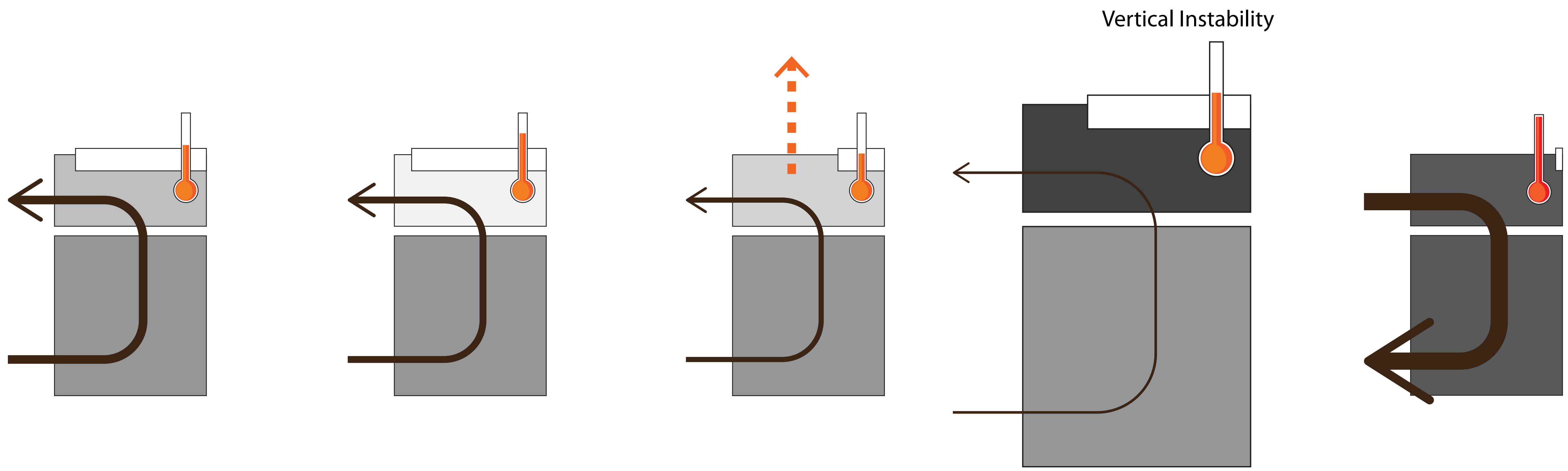


Mechanism of Oscillations

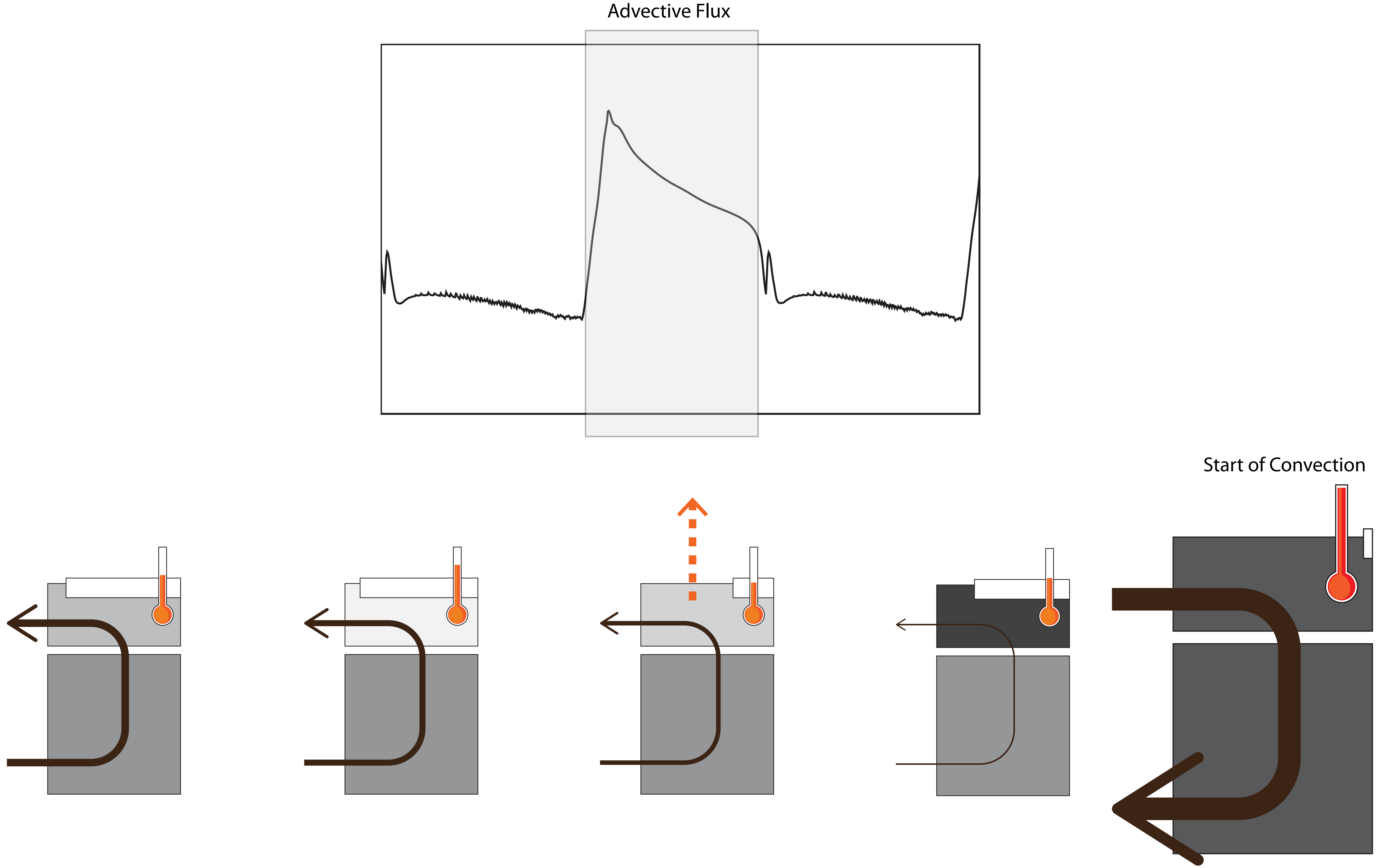


Mechanism of Oscillations

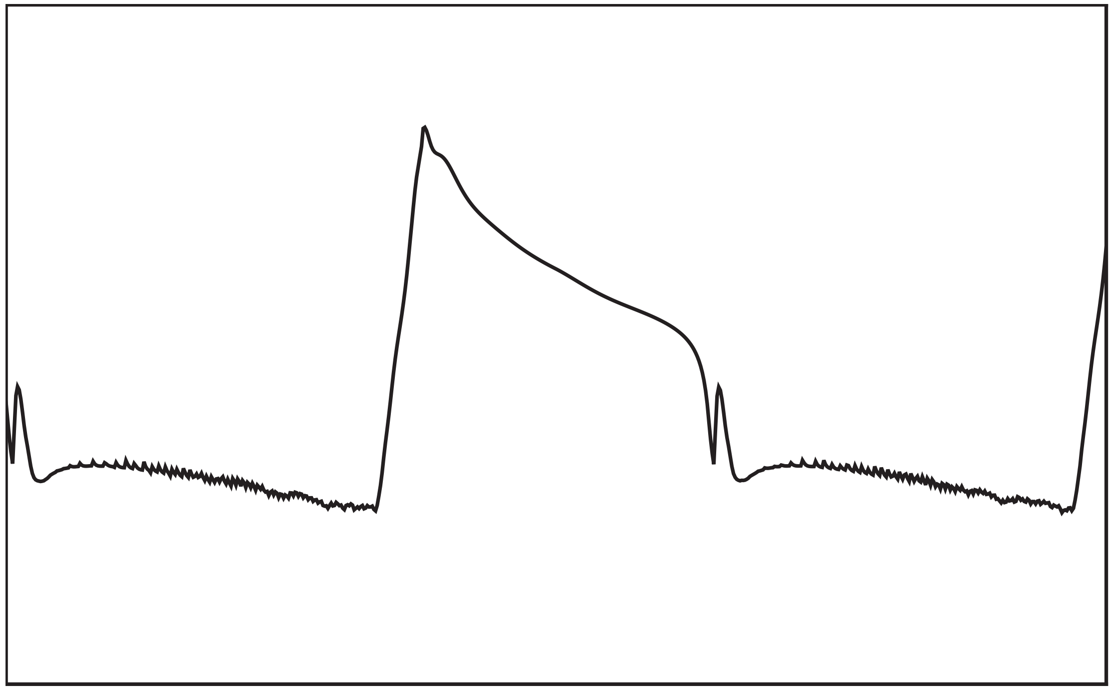




Mechanism of Oscillations



Mechanism of Oscillations



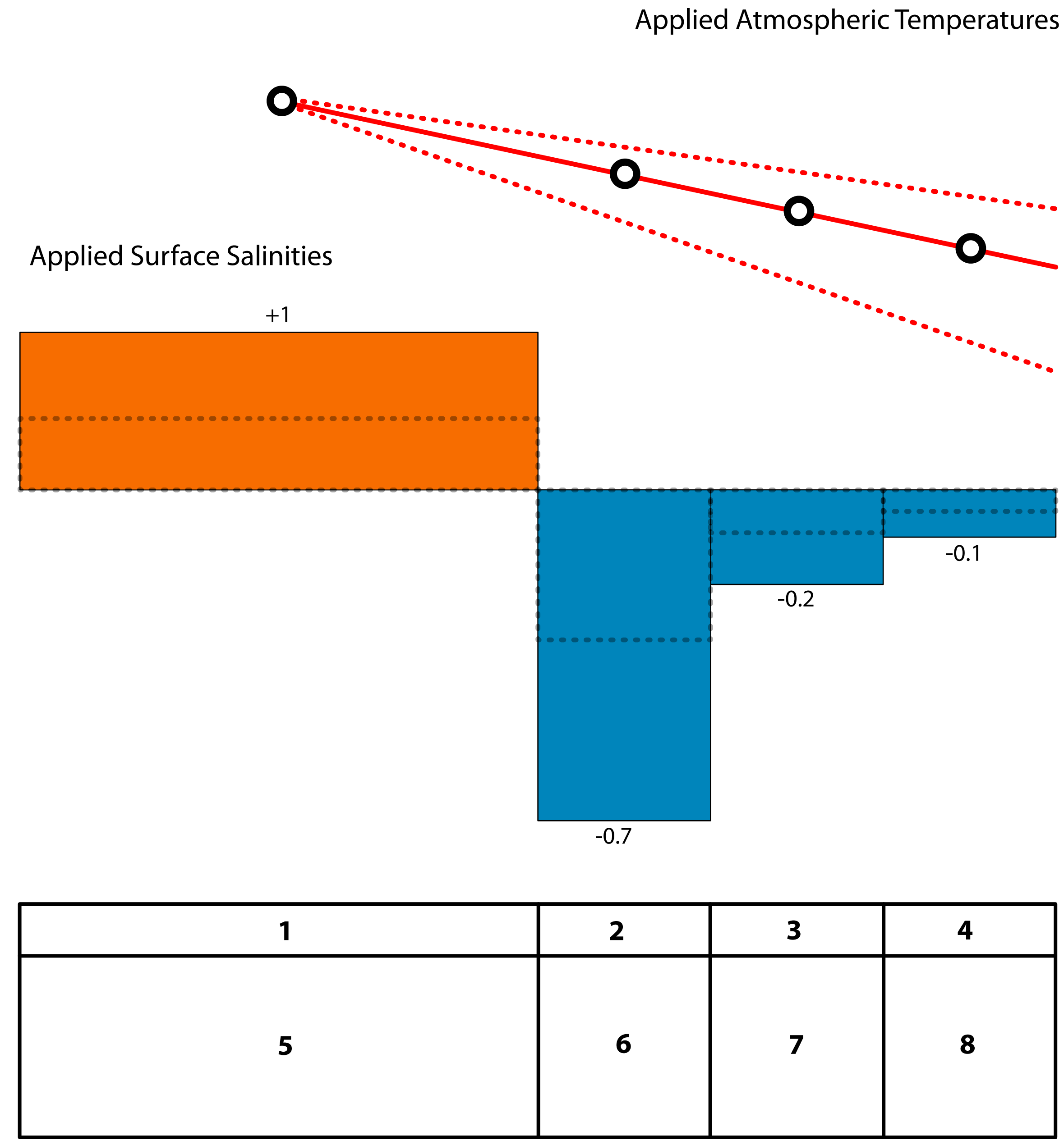
Large heat loss from the polar surface ocean during sea ice retreats cool the water, making it more dense and creating conditions for convection

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

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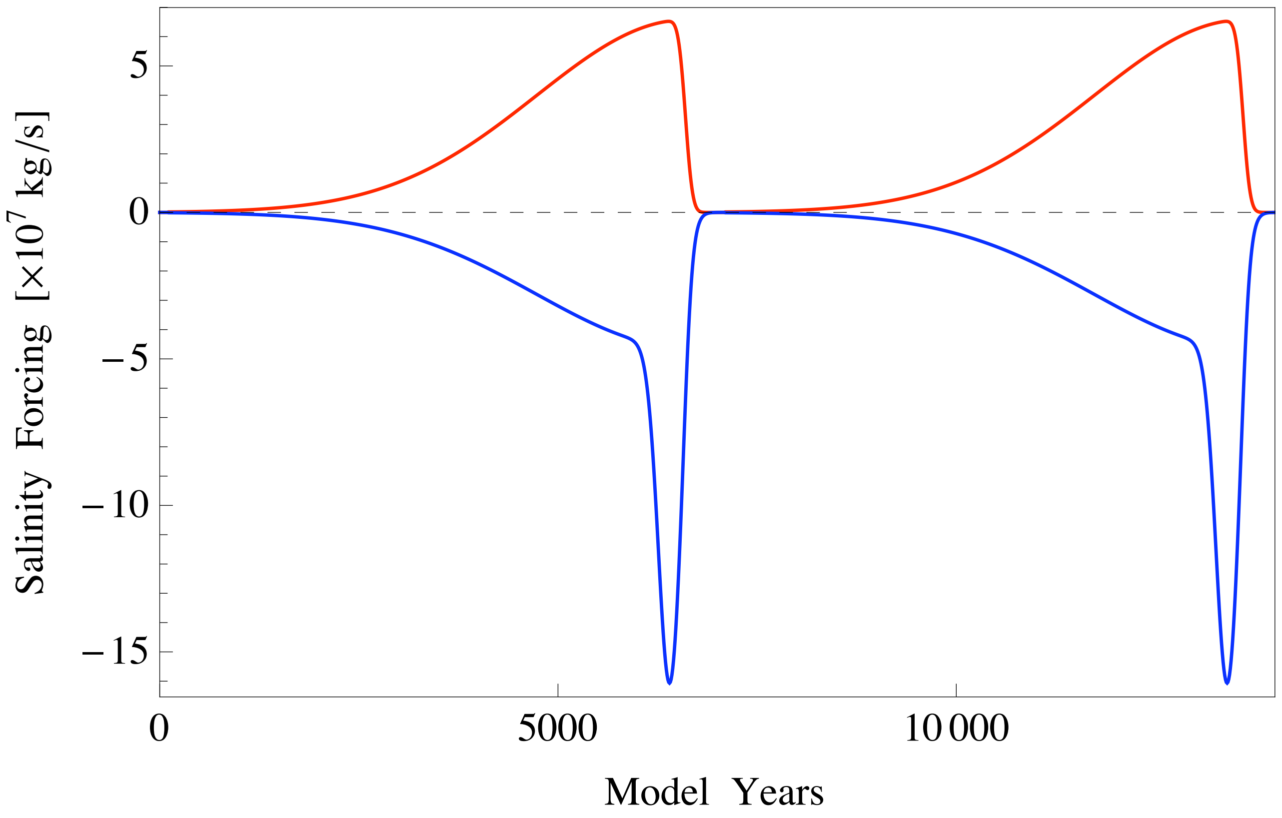

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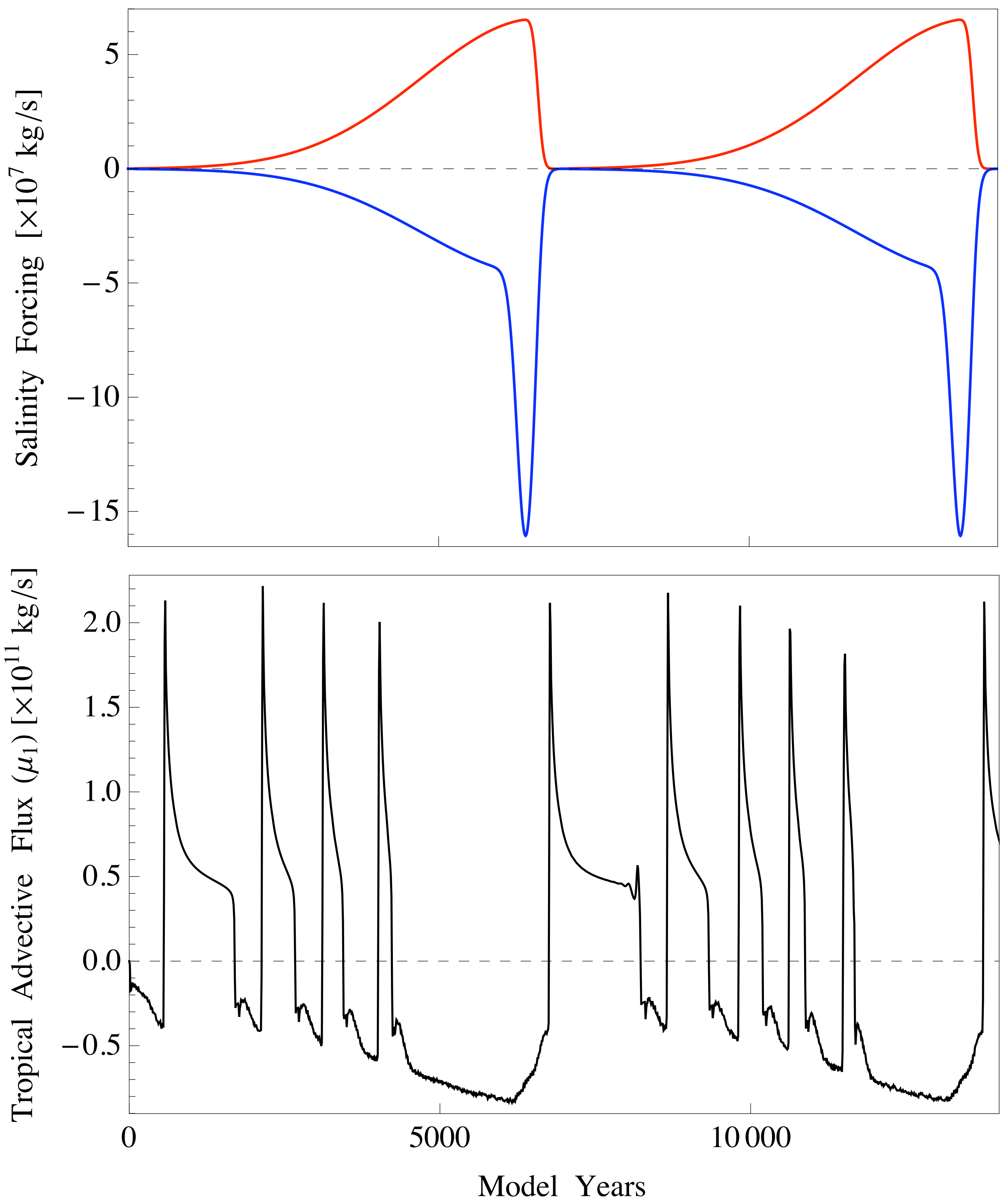
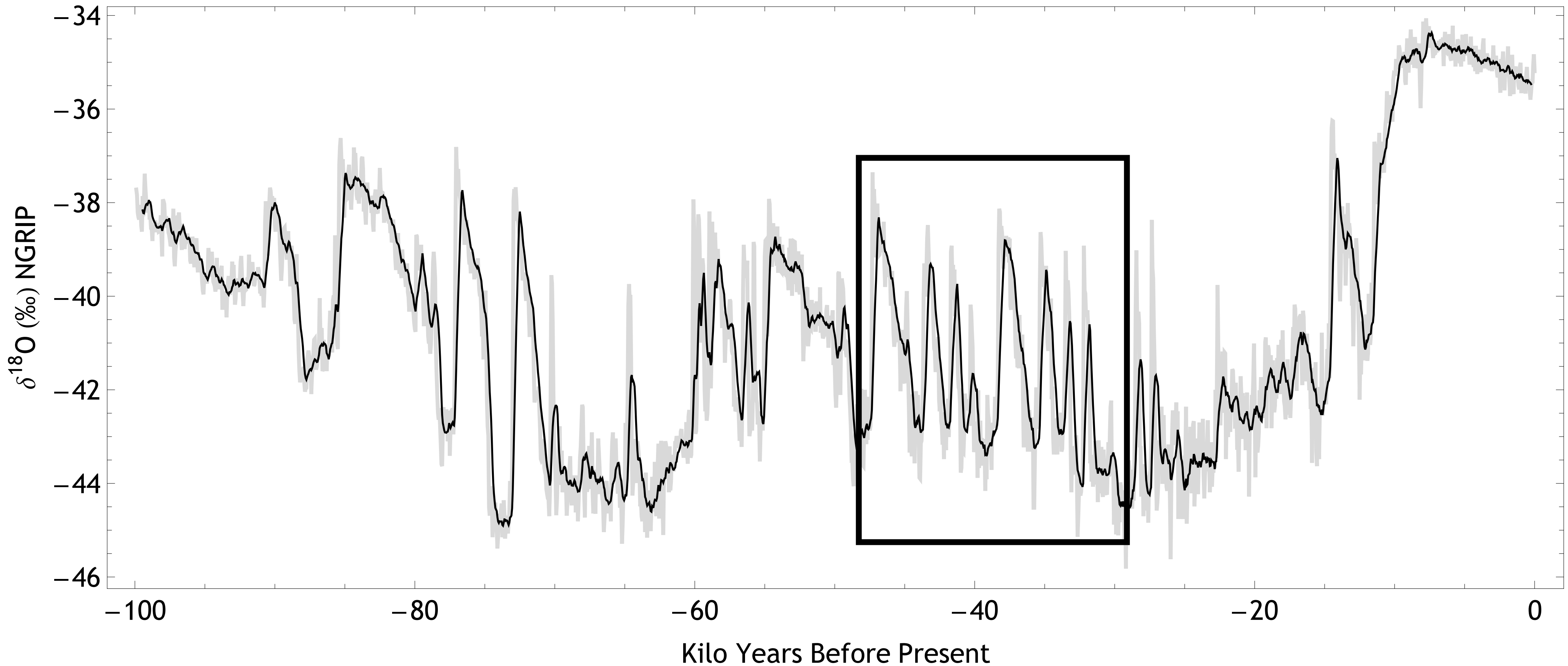
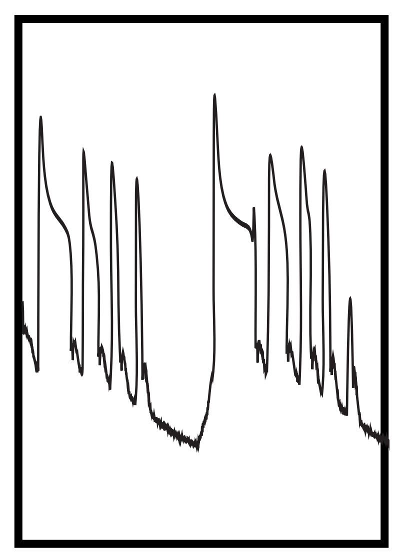


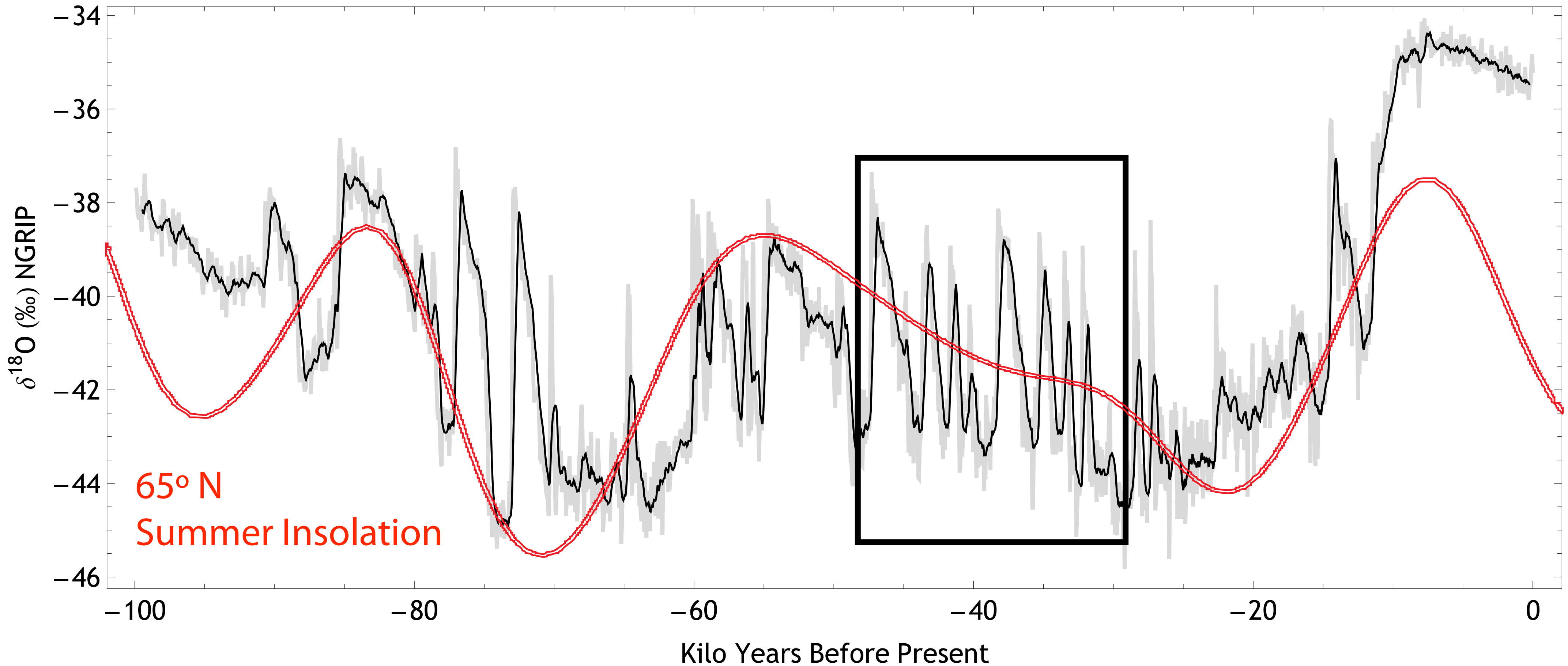
Observation and Model

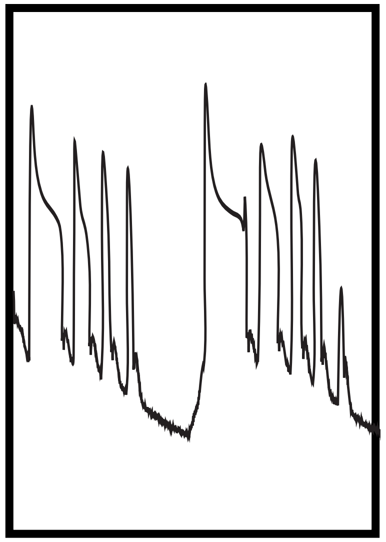


¡ Model !



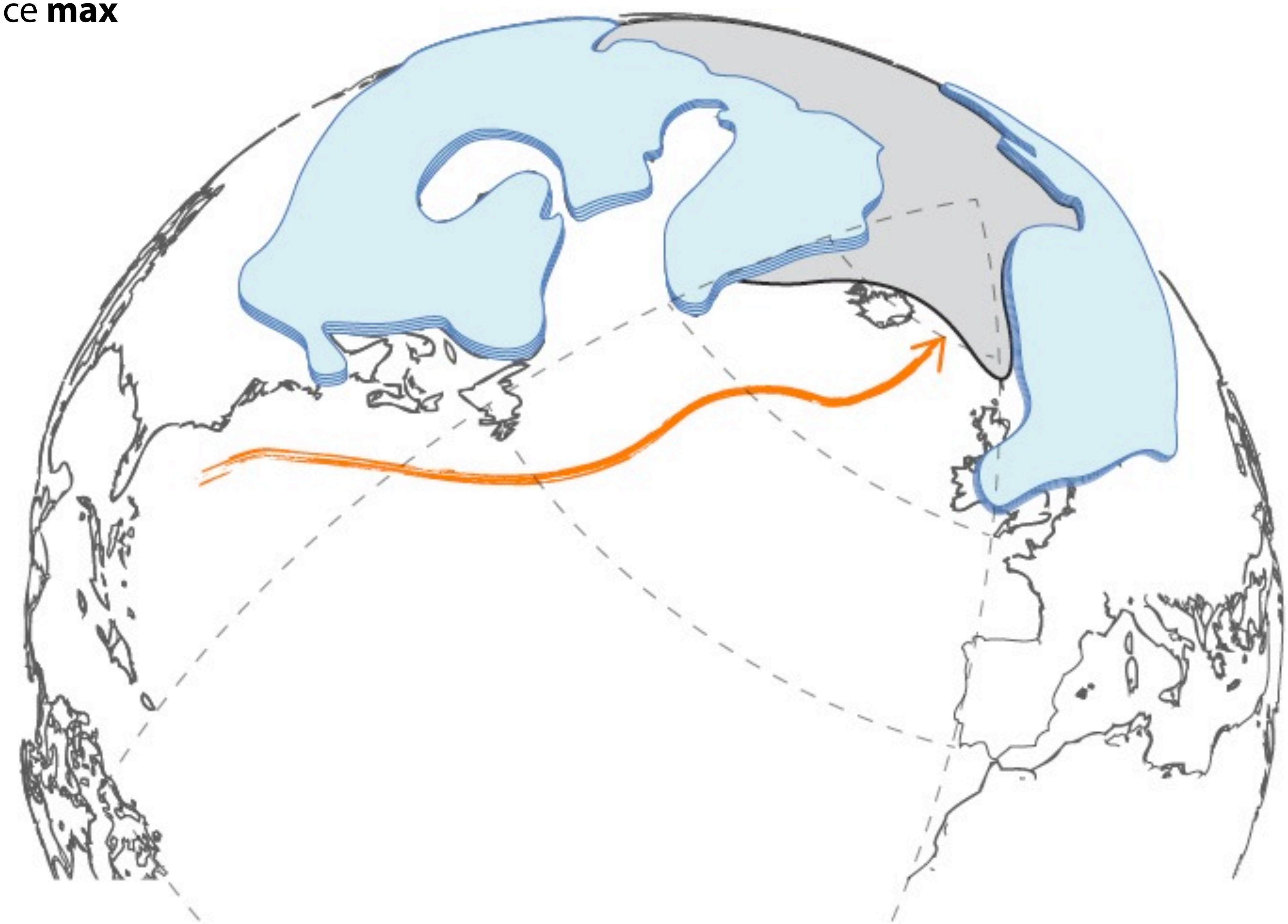
Observation and Model





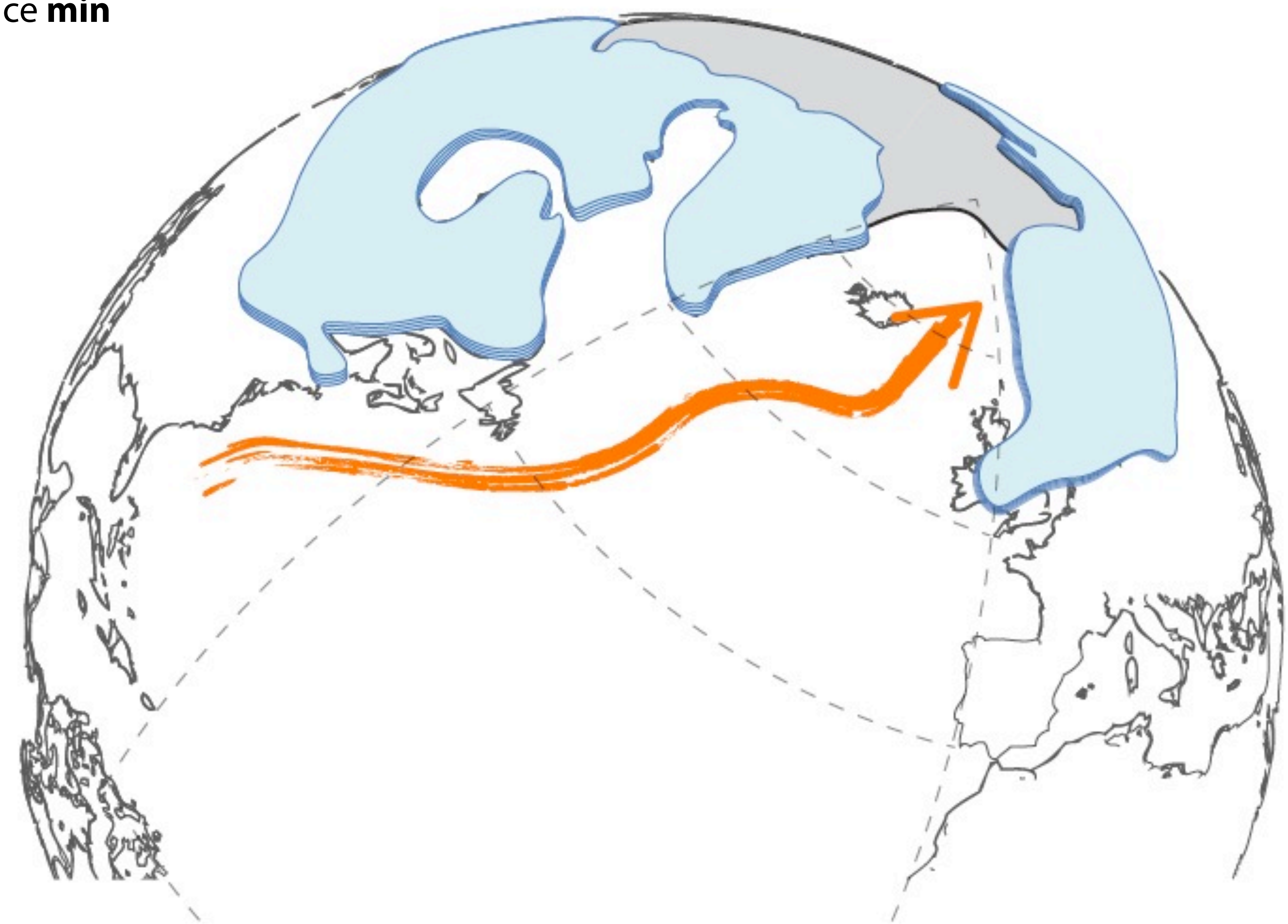
A *Cartoon* of the Ice Sheet Cycles and D-O events

Ice sheet growth phase
Sea ice **max**



A *Cartoon* of the Ice Sheet Cycles and D-O events

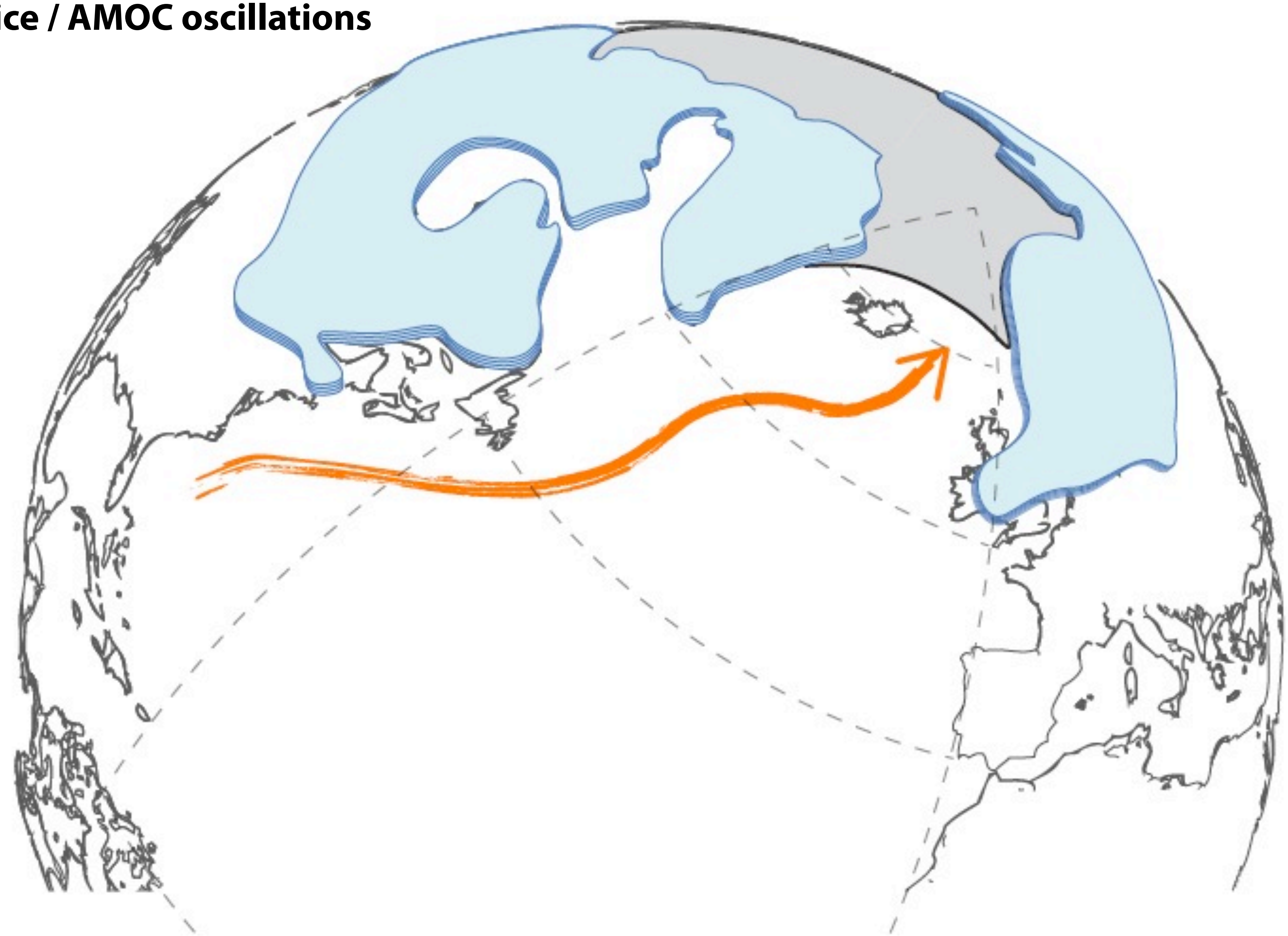
Ice sheet growth phase
Sea ice **min**



A *Cartoon* of the Ice Sheet Cycles and D-O events

Ice sheet growth phase

Sea ice / AMOC oscillations



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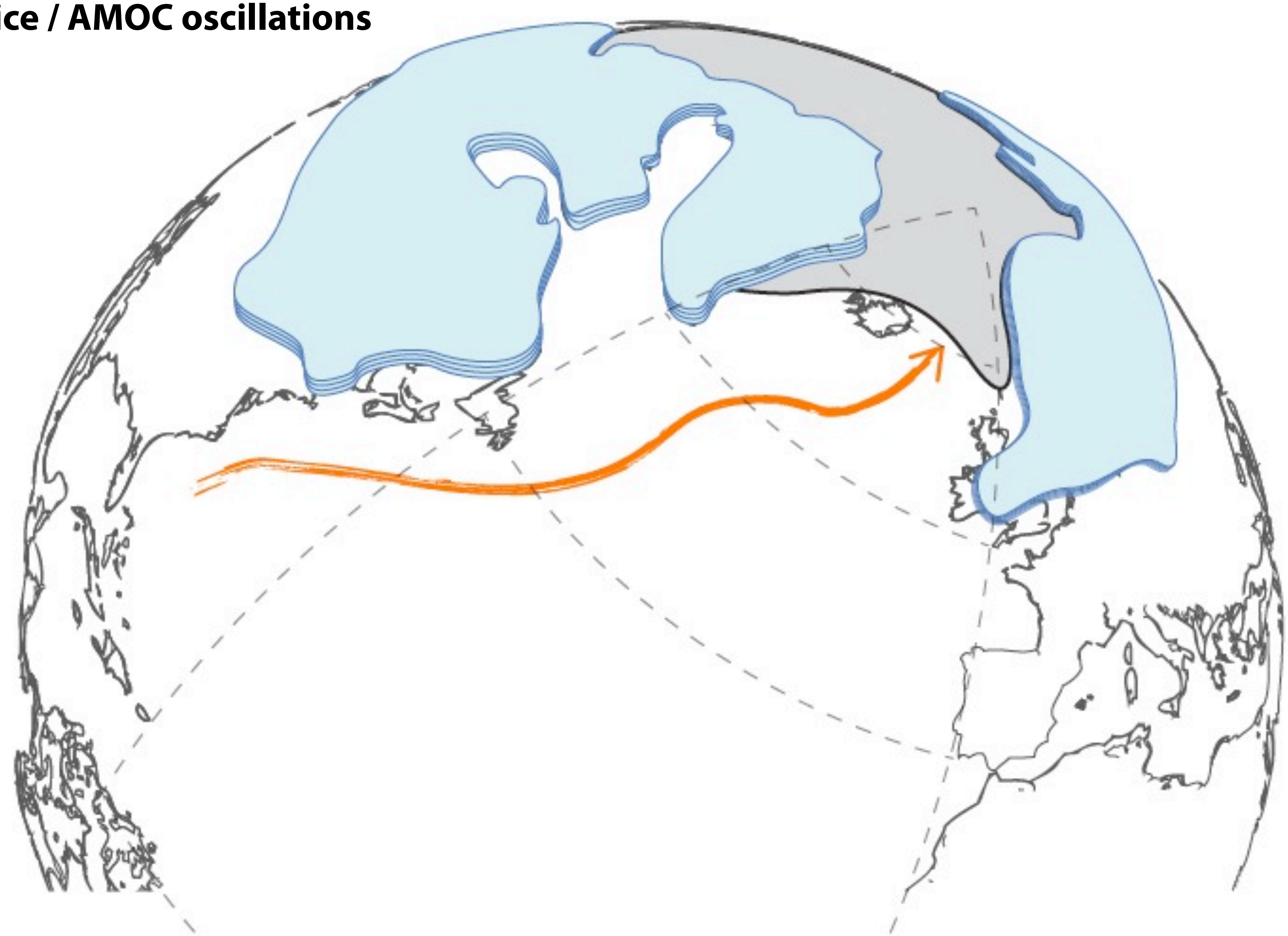
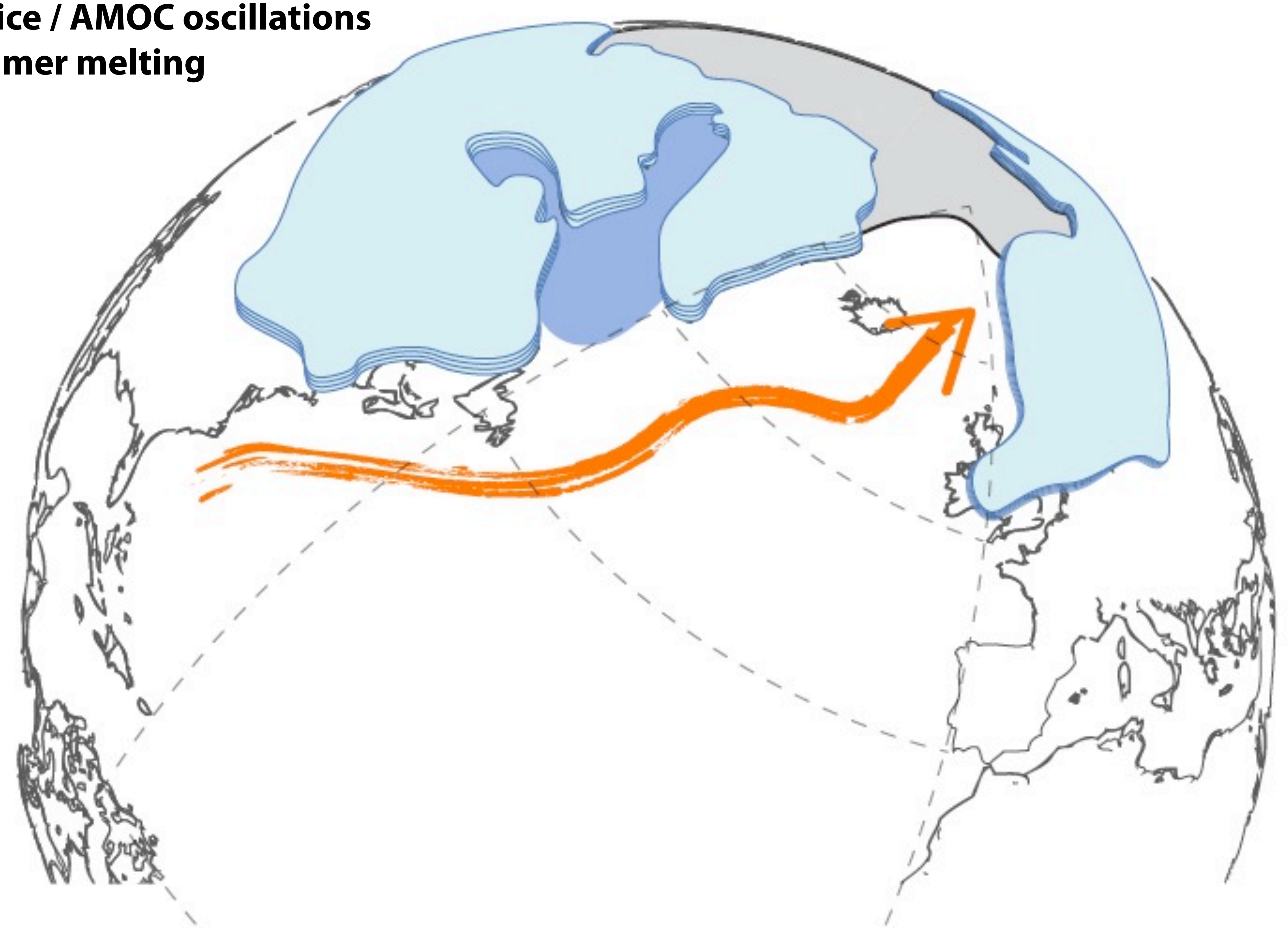


A *Cartoon* of the Ice Sheet Cycles and D-O events

Ice sheet growth phase
Sea ice / AMOC oscillations
Summer melting



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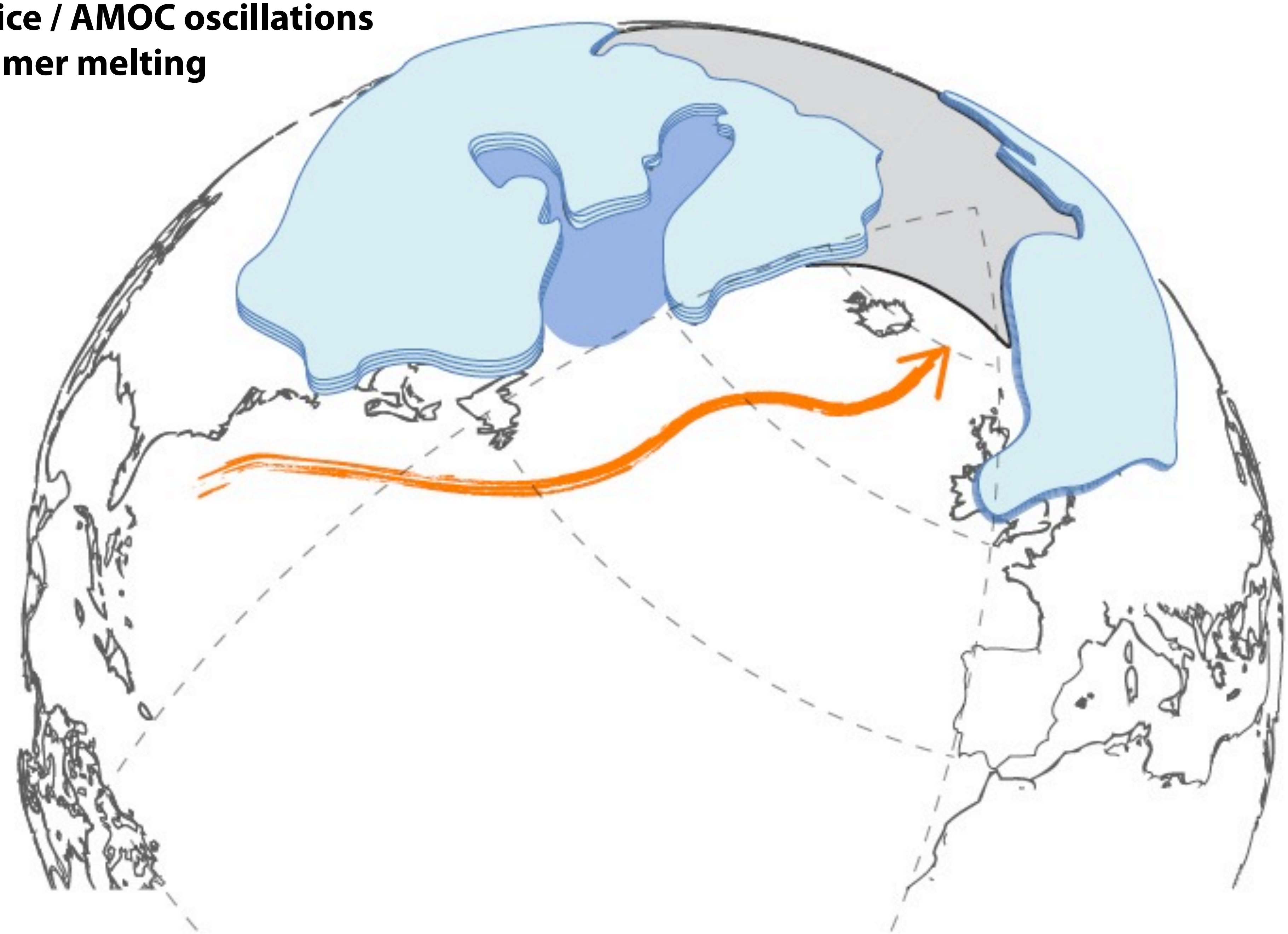
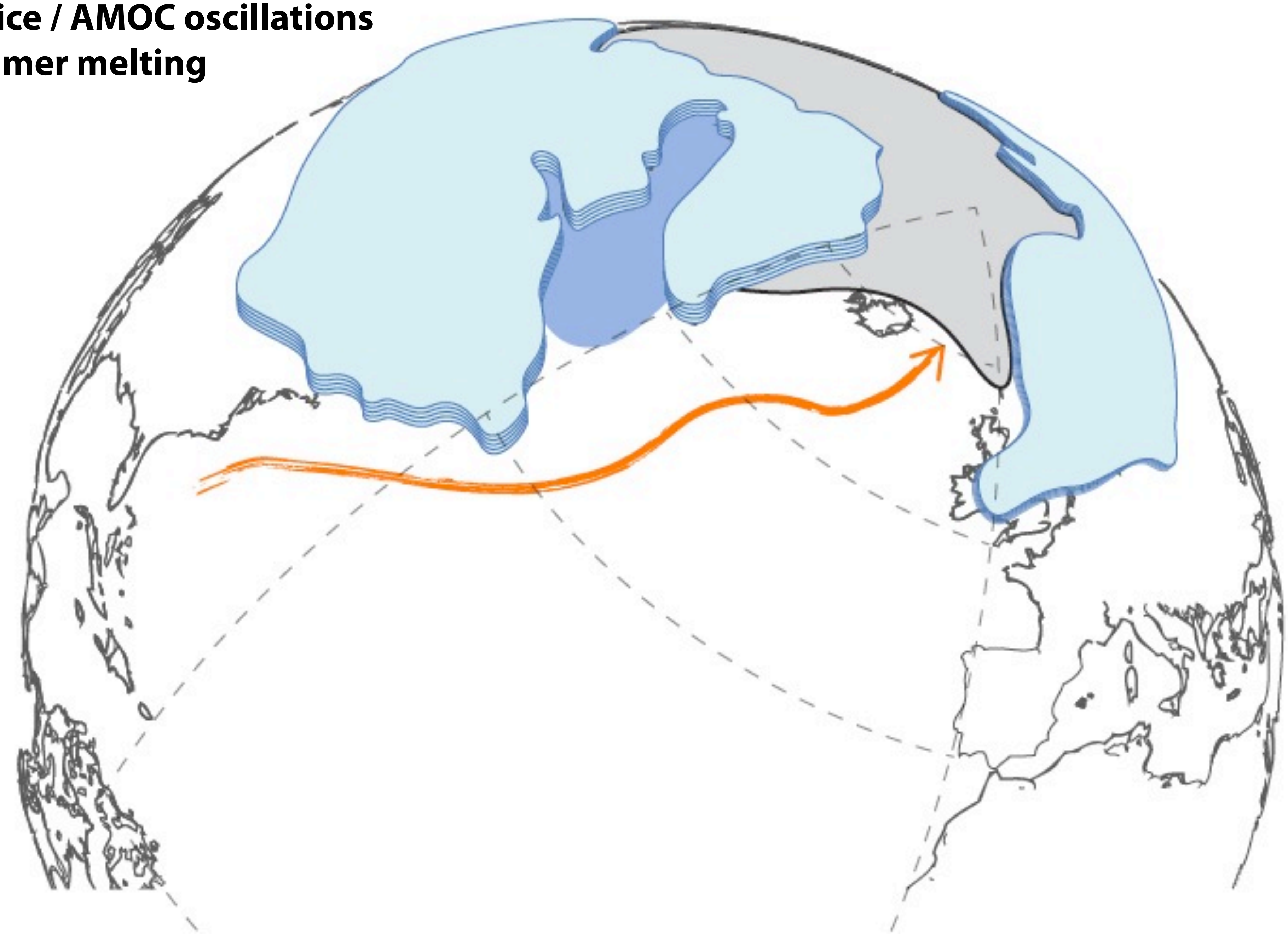


A *Cartoon* of the Ice Sheet Cycles and D-O events

Ice sheet growth phase

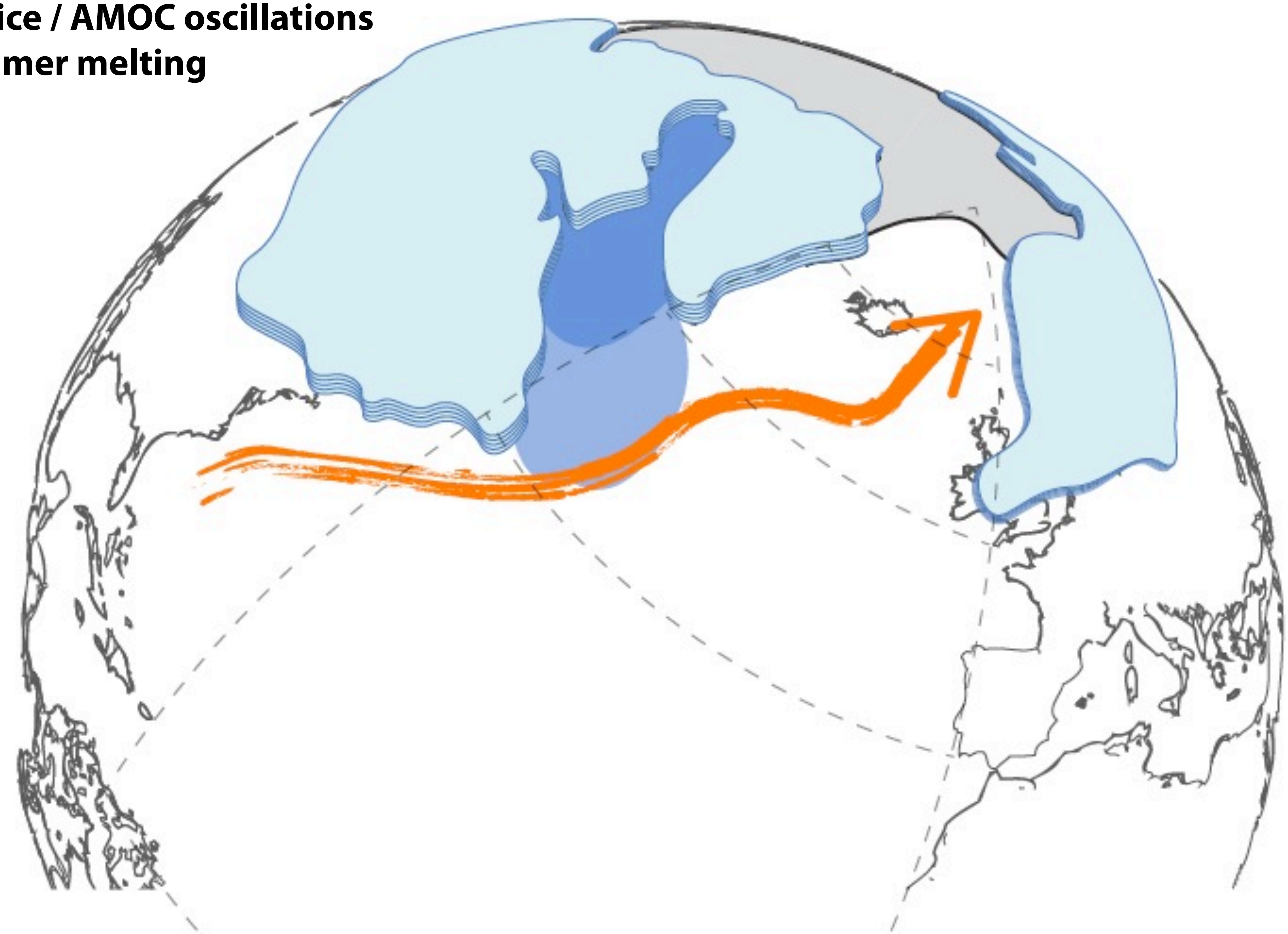
Sea ice / AMOC oscillations

Summer melting



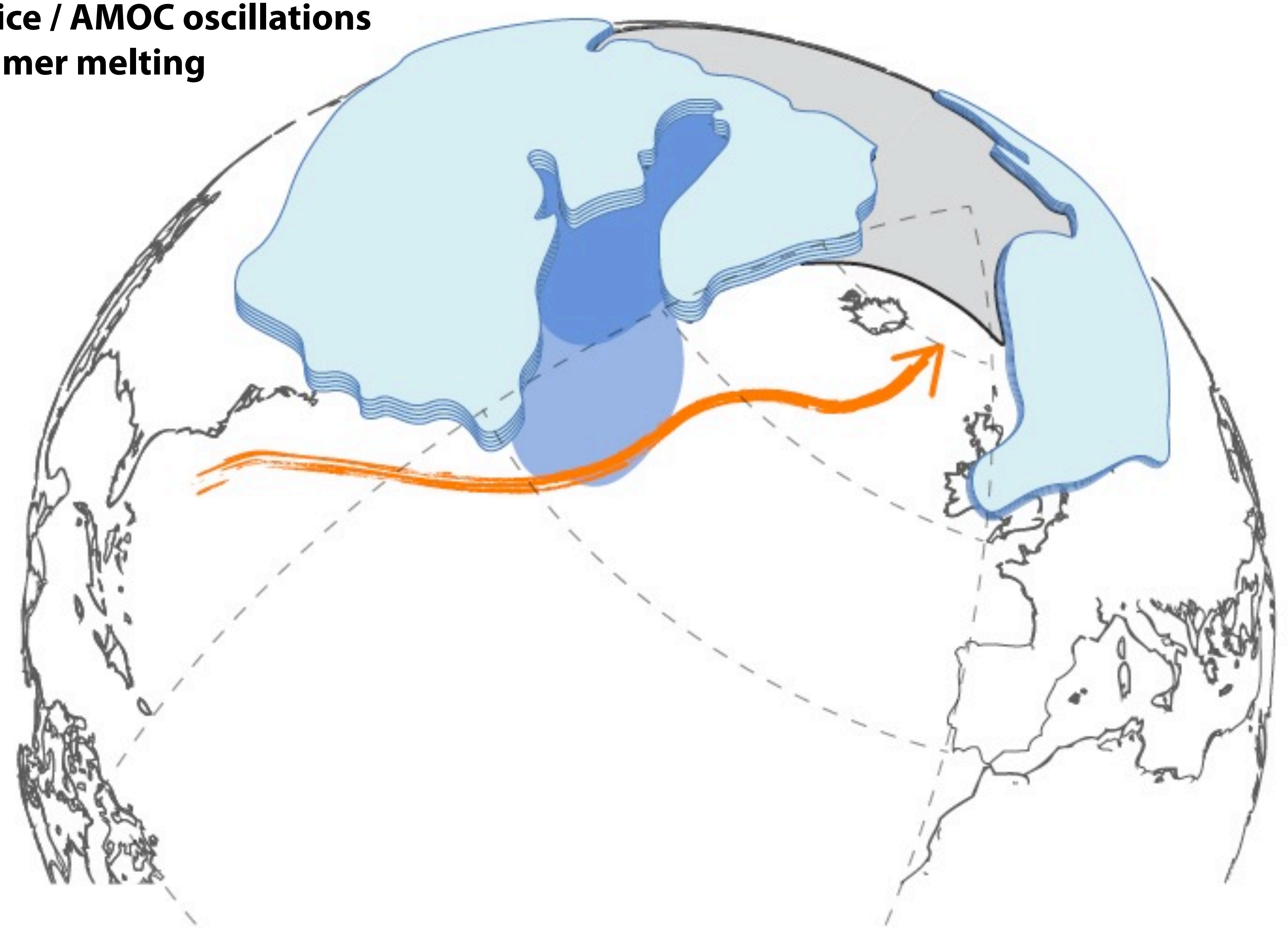
A *Cartoon* of the Ice Sheet Cycles and D-O events

Ice sheet growth phase
Sea ice / AMOC oscillations
Summer melting



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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Sea ice / AMOC oscillations

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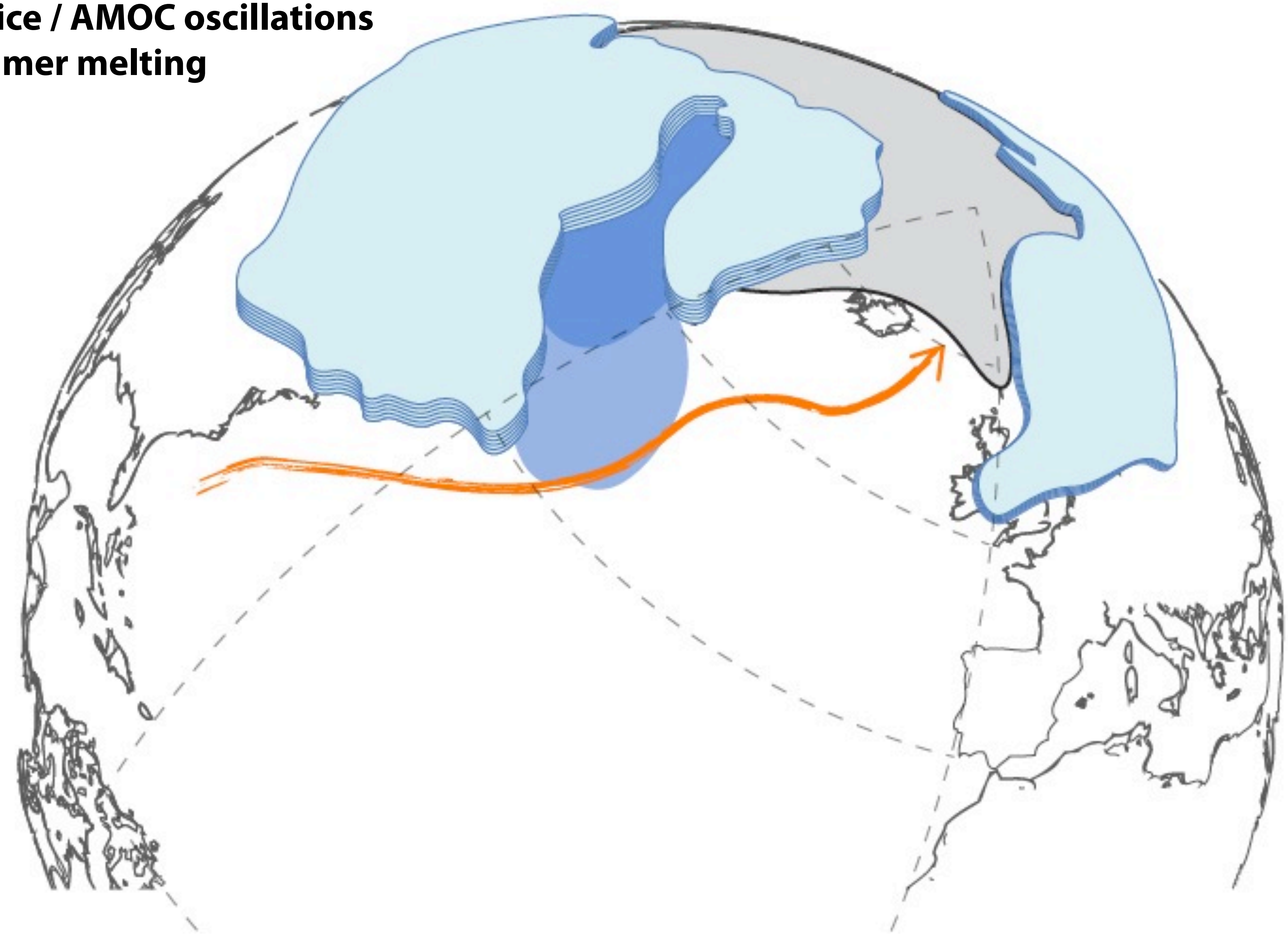

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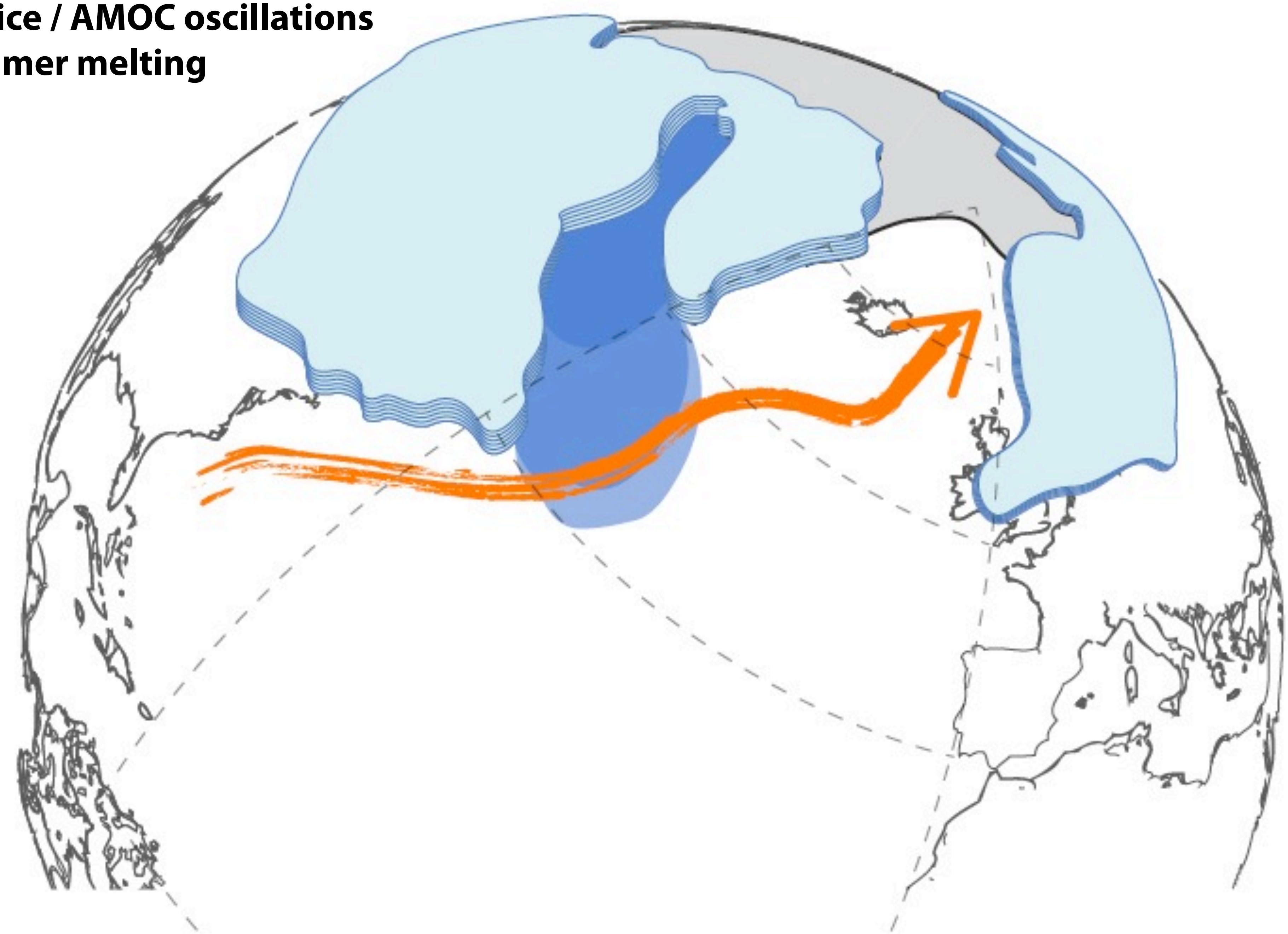

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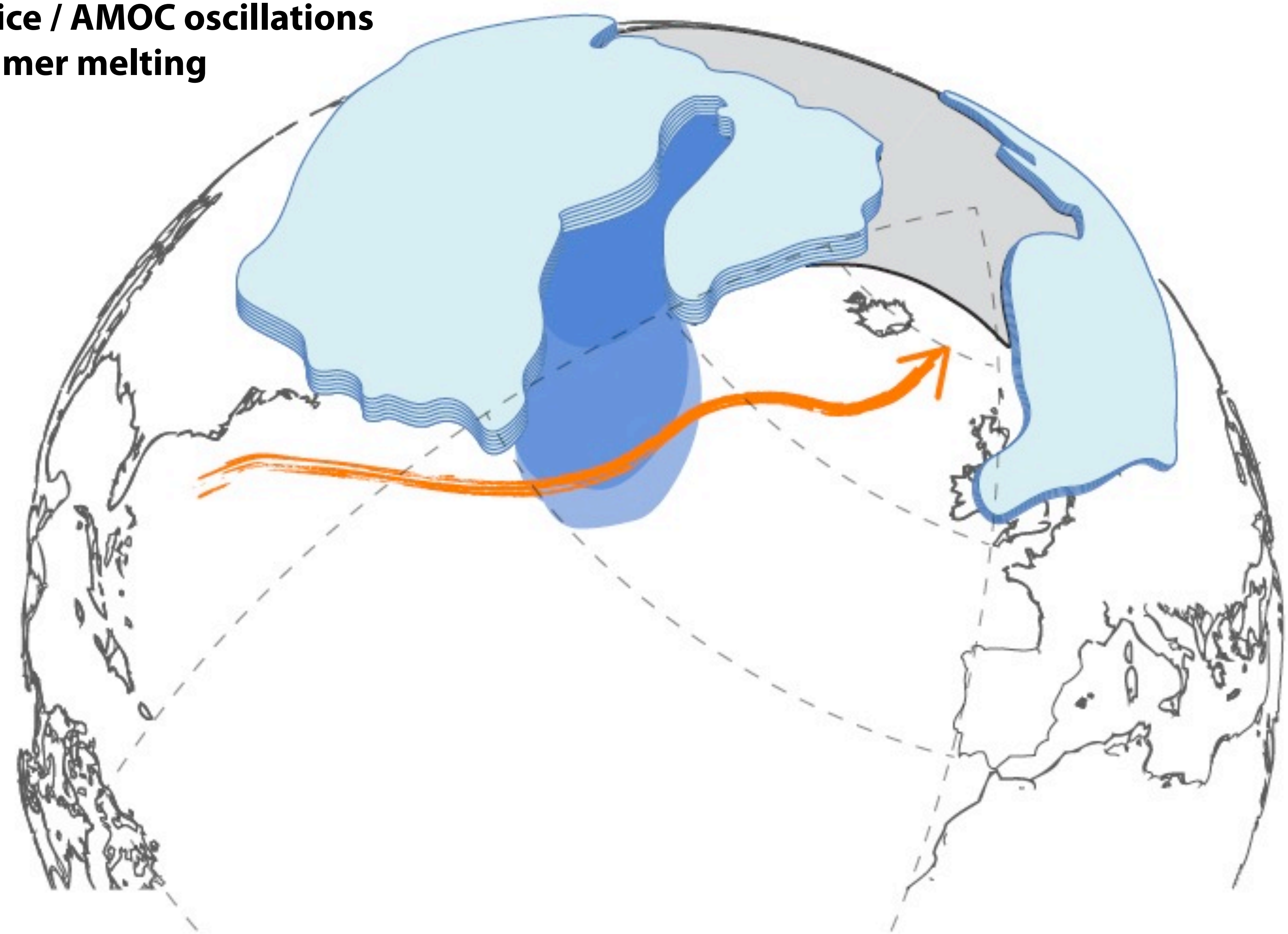

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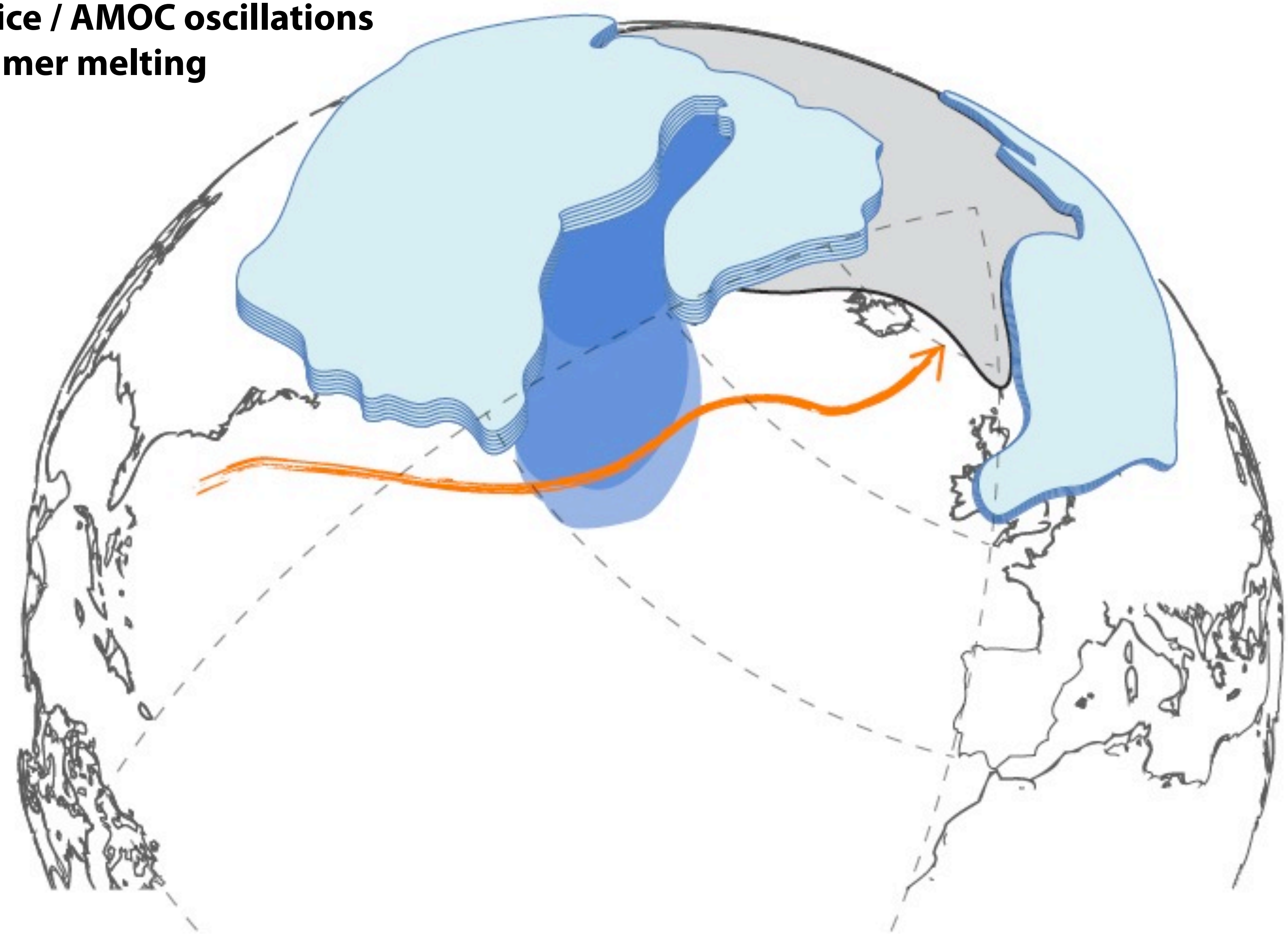
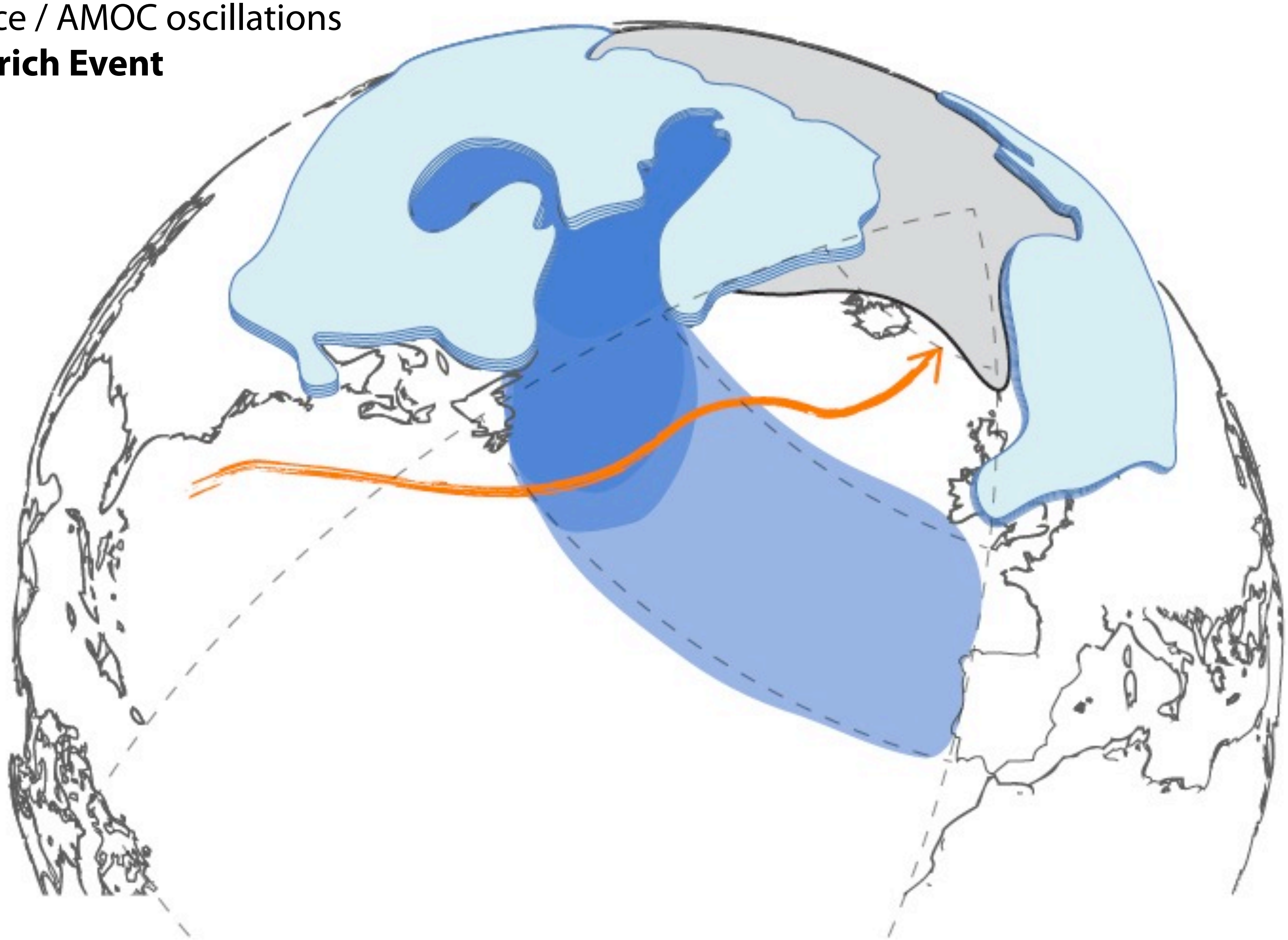
Summer melting



A *Cartoon* of the Ice Sheet Cycles and D-O events

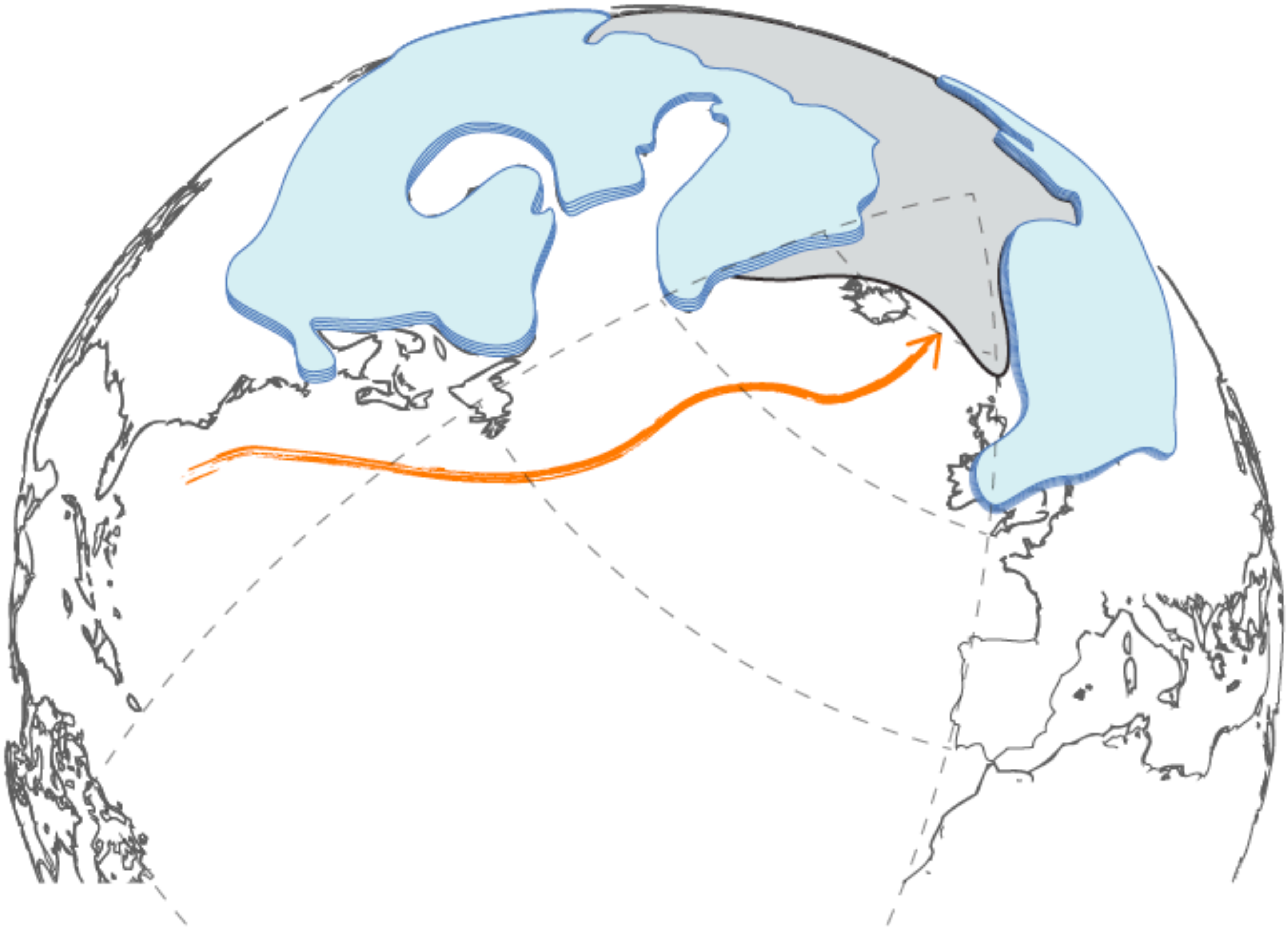
Sea ice / AMOC oscillations

Heinrich Event



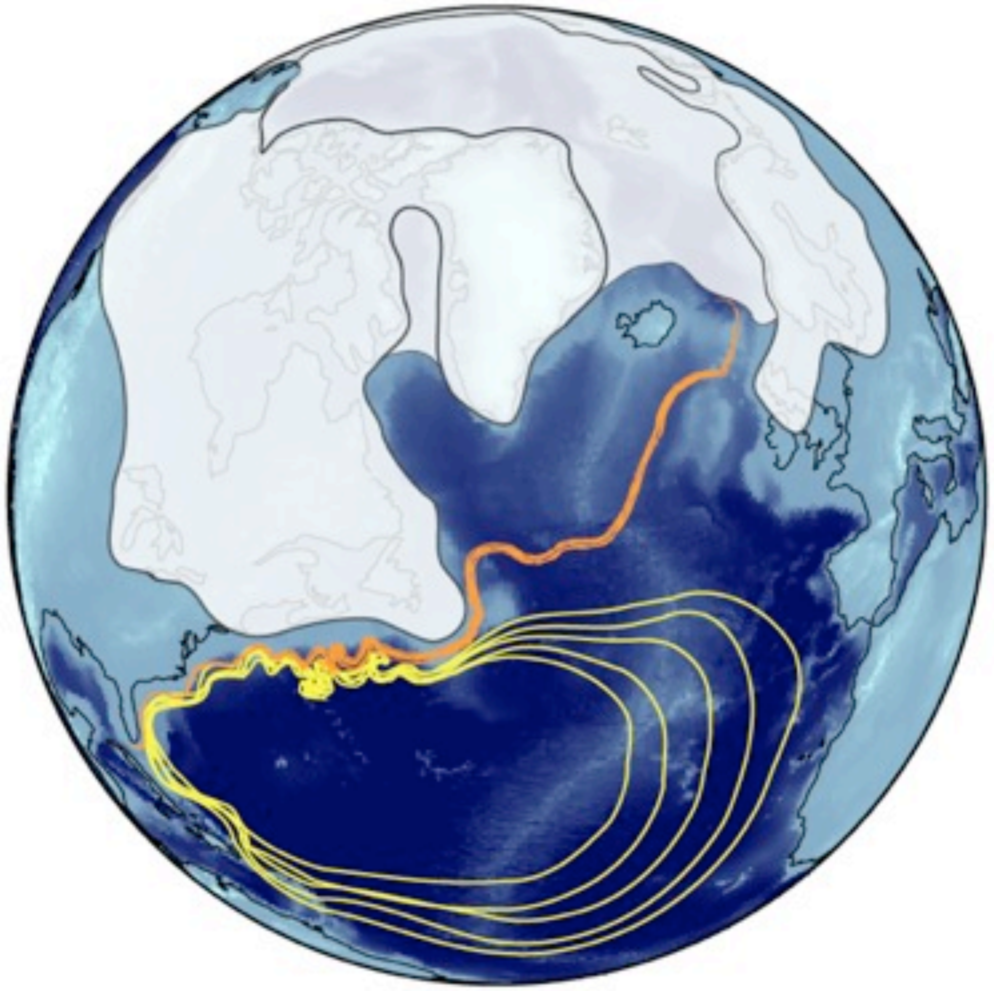
Animated Cartoon

Animated Cartoon



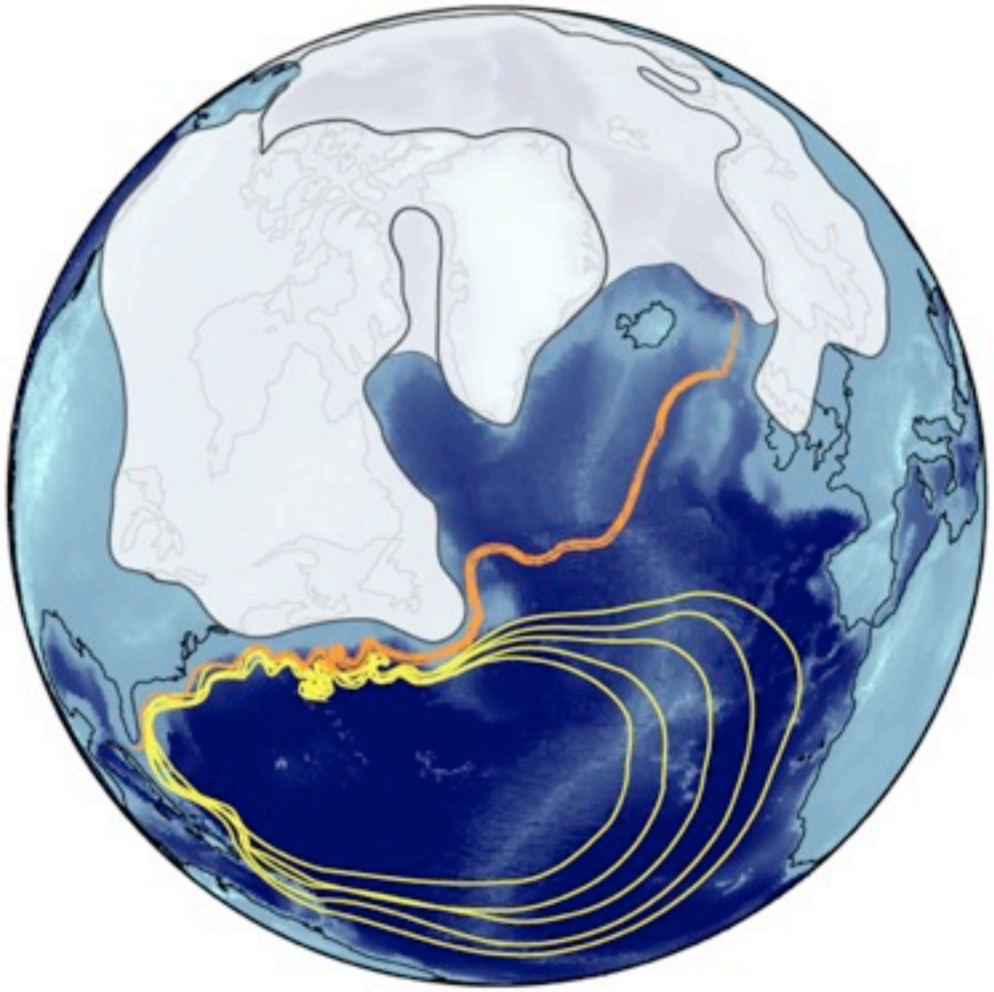
Conclusion

Conclusion



Conclusion

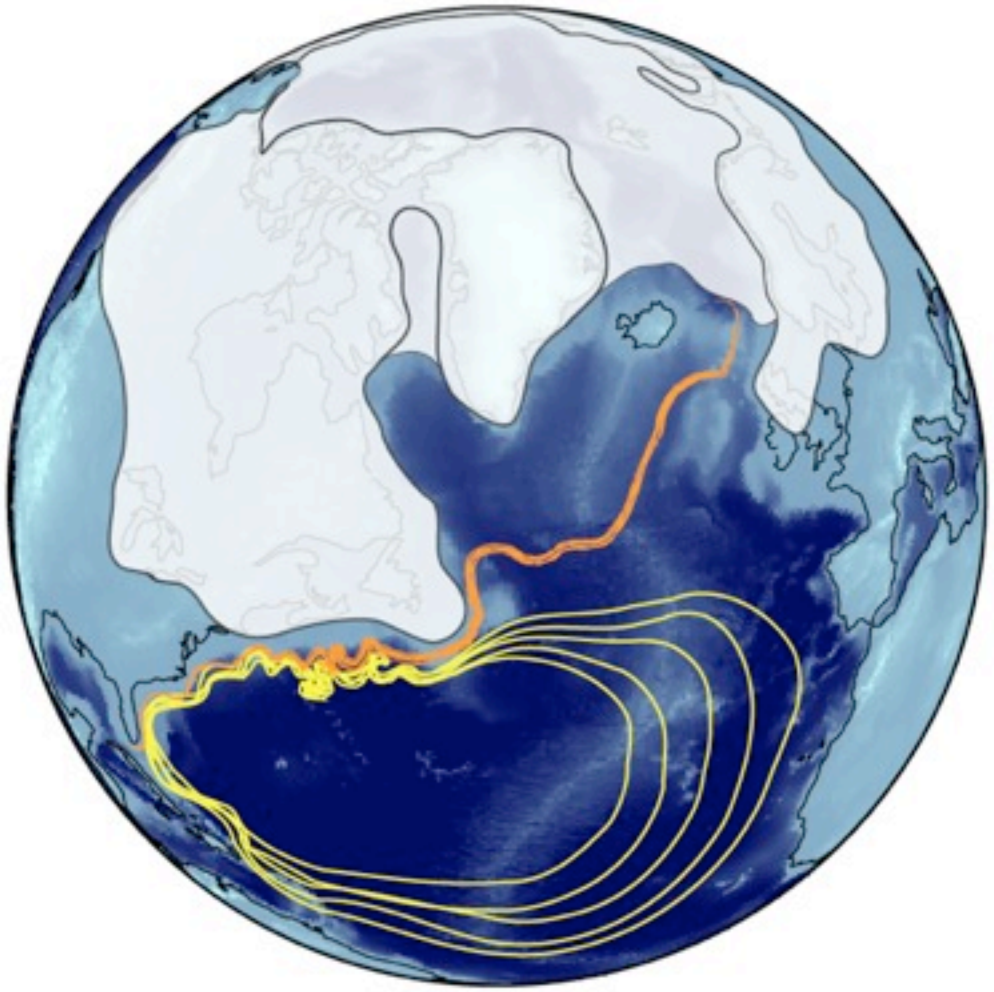
Sea Ice initiates oscillations of the circulation



Conclusion

Sea Ice initiates oscillations of the circulation

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



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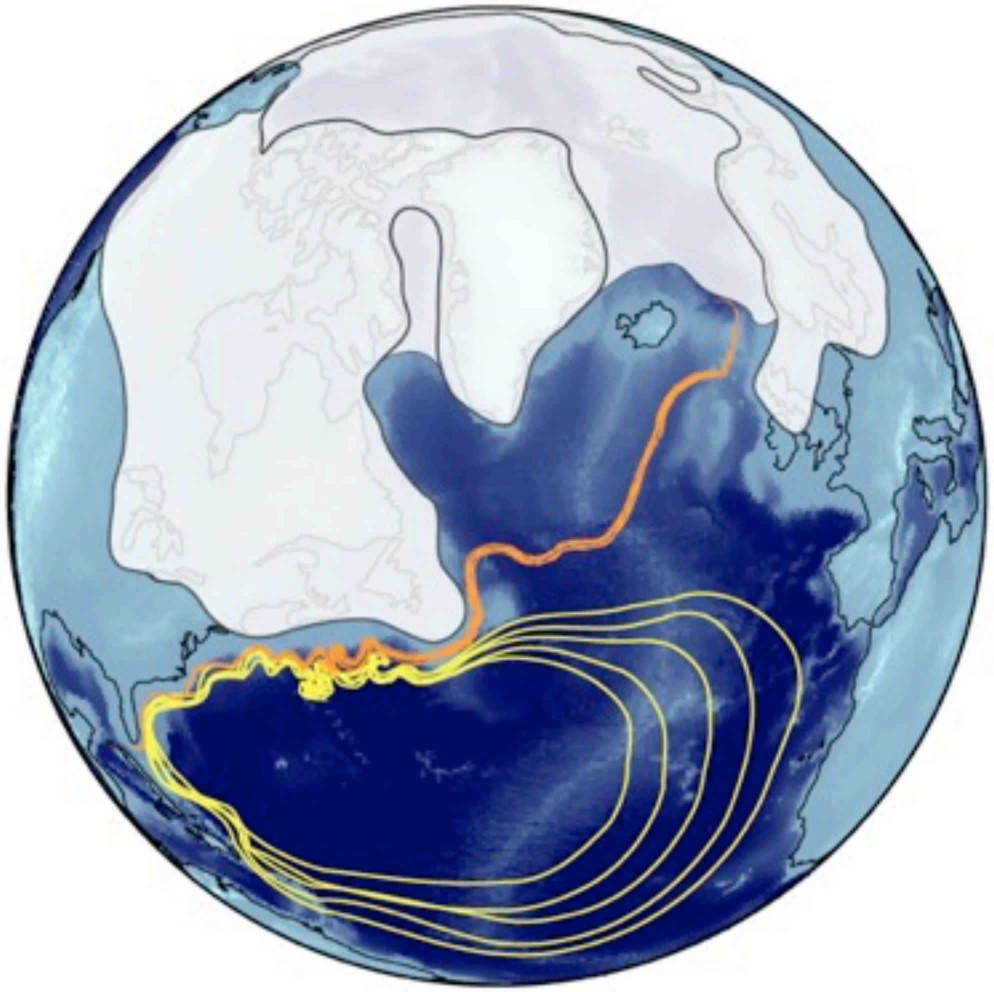

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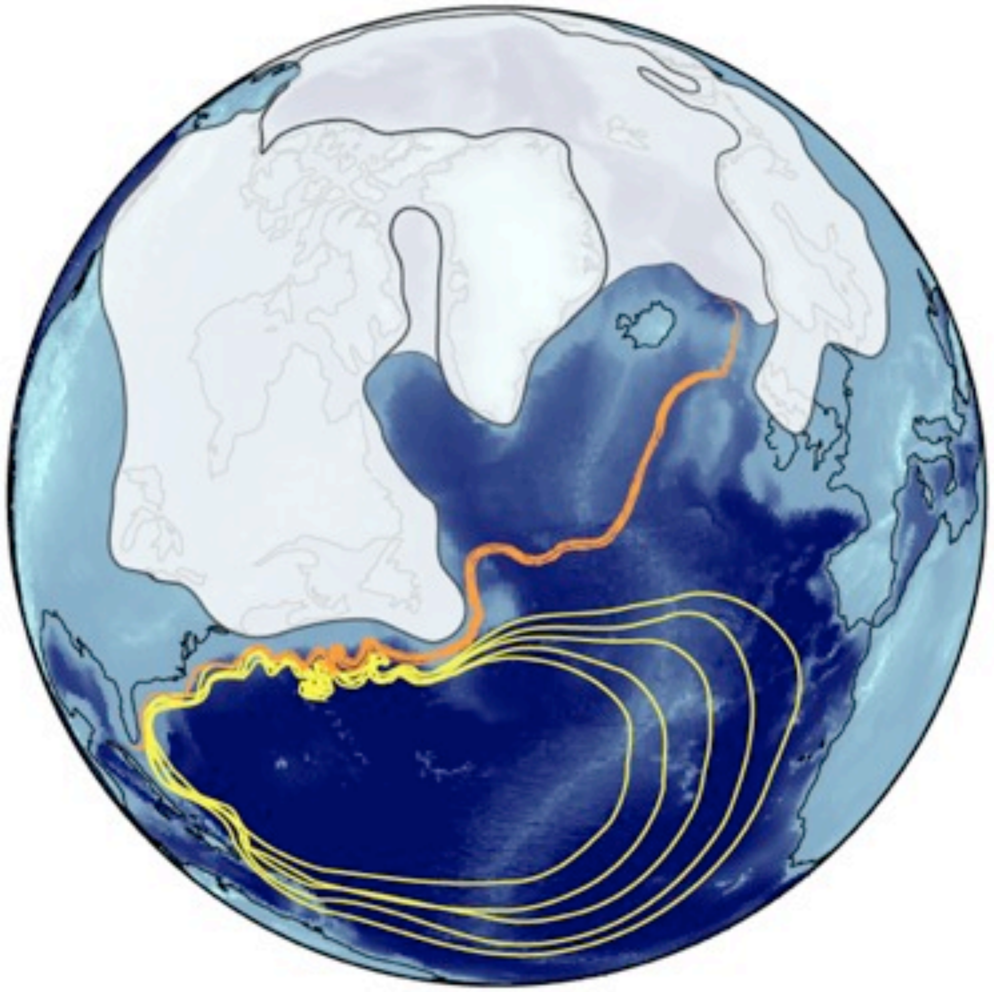


Weak (and therefore unstable) overturning circulation during glacial periods

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

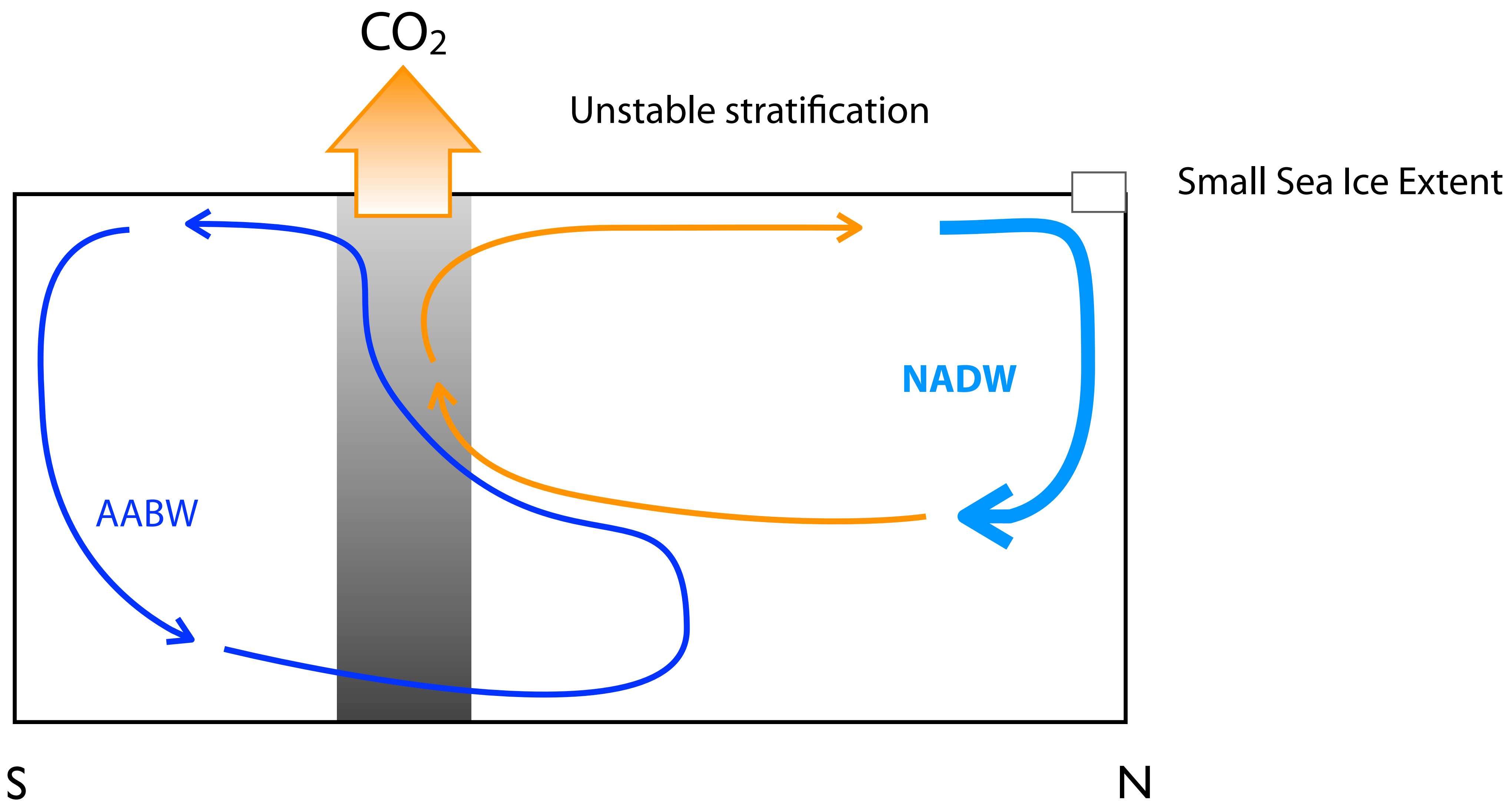
Sea ice may also serve as a similar trigger for glacial-interglacial cycles *(Gildor and Tziperman, 2001)*

Future Work

Carbon Storage in the Ocean: Dr. Irina Marinov, UPenn

Glacial - Interglacial Cycles

Interglacial Circulation

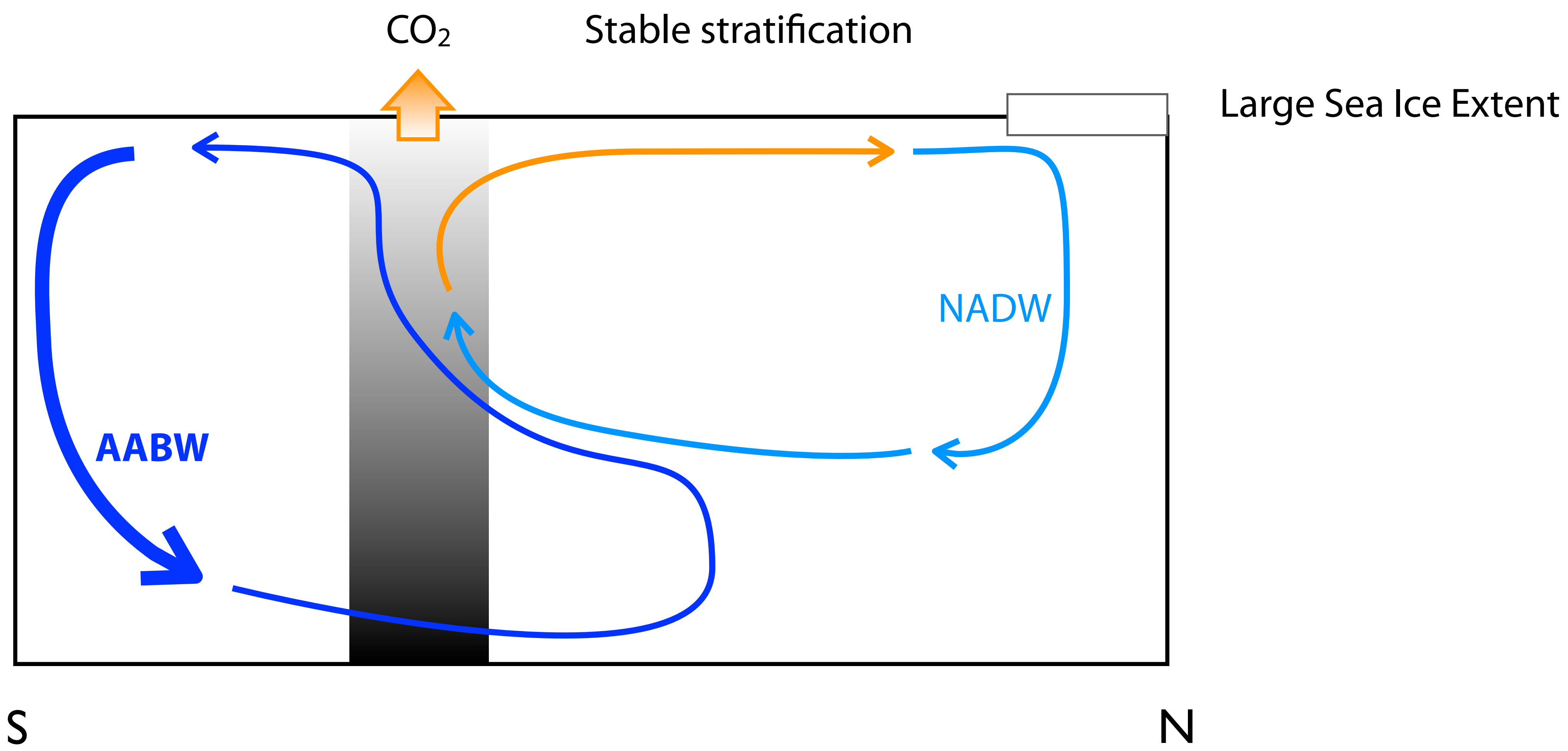


Gildor ,Tziperman, Toggweiler (2002)

Carbon Storage in the Ocean: Dr. Irina Marinov, UPenn

Glacial - Interglacial Cycles

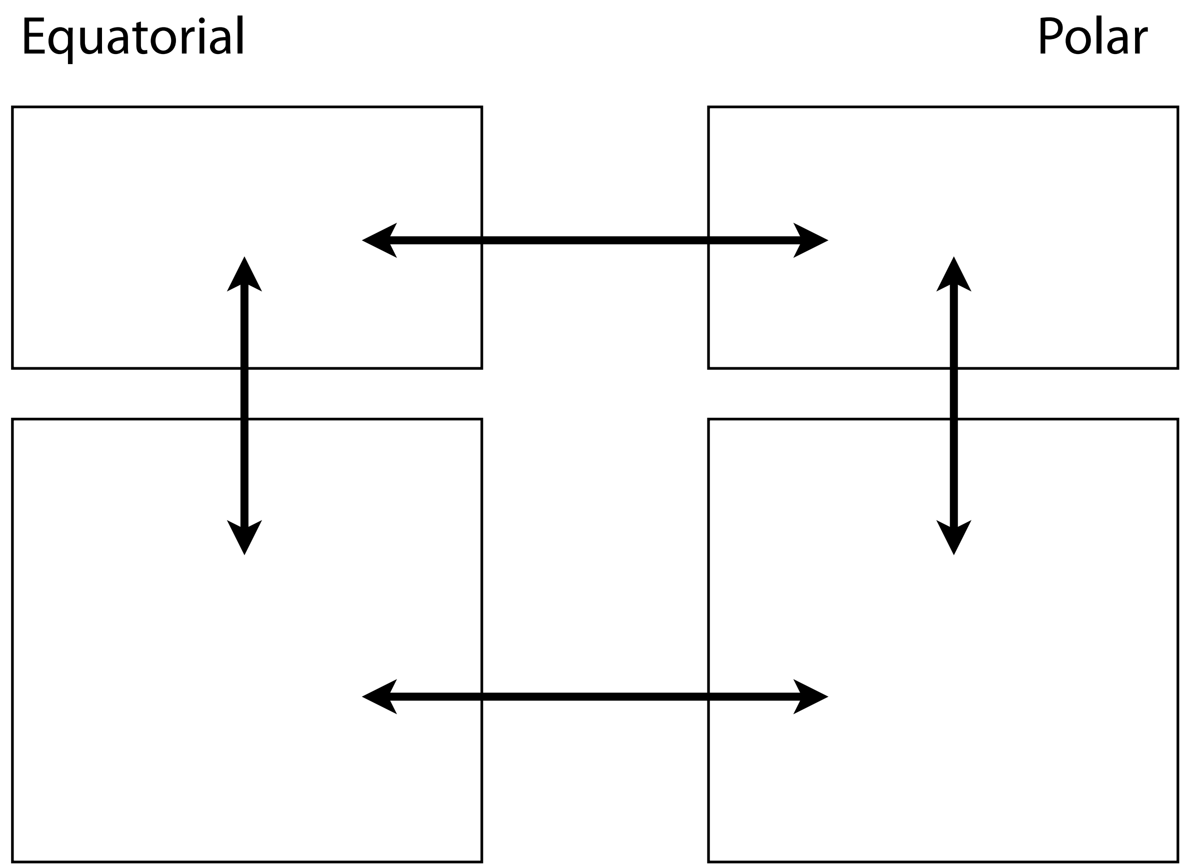
Glacial Circulation



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

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Questions?