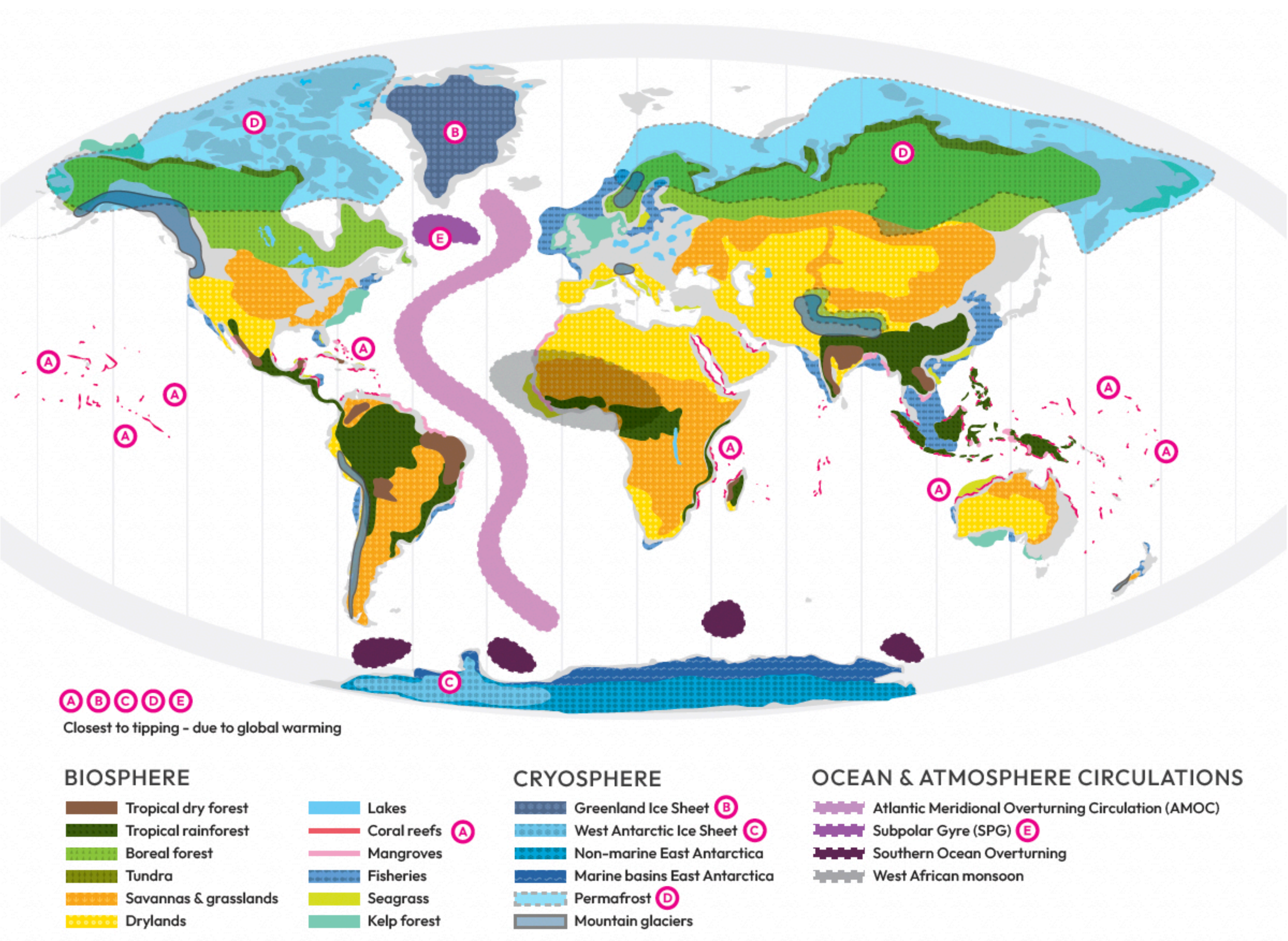
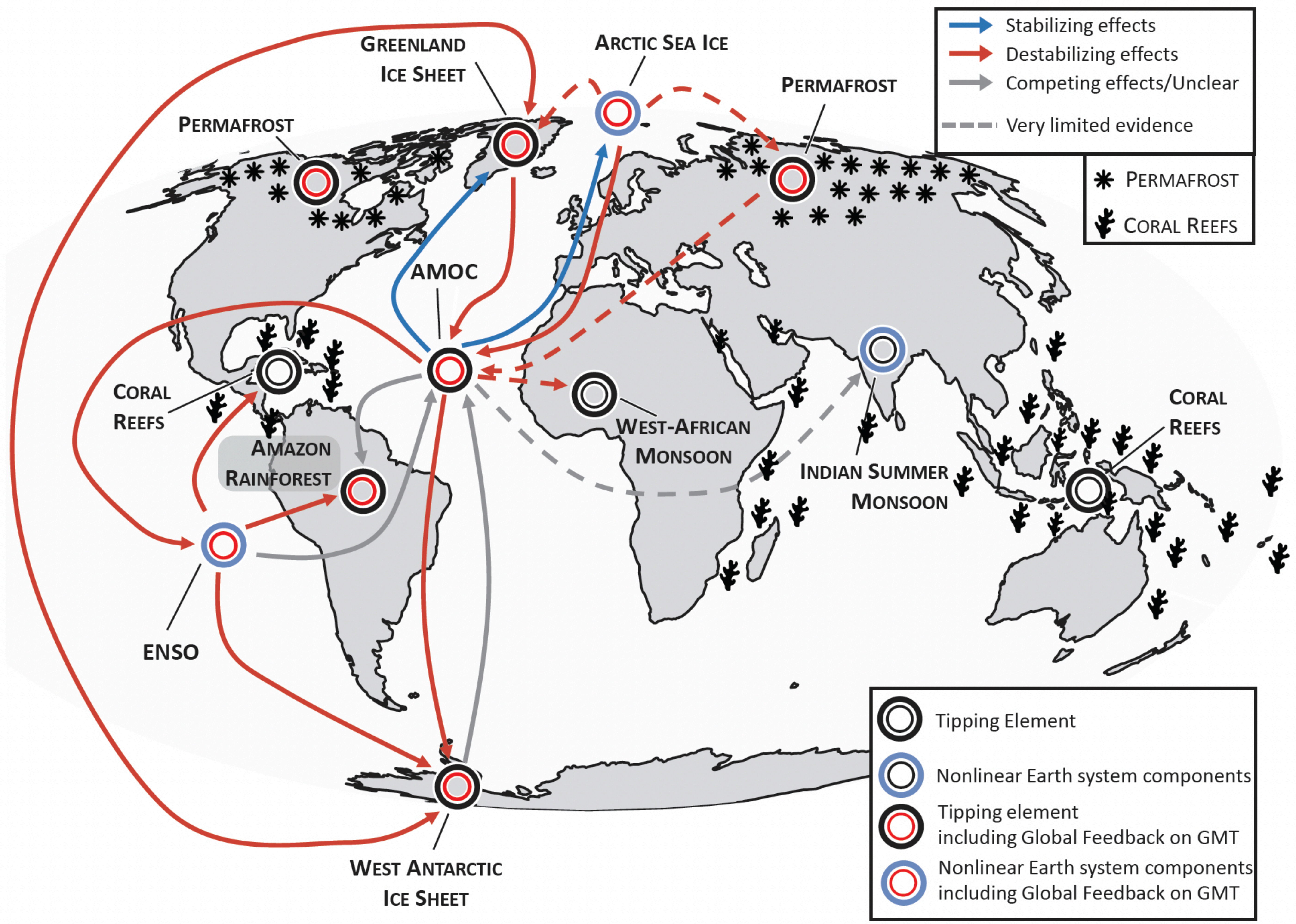
Tipping Behavior in the Climate System



Henk Dijkstra,
Department of Physics,
Utrecht University, NL
&
DICAM,
University of Trento, IT

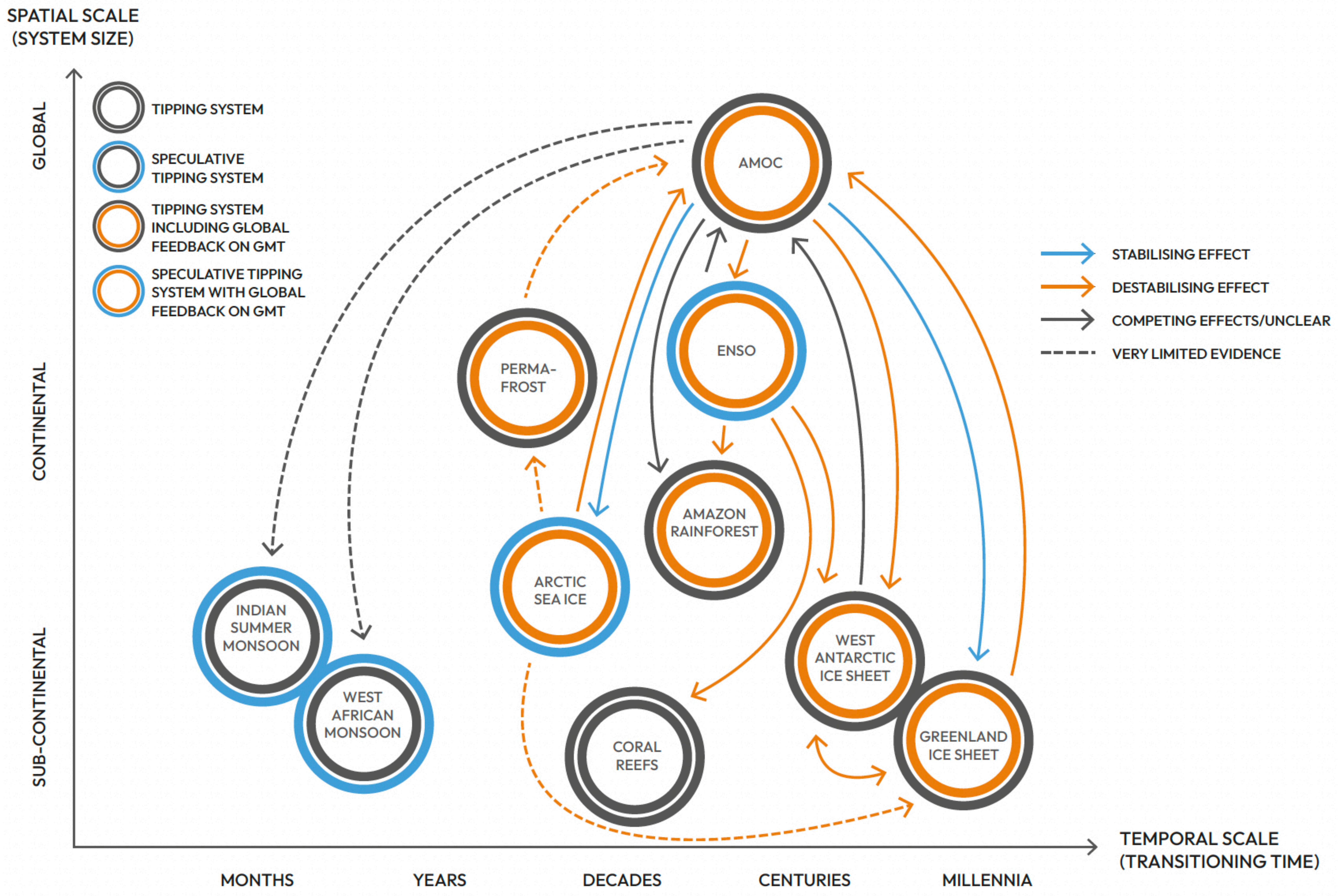
Tipping Cascades



Tipping in subsystem A (leading system) causes tipping in the subsystem B (following system)

Dekker et al. (2018)

Spatial-temporal scales of coupling



Coupling of Subsystems

From \ To	GIS	WAIS	AMOC	ASI	AMAZ	ENSO	Coral	ISM	WAM	PERM
GIS		M	S							
WAIS	W		M/W							
AMOC	S	U		M/W	M	W		U	U	
ASI	W		M/W							W
AMAZ										
ENSO		M/W	U		S		S			
Coral										
ISM										
WAM										
PERM			U							

Stabilising effects

Destabilising effects

Competing effects/Unclear

S = Strong
M = Moderate
W = Weak
U = Unclear

Cascading Tipping: Theory

Earth Syst. Dynam., 9, 1243–1260, 2018
https://doi.org/10.5194/esd-9-1243-2018

Earth System Dynamics
Open Access

Cascading transitions in the climate system

Mark M. Dekker[1,2,3], **Anna S. von der Heydt**[1,2], **and Henk A. Dijkstra**[1,2]

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[3]Department of Information and Computing Science, Utrecht University, Utrecht, the Netherlands

Cascading transition: two back-to back saddle nodes

$$\begin{cases} \dfrac{\mathrm{d}x}{\mathrm{d}t} = a_1 x^3 + a_2 x + \phi \\ \dfrac{\mathrm{d}y}{\mathrm{d}t} = b_1 y^3 + b_2 y + \gamma(x), \end{cases}$$

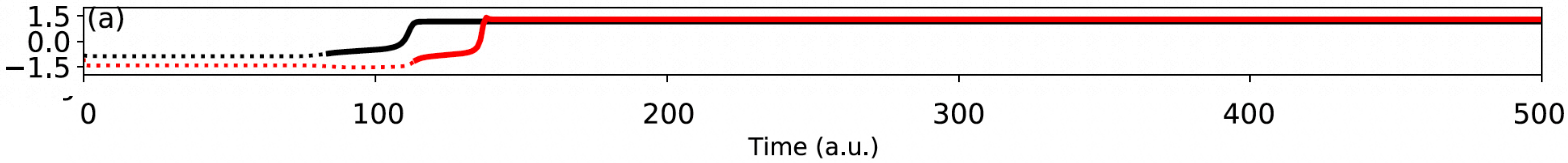
$$\gamma = 0.48x$$

$a_1 = -0.5$

$a_2 = 0.5$

$b_1 = -0.5$

$b_2 = 1.0$



Dekker et al. (2018)

Utrecht University

Cascading transition: saddle node - Hopf

$$
\begin{cases}
\frac{\mathrm{d}x}{\mathrm{d}t} = a_1 x^3 + a_2 x + \phi \\
\frac{\mathrm{d}y}{\mathrm{d}t} = b_1 z + b_2(\gamma(x) - (y^2 + z^2))y \\
\frac{\mathrm{d}z}{\mathrm{d}t} = c_1 y + c_2(\gamma(x) - (y^2 + z^2))z,
\end{cases}
$$

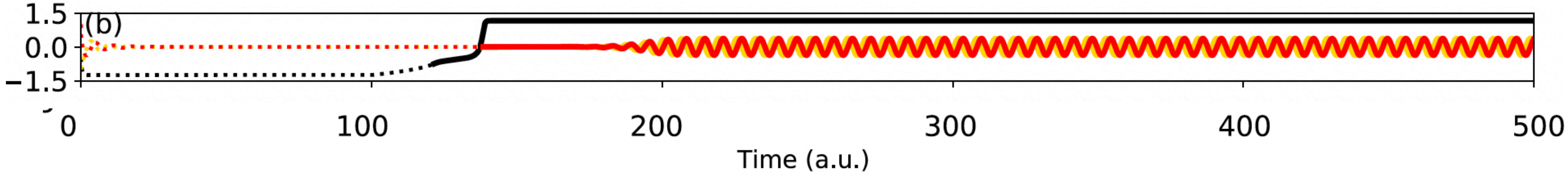
$$\gamma = -0.1 + 0.12x$$

$$a_1 = -1$$

$$a_2 = 1$$

$$b_1 = b_2 = 1$$

$$c_1 = -1; c_2 = 1$$



Dekker et al. (2018)

Cascading transition: Hopf -saddle node

$$\begin{cases} \frac{\mathrm{d}x}{\mathrm{d}t} = a_1 y + a_2(\phi - (x^2 + y^2))x \\ \frac{\mathrm{d}y}{\mathrm{d}t} = b_1 x + b_2(\phi - (x^2 + y^2))y \\ \frac{\mathrm{d}z}{\mathrm{d}t} = c_1 z^3 + c_2 z + \gamma(x), \end{cases}$$

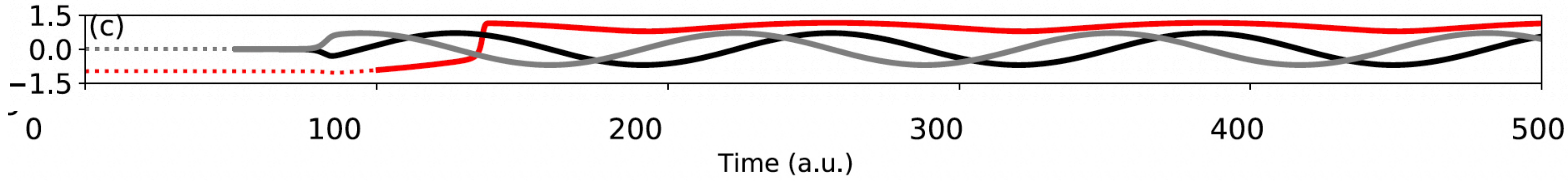
$$\gamma = 0.05 + 0.5x$$

$a_1 = 0.05;\ a_2 = 1$

$b_1 = -0.05;\ b_2 = 1$

$c_1 = -1$

$c_2 = 1$



Dekker et al. (2018)

Cascading transition: Hopf - Hopf

$$\begin{cases} \frac{\mathrm{d}x}{\mathrm{d}t} = a_1 y + a_2(\phi - (x^2 + y^2))x \\ \frac{\mathrm{d}y}{\mathrm{d}t} = b_1 x + b_2(\phi - (x^2 + y^2))y \\ \frac{\mathrm{d}u}{\mathrm{d}t} = c_1 v + c_2(\gamma(x) - (u^2 + v^2))u \\ \frac{\mathrm{d}v}{\mathrm{d}t} = d_1 u + d_2(\gamma(x) - (u^2 + v^2))v, \end{cases}$$

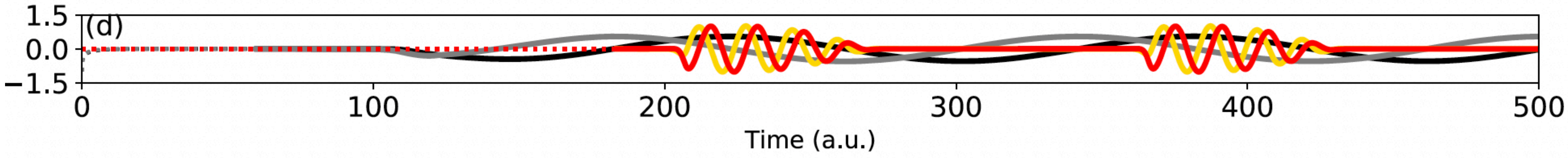
$$\gamma = -0.05 + 2x$$

$a_1 = 0.04;\ a_2 = 2$

$b_1 = -0.04;\ b_2 = 2$

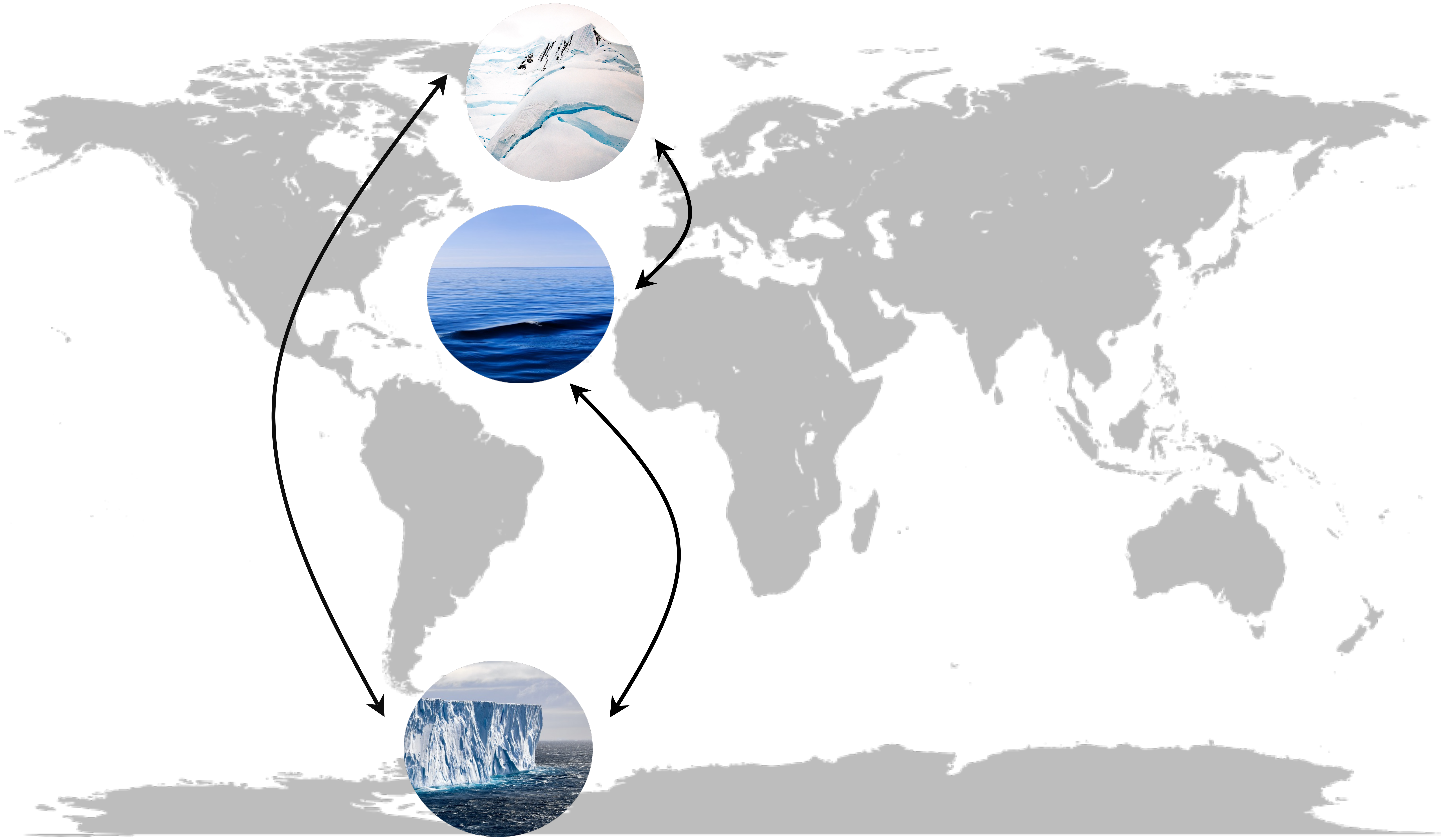
$c_1 = 0.4;\ c_2 = 1$

$d_1 = -0.4;\ d_2 = 1$



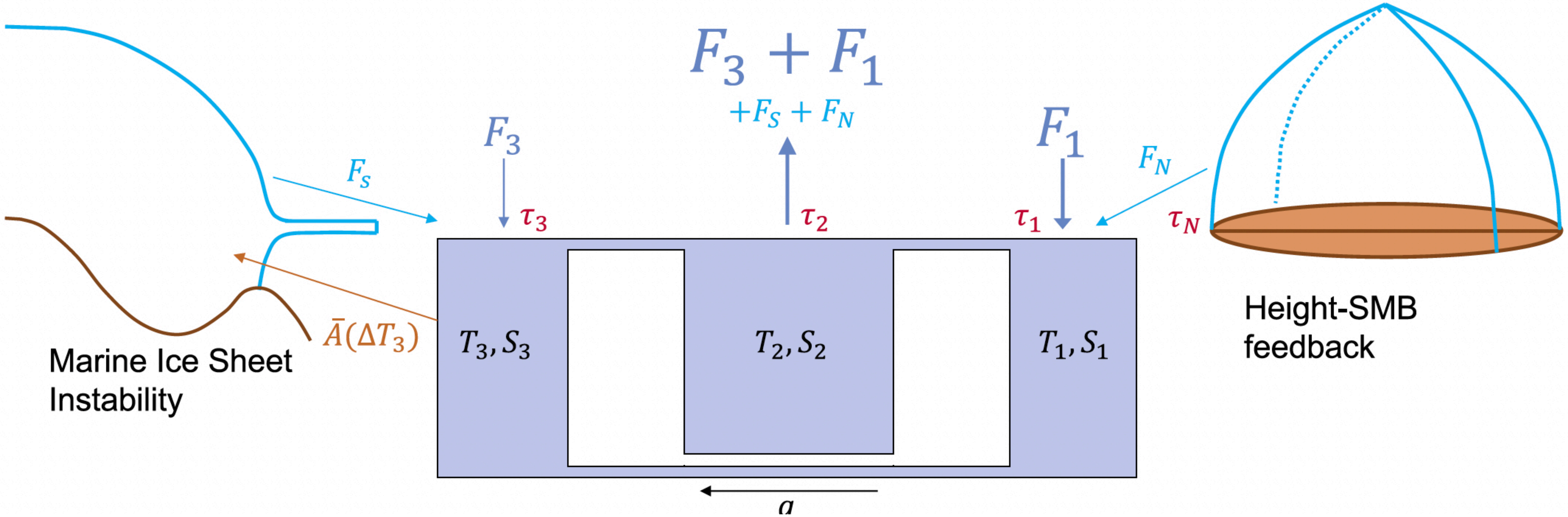
Dekker et al. (2018)

Example: AMOC-GIS-WAIS



Lenton & al. (2008)
Wunderling & al. (2024)

AMOC stabilisation through WAIS tipping



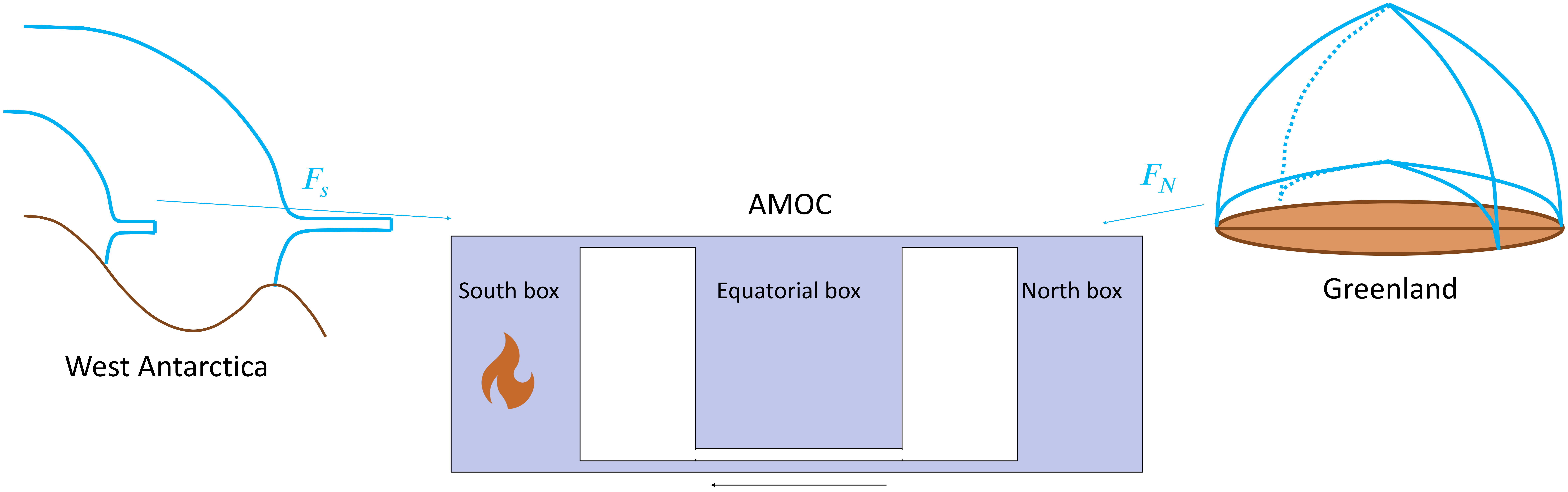
Geophysical Research Letters®

RESEARCH LETTER
10.1029/2022GL100305

AMOC Stabilization Under the Interaction With Tipping Polar Ice Sheets

S. Sinet[1,2], A. S. von der Heydt[1,2], and H. A. Dijkstra[1,2]

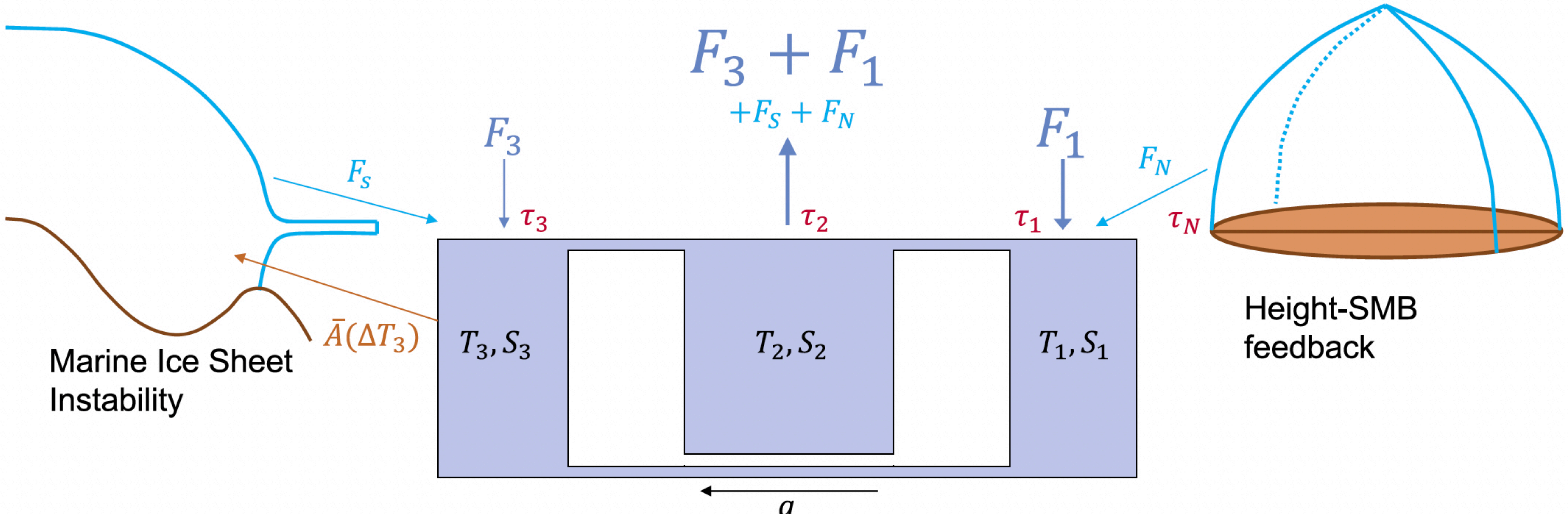
Key Points:



No Collapse !

Sinet & al. (2023a)

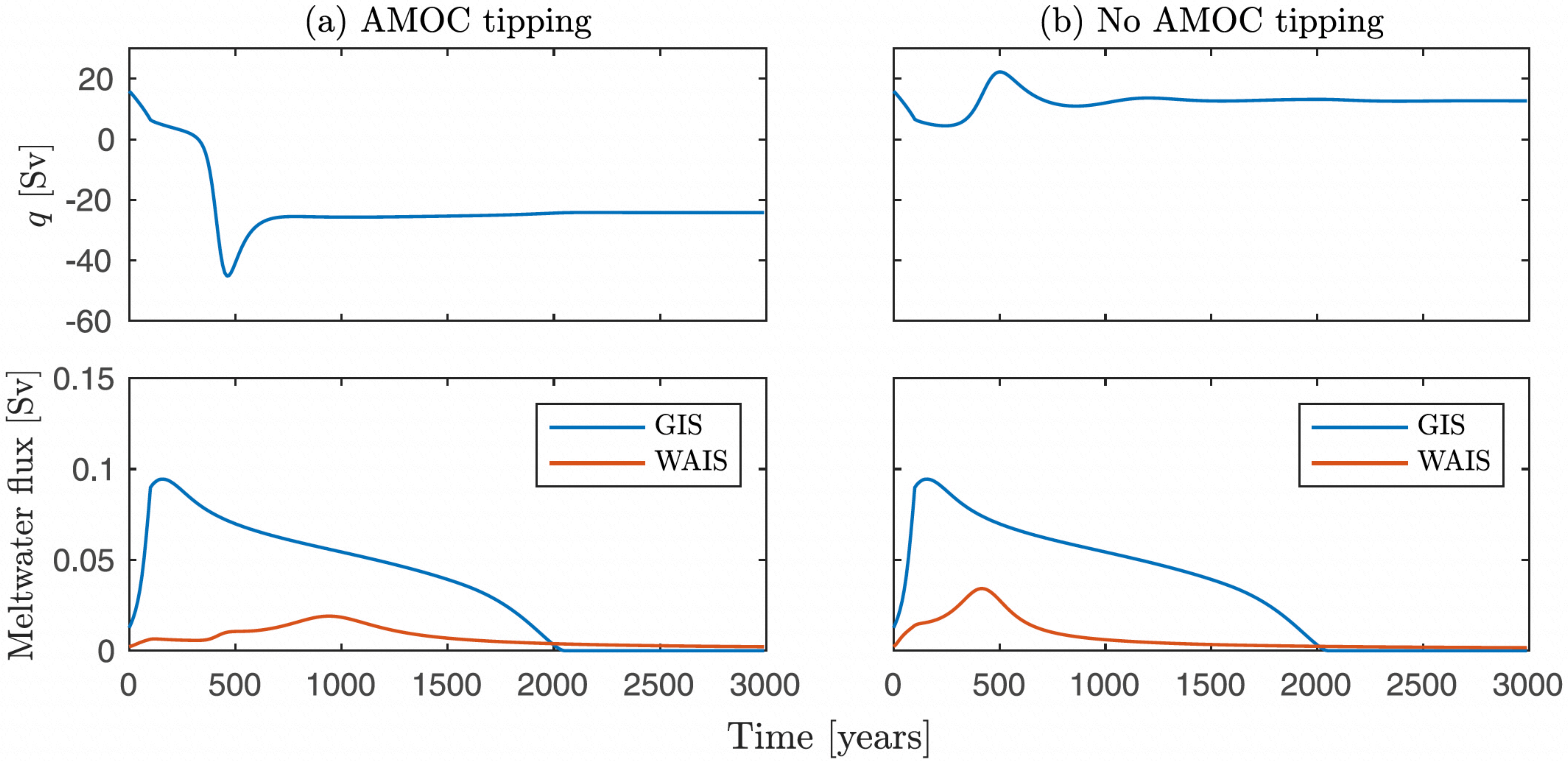
Model



$$\bar{A}(\Delta T_3) = \frac{\bar{A}^0}{T_3^0}\left[T_3^0 + c_S \Delta T_3\right].$$

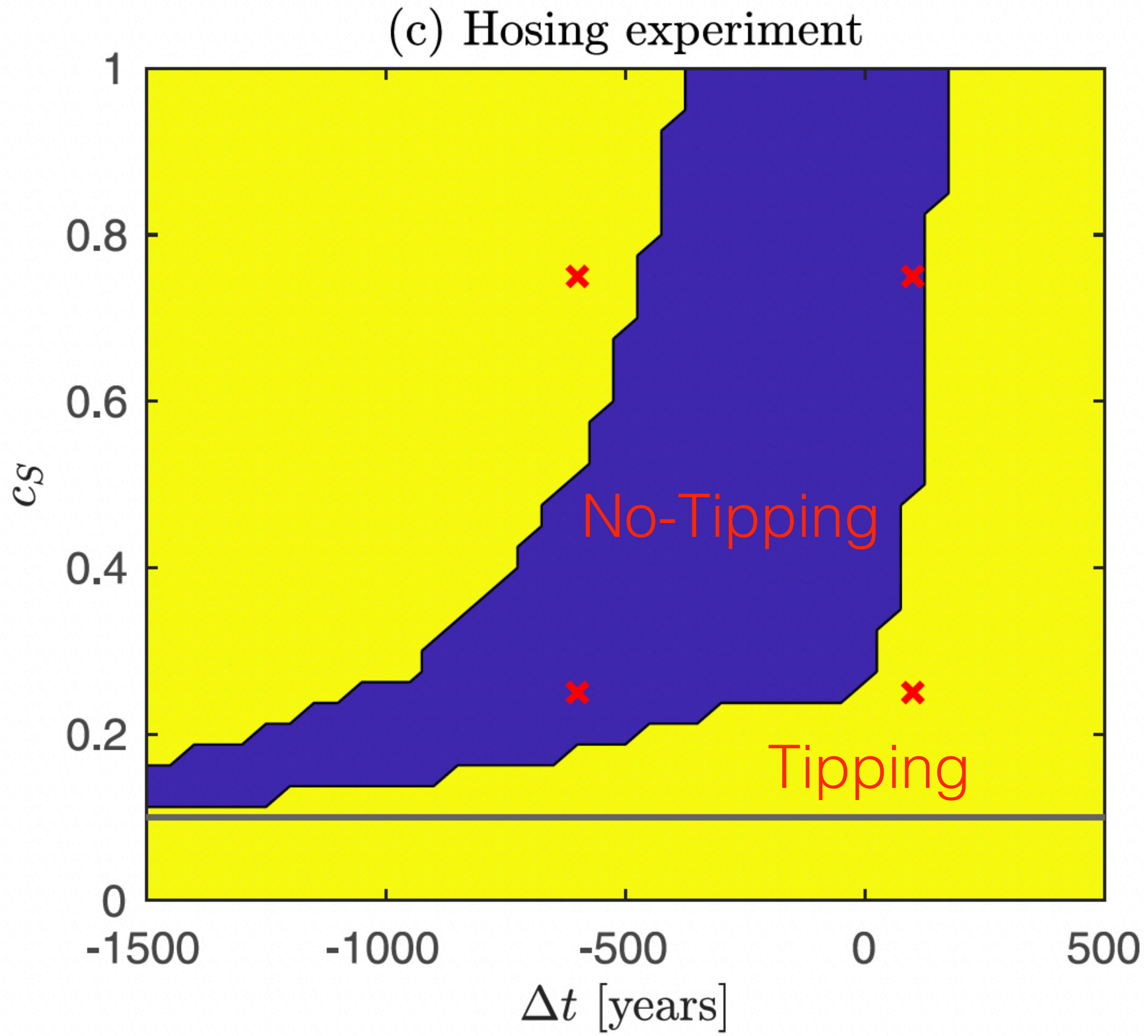
$$\tau_j(t) = \tau_j(0) + \gamma_j \frac{\Delta \tau_2}{100} t.$$

Result



(a) $c_S = 0.2$ and (b) $c_S = 0.8$.

AMOC stabilisation



Time delay between GIS and WAIS tipping

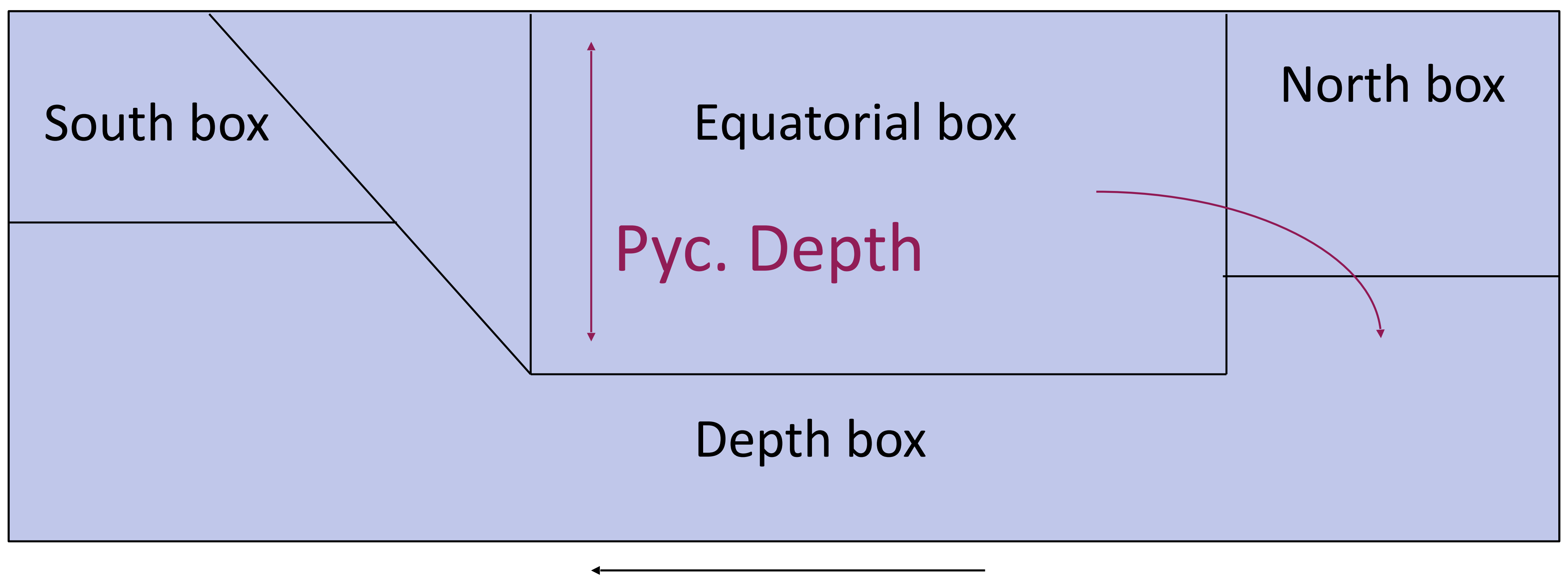
Detailed Explanation

https://doi.org/10.5194/egusphere-2023-2661
Preprint. Discussion started: 6 December 2023

EGUsphere
Preprint repository

AMOC Stability Amid Tipping Ice Sheets: The Crucial Role of Rate and Noise

Sacha Sinet[1,2], Peter Ashwin[3], Anna S. von der Heydt[1,2], and Henk A. Dijkstra[1,2]

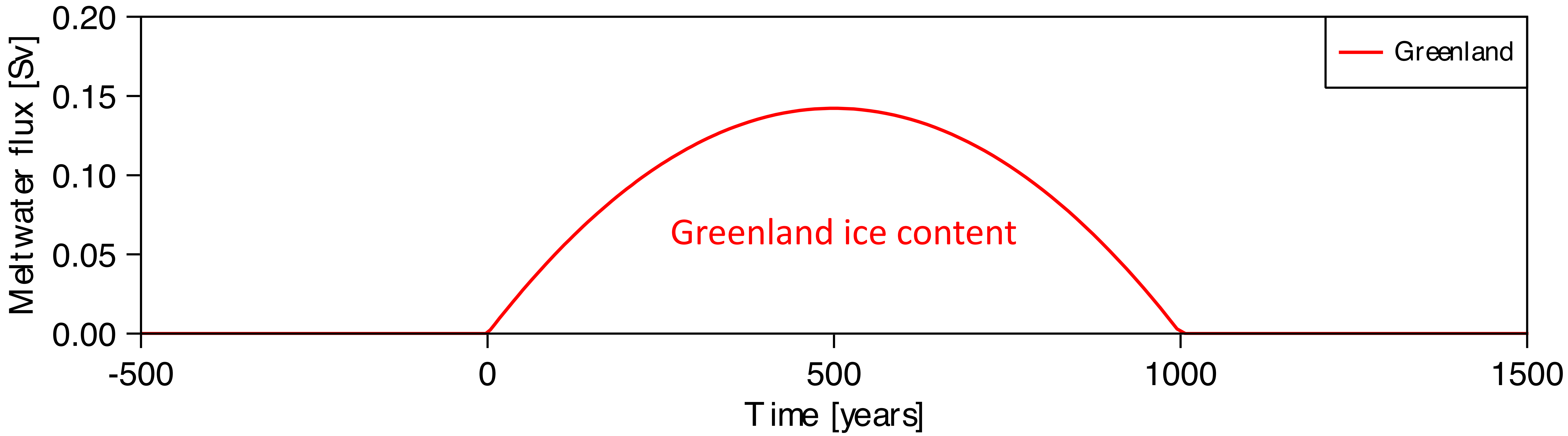


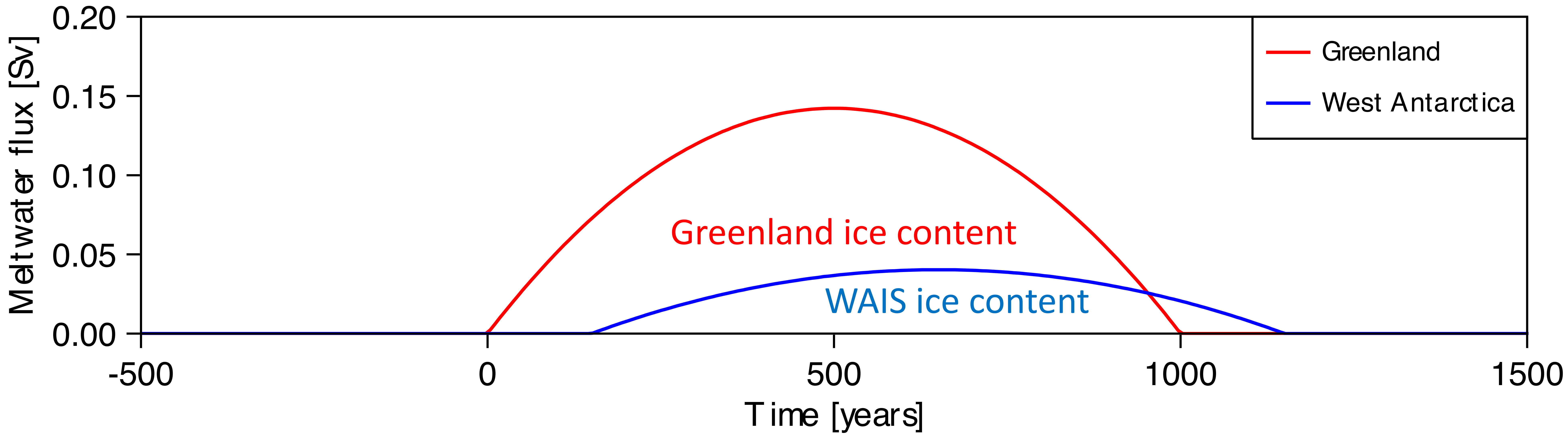
I. No warming

II. Better AMOC model
Cimatoribus & al. (2014)

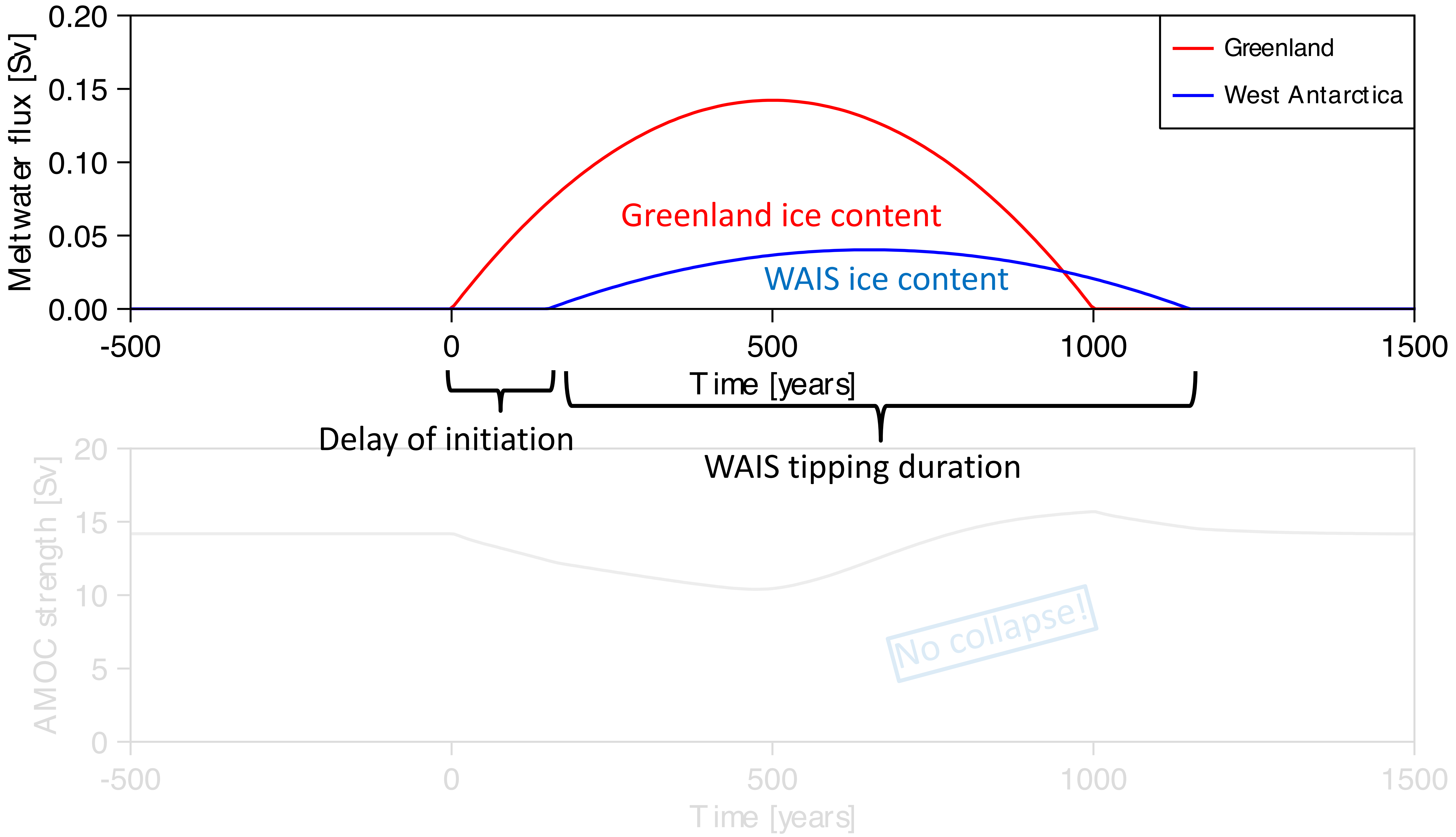
III. No dynamical Ice Sheet
Only parametrization

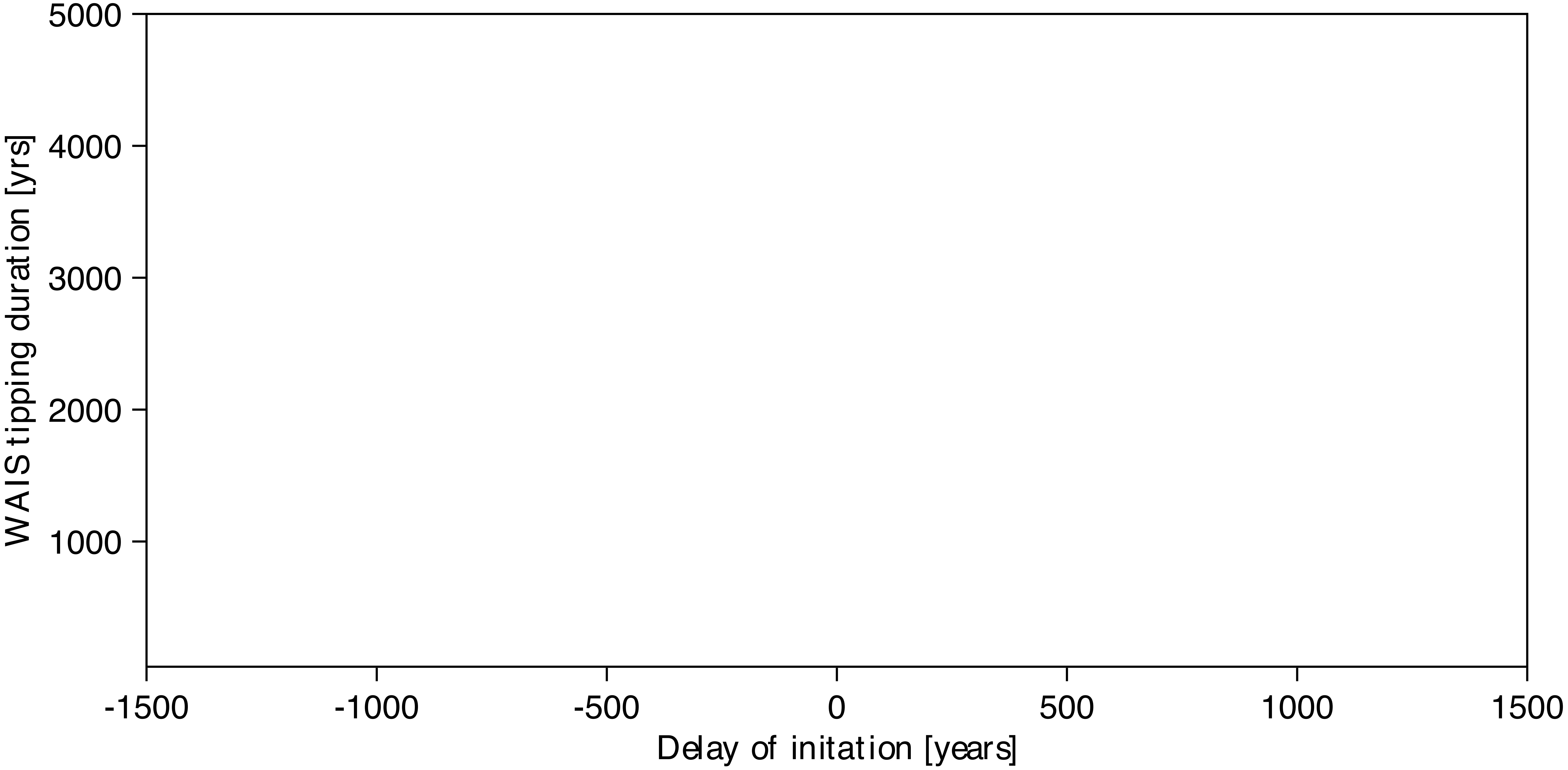
$$F_N(t;P_N) = \begin{cases} -\dfrac{6V_N}{P_N^3}t(t-P_N) & \text{if } 0 < t < P_N, \\ 0 & \text{otherwise,} \end{cases} \qquad F_S(t;P_S,\Delta t) = \begin{cases} -\dfrac{1}{4}\dfrac{6V_S}{P_S^3}(t-\Delta t)(t-\Delta t-P_S) & \text{if } 0 < t-\Delta t < P_S, \\ 0 & \text{otherwise,} \end{cases}$$

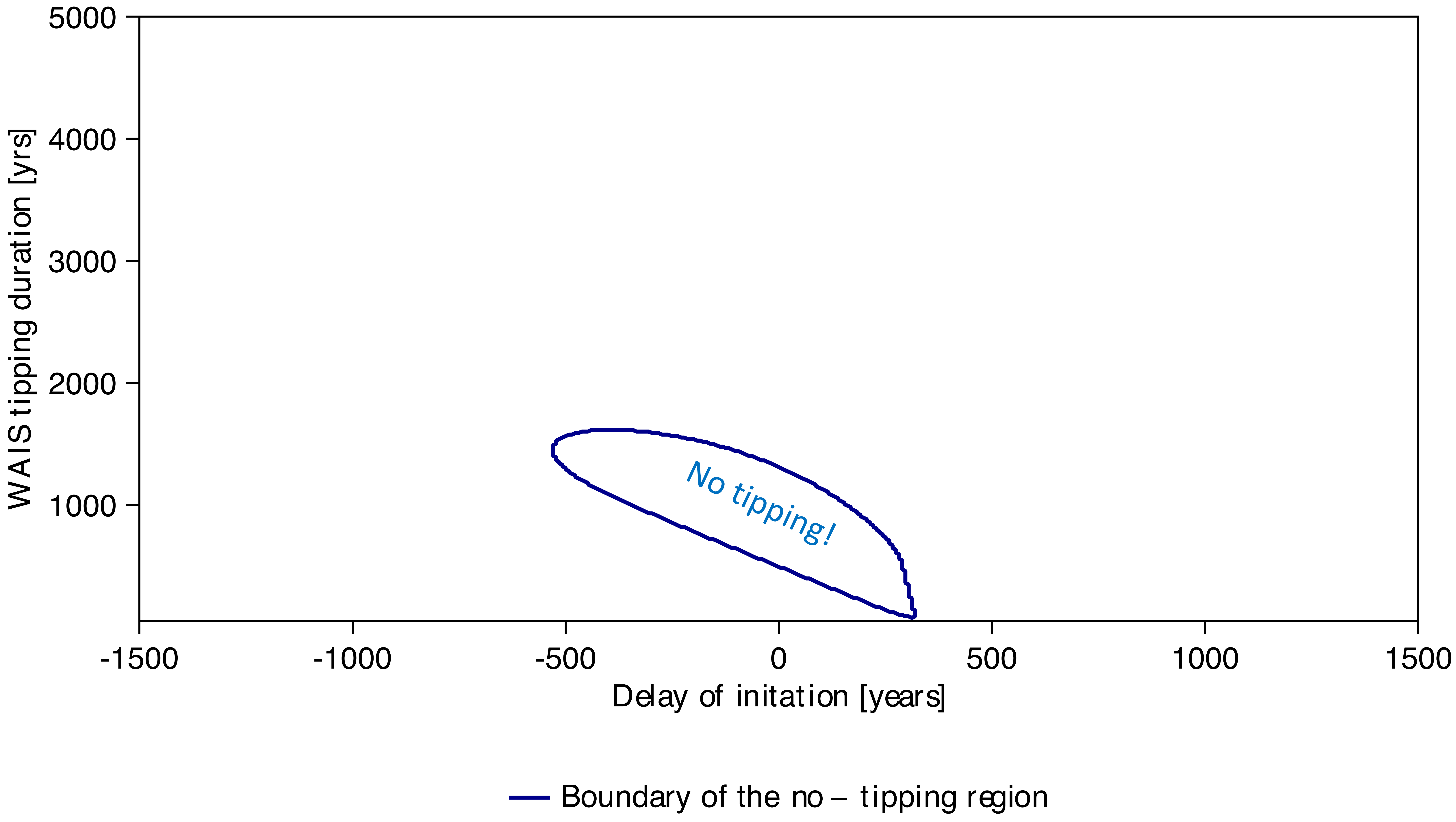


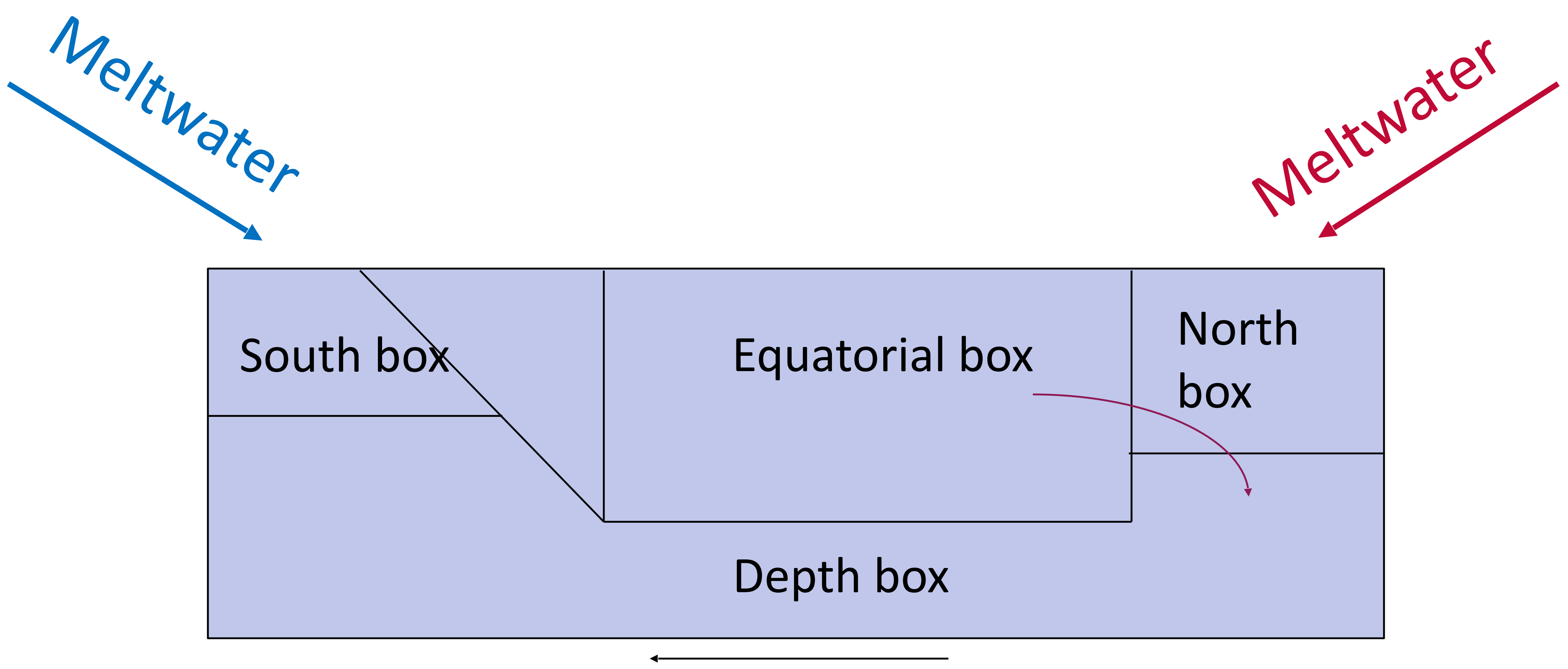


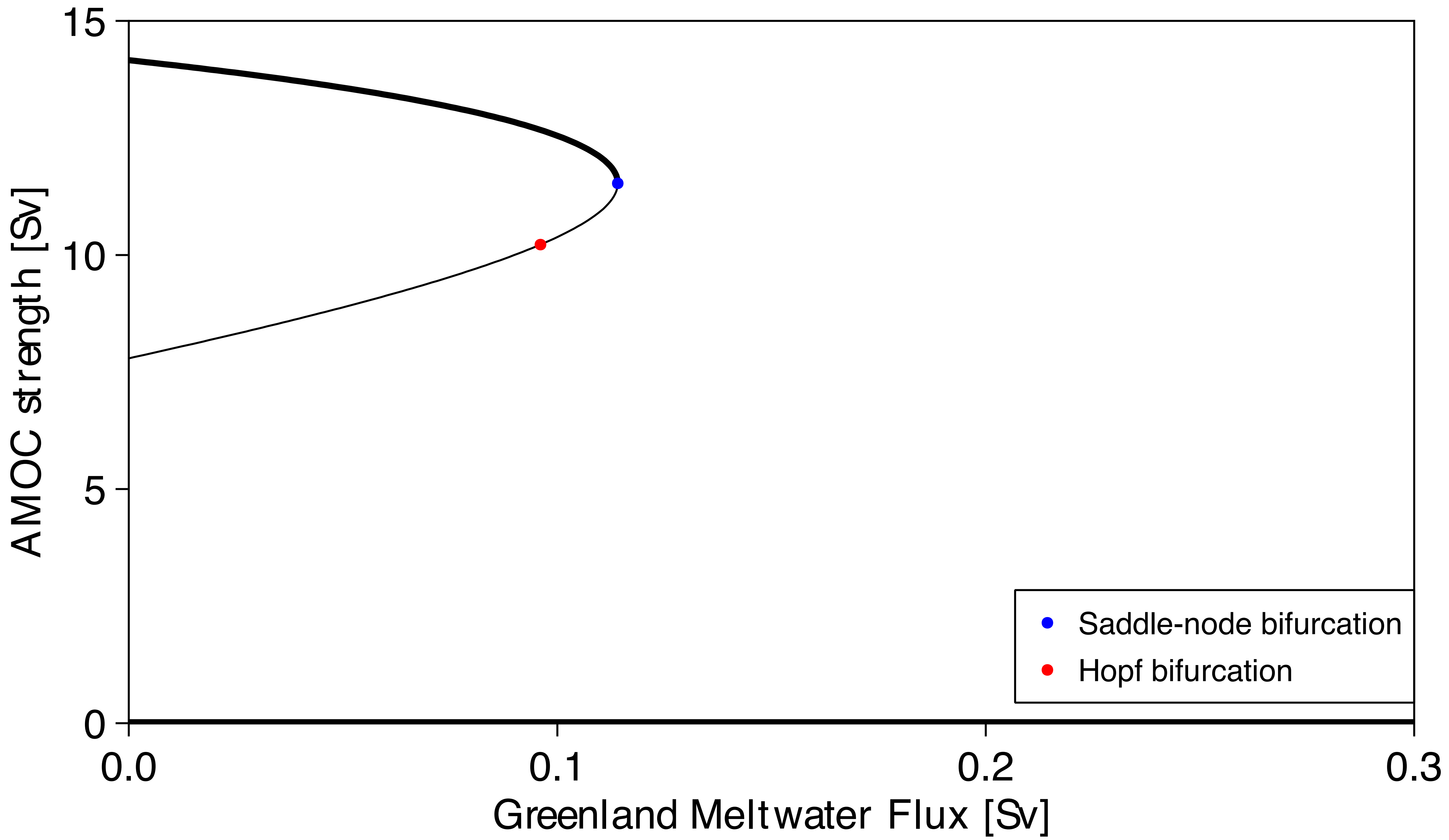
Meltwater flux [Sv]
0.20
0.15
0.10
0.05
0.00
-500
0
500
1000
1500
Time [years]
Greenland
West Antarctica
Greenland ice content
WAIS ice content

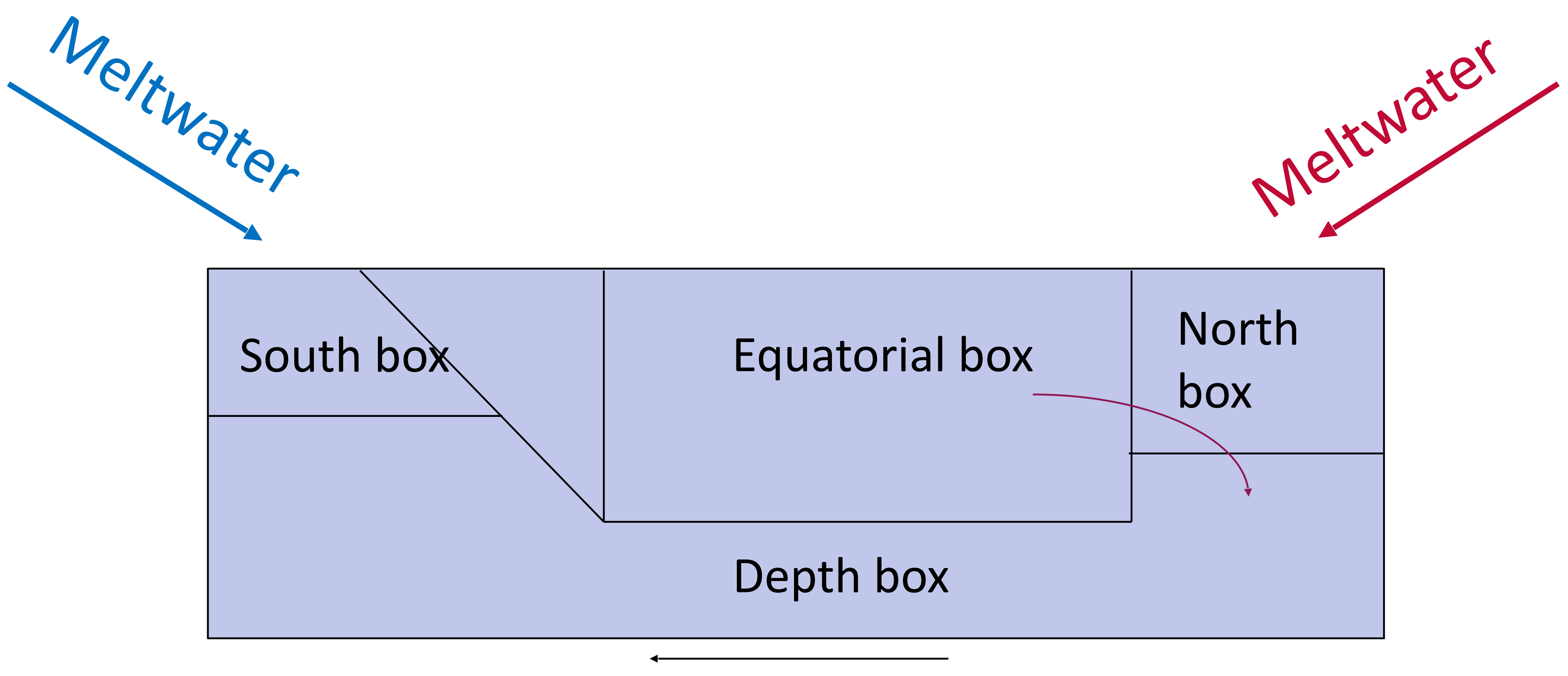

Greenland
West Antarctica
Meltwater flux [Sv]
0.20
0.15
0.10
0.05
0.00
-500
0
500
1000
1500
Time [years]
Greenland ice content
WAIS ice content
Delay of initiation
WAIS tipping duration
AMOC strength [Sv]
20
15
10
5
0
No collapse!

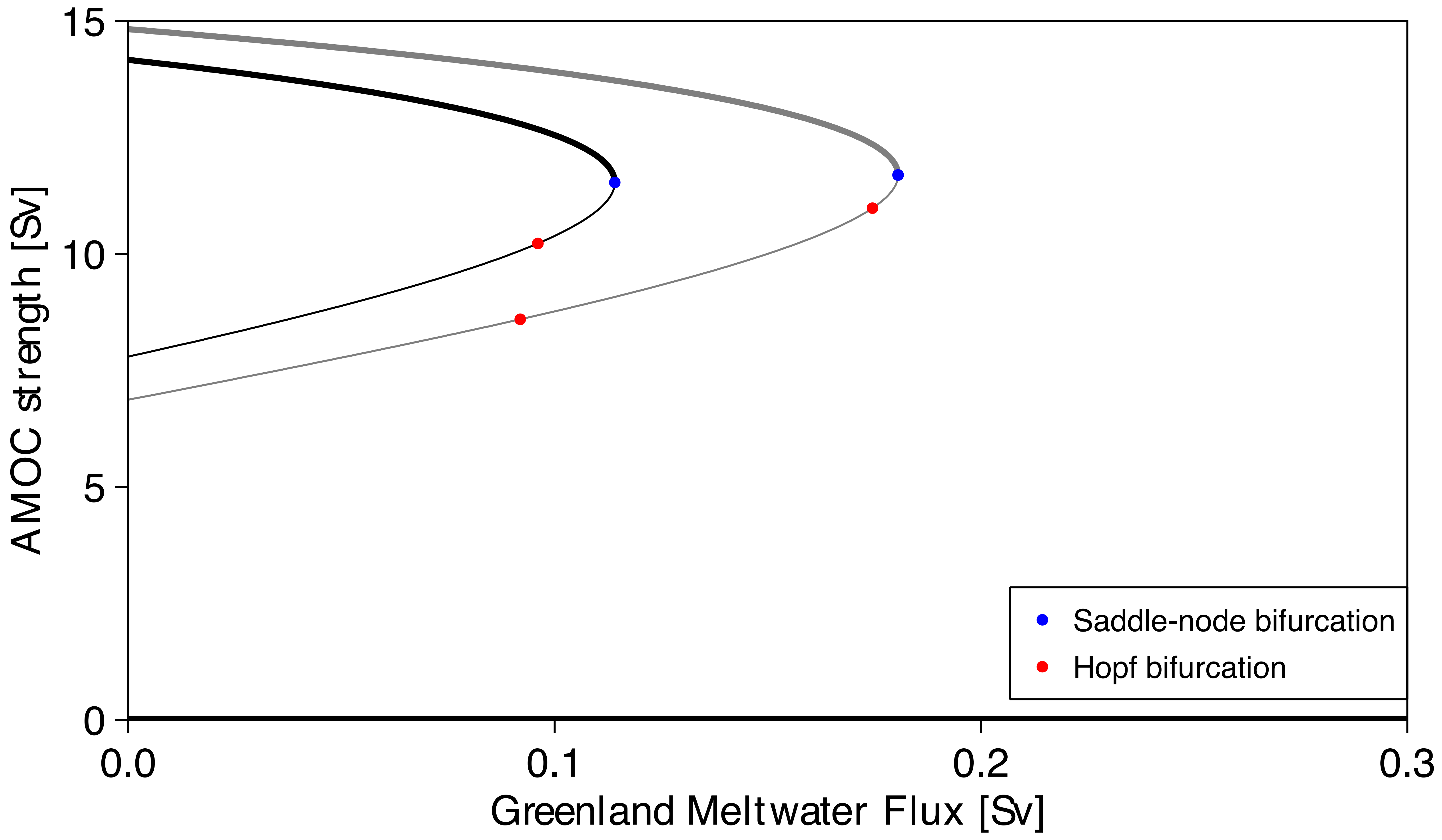

5000
4000
3000
2000
1000
WAIS tipping duration [yrs]
-1500
-1000
-500
0
500
1000
1500
Delay of initation [years]

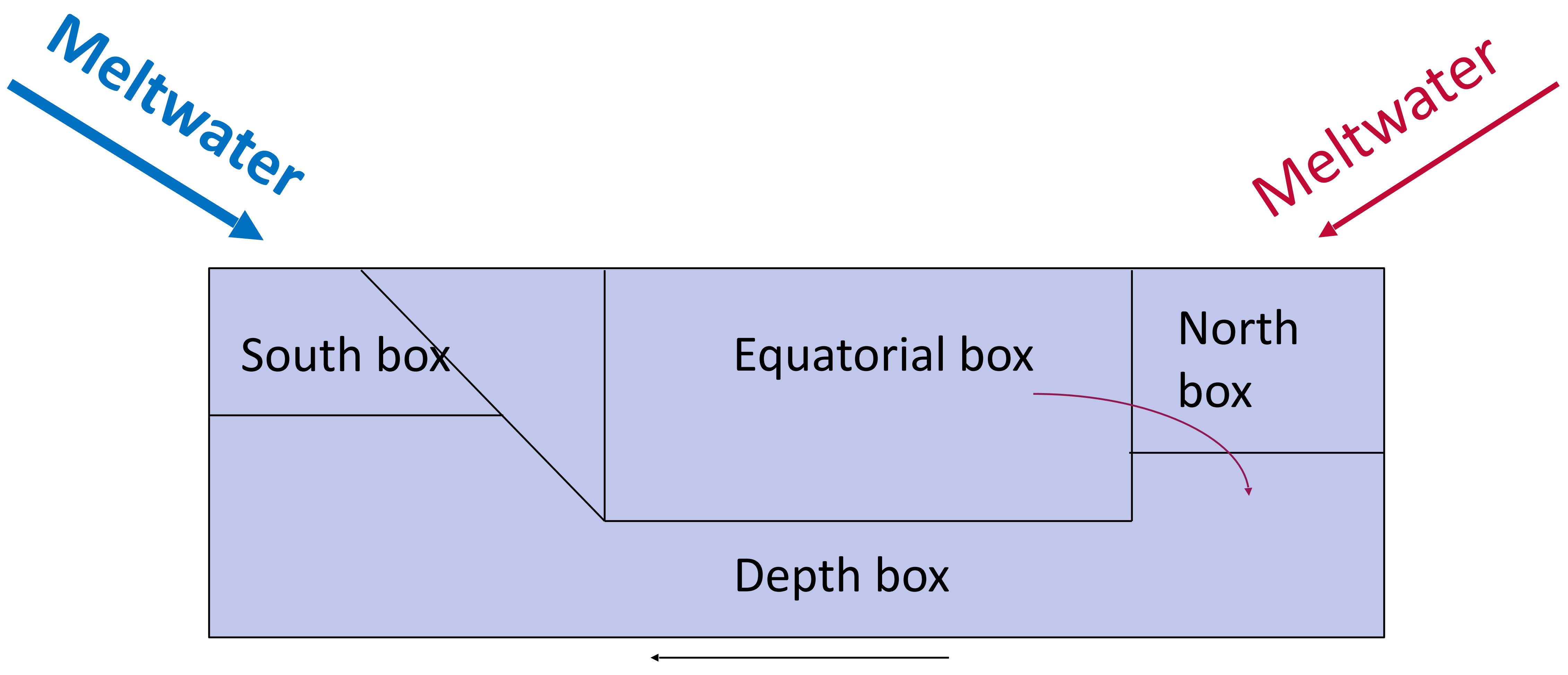

5000
4000
3000
2000
1000
WAIS tipping duration [yrs]
No tipping!
-1500
-1000
-500
0
500
1000
1500
Delay of initation [years]
Boundary of the no – tipping region

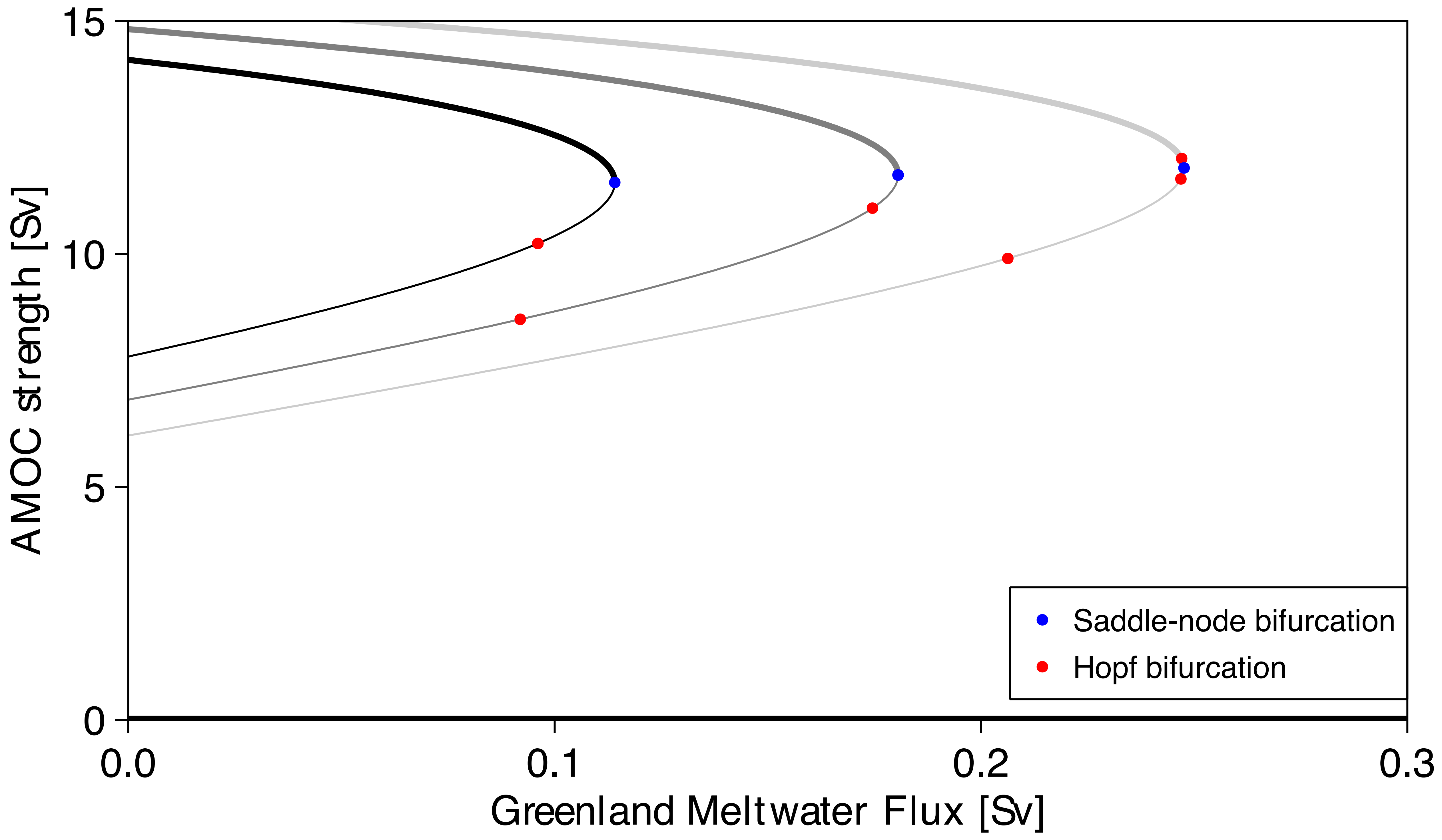

Meltwater
Meltwater
South box
Equatorial box
North
box
Depth box


15
10
5
0
AMOC strength [Sv]
0.0
0.1
0.2
0.3
Greenland Meltwater Flux [Sv]
Saddle-node bifurcation
Hopf bifurcation


Meltwater
Meltwater
South box
Equatorial box
North box
Depth box


AMOC strength [Sv]
Greenland Meltwater Flux [Sv]
Saddle-node bifurcation
Hopf bifurcation
0
5
10
15
0.0
0.1
0.2
0.3

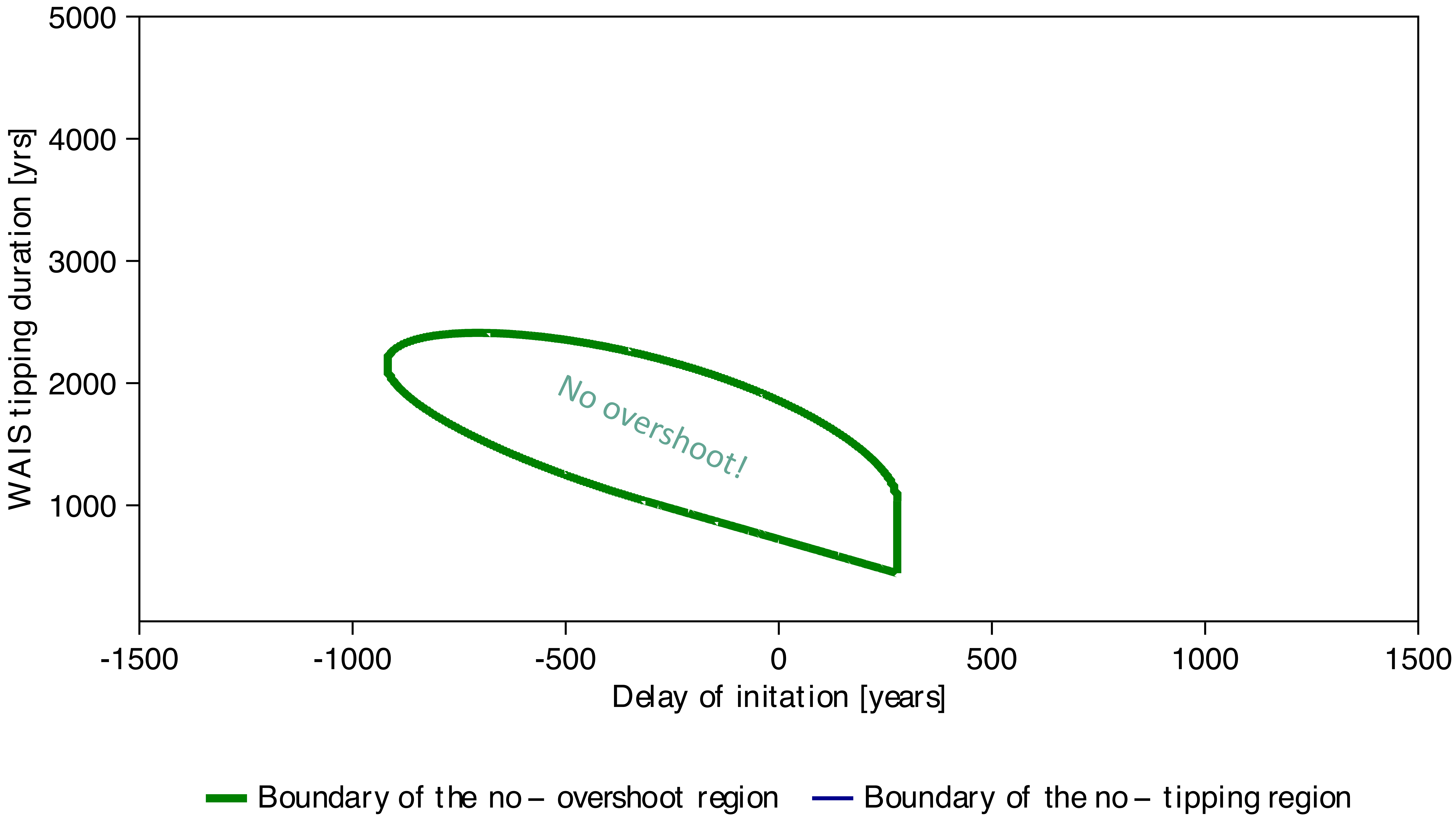


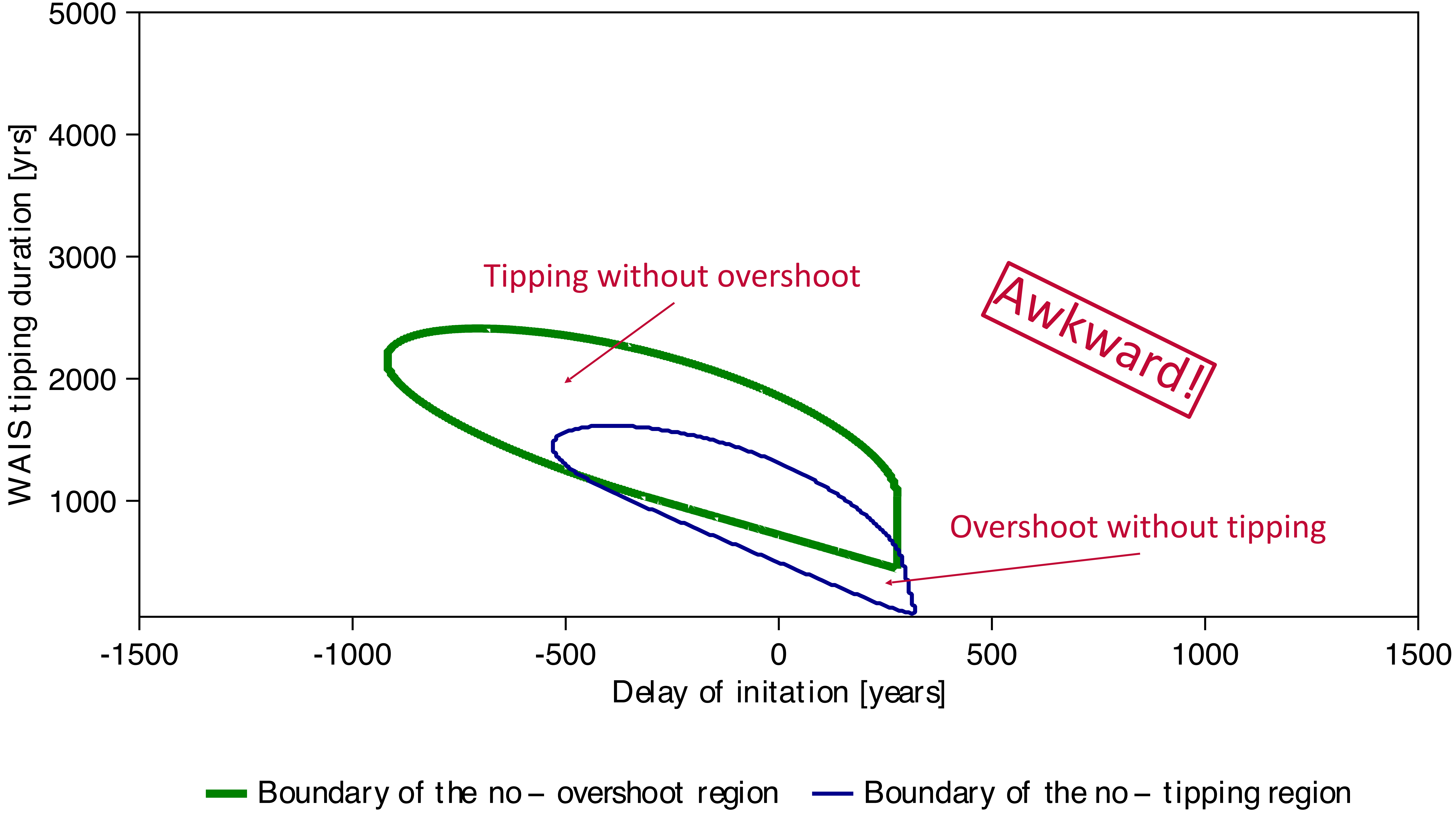


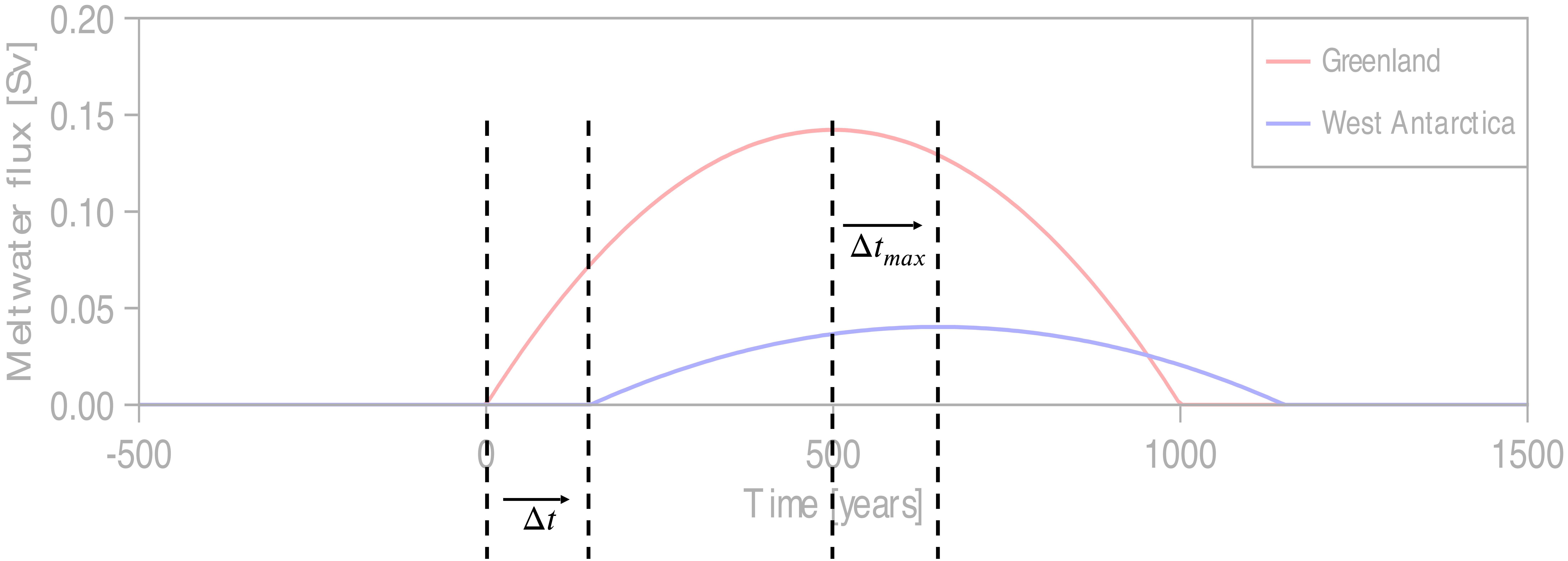
No overshoot of saddle-node if at all time:

$$F_N(t) - \delta F_S(t) < F_{N,c},$$

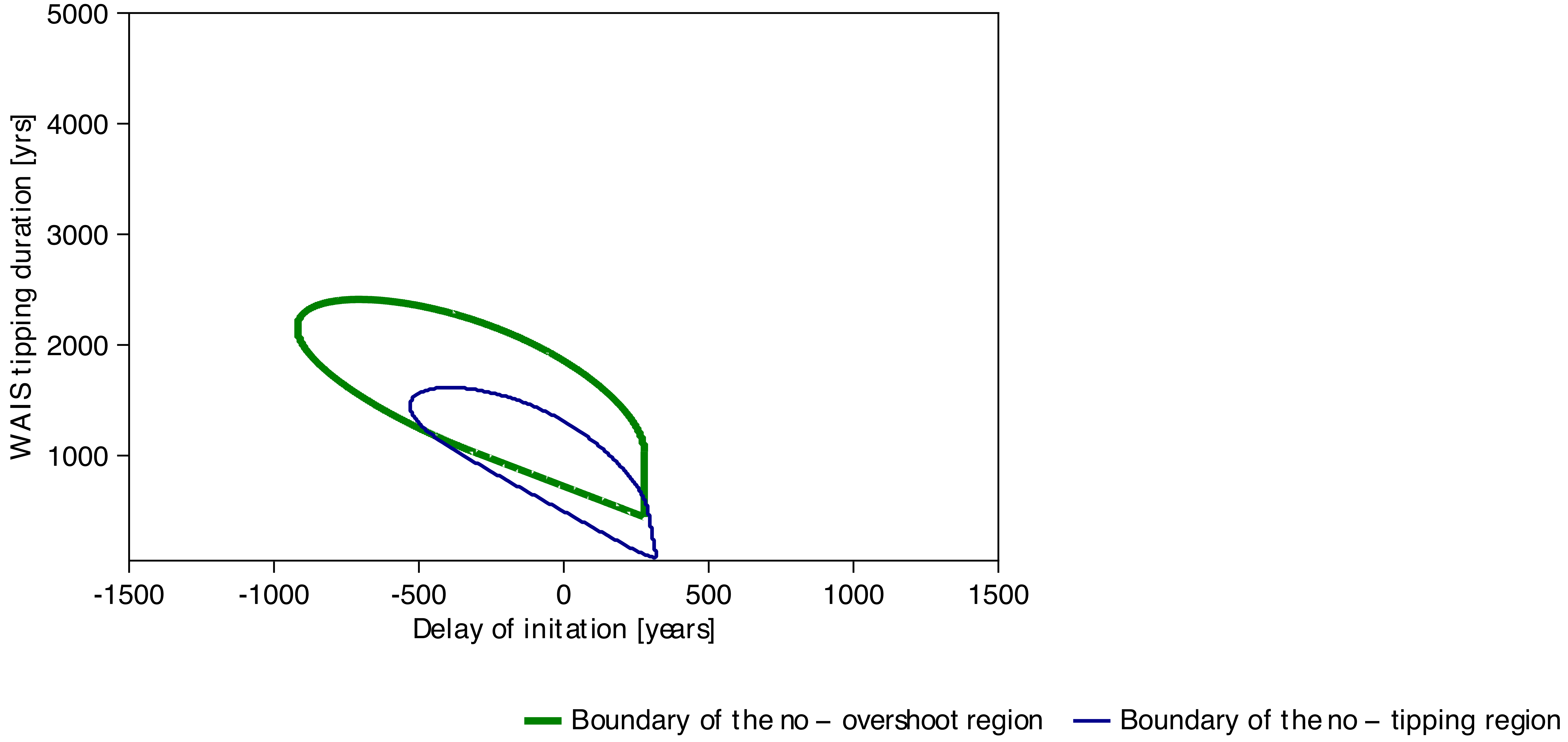
$$F_{N,c} = 0.11 \ ; \ \delta = 1.68$$


5000
4000
3000
2000
1000
WAIS tipping duration [yrs]
No overshoot!
-1500
-1000
-500
0
500
1000
1500
Delay of initation [years]
Boundary of the no – overshoot region
Boundary of the no – tipping region

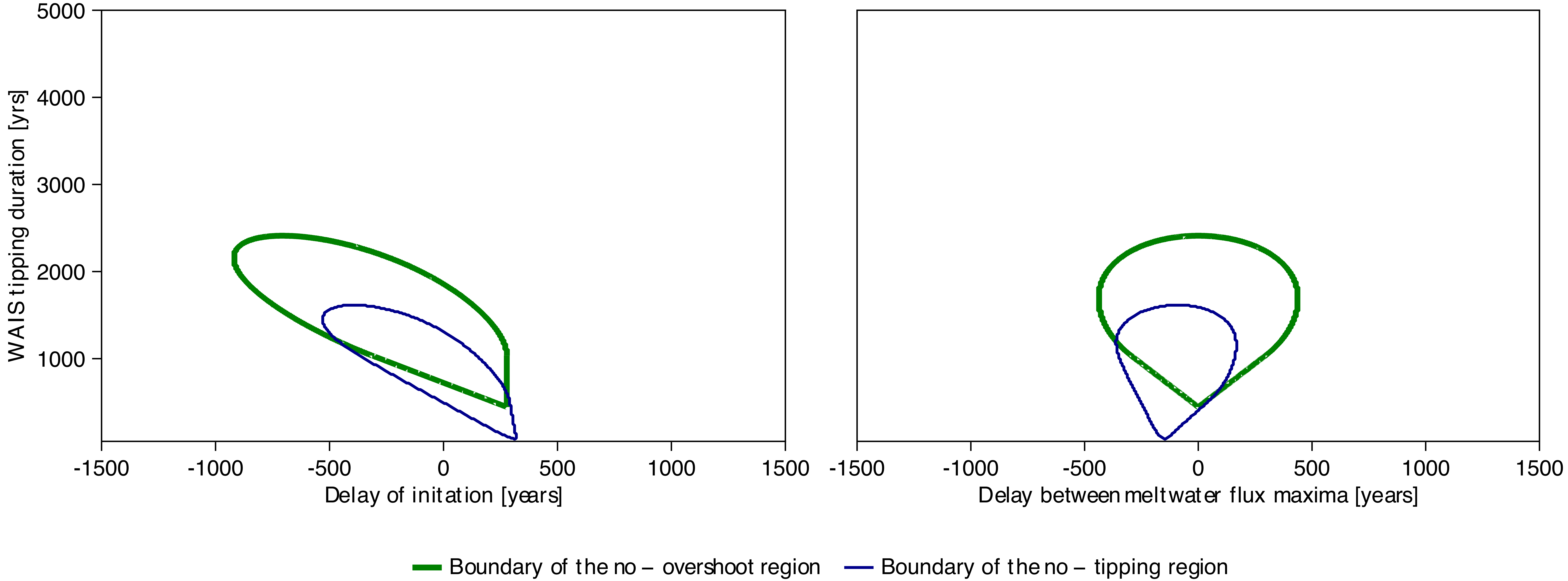

5000
4000
3000
2000
1000
WAIS tipping duration [yrs]
-1500
-1000
-500
0
500
1000
1500
Delay of initation [years]
Tipping without overshoot
Awkward!
Overshoot without tipping
Boundary of the no – overshoot region
Boundary of the no – tipping region



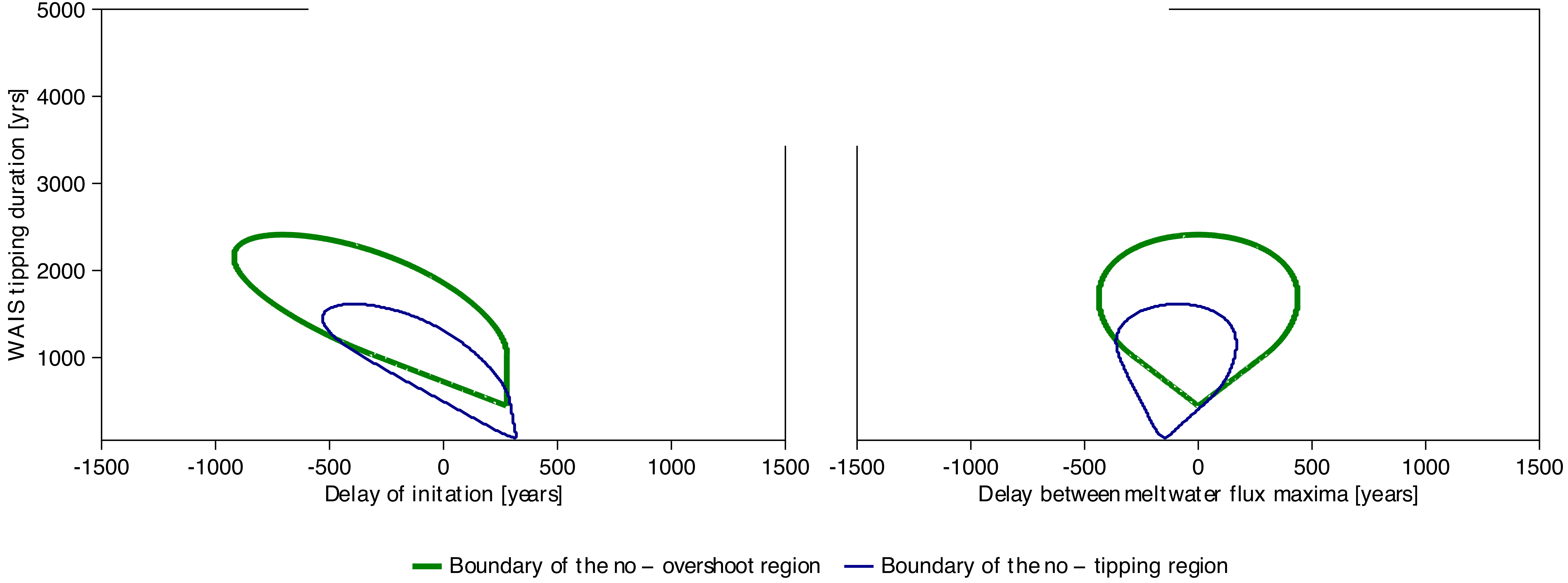
Greenland
West Antarctica
Meltwater flux [Sv]
0.20
0.15
0.10
0.05
0.00
-500
0
500
1000
1500
Time [years]
Δt
Δt_{max}



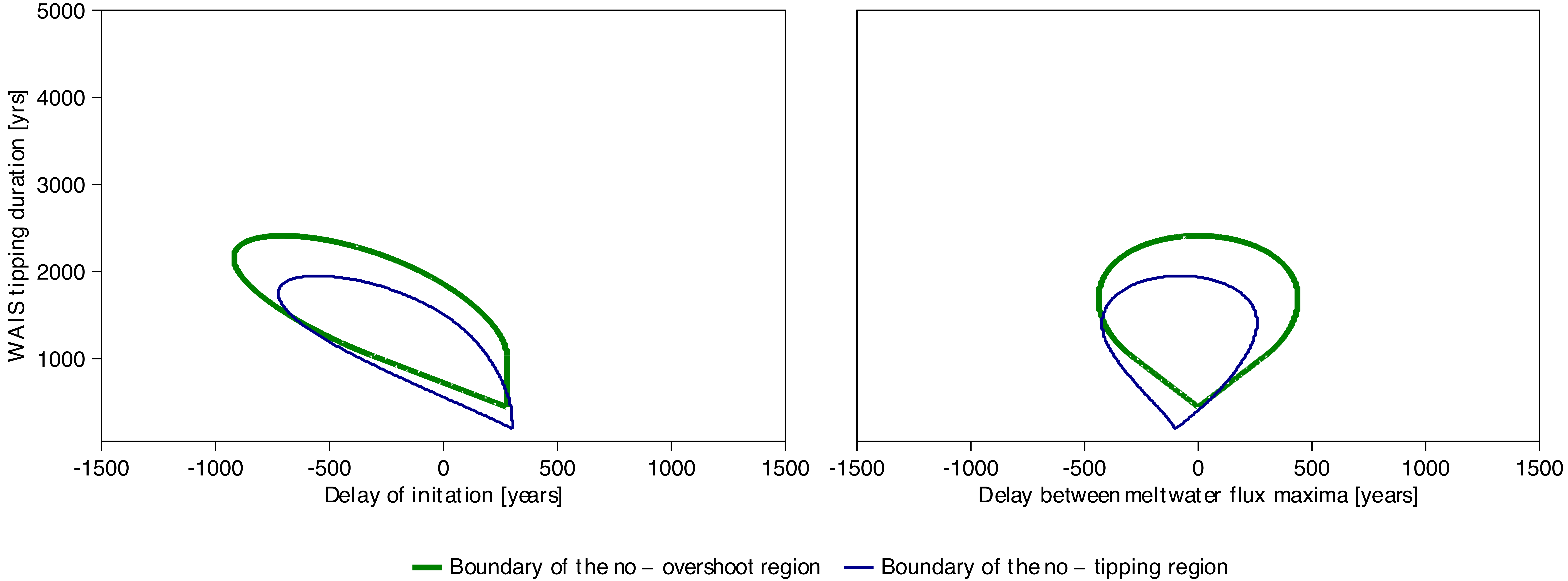
5000
4000
3000
2000
1000
WAIS tipping duration [yrs]
-1500
-1000
-500
0
500
1000
1500
Delay of initation [years]
Boundary of the no – overshoot region
Boundary of the no – tipping region



5000
4000
3000
2000
1000
WAIS tipping duration [yrs]
-1500
-1000
-500
0
500
1000
1500
Delay of initation [years]
Delay between meltwater flux maxima [years]
Boundary of the no – overshoot region
Boundary of the no – tipping region

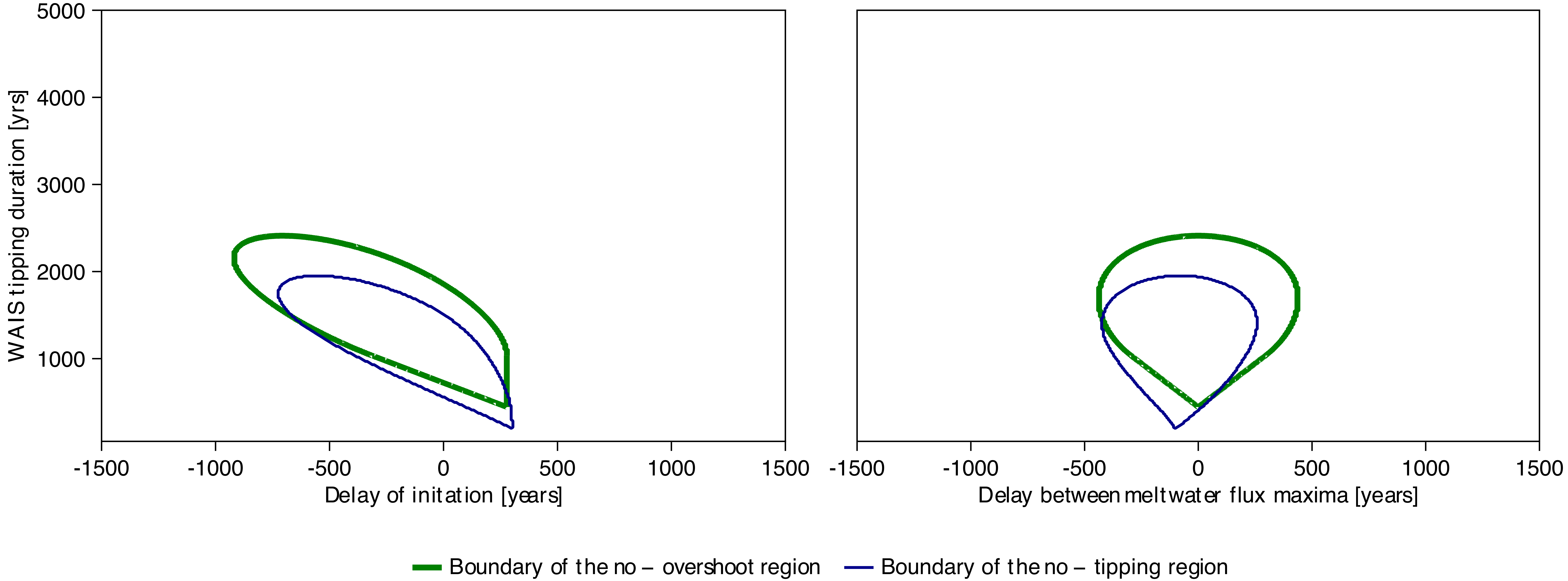


Rate-induced Effects



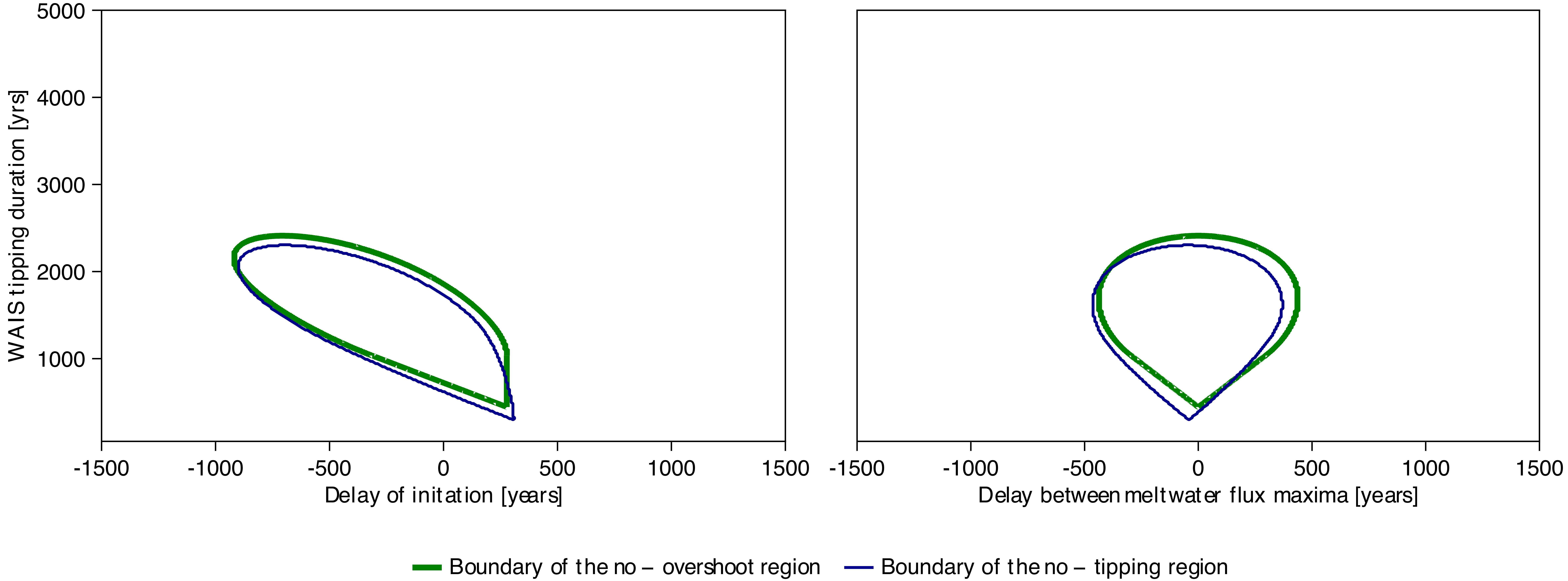
Let’s slow down forcing rate

Forcing(t) → Forcing (t/2)



Let’s slow down forcing rate

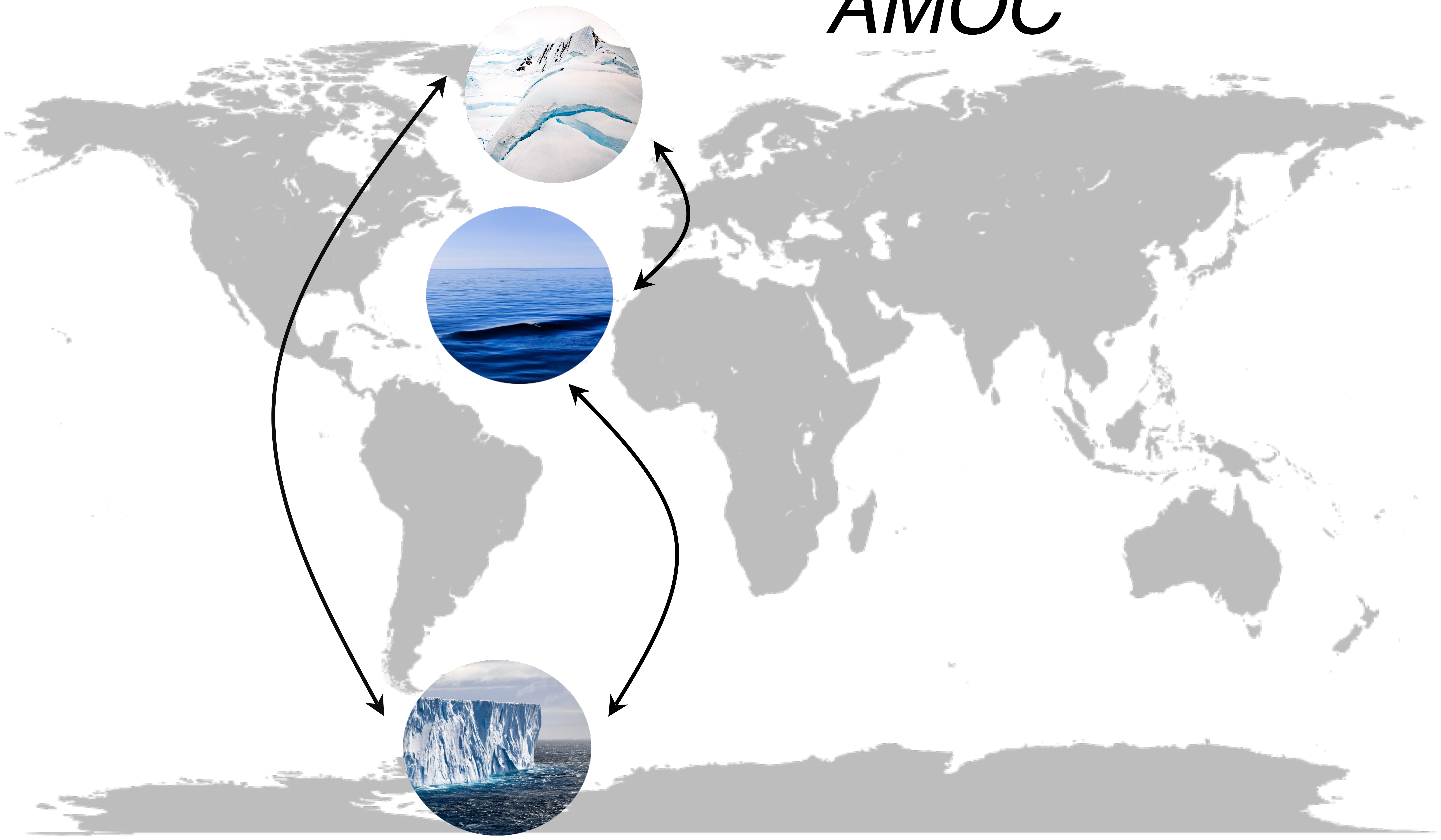
Forcing(t) → Forcing (t/4)



Let's slow down forcing rate

Forcing(t) → Forcing (t/4)

Main point: WAIS collapse can stablize the AMOC



Exercises!