Rate- and bifurcation-induced tipping of the AMOC in a global oceanic box model

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Tipping Points Reading Group
University of Exeter
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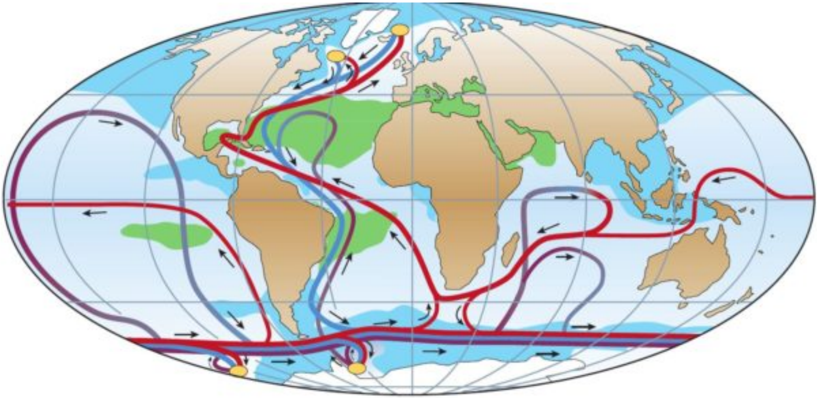
Atlantic Meridional Overturning Circulation (AMOC)



[Rahmstorf, 2002]

Atlantic Meridional Overturning Circulation (AMOC)

- Competing thermohaline circulation effects
  $\rightarrow$ multiple stable states,'on' and 'off'
- Observed in heirarchy of models
  - simple box models [Stommel, 1961]
  - intermediate complexity climate models [Lenton et al., 2007]
  - full general circulation models [Dijkstra, 2007]
- Evidence of 'off' state
  - Dansgaard-Oeschgar events (significant changes in AMOC transport)
- Driving force - freshwater input at high latitudes
  - Greenland ice sheet, Labrador/Nordic Seas
  - known as 'hosing'

PEN/ReCoVER meeting -
"Pacing and synchronization of palaeoclimate variability" (June 2017)

Global oceanic box model

FAMOUS

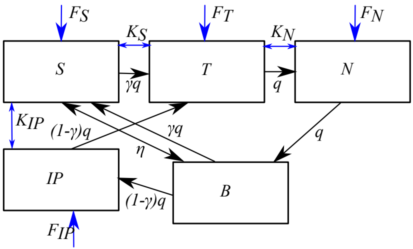
- coarse-resolution coupled Atmosphere-Ocean General Circulation Model (AOGCM)
- atmosphere: horizontal $5^\circ \times 7.5^\circ$, vertical 11 levels
- ocean: horizontal $2.5^\circ \times 3.75^\circ$, vertical 20 levels
- no artificial flux adjustments (distorts AMOC hysteresis [Dijkstra and Neelin, 1999])

Wood et al., 2019

- Analysed FAMOUS AOGCM
  $\rightarrow$ reduced to low order dynamical processes, box model
- calibrated the box model to a data-assimilating ocean reanalysis
- directly calculated the AMOC hysteresis curve in the FAMOUS AOGCM, for present climate state and with increased atmospheric CO_2

Wood et al. (2019) Box Model

Five-box model: Each box corresponds to a large-scale water mass structure



- q - overturning strength (controlled by boxes S and N)
- F_i - surface freshwater fluxes
- K_i - wind-driven transport
- γ - proportion of cold water path
- η - S-B box mixing parameter
- λ - pipe constant

Cold water path: AMOC flow via South Pacific & Drake passage
Warm water path: AMOC flow via Indo-Pacific thermocline

Model equations

$$q = \frac{\lambda[\alpha(T_S - T_0) + \beta(S_N - S_S)]}{1 + \lambda\alpha\mu}$$

$q \geq 0$:

$$\begin{aligned}
V_N \dot{S_N} &= q(S_T - S_N) + K_N(S_T - S_N) - F_N S_0, \\
V_T \dot{S_T} &= q[\gamma S_S + (1-\gamma)S_{IP} - S_T] + K_S(S_S - S_T) + K_N(S_N - S_T) - F_T S_0, \\
V_S \dot{S_S} &= \gamma q(S_B - S_S) + K_{IP}(S_{IP} - S_S) + K_S(S_T - S_S) + \eta(S_B - S_S) - F_S S_0, \\
V_{IP} \dot{S_{IP}} &= (1-\gamma)q(S_B - S_{IP}) + K_{IP}(S_S - S_{IP}) - F_{IP} S_0 \\
V_B \dot{S_B} &= q(S_N - S_B) + \eta(S_S - S_B)
\end{aligned}$$

$q < 0$:

$$\begin{aligned}
V_N \dot{S_N} &= |q|(S_B - S_N) + K_N(S_T - S_N) - F_N S_0 \\
V_T \dot{S_T} &= |q|(S_N - S_T) + K_S(S_S - S_T) + K_N(S_N - S_T) - F_T S_0 \\
V_S \dot{S_S} &= \gamma|q|(S_T - S_S) + K_{IP}(S_{IP} - S_S) + K_S(S_T - S_S) + \eta(S_B - S_S) - F_S S_0 \\
V_{IP} \dot{S_{IP}} &= (1-\gamma)|q|(S_T - S_{IP}) + K_{IP}(S_S - S_{IP}) - F_{IP} S_0 \\
V_B \dot{S_B} &= \gamma|q|S_S + (1-\gamma)|q|S_{IP} - |q|S_B + \eta(S_S - S_B)
\end{aligned}$$

Model equations

Total salt content

$$C = V_N S_N + V_T S_T + V_S S_S + V_{IP} S_{IP} + V_B S_B$$

implies

$$dC/dt = -(F_N + F_T + F_S + F_{IP}) S_0$$

For constant C, total surface fresh water fluxes satisfy

$$F_N + F_T + F_S + F_{IP} = 0$$

Reduce by one dimension → write one box as function of other four

Bifurcation parameter will be hosing H,

F_N	$0.384 + 0.1311H$	F_S	$1.078 - 0.2626H$
F_T	$-0.723 + 0.6961H$	F_{IP}	$-0.738 - 0.5646H$

Three-box model

$q \geq 0$:

$$\begin{aligned} V_N \dot{S}_N &= q(S_T - S_N) + K_N(S_T - S_N) - F_N S_0 \\ V_T \dot{S}_T &= q[\gamma S_S + (1-\gamma) S_{IP} - S_T] + K_S(S_S - S_T) + K_N(S_N - S_T) - F_T S_0 \end{aligned}$$

$q < 0$:

$$\begin{aligned} V_N \dot{S}_N &= |q|(S_B - S_N) + K_N(S_T - S_N) - F_N S_0 \\ V_T \dot{S}_T &= |q|(S_N - S_T) + K_S(S_S - S_T) + K_N(S_N - S_T) - F_T S_0 \end{aligned}$$

S_S and S_B taken to be constant, S_{IP} eliminated through conservation of salt

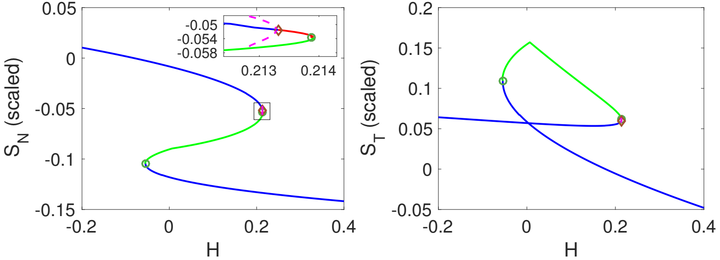
For numerics we use scaling

$$\tau = tY^{-1}, \qquad Y = 3.15 \times 10^7$$

$$\tilde{S}_i = 100(S_i - S_0), \qquad i \in [N, T, S, IP, B].$$

Bifurcation analysis of Box Model

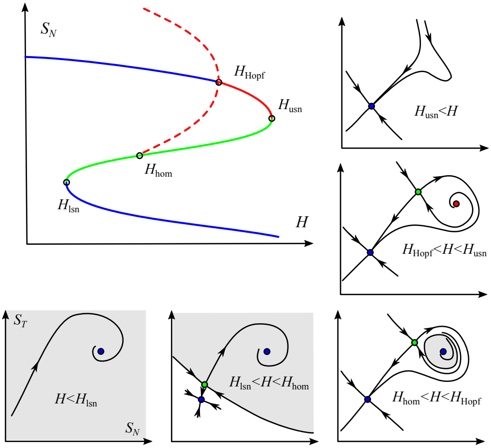
COCO continuation software is used to study effects of varying H



		Five box numerical	Three box numerical	Three box Maple
Lower saddle node	$H_{\rm lsn}$	−0.07996	−0.05446	−0.05445
Upper homoclinic	$H_{\rm hom}$	0.2165	0.2128	NA
Upper Hopf	$H_{\rm Hopf}$	0.2191	0.2134	0.2133
Upper saddle node	$H_{\rm usn}$	0.2214	0.2139	0.2138

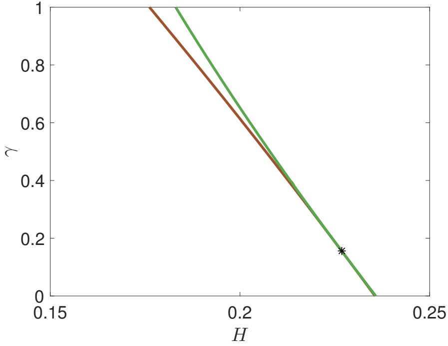
Bifurcation analysis of Box Model

Schematic diagram of area near upper saddle node



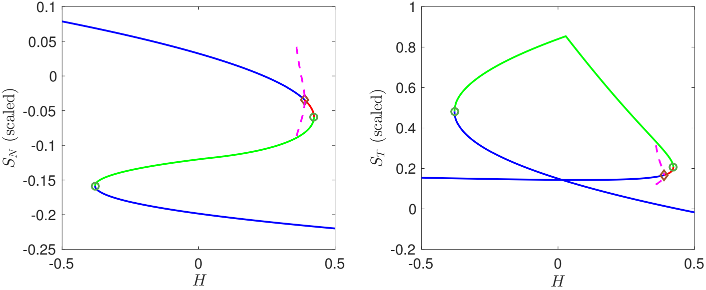
Bifurcation analysis of Box Model

Two parameter bifurcation diagram with γ (proportion of cold water path)



Hopf (brown), upper saddle node (green), Bogdanov-Takens point (star)
Note that $\gamma = 0.39$ was used for one-parameter analysis

Effect of doubled preindustrial CO_2

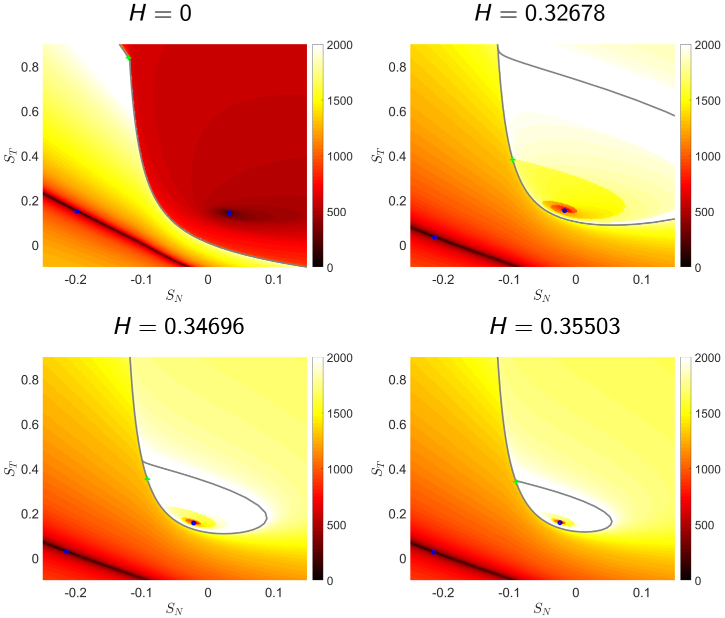


- increased value of H at upper saddle node ($H_{usn} = 0.4225$)
- increased region of instability before upper saddle node ($H_{Hopf} = 0.3888$)

Effect of doubled preindustrial CO_2

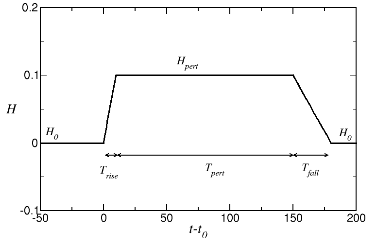
Basins of attraction - show video

Effect of doubled preindustrial CO_2



Time-dependent hosing

We consider a piecewise linear hosing function



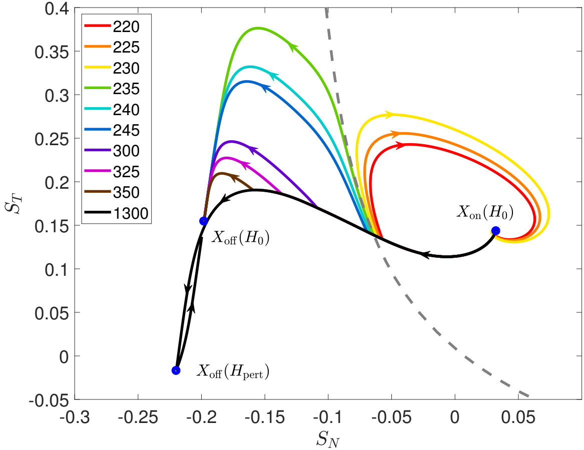
$$H_{pwl}(t) = \begin{cases} H_0 & t < 0, \\ \alpha(t) & t \in [0, T_{\text{rise}}], \\ H_{\text{pert}} & t - T_{\text{rise}} \in [0, T_{\text{pert}}], \\ \beta(t) & t - T_{\text{rise}} - T_{\text{pert}} \in [0, T_{\text{fall}}], \\ H_0 & t \geq T_{\text{rise}} + T_{\text{pert}} + T_{\text{fall}}, \end{cases}$$

$$r_{\text{rise}} = \frac{|H_0 - H_{\text{pert}}|}{T_{\text{rise}}}, \qquad r_{\text{fall}} = \frac{|H_0 - H_{\text{pert}}|}{T_{\text{fall}}},$$

$$\alpha(t) = r_{\text{rise}}\, t, \qquad \beta(t) = r_{\text{fall}}(t - T_{\text{rise}} - T_{\text{pert}}),$$

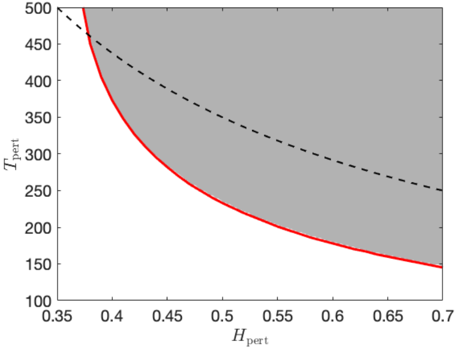
Instantaneous forcing changes

$T_{\text{rise}} = T_{\text{fall}} = 0$, varying T_{pert}



Instantaneous forcing changes

Critical time of perturbation as a function of H_{pert}, ($T_{\text{rise}} = T_{\text{fall}} = 0$)



Red line - threshold where there is a source-saddle connection
Black dashed - constant perturbation volume ($H_{\text{pert}} \times T_{\text{pert}} = 175$)

Gradual forcing changes - B-tipping

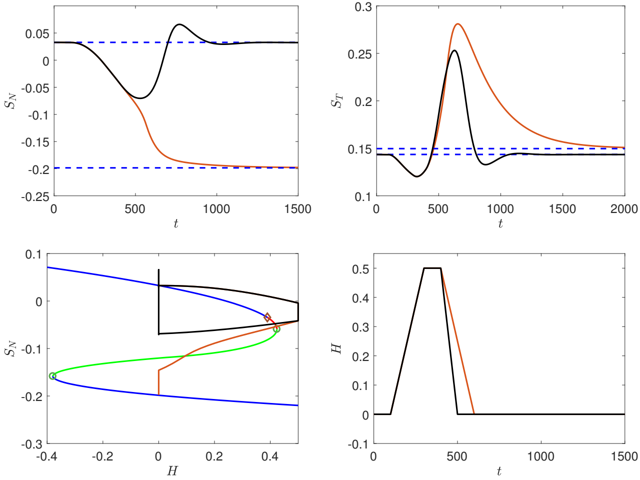
Consider case $H_0 = 0$, $H_{\mathrm{pert}} = 0.5$ (after saddle node)

Tips:
$T_{\mathrm{rise}} = 200$, $T_{\mathrm{pert}} = 200$, $T_{\mathrm{fall}} = 200$

Does not tip:
$T_{\mathrm{rise}} = 200$, $T_{\mathrm{pert}} = 200$, $T_{\mathrm{fall}} = 100$

show B-tip videos

Gradual forcing changes - B-tipping



Black - $T_{\text{fall}} = 100$ Red - $T_{\text{fall}} = 200$

Gradual forcing changes - R-tipping

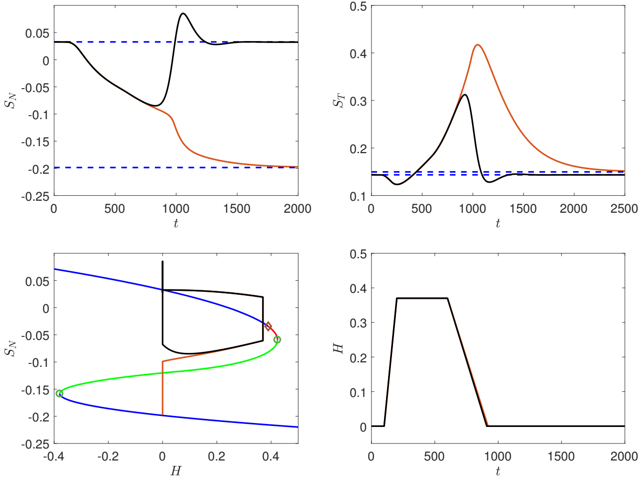
Consider case $H_0 = 0$, $H_{\text{pert}} = 0.37$ ((before homoclinic connection)

Tips:
$T_{\text{rise}} = 100$, $T_{\text{pert}} = 400$, $T_{\text{fall}} = 320$

Does not tip:
$T_{\text{rise}} = 100$, $T_{\text{pert}} = 400$, $T_{\text{fall}} = 310$

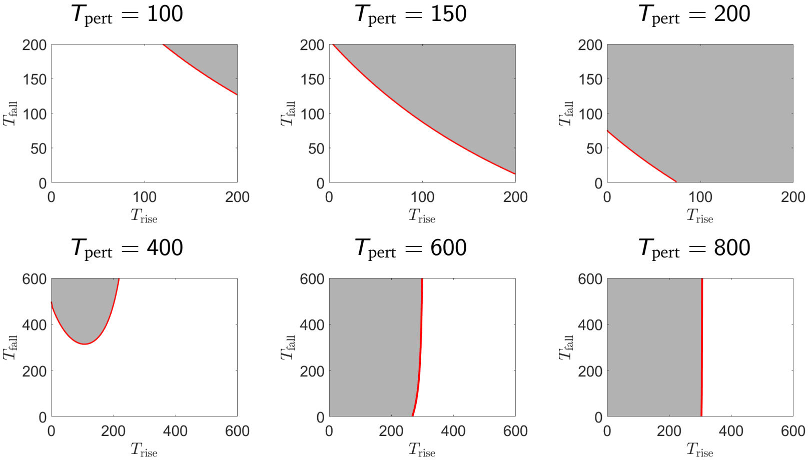
show R-tip videos

Gradual forcing changes - R-tipping



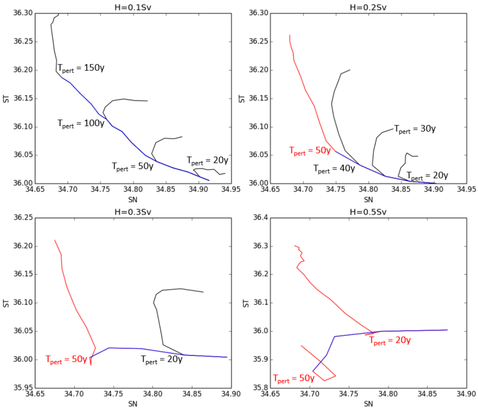
Black - $T_{\mathrm{fall}} = 310$ Red - $T_{\mathrm{fall}} = 320$

Gradual forcing changes - Tipping thresholds



Connecting to AMOC tipping in GCMs

Trajectories in S_N, S_T phase space for the 'press' experiments using the AOGCM HadGEM3-GC2

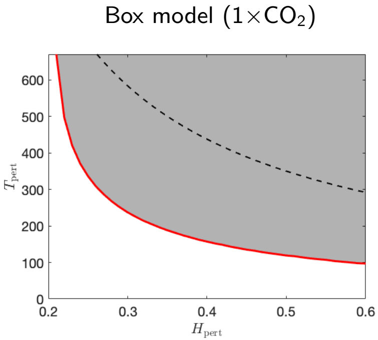


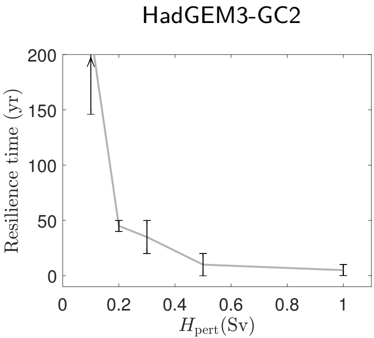
Blue - hosed phase

Black - AMOC recovers

Red - AMOC remains weak, further integration of the AOGCM needed to determine the final state

Connecting to AMOC tipping in GCMs





Bars indicate range between the greatest T_{pert} with return to initial state and smallest T_{pert} with possible tipping

Conclusions

- Low-dimensional global oceanic box model to investigate the AMOC derived from and calibrated to FAMOUS (AOGCM) runs
- Hysteresis between ‘on’ and ‘off’ states found in box model and GCM
- First loss of stability is through a subcritical Hopf bifurcation
- Basin of attraction of ‘on’ state goes from infinite volume to finite volume at homoclinic connection
- Doubled atmospheric CO_2 conditions increases unstable region and region of finite basin of attraction
- Time-dependent hosing allows for different cases of rate-induced tipping and tipping prevention
- Evidence of similar resilience curve which separates tipping and non-tipping behaviour found in GCM

Alkhayuon, H., Ashwin, P., Jackson, L. C., Quinn, C., & Wood, R. A. (2019). Basin bifurcations, oscillatory instability and rate-induced thresholds for Atlantic meridional overturning circulation in a global oceanic box model. *Proceedings of the Royal Society A, 475*(2225), 20190051.

Thank you for your attention.

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