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Климатические Tipping Points. Арктическая перспектива
Climate Tipping Points. Arctic Perspective

Arctic and Antarctic Research Institute
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Climate tipping point – критический порог воздействия, за которым климатическая система реорганизуется, обычно резко и необратимо. Abrupt Climate Changes. IPCC A6 WGI AnnexVII

Tipping Elements -

1. Atlantic Meridional Overturning Circulation (АМОС)
2. Atlantic Subpolar Gyre
3. Ледниковый щит Гренландии
4. Ледниковый щит Западной Антарктиды
5. Вечная мерзлота
6. Зимний дрейфующий лёд СЛО
7. Бореальные леса
8. Леса Амазонии
9. Муссонная циркуляция

Критические переходы

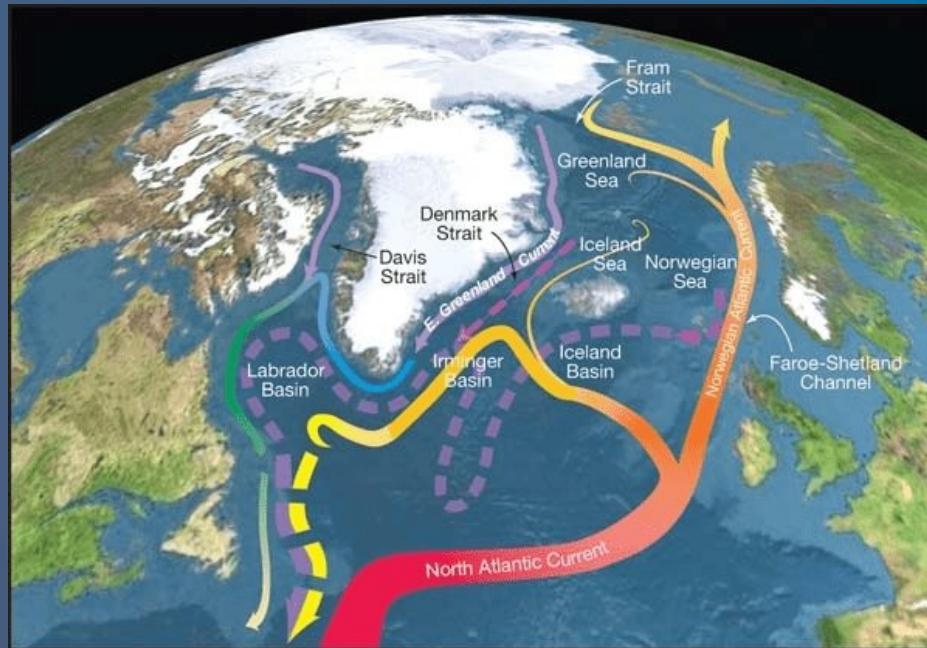
- I. Происходят относительно быстро
- II. Определяются **нелинейными процессами**
 - I. Необратимы

Временные масштабы ТР -

Дрейфующие льды Арктики – годы (?),
Atlantic Meridional Overturning Circulation – десятилетия или столетия,
Ледниковые щиты – столетия и тысячелетия



Atlantic Meridional Overturning Circulation and North Atlantic Deepwater Formation



Surface currents (solid curves) and deep currents (dashed curves)

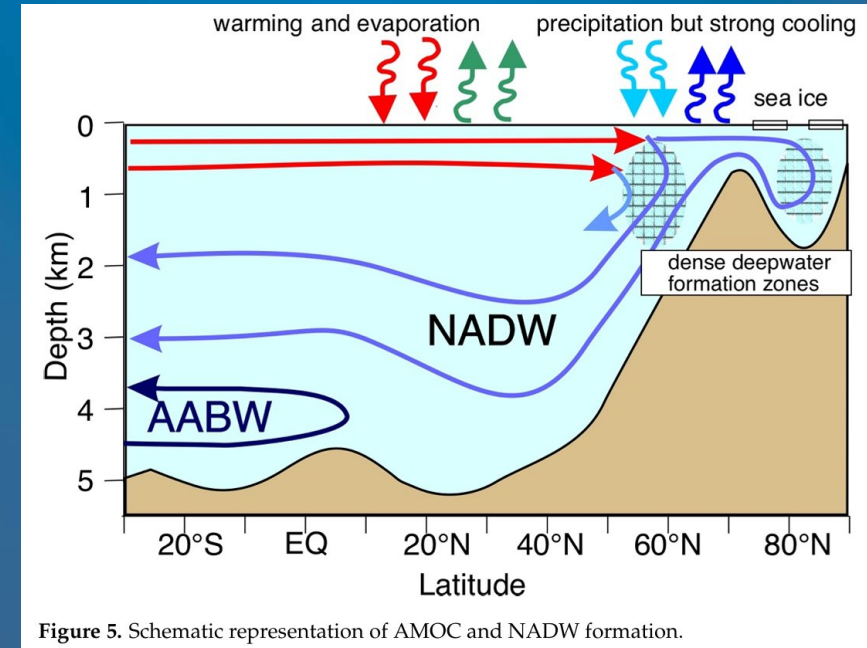
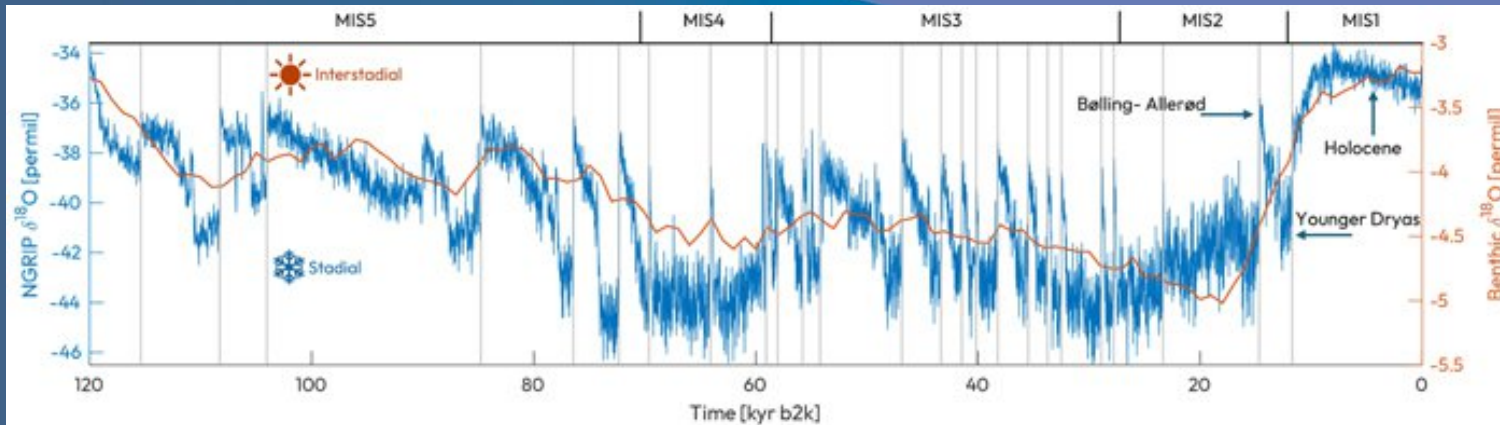


Figure 5. Schematic representation of AMOC and NADW formation.

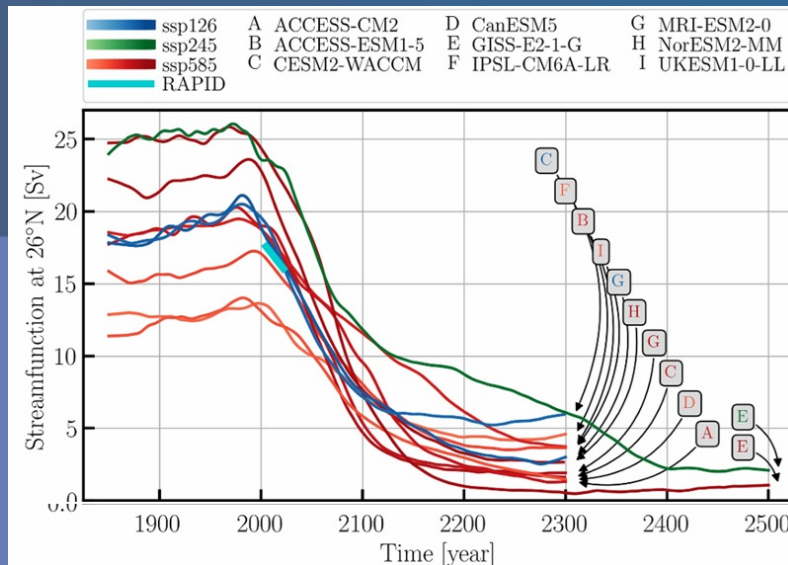
Seidov et al,
2025, *Oceans*

Paleoclimatic analogs – Dansgaard- Oeschger events. Last Glacial Period 115-12 Ky bp



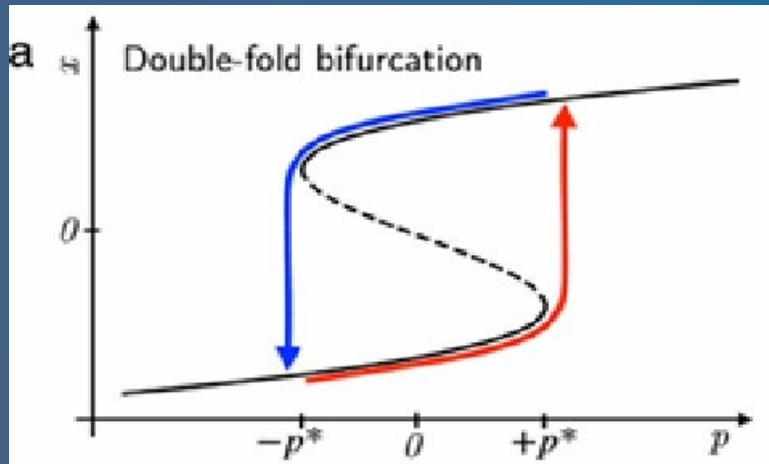
Hobden, Ashwin & Ritchie, 2025, *Chaos*

CMIP6 Scenario Experiments. Simulated Decline (Shutdown) of the AMOC



AMOC strength, at 26°N
Drijfhout et al, 2025, *Environ.
Res.Lett.*

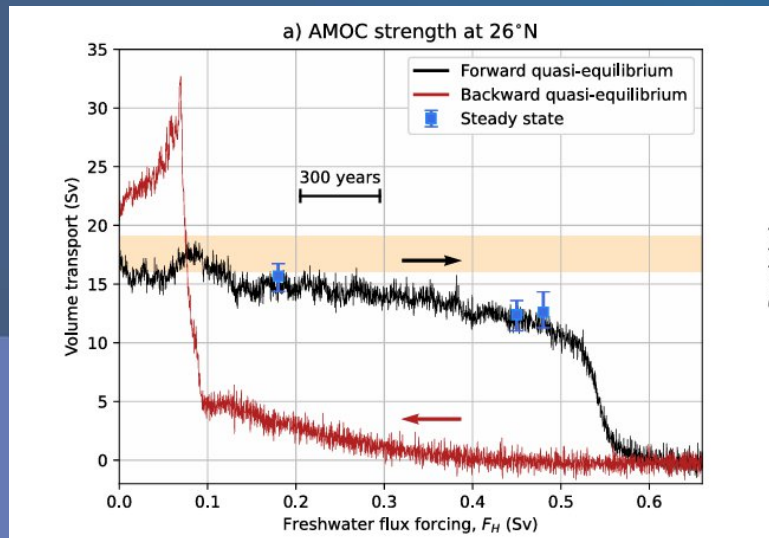
Tipping Points - Bifurcation mechanisms, 1



Bifurcation (B) Tipping points

Double-fold bifurcation

Boer, Ghil, Stocker, 2022,
Environ. Res. Lett.



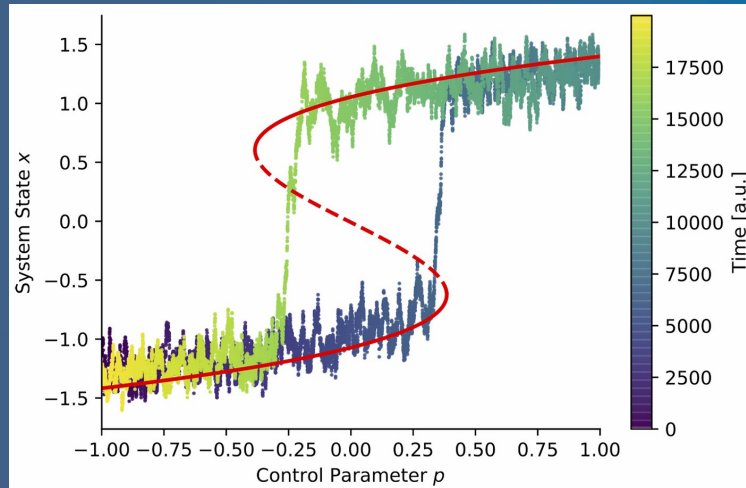
Pioneering research

Henry Stommel, 1961, *Tellus*

van Westen, Vanderborght, Kliphuis &
Dijkstra, 2025, *JGR: Oceans*

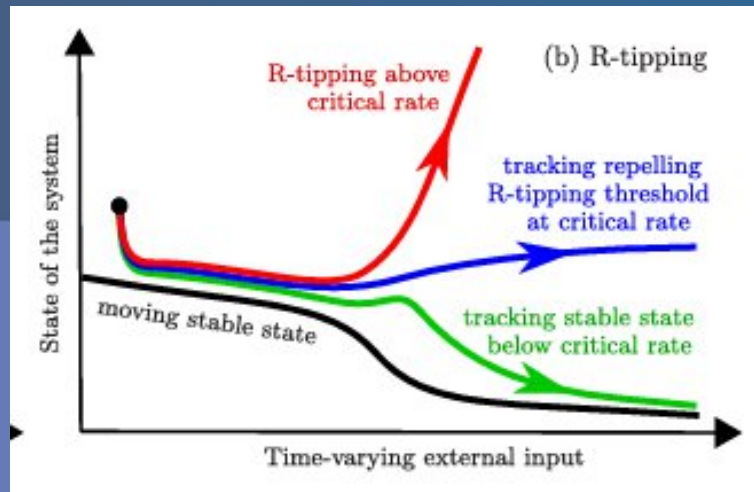
Community Earth System Model (CESM)

Tipping Points - Bifurcation mechanisms, 2



Noise (N) Tipping Points

Boer, Ghil, Stocker, 2022,
Environ. Res. Lett.



Rate (R) Tipping Points

Wieczorek et al,
2023,
Nonlinearity

Tipping Points - Bifurcation mechanisms



3

S - Shock Tipping Point

Ulrike Feudel, 2021

Shock Tipping Point – переход в новое статистически стационарное состояние в результате единичного катастрофического внешнего воздействия

S-tippings on the Cretaceous-Paleocene boundary 66.5 ml ya.

Brunetti & Ragon, 2023, *Phys. Rev. E*

Fu, Abbot, Koeberl & Fedorov A., 2024, *Science Advances*

The Cryogenian of Neoproterozoic, 720-635 ml ya. (Sturtian и Marinoan)

Community Earth System Model version 1 (CESM1)

Stratospheric SO₂ injection 200 Gt.



Tipping Points – Bifurcation Mechanisms, 4

I. Subcritical & Supercritical Hopf Bifurcations

II. Codimension 2 Bifurcation

1. Fold-Hopf bifurcation
2. Bogdanov-Takens bifurcation

Sinet, Ashwin, von der Heydt &
Dijkstra, 2024, *Earth System
Dynamics*

Alkhayuon et al, 2019,
Proceedings of the Royal Society A

Tipping Points in Modified Lorenz System



$$\frac{\partial X}{\partial \tau} = \sigma Y - \sigma X,$$

Sévellec & Fedorov, 2014
J. Climate

$$\frac{\partial Y}{\partial \tau} = -XZ + rX - Y + a,$$

Mosto et al, 2025, *Chaos*

$$\frac{\partial Z}{\partial \tau} = XY - bZ.$$

Le Bras et al, 2024,
*Nonlinear processes in
Geophysics*

1. Double fold bifurcation

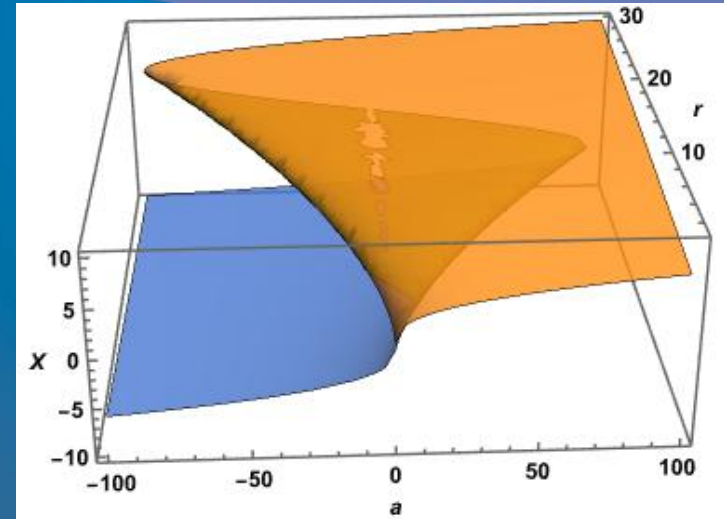
$$a = \pm \frac{2\sqrt{b}(r-1)^{3/2}}{3\sqrt{3}}$$

2. Subcritical Hopf bifurcation

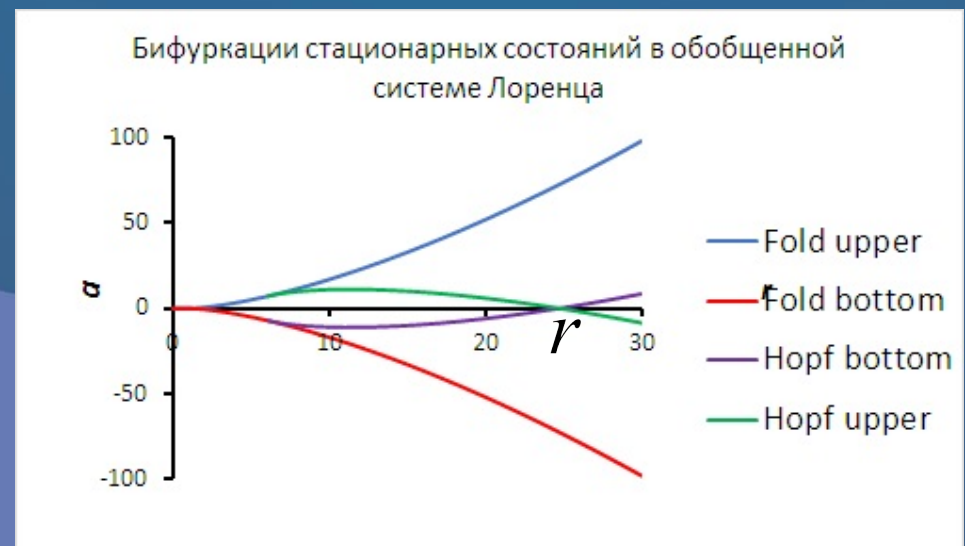
3. Bogdanov-Takens bifurcations

$$r_{cr} = \frac{3\sigma b + 2(\sigma + b)}{2\sigma - b},$$

$$a_{cr} = \pm 2b^2 \left(\frac{\sigma + 1}{2\sigma - b} \right)^{3/2}$$



Stationary states of X as a function of parameters a and r





Critical Slowdown (CSD) and Early Warning Signals

CSD into vicinity of bifurcation points –
Increase of variance and autocorrelation

Formal description of fold CSD

Normal form of fold + stochastic forcing

$$dX = (\mu - X^2) dt + \sigma dW_t,$$

Tipping point: $\mu = 0$

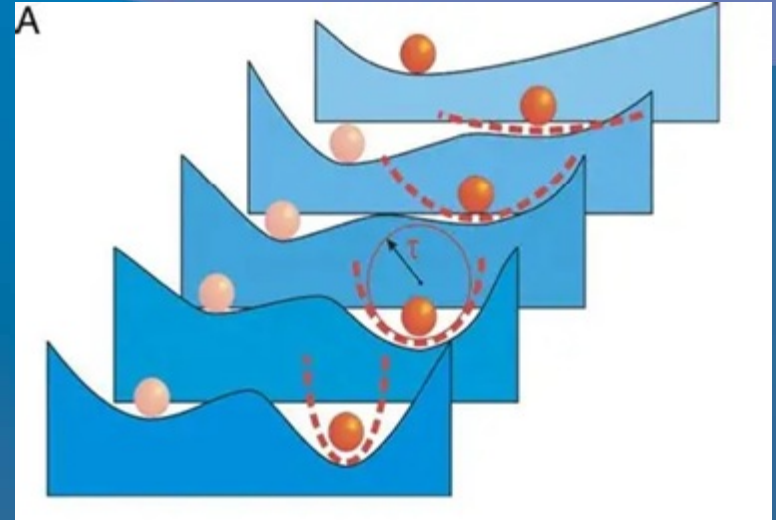
Into vicinity of stable point $X_1 = \sqrt{\mu}$

$$d(X - X_1) = -2\sqrt{\mu} (X - X_1) dt + \sigma dW_t,$$

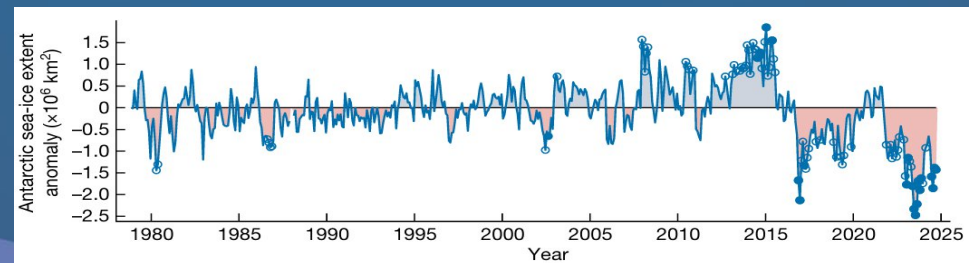
– процесс Орнштейна-Уленбега, =>

$$\text{Var}[X] = \frac{\sigma^2}{4\sqrt{\mu}},$$

$$\text{AC}(X(s), X(t)) = \exp(-2\sqrt{\mu} |t-s|).$$



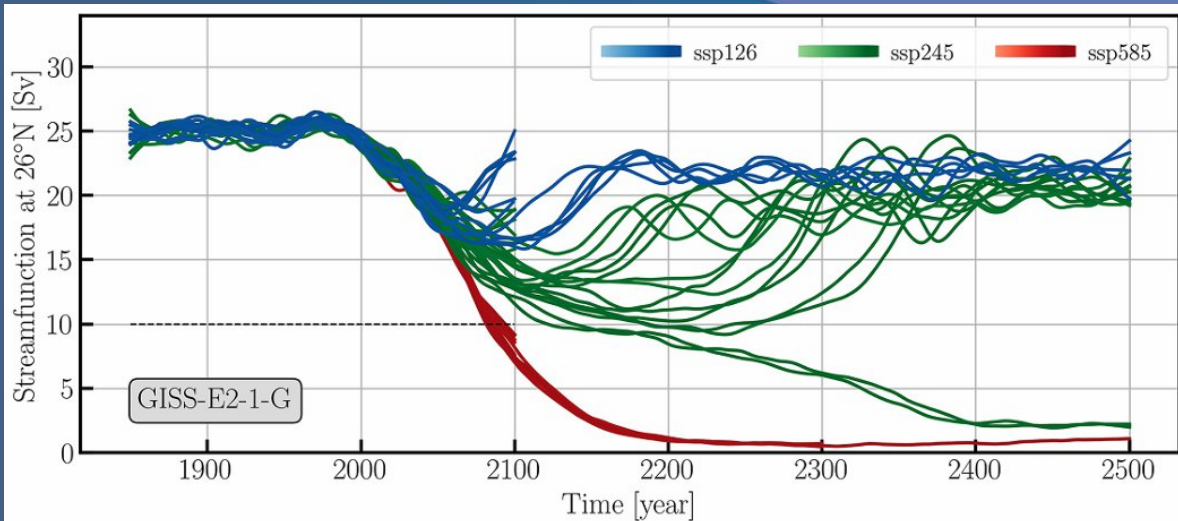
Lenton et al, 2008,
PNAS



Monthly Antarctic Sea Ice Extent
Anomalies

Abram et al, 2025, *Nature*

Splitting of trajectories and loss of climatic predictability

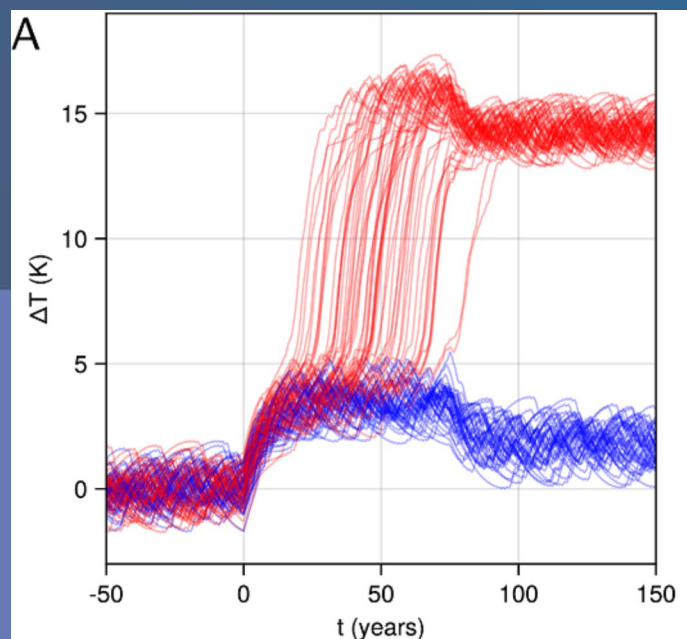


AMOC strength (Sv) at 26°N,
GISS-E2-1-G

Romanou et al, 2023,
J.Climate

Drijfhout et al, 2025, *Environ.
Res.Lett.*

Slightly changed initial
conditions !!



Predictability of possible storylines

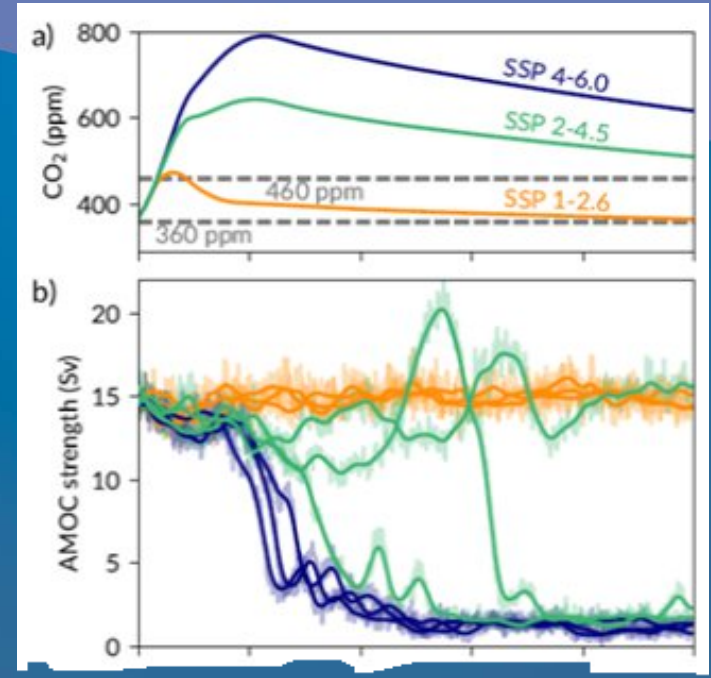
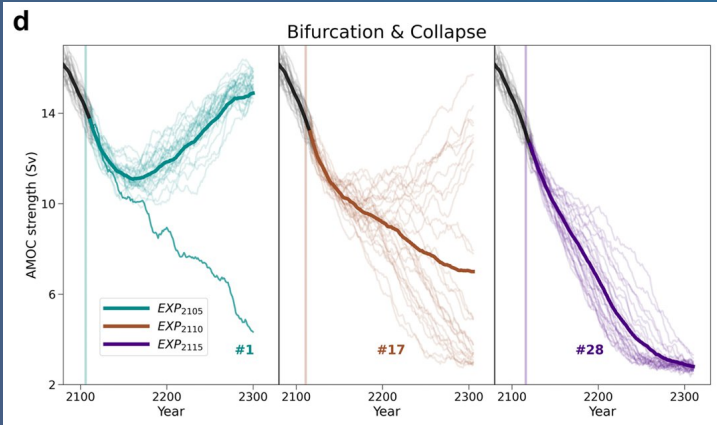
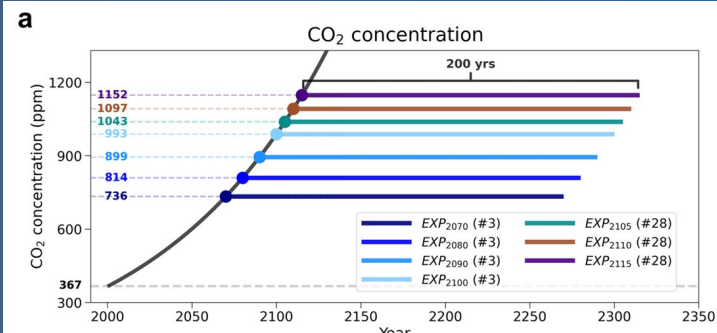
Ensemble of 100 simulations, uniformly placed initial conditions for $t = -100$ yr to a quadrupling of CO₂ in the period 0–75 yr and halving thereafter;

ΔT - the change from the mean temperature before the forcing. If $\Delta T > 5$ red, If $\Delta T < 5$ blue.

GEBM of Budyko–Sellers–Ghil type + Lorenz 63 as forcing.

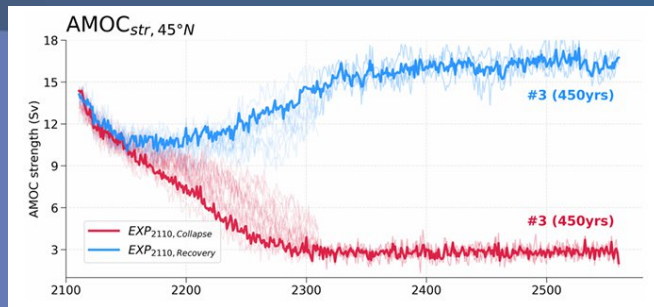
Lohmann et al, 2024, *Journal of Physics: Complexity*

Splitting of trajectories and lost of climatic predictability



Design of CO₂ stabilization simulations and their AMOC response. CESM-1

AMOC in PlaSim-LSG under three SSP scenarios from 2000 to 3000 CE.



Börner, Mehling, Hardenberg & Lucarini, 2025

Фрактальность бассейнов притяжения в системе Lorenz-63

$$r = 20, b = 8/3, \sigma = 10$$

Стационарные состояния

$$Z_c = r - 1, X_c = Y_c = \pm \sqrt{b(r-1)} \approx \pm 7.12$$

Притяжение к “+” голубой цвет, к “-” белый

Телескопизация –

Вверху X,Y диапазон (-40, 40)

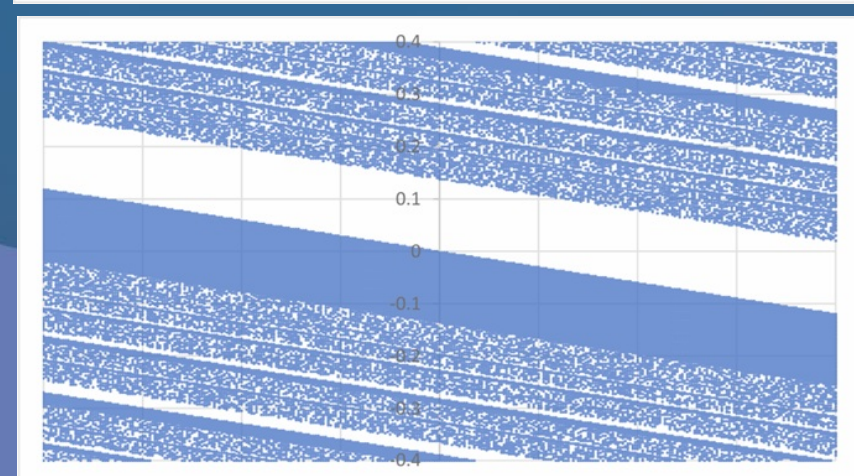
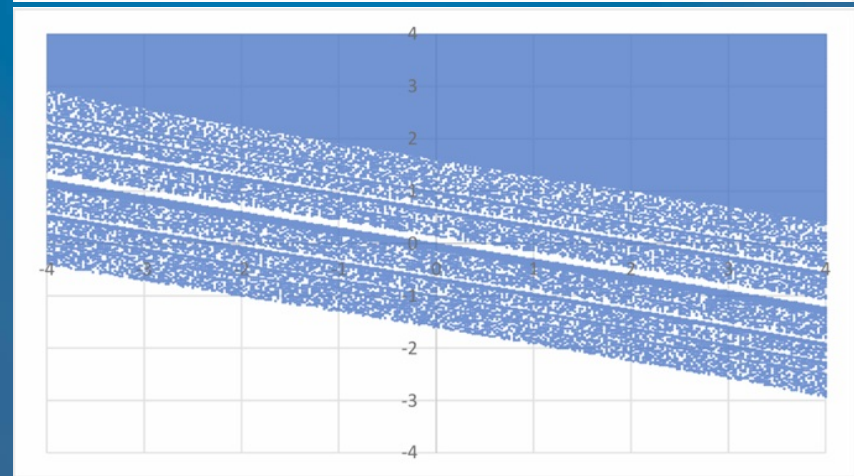
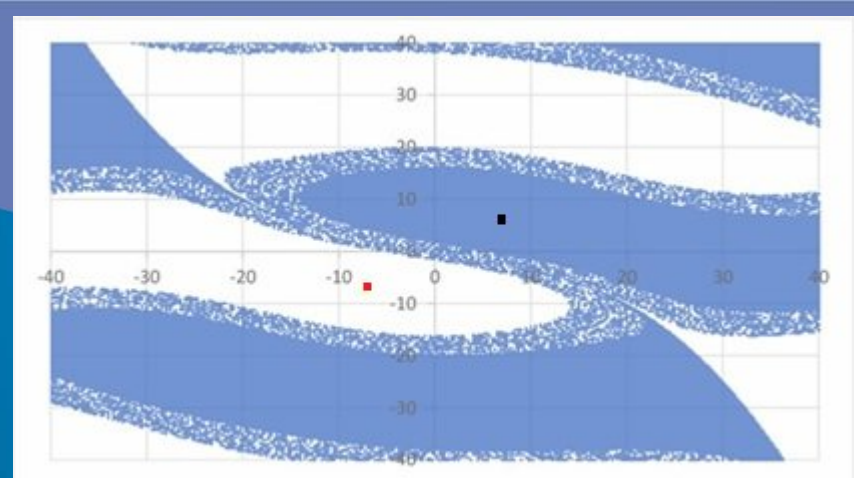
середн X,Y (-4, 4)

внизу X,Y (-0.4, 0.4)

Фрактальные границы бассейнов

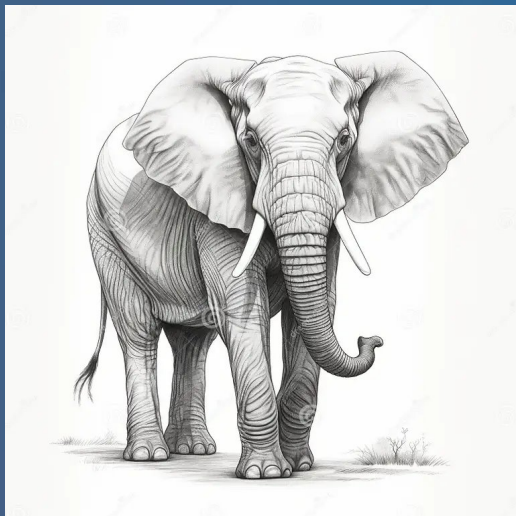
аттракторов →

Потеря предсказуемости второго рода (!)

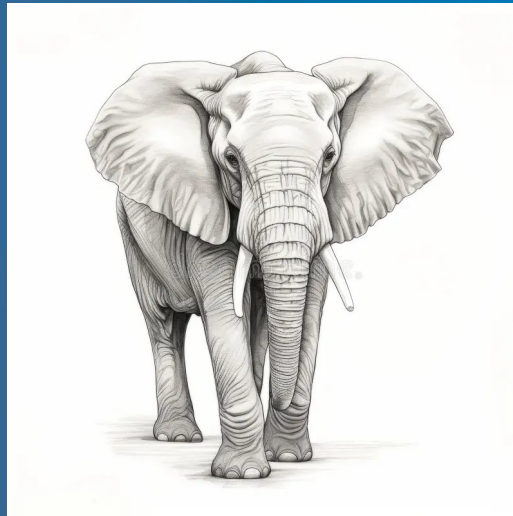




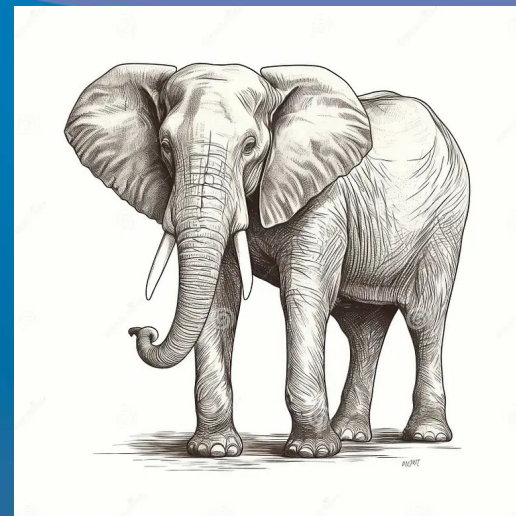
Climate Tipping Points – часть Nonlinear Climate Theory



Теория Климата



Теория Нелинейных
Динамических Систем



Статистическая
физика

Концепция ТР Красива, Интересна, Многогранна

Благодарю за внимание!