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ГЕОФИЗИЧЕСКАЯ
ОБСЕРВАТОРИЯ
им. А.И.ВОЕЙКОВА

Роман Бекряев

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Критические переходы в климатической системе. Сигналы раннего предупреждения

Climate tipping points. Early warning signals

Институт глобального климата и экологии имени академика Ю.А. Израэля (ИГКЭ)

Вторые научные чтения памяти Георгия Вадимовича Грузы «СТАТИСТИЧЕСКАЯ КЛИМАТОЛОГИЯ И МОНИТОРИНГ КЛИМАТА»

12 марта 2026 г.

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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 (AMOC)
2. Atlantic Subpolar Gyre
3. Ледниковый щит Гренландии (и Западной Антарктиды)
4. Вечная мерзлота
5. Зимний дрейфующий лёд СЛО
6. Бореальные леса
7. Леса Амазонии
8. Муссонная циркуляция

I. Происходят относительно быстро
II. Определяются нелинейными процессами
I. Необратимы (обычно)

Временные масштабы TP -

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

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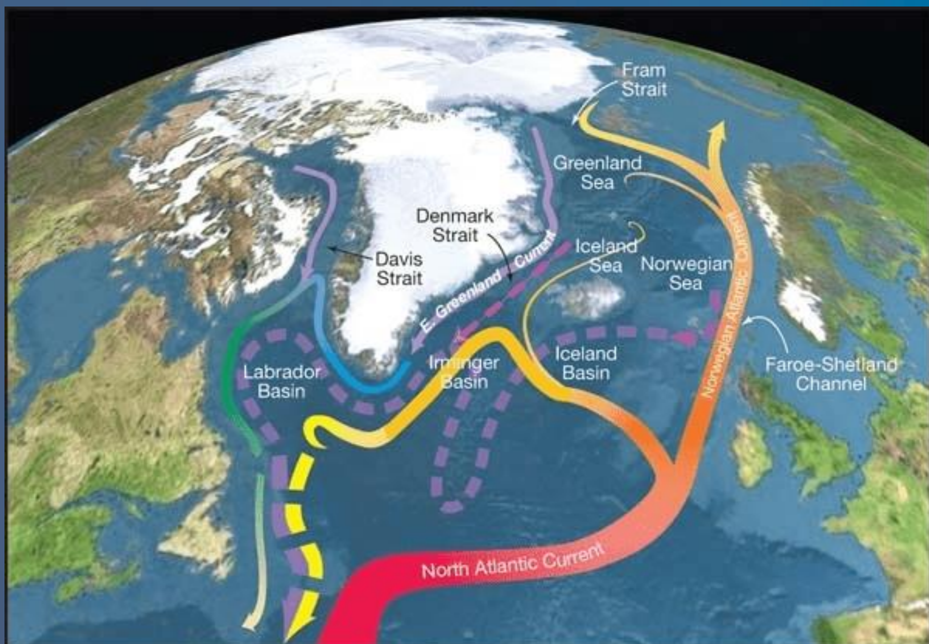
Atlantic Meridional Overturning Circulation and North Atlantic DeepWater Formation



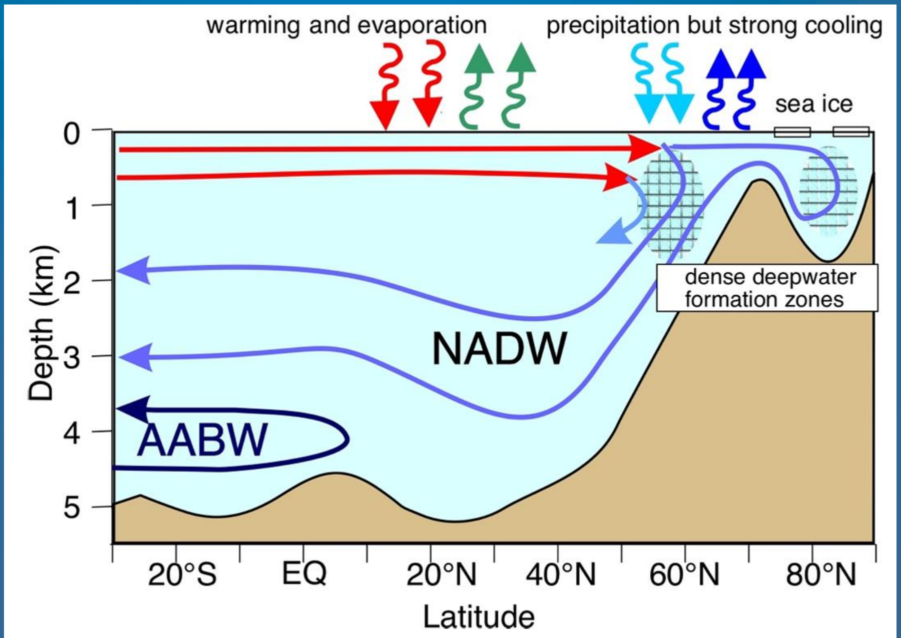


Figure 5. Schematic representation of AMOC and NADW formation.

Surface currents (solid curves) and deep currents (dashed curves) that form a portion of the Atlantic meridional overturning circulation.

Seidov et al, 2025, *Oceans*

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Палеоклиматические аналоги – события Dansgaard- Oeschger. Last Glacial Period 115-12 Ky bp

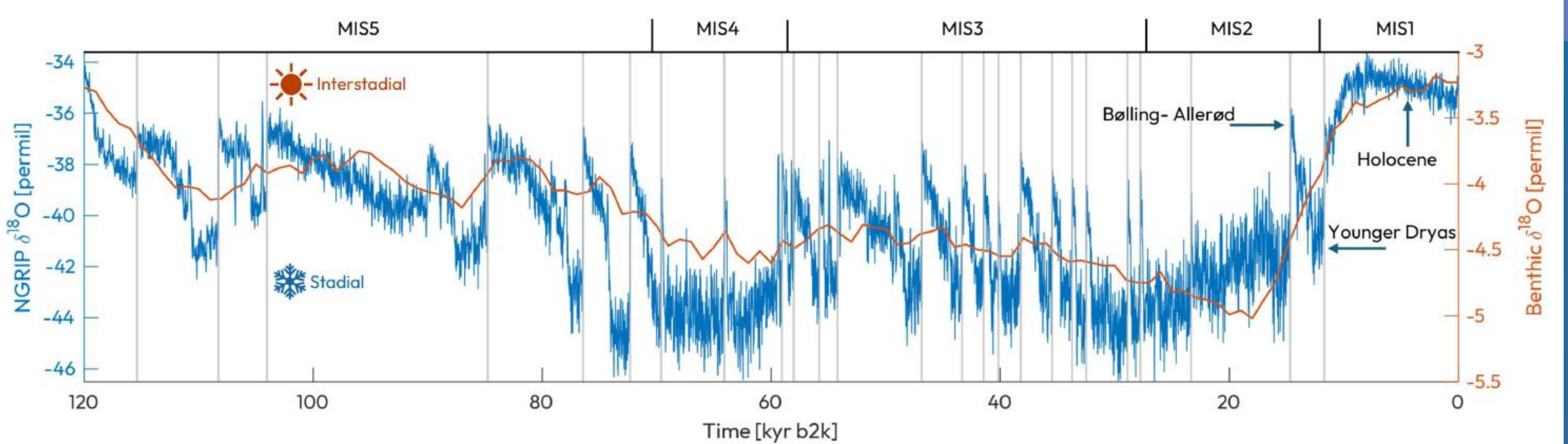

FIG. 1. Variability of the stable oxygen isotope ratio (δ^{18}O) during the last glacial period. In this figure and throughout the paper, kyr b2k refers to "millennia before the year 2000." The blue line indicates the Northern Greenland Ice Core Project (NGRIP) δ^{18}O data with regular sampling of 20 years.[9] The ratio of stable oxygen isotopes ^{16}O and ^{18}O (δ^{18}O) is often used as a proxy for atmospheric temperature at the site of the ice core, with more negative values indicating colder temperatures and less negative values indicating warmer temperatures. The orange line is the benthic record[10] of δ^{18}O, which is a proxy for total global ice volume and, thus, a proxy for the background global mean temperature. Thin gray lines indicate the observed DO events. Marine Isotope Stages (MISs) are indicated at the top of the figure.

Переход от ледниковой (stadial) к межледниковой фазе (interstadial) во время событий D-O происходил за несколько десятилетий. Температура воздуха в регионе Северной Атлантики вырастала на 5-15 К за время жизни одного поколения (20-30 лет).

Hobden, Ashwin & Ritchie, 2025, *Chaos*

Simulated Shutdown of the AMOC

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Henry Stommel, 1961 – box model

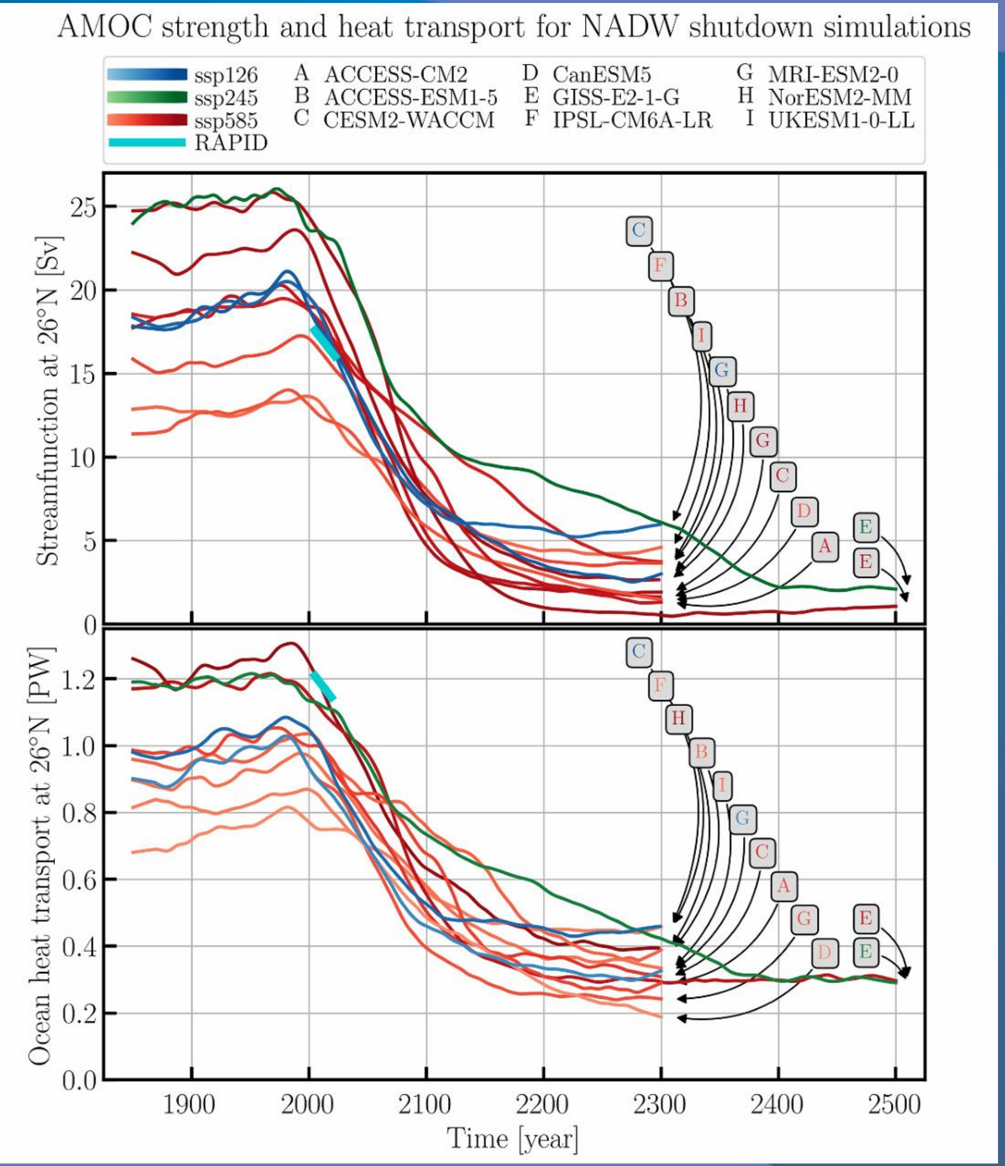
CGCM, Hosing experiments

Hawkins et al, 2011, *GRL*

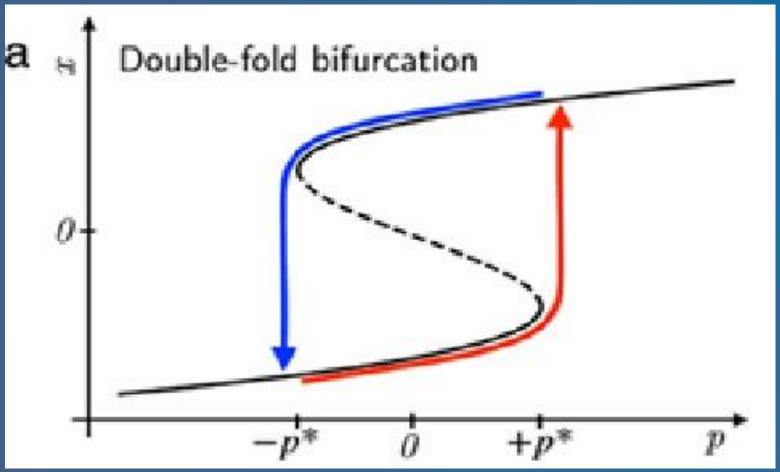
Jackson & Wood, 2018, *GRL*

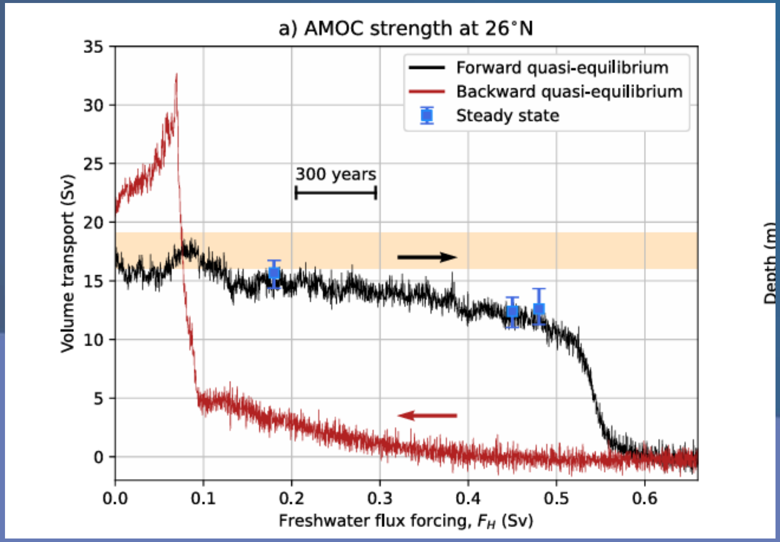
CMIP6 scenario experiments.
Shutdown after 2100.
NO prescribed freshwater perturbations

AMOC strength and heat transport, at 26ºN
Drijfhout S. et al, 2025, *Environ. Res.Lett.*



Tipping Points - Bifurcation mechanisms, 1





Bifurcation (B) Tipping points

Double-fold bifurcation

Boer N., Ghil M. , Stocker T, 2022,
Environ. Res. Lett.

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

Community Earth System Model (CESM)

Tipping Points - Bifurcation mechanisms, 2

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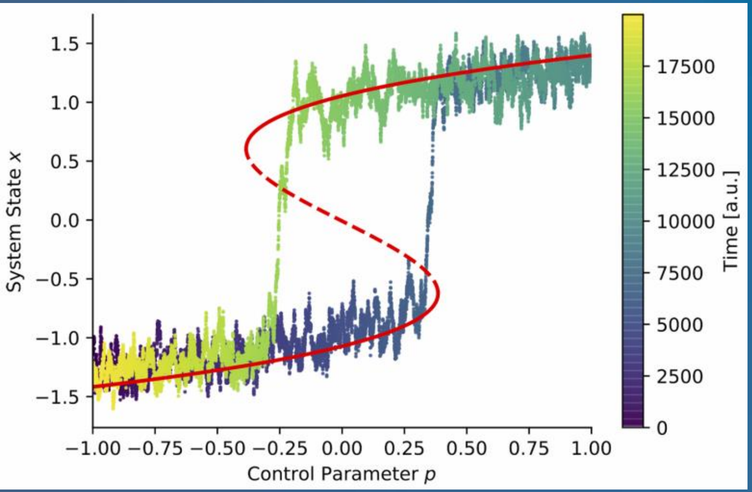
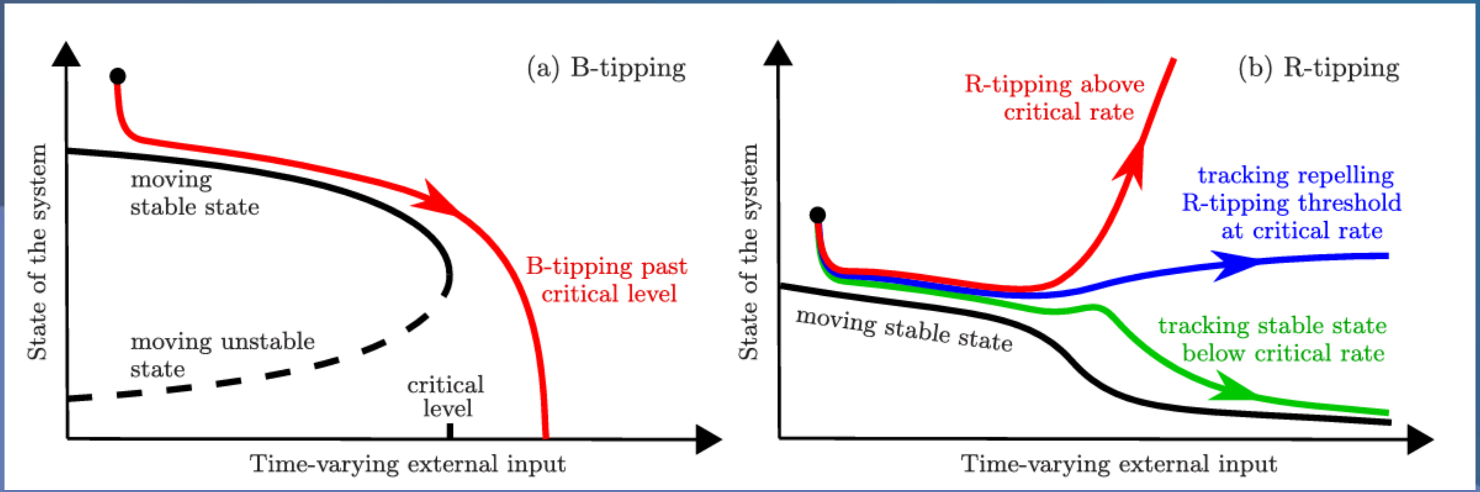


Noise (N) Tipping Points

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

Rate (R) Tipping Points



Wieczorek et al, 2023,
Nonlinearity

Tipping Points - Bifurcation mechanisms, 3

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S - Shock Tipping Point

Introduced by Ulrike Feudel, 2021

Klose, Donges, Feudel & Winkelmann, 2024, *Earth System Dynamics*

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

Brunetti & Ragon, 2023, *Phys. Rev. E,* suggested that S-tippings could explain the events on the Cretaceous-Paleocene boundary 66.5 ml ya.

Неопротерозой, 720-635 ml ya. (Sturtian и Marinoan)

Shock Tipping Points in ESM simulations

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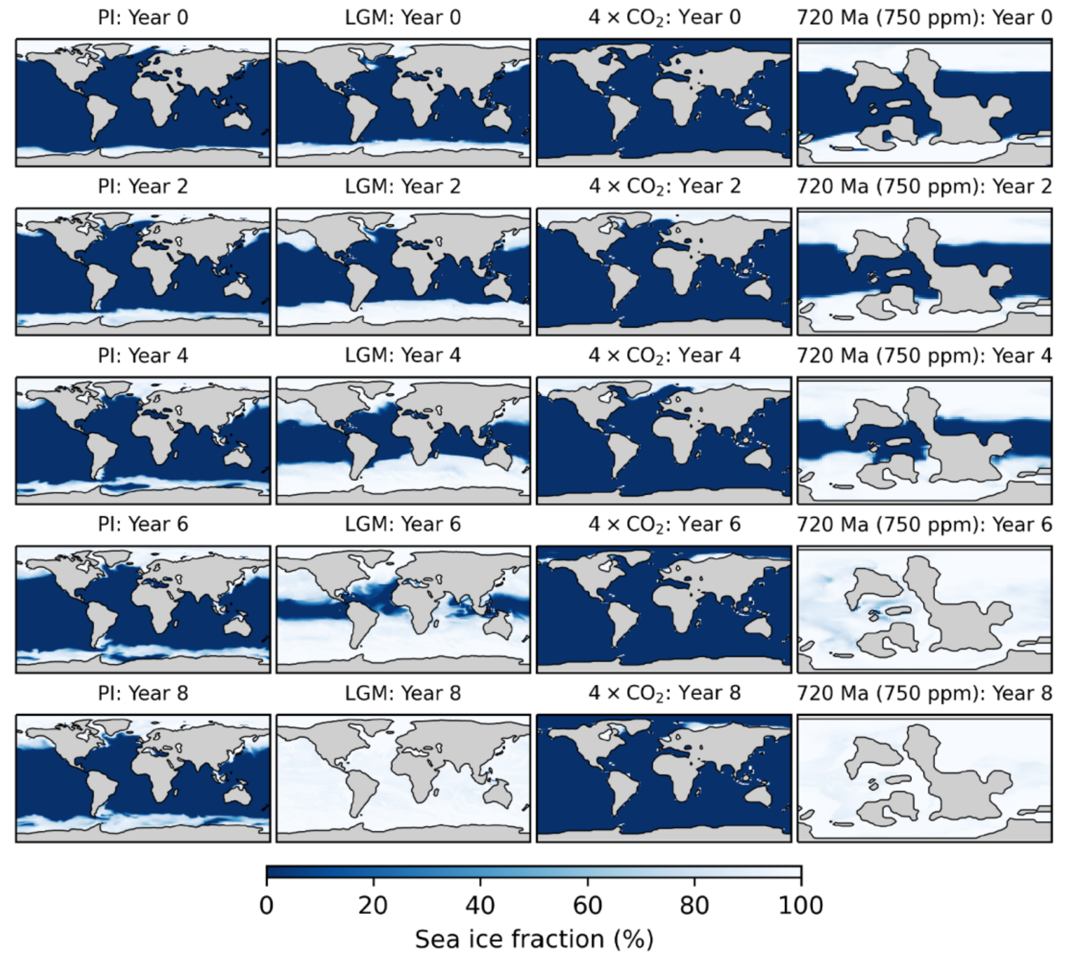

Fig. 3. Snapshots of sea ice coverage during the decade following the 200-Gt radiative forcing scenario for selected experiments. From left to right, columns show the sea ice response of the preindustrial (PI), LGM, 4 × CO_2, and 720-Ma (750-ppm) simulations, respectively.

Community Earth System Model version 1 (CESM1)

Stratospheric SO2 injection 200 Gt.

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

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Какие ещё бифуркации?

I. Бифуркации Хопфа (Subcritical & Supercritical)

II. Бифуркации коразмерности 2

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*

Критические переходы (TP) в модифицированной системе Лоренца (MLS)

$$\frac{\partial X}{\partial \tau} = \sigma Y - \sigma X,$$
$$\frac{\partial Y}{\partial \tau} = -XZ + rX - Y + a,$$
$$\frac{\partial Z}{\partial \tau} = XY - bZ.$$

Sévellec & Fedorov, 2014 *J.Climate*
Mosto et al, 2025, *Chaos*
Le Bras et al, 2024, *Nonlinear processes in Geopysics*

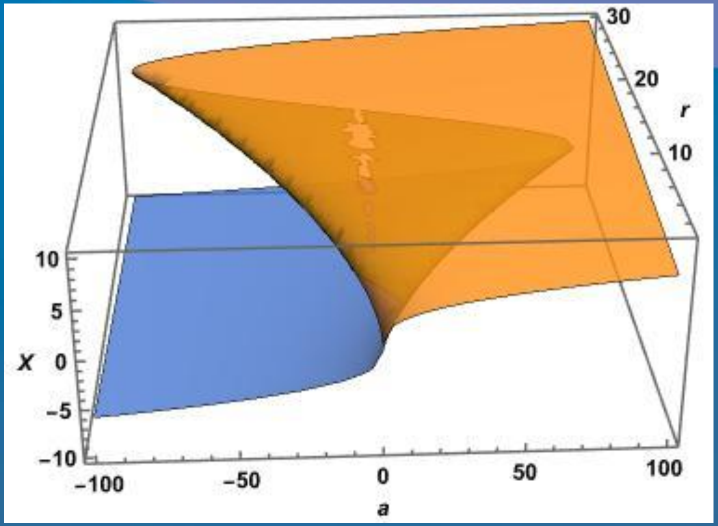
$$a = \pm \frac{2\sqrt{b}(r-1)^{\frac{3}{2}}}{3\sqrt{3}}$$

- Double fold bifurcation

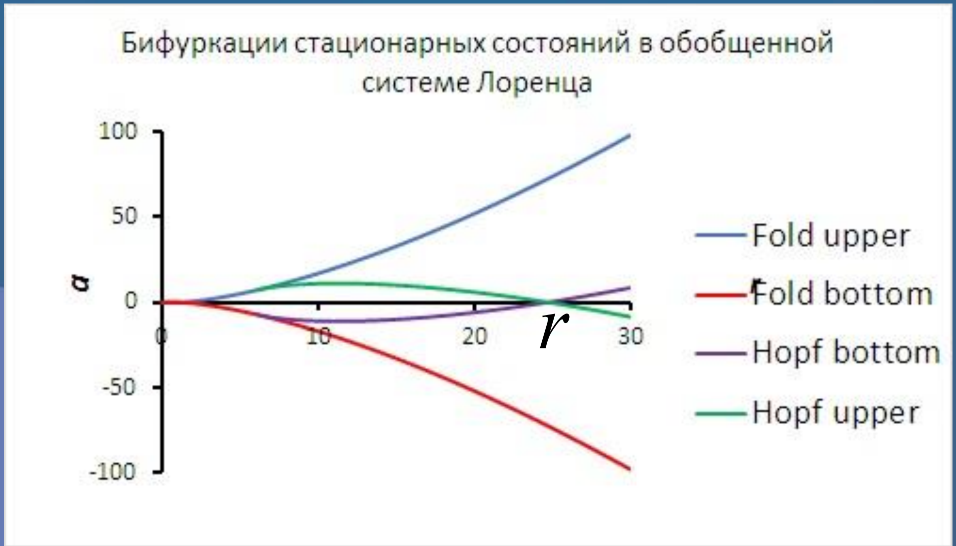
Bogdanov-Takens bifurcations

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

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



Стационарные состояния X
в зависимости от параметров a и r



Critical Slowdown (CSD) and Early Warning Signals
Признаки приближения к опасной границе

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В окрестностях особых точек –
Critical Slowdown – Замедление движений =>
Увеличение дисперсии и рост автокорреляций

Formal description of fold CSD

Normal form of fold + stochastic forcing

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

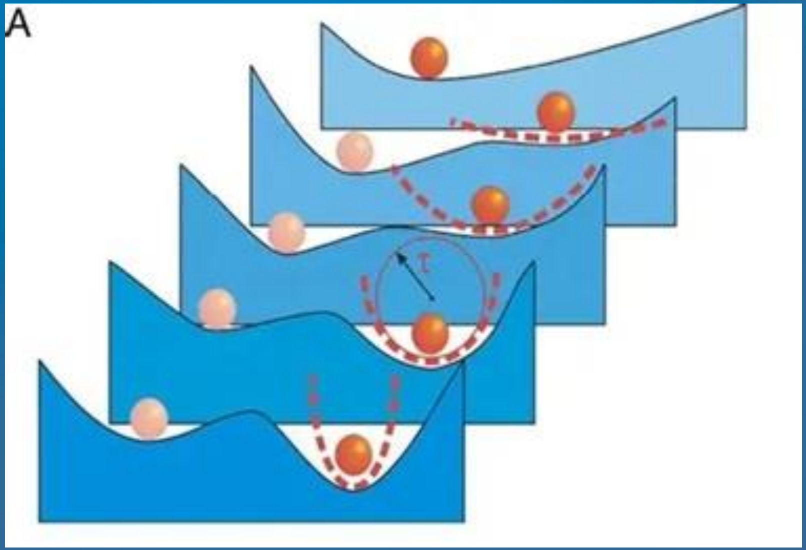
Tipping point: $\mu = 0$
Into vicinity of stable point $X_1 = \sqrt{\mu}$

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

– процесс Орнштейна-Уленбега, =>

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

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



Lenton et al, 2008, *PNAS*

Peter Ditlevsen & Susanna Ditlevsen, 2023, *Nature Communications*
Прогнозное время коллапса AMOC 2057г
с 95% доверит. границами 2025-2095.

Splitting of trajectories and lost of climatic predictability, 1

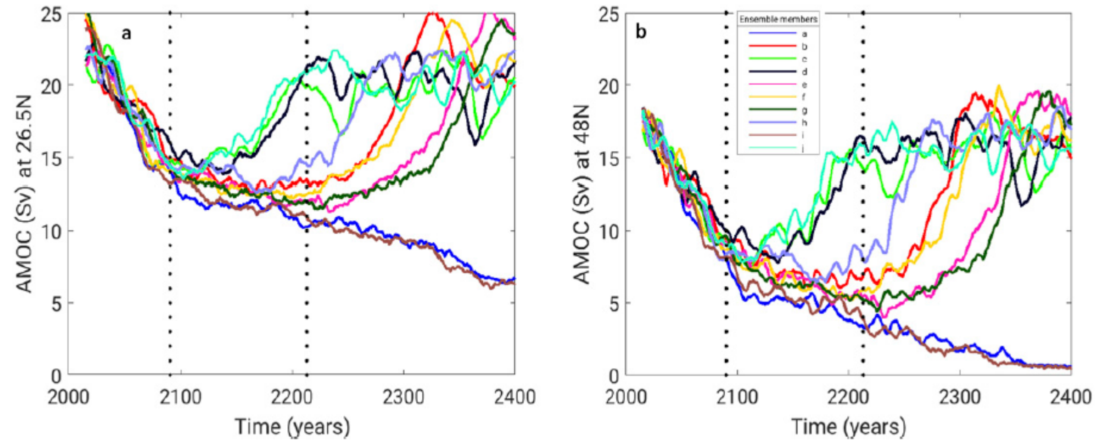
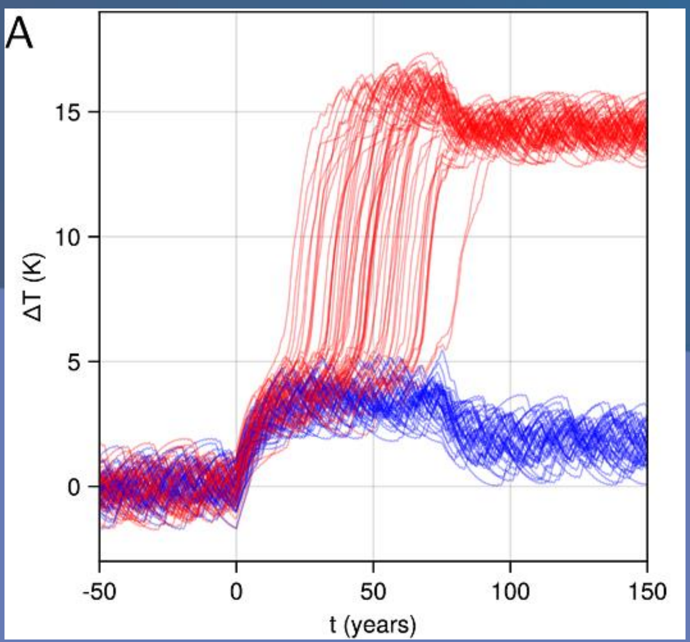


FIG. 1. AMOC strength, defined as the maximum overturning streamfunction below 500 m at (a) 26.5° and (b) 48°N, from 10 ensemble members of the SSP2–4.5 scenario simulation. Vertical dotted lines correspond to times of change in GHG forcing (see Fig. 2a). All fields are smoothed using a 10-yr moving average filter.

AMOC strength (Sv) at 26º and 48ºN,

GISS-E2-1-G, SSP2-4.5, 10 ensemble members.

Romanou et al, 2023, *J.Climate*



Predictability of possible storylines –
Probabilistic prediction of future attractor

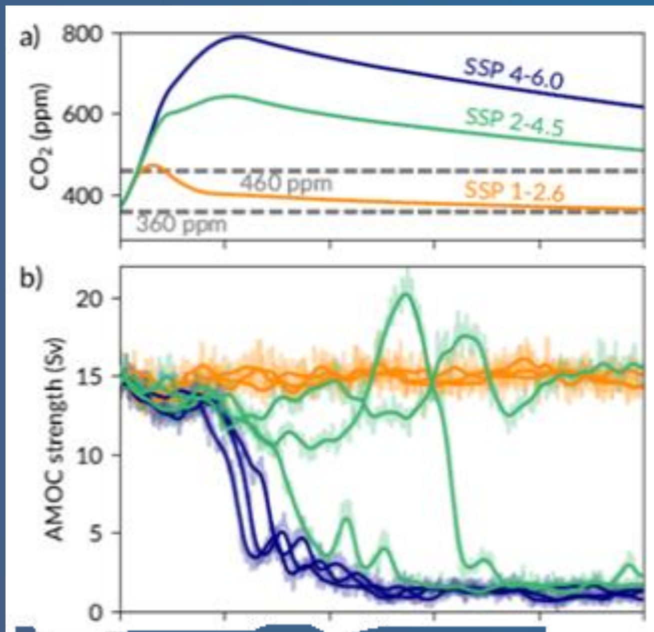
Ensemble of 100 simulations, uniformly placed initial conditions for $t = -100$ yr to a quadrupling of CO_2 in the period 0–75 yr and halving thereafter;

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

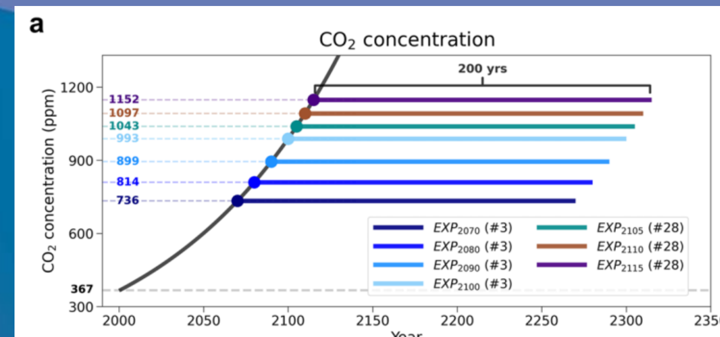


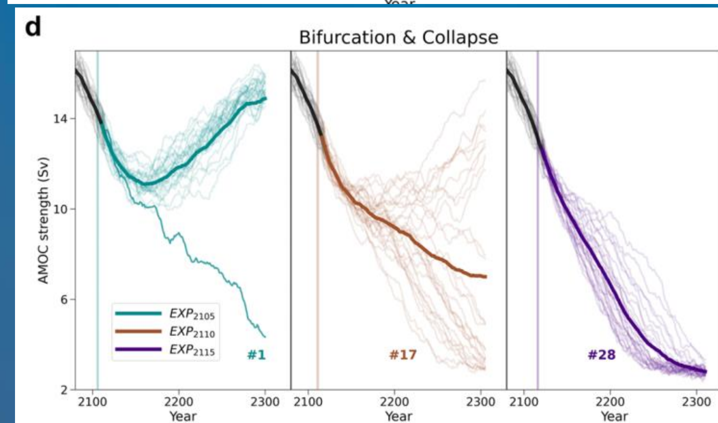
AMOC in PlaSim-LSG under three SSP scenarios from 2000 to 3000 CE.

a) Atmospheric CO2 concentration

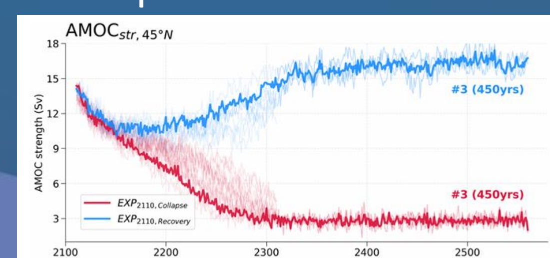
b) AMOC strength for simulations (three ensemble members each).

Börner, Mehling, Hardenberg & Lucarini, 2025





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



Oh et al, 2025, *Nature Communications*

Фрактальность бассейнов притяжения в системе Lorenz-63

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

Стационарные состояния

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

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

Телескопизация –

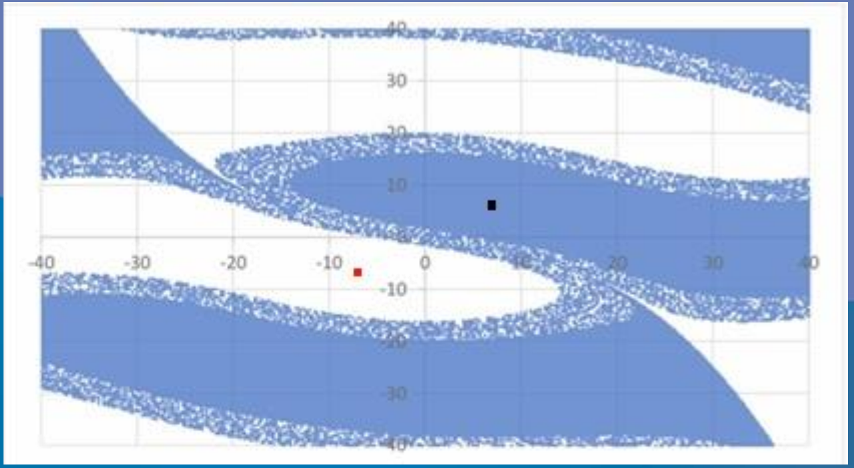
Вверху X,Y диапазон (-40, 40)

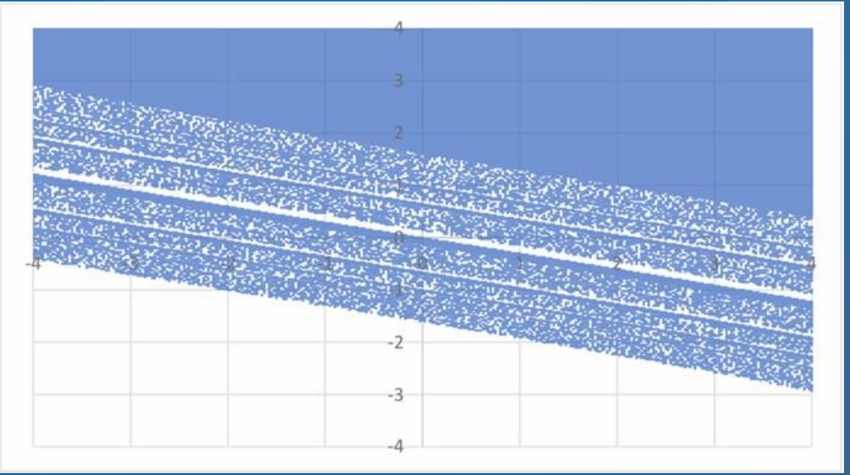
середн X,Y (-4, 4)

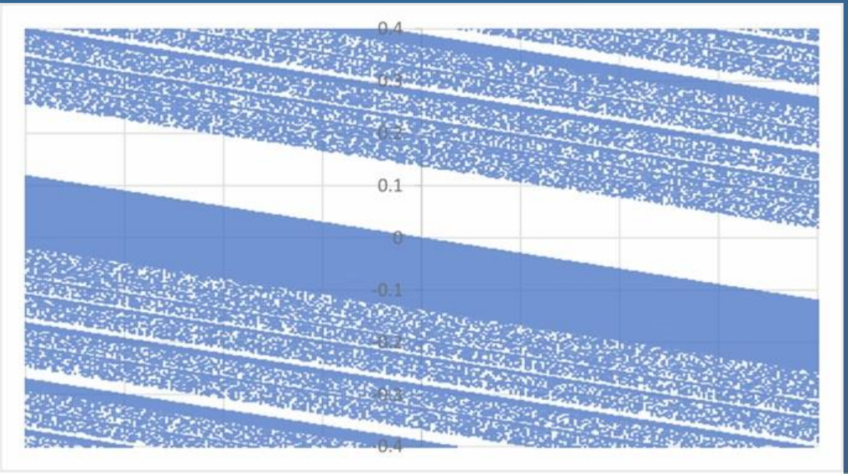
внизу X,Y (-0.4, 0.4)

Фрактальные границы бассейнов аттракторов ➔

Потеря предсказуемости второго рода







Kaszás, Feudel & Tél, 2019, *Scientific reports*

…fractality-induced tipping…. as a consequence of the ubiquitous presence of fractal basin boundaries.

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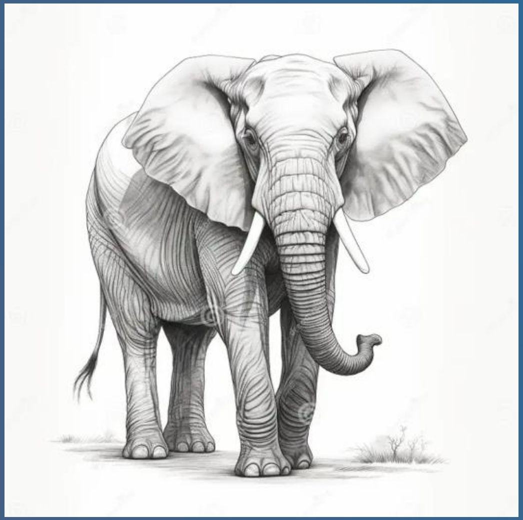
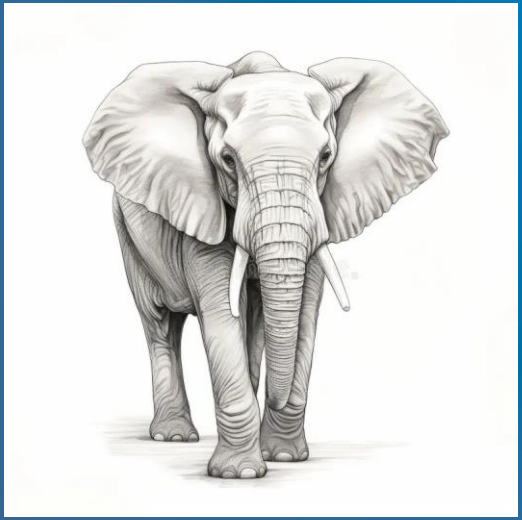
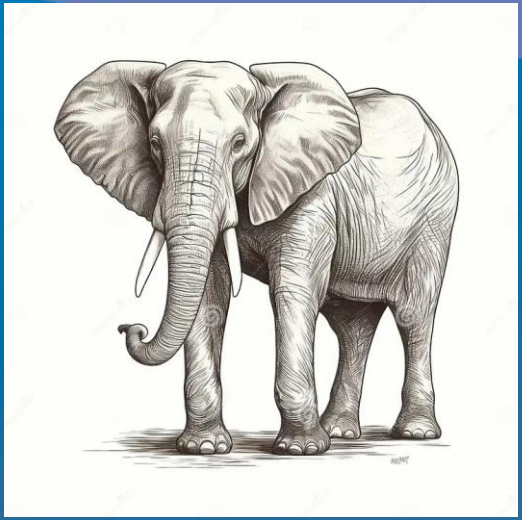
Climate Tipping Points – часть Nonlinear Climate Theory



Теория Климата



Теория Нелинейных Динамических Систем



Статистическая физика

Концепция TP Красива, Интересна, Многогранна

Благодарю за внимание!

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