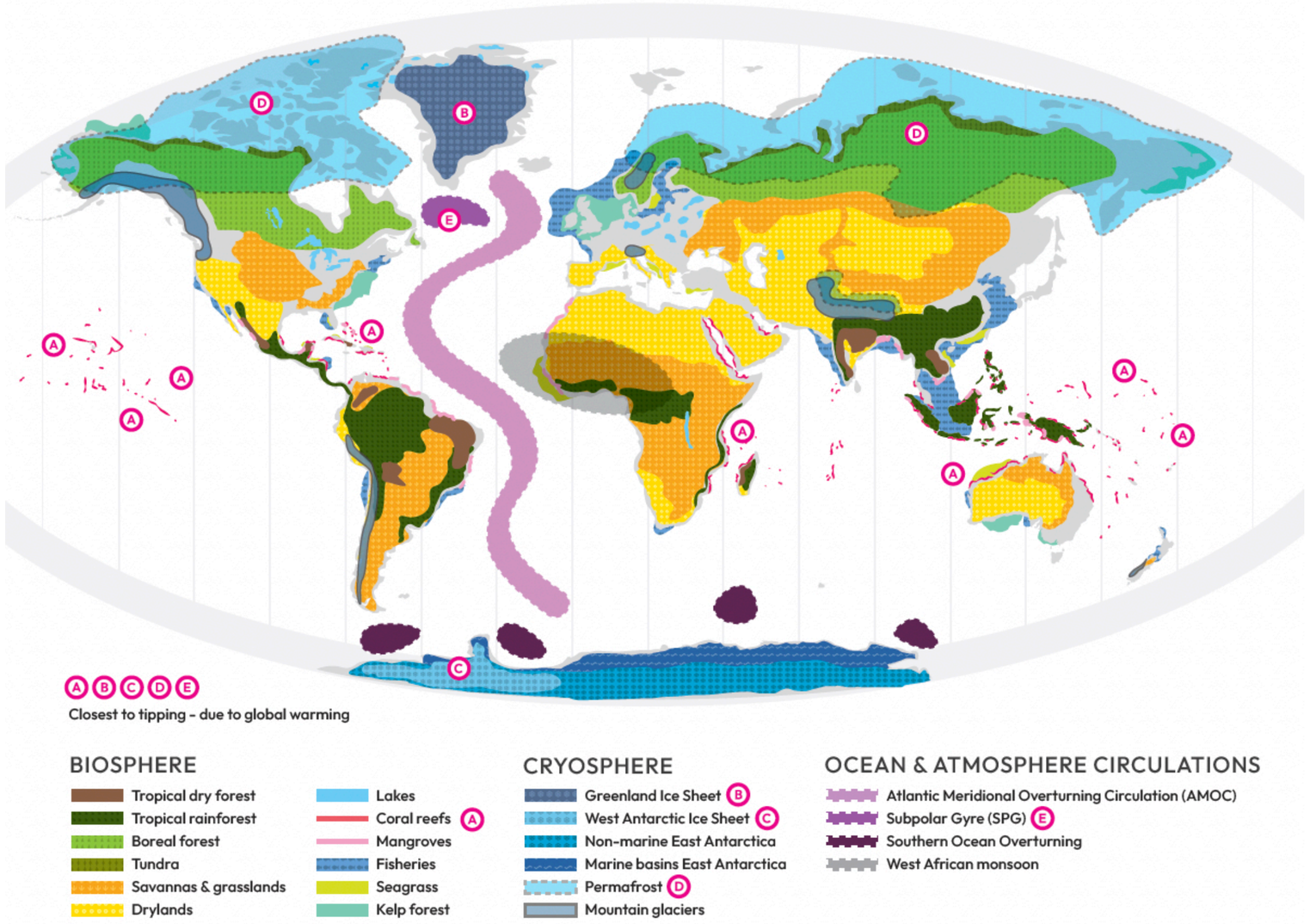
Tipping Behavior in the Climate System



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

Utrecht University

Overview of Course

Date	10:00-10:45	11:00-11:45	12:00-12:45
Mo 5-2	General Intro Tipping Elements Lenton et al., Section 0 + 1.1	Dynamical Systems + Bifurcation induced TB Strogatz, Chapters 1 + 2	Exercises
We 7-2	Oceans Lenton et al., Section 1.4	Noise induced TB Dijkstra, Chapter 10	Exercises
Fr. 9-2	Cryosphere Lenton et al., Section 1.2	Early Warning Signals of TB Lenton, Section 0 + Dijkstra, Chapter 5	Exercises
Mo 12-2	Atmosphere Lenton et al., Section 1.4	Overshoot + Rate induced TB Lenton, Section 1.6	Exercises
We 14-2	Climate Impact of TB Lenton et al., Section 1.5	Cascading TB Lenton, Section 1.5	Exercises + Question Time
Fr 16-2	Exam	Exam	Exam

1. T. M. Lenton et al. (eds), 2023, The Global Tipping Points Report 2023. University of Exeter, Exeter, UK.
2. Strogatz, S, 2015, Nonlinear Dynamics and Chaos, Westview Press, USA.
3. Dijkstra, H.A., 2013, Nonlinear Climate Dynamics, Cambridge University Press, UK.

Grading: Exam (100%)

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Material

Global Tipping Points

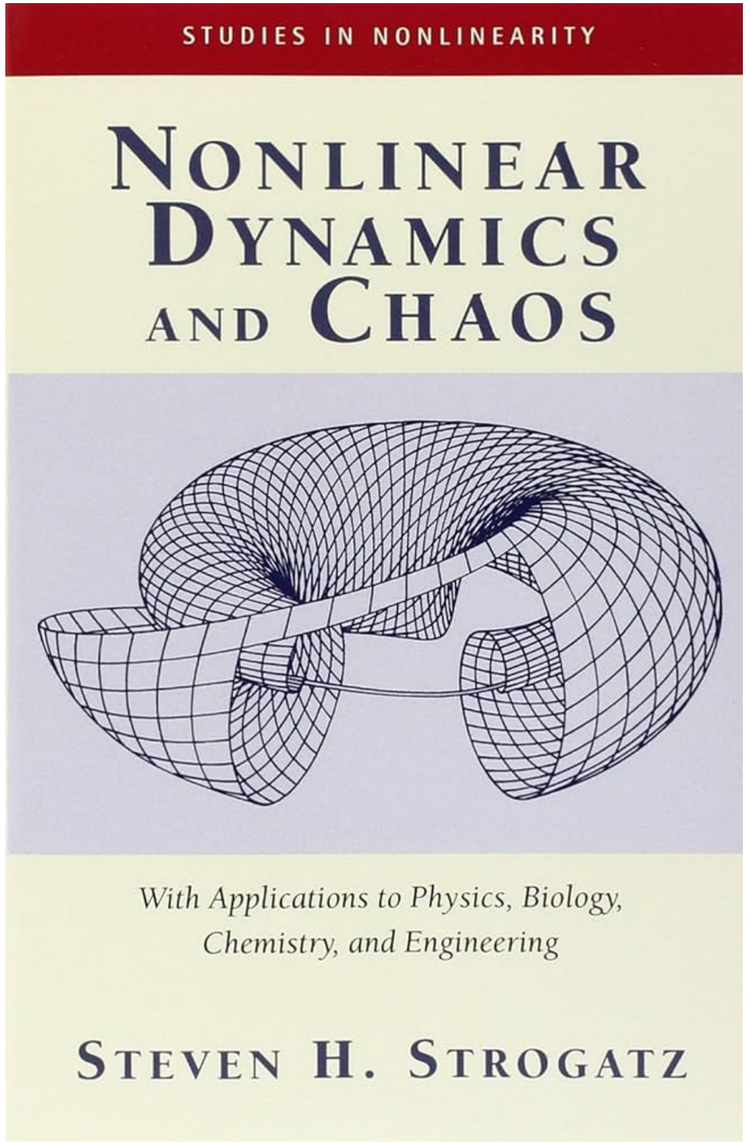
Report 2023

Led by:

University of Exeter | Global Systems Institute

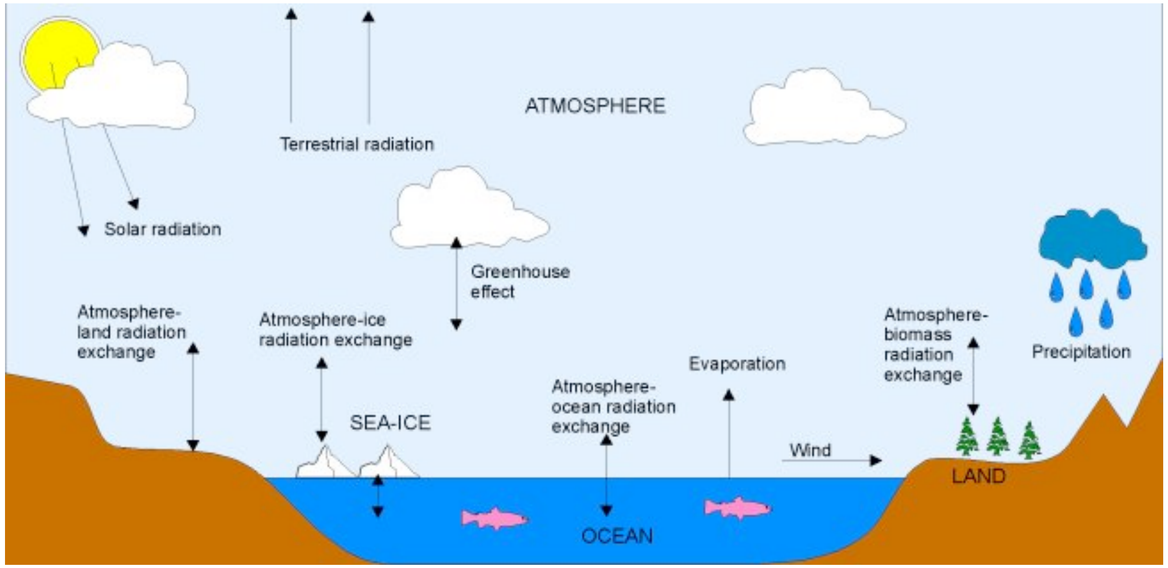
Funded by:

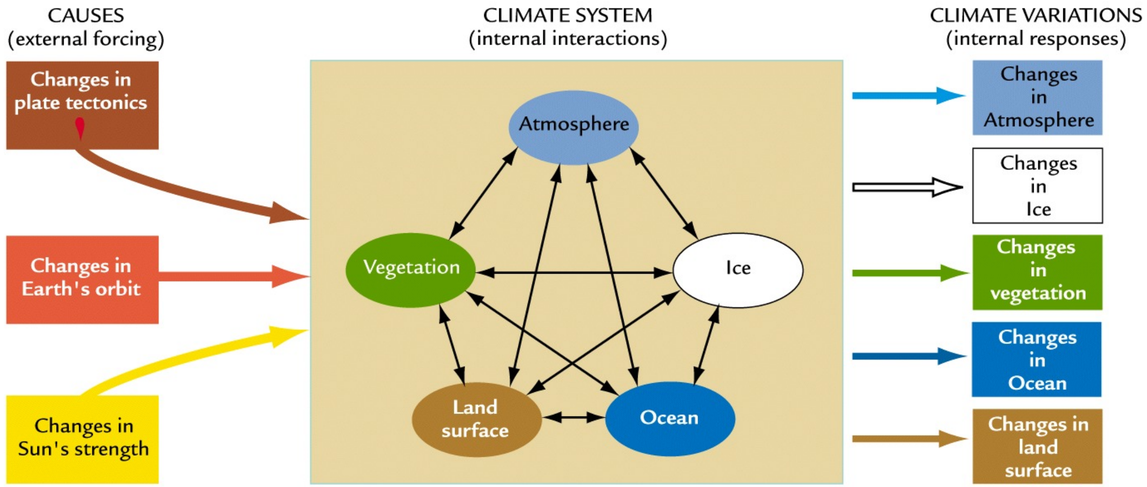
BEZOS EARTH FUND



Climate System

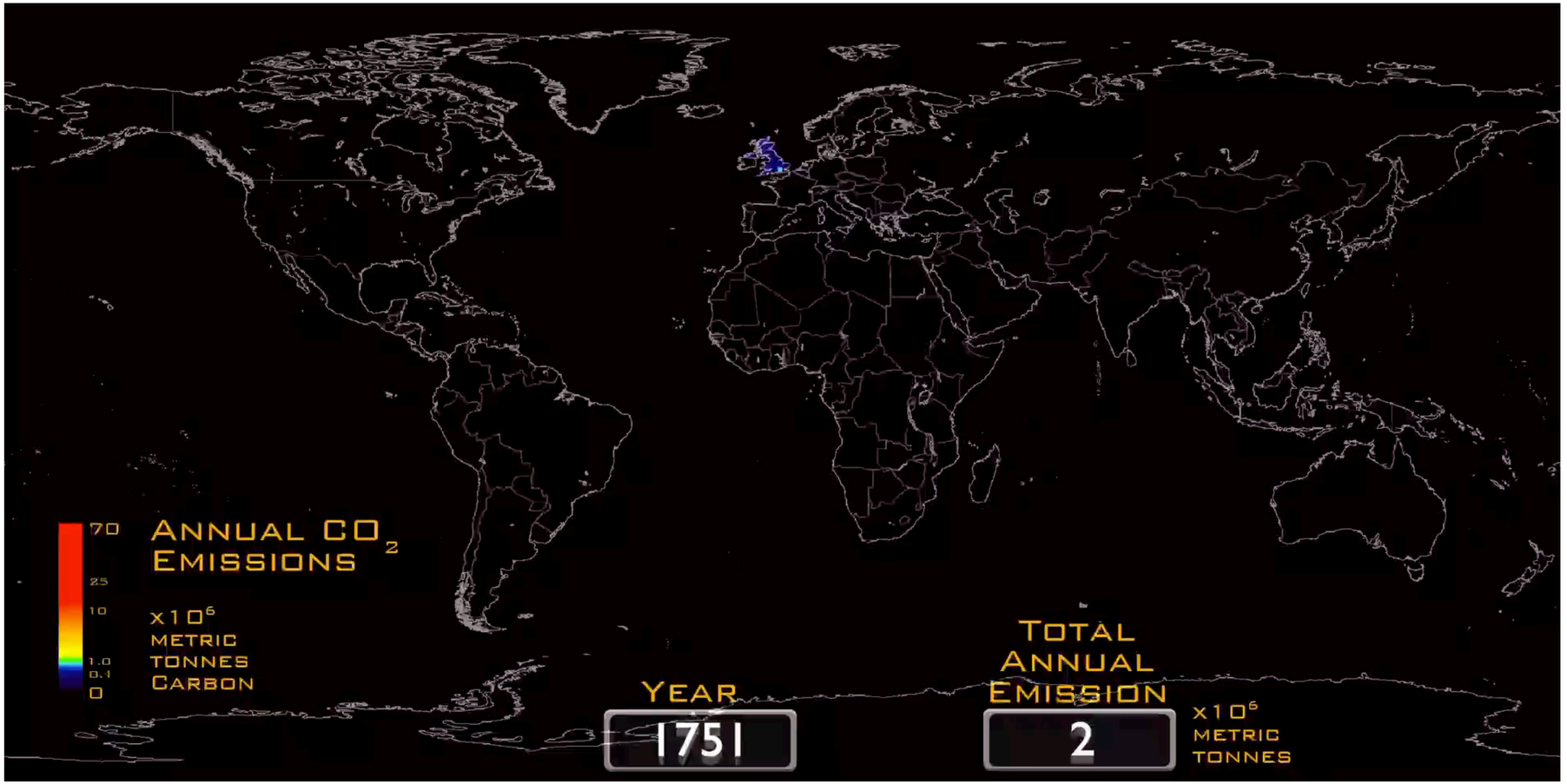
Complex: Multi-scale interactions between different components





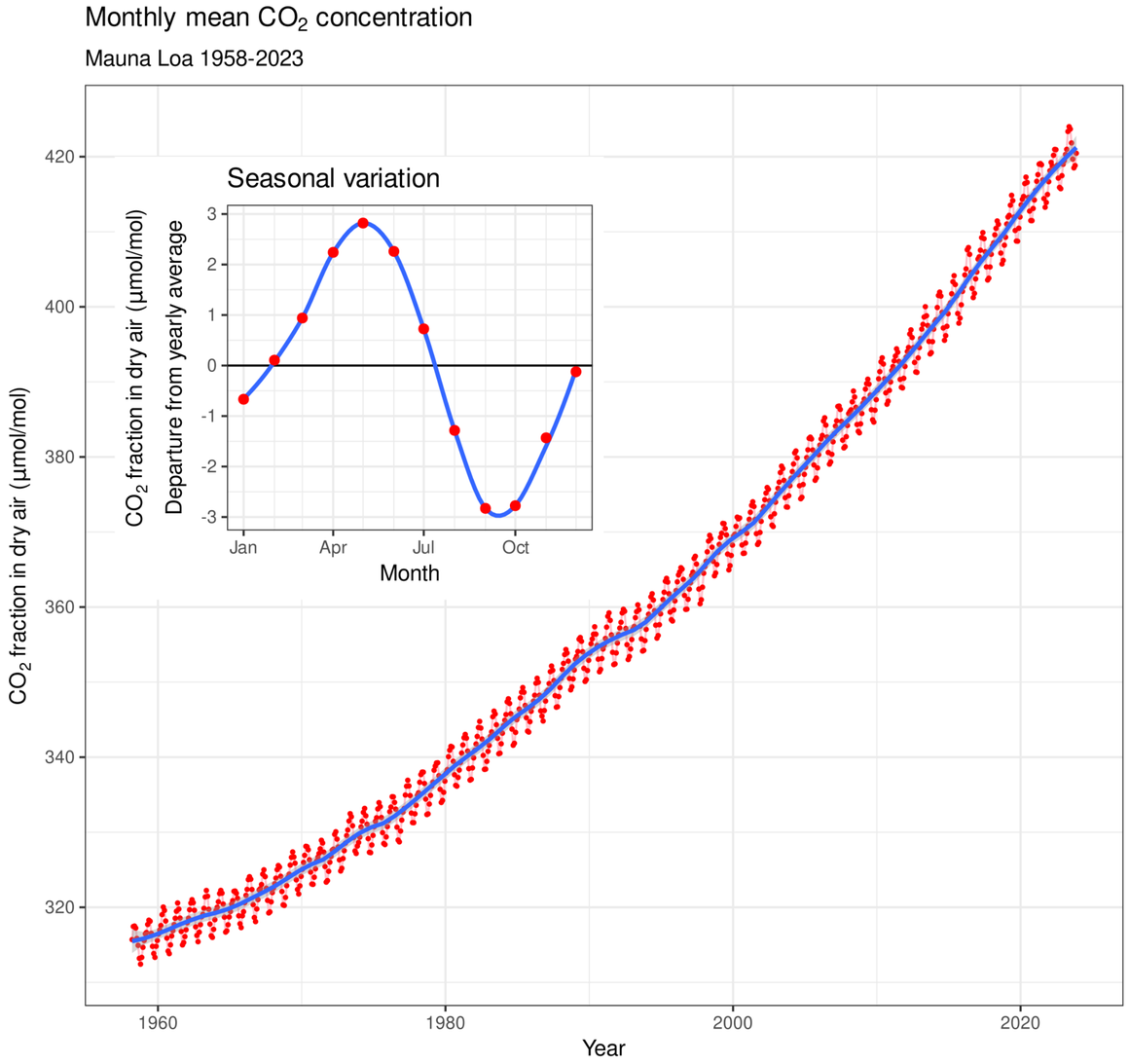
Complex: Turbulent Flows (Ocean and Atmosphere)

Anthropogenic Climate Change

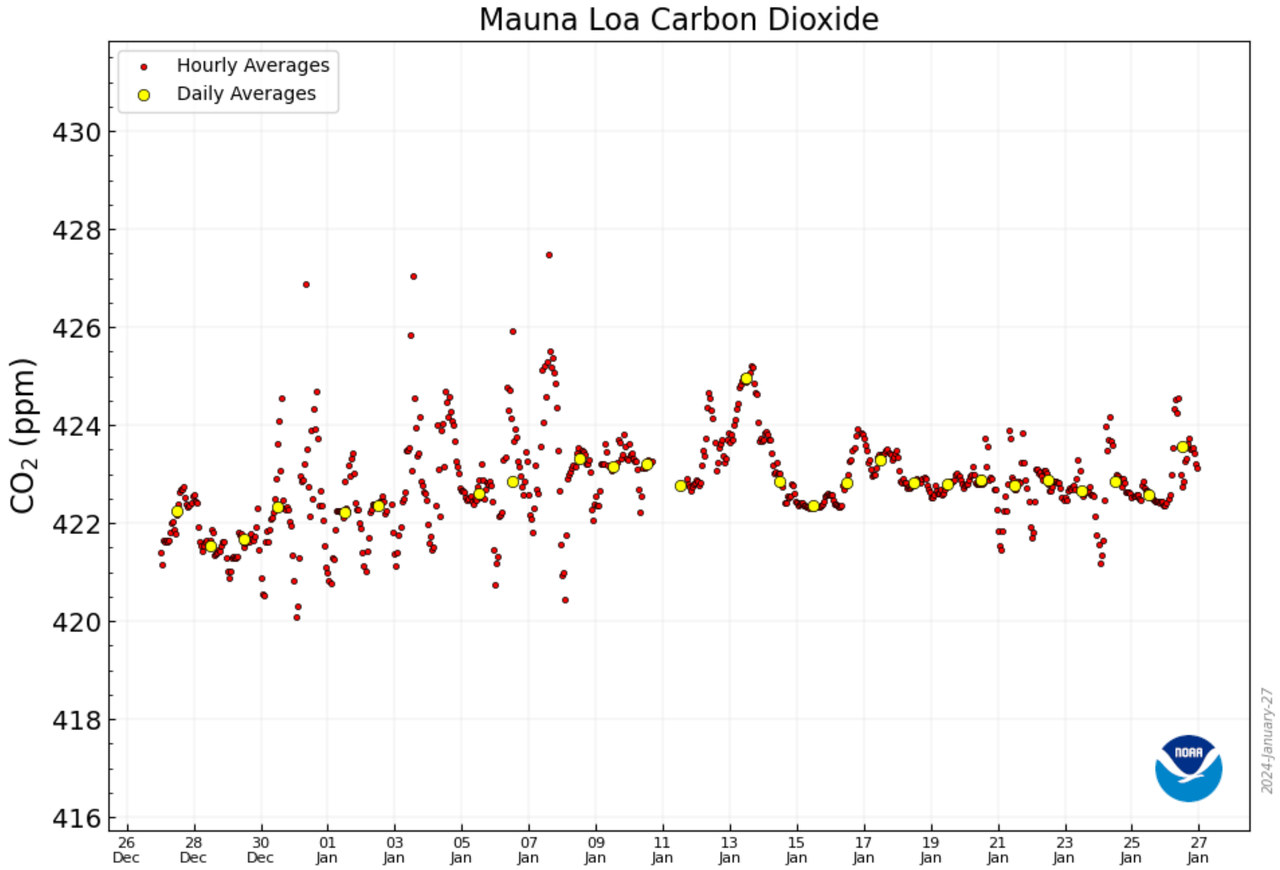


From 1870 to 2014, cumulative carbon emissions totaled about 545 GtC. Emissions were partitioned among the atmosphere (approx. 230 GtC or 42%), ocean (approx. 155 GtC or 28%) and the land (approx. 160 GtC or 29%).

Changes in atmospheric CO2



Data : Dr. Pieter Tans, NOAA/ESRL (https://gml.noaa.gov/ccgg/trends/) and
Dr. Ralph Keeling, Scripps Institution of Oceanography (https://scrippsco2.ucsd.edu/). Accessed 2023-12-15
https://w.wiki/4ZWn



Increase: ~ 4 ppm per year

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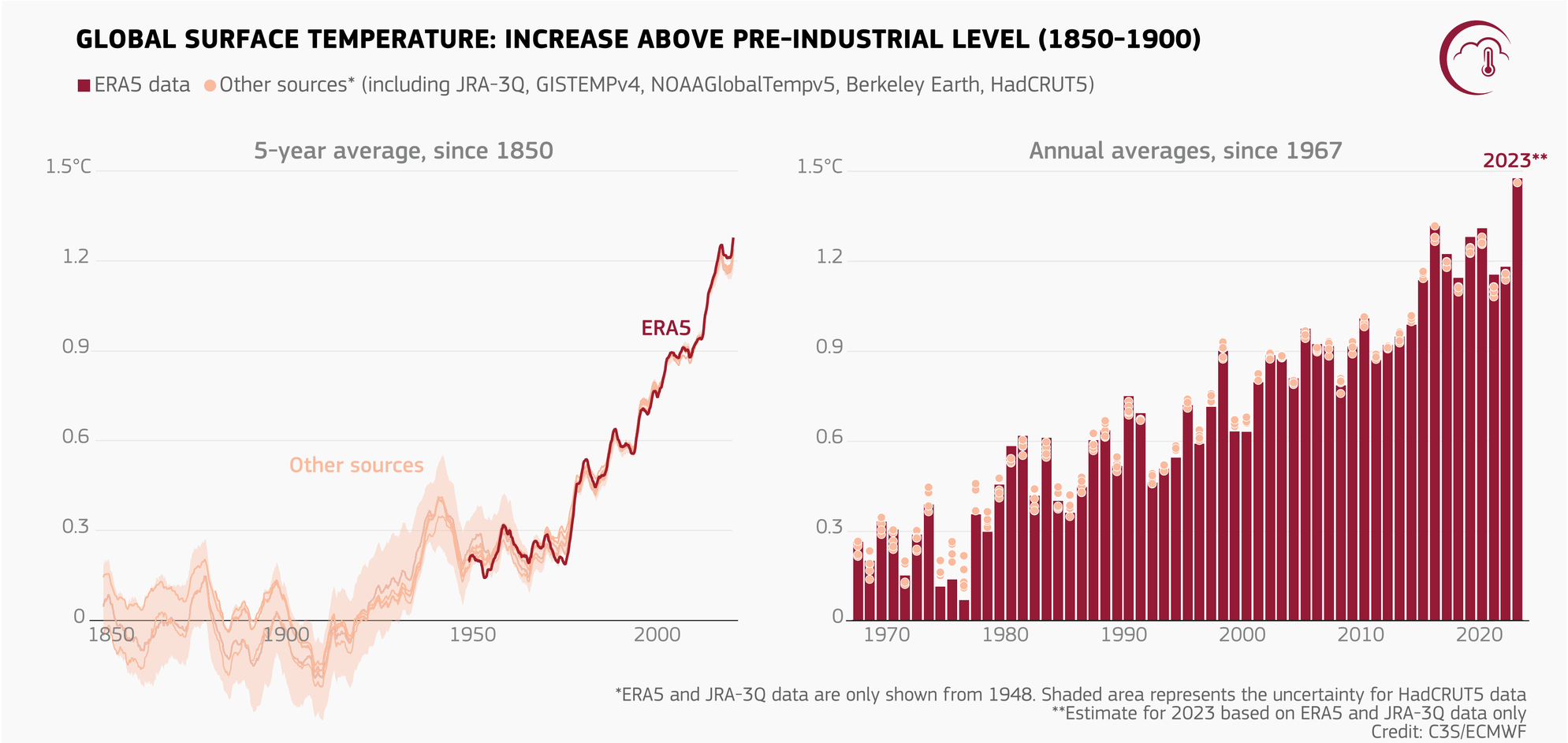
Global Mean surface temperature (GMST)



PROGRAMME OF THE EUROPEAN UNION

opernicus Europe's eyes on Earth

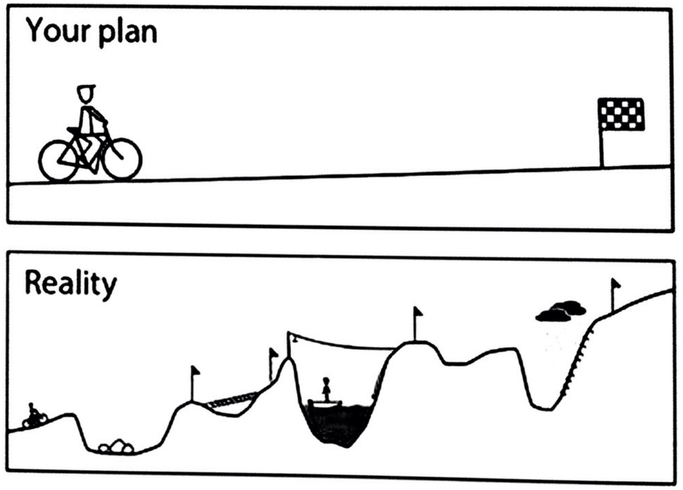
ECMWF

Climate Change Service
climate.copernicus.eu

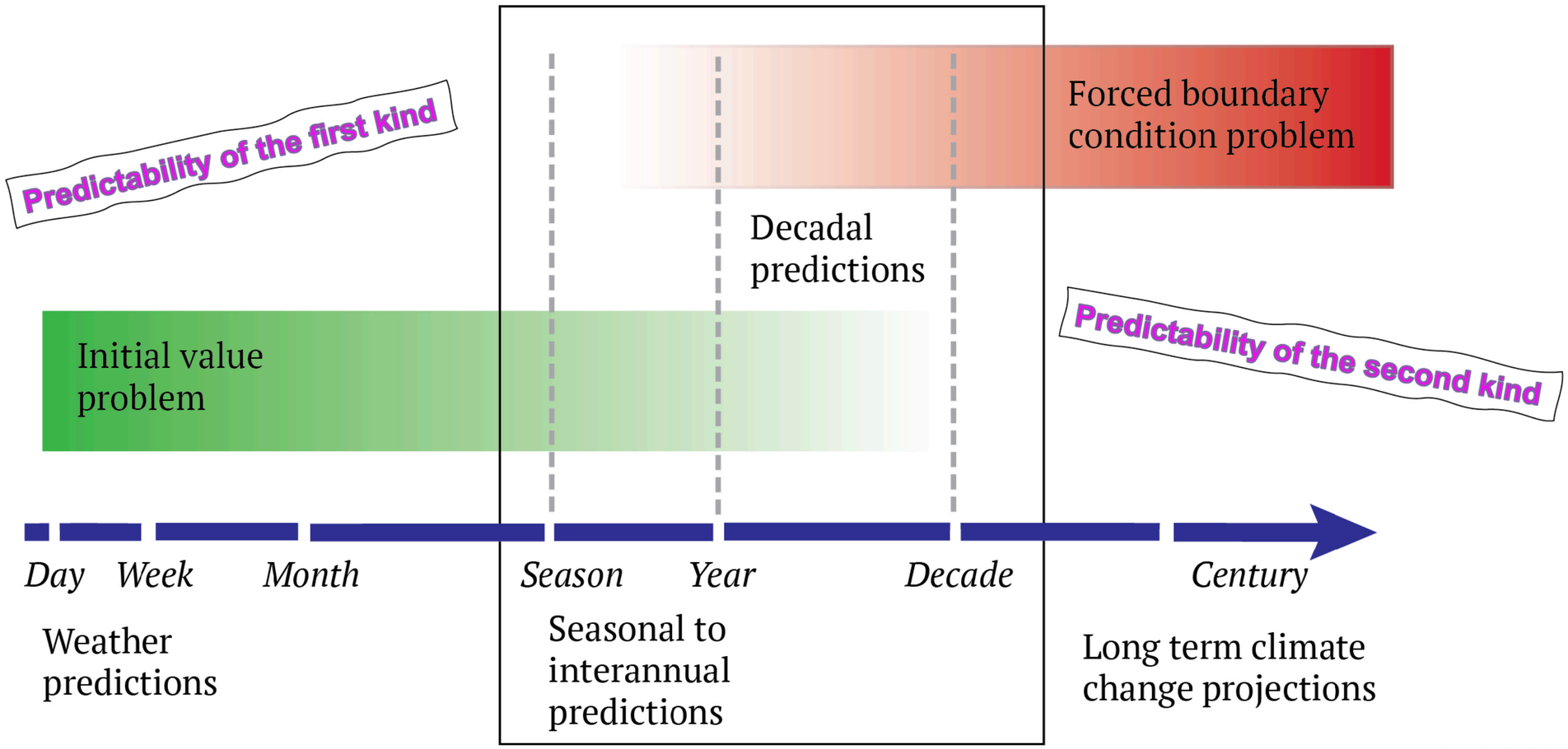
Main questions

1. How warm is it going to be in 2100?

2. Are the changes going to be ‘smooth’ or ‘bumpy’?

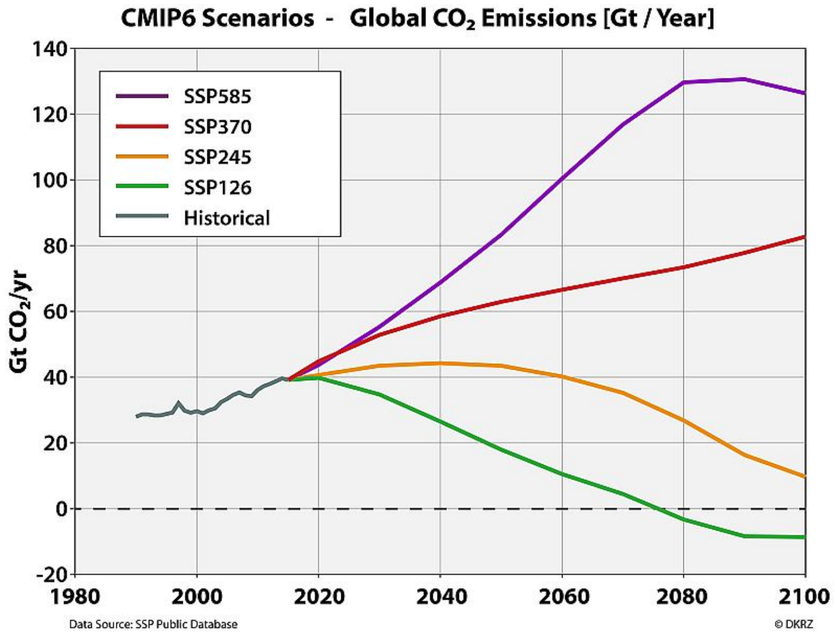


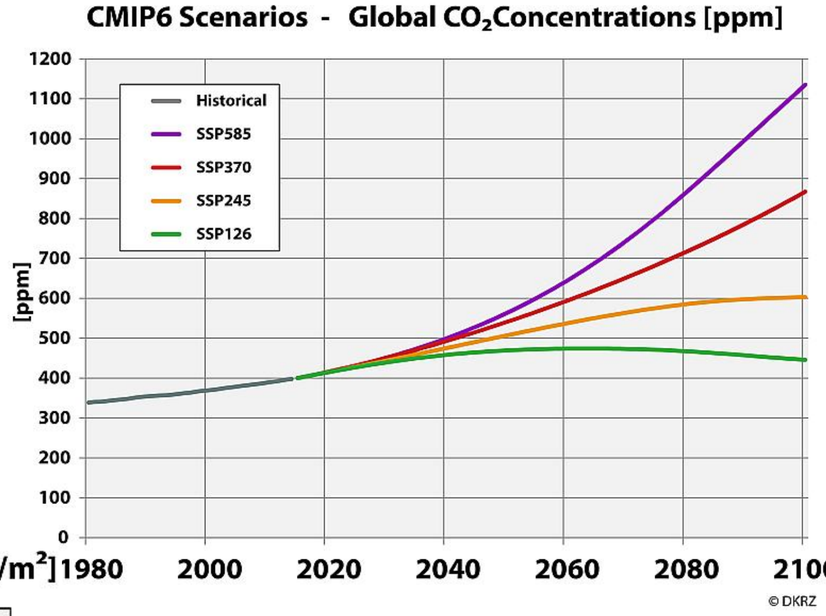
Future Climate Change

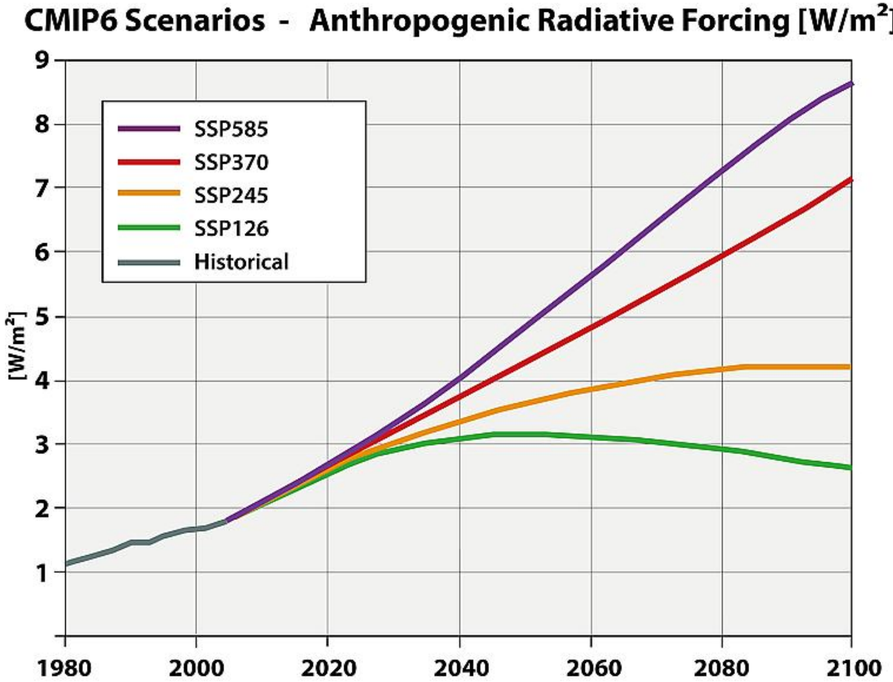


IPCC AR5

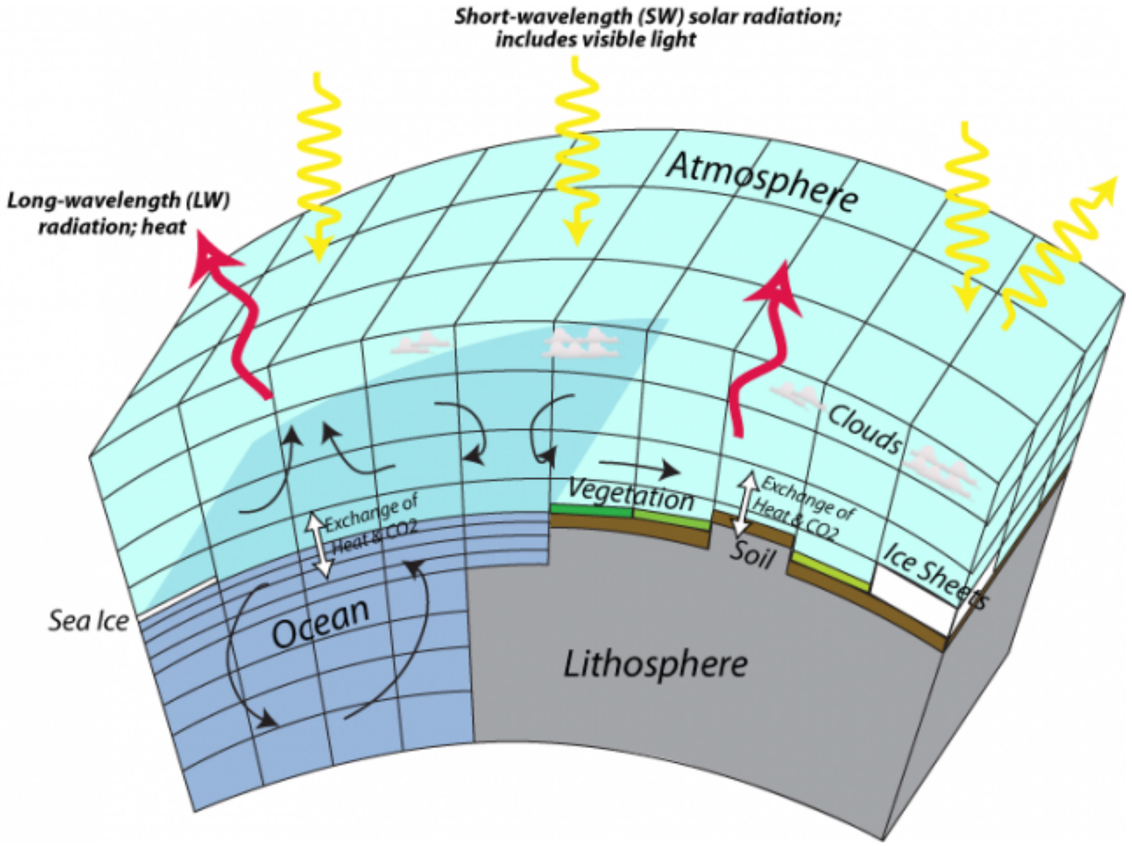
Emission Scenarios

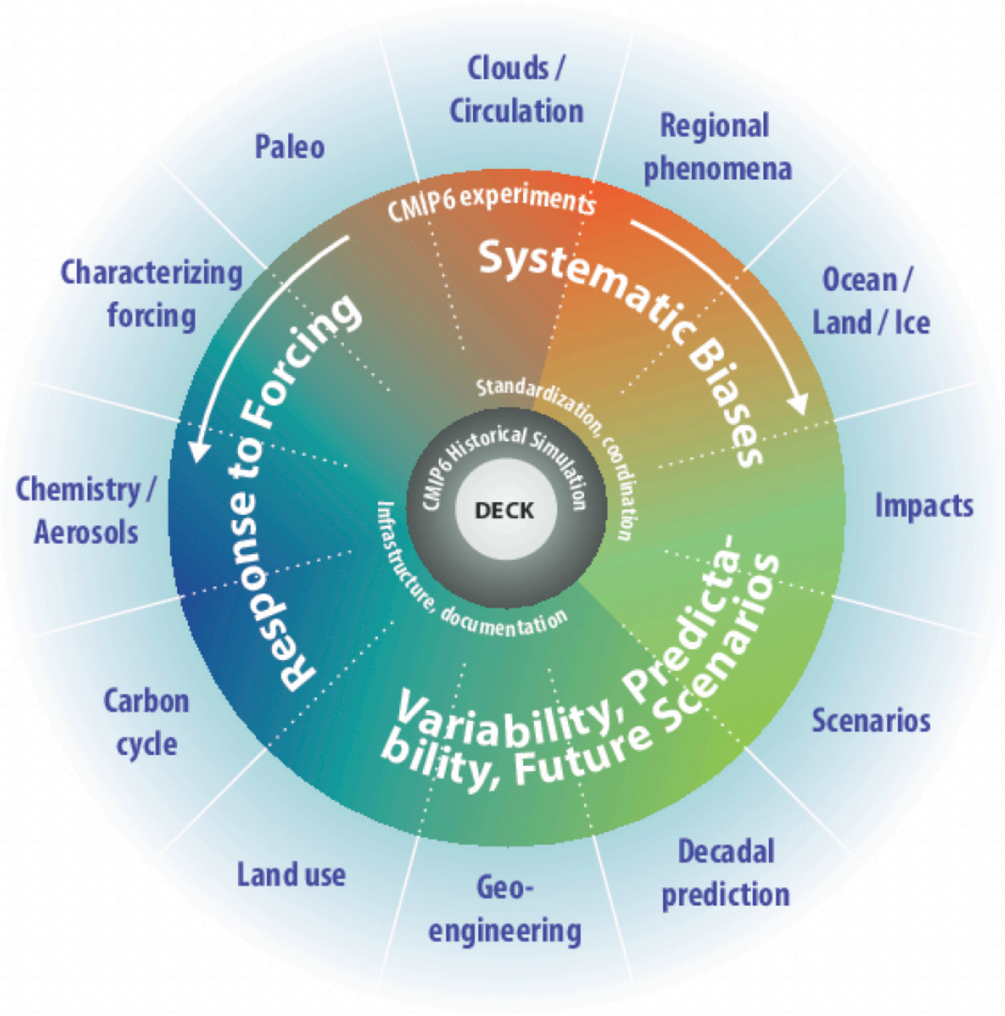






Climate Models



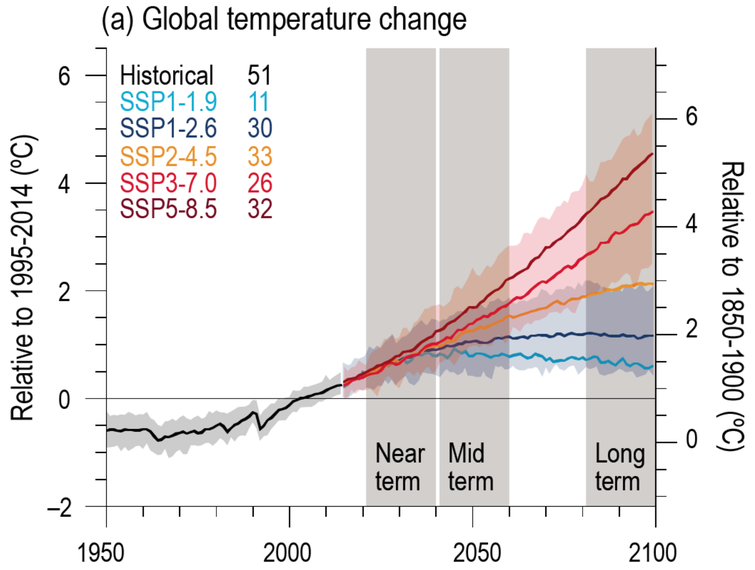


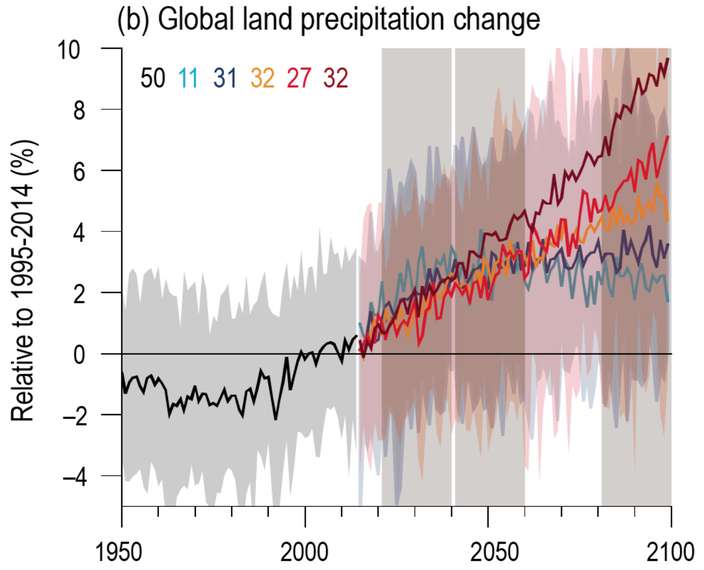
Typical horizontal resolution:
ocean, sea-ice: 0.5-1 degree
atmosphere, land: 1-2 degree

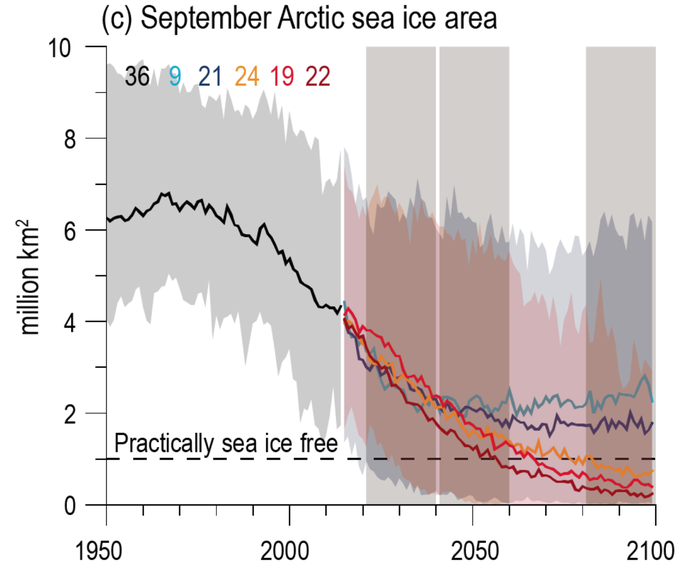
Eyring et al. (2016)

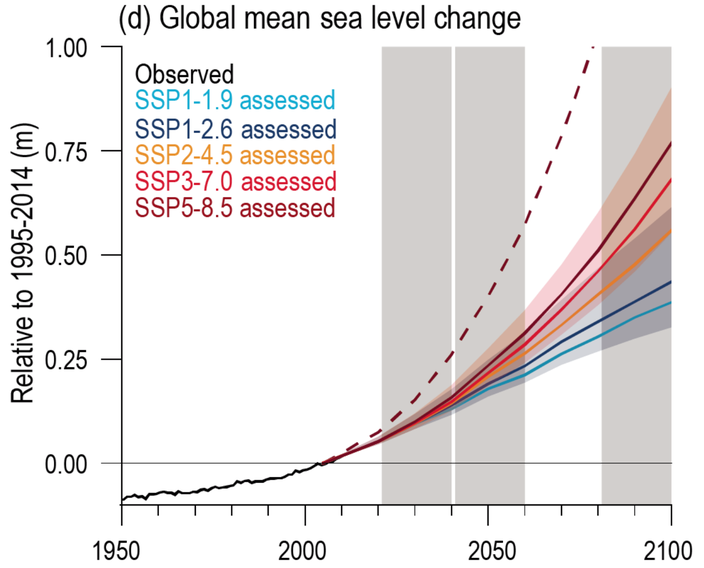
~ 20 modeling groups
~ 50 different models
Ensemble simulations

Future Climate Change









How warm is it going to be in 2100?

+1.5-5.5 C wrt pre-industrial

IPCC-AR6-WG1

Why worry about 'bumpy' future climate change?

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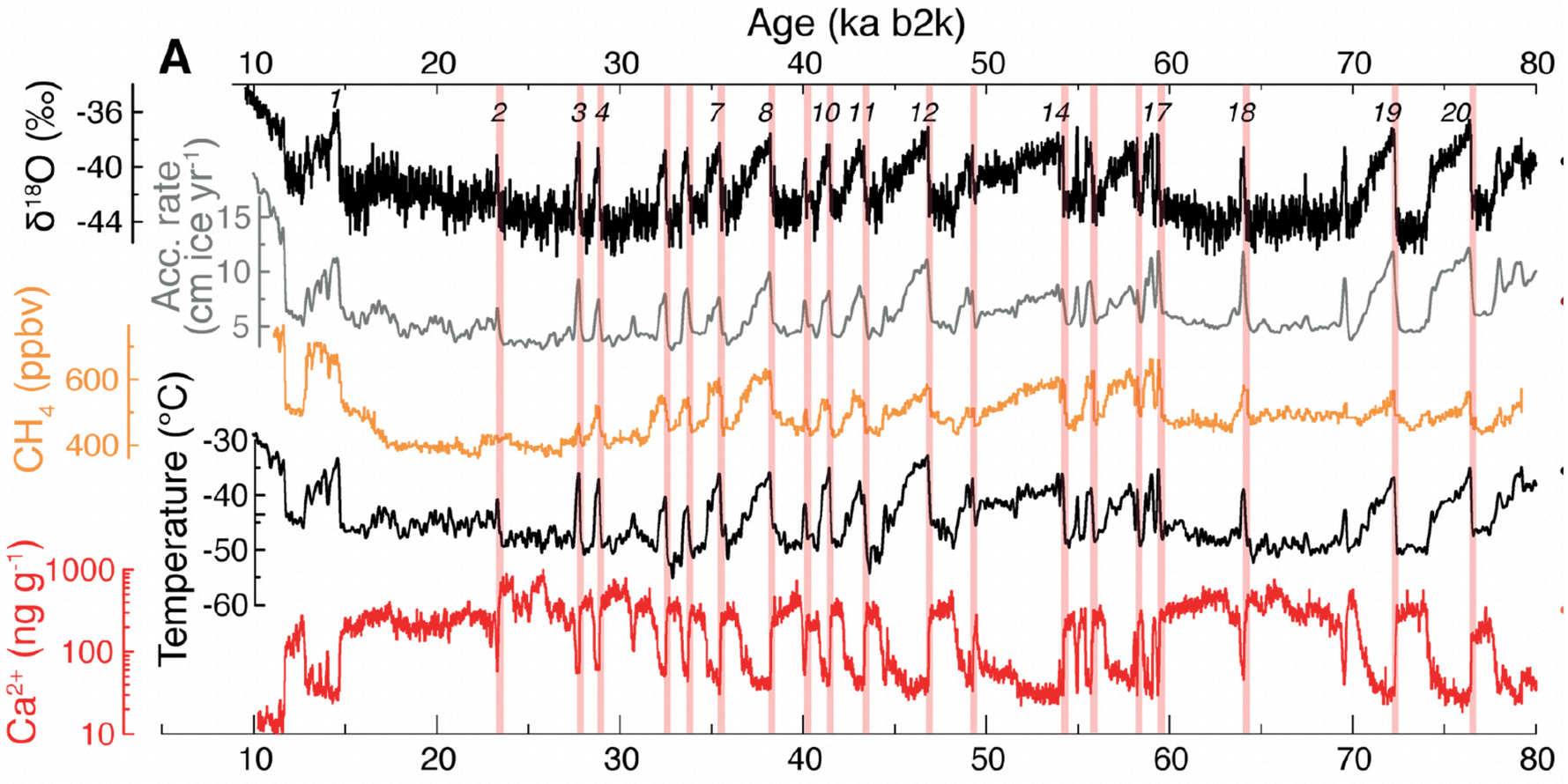
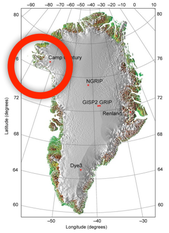
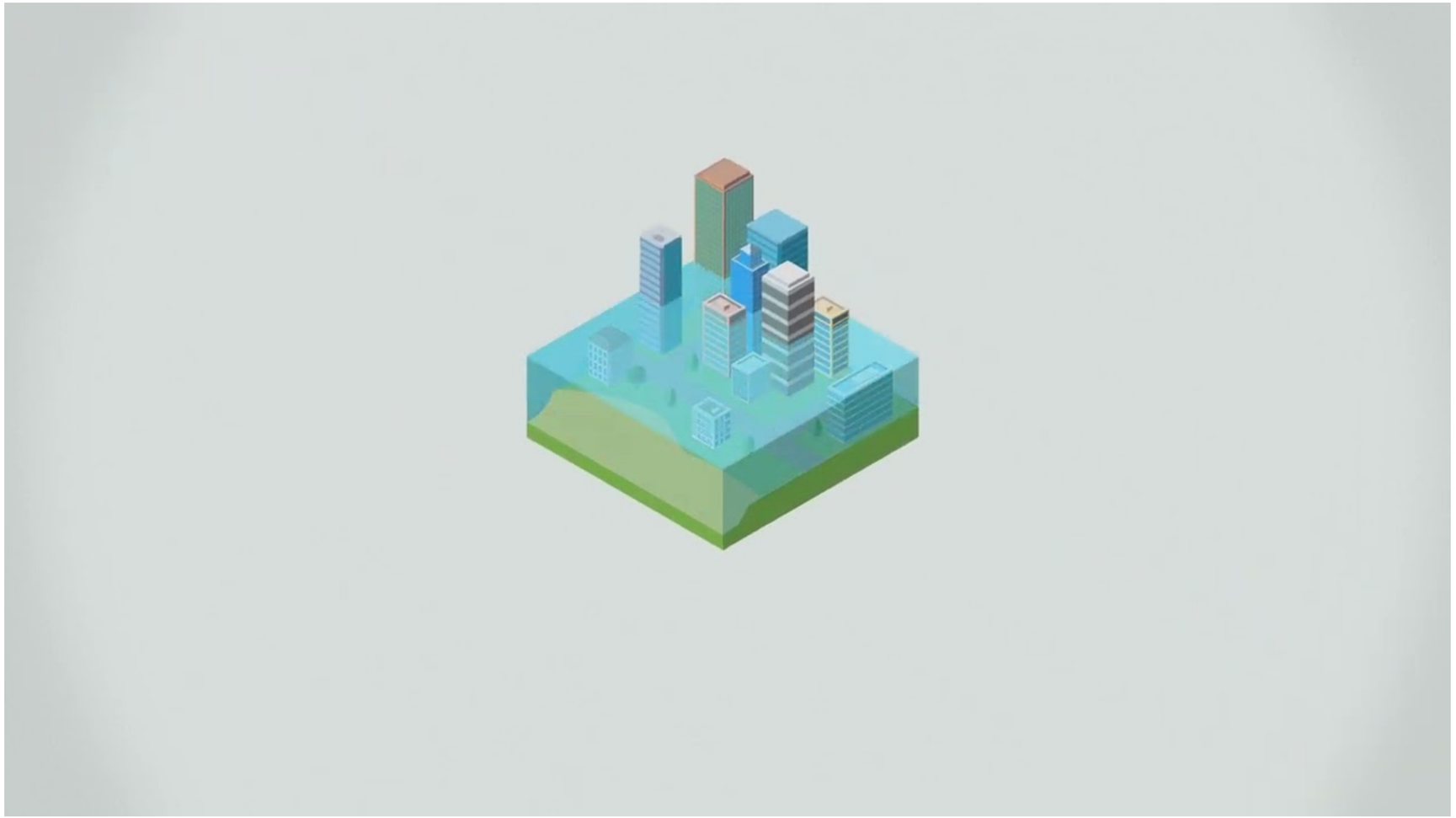
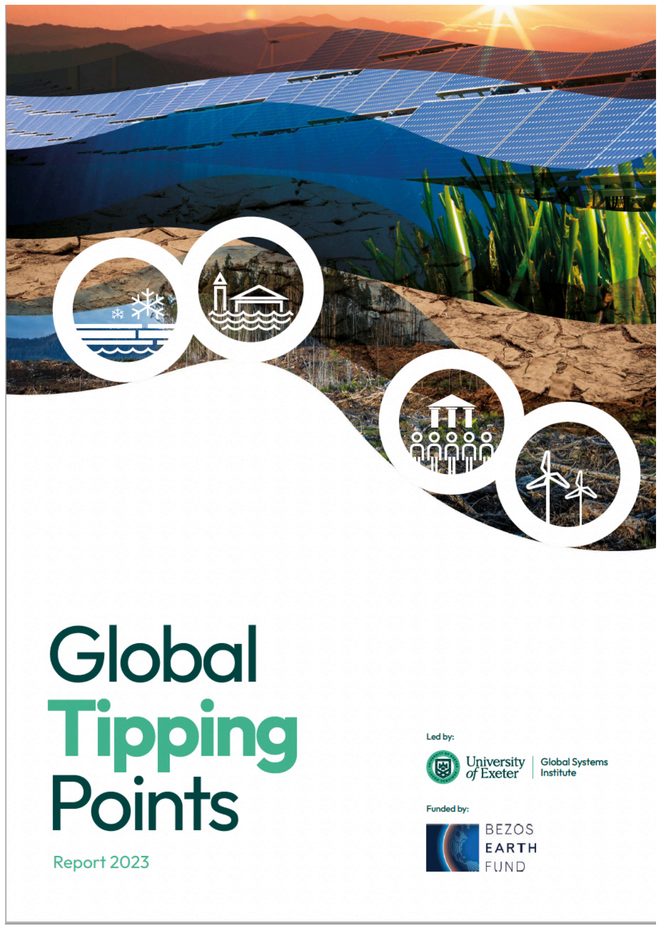


Proxy data
(geological past)



Tipping Behavior





Mathematical Basis of Tipping Behavior

Dynamical System: $$\frac{d\mathbf{x}}{dt} = \mathbf{f}(\mathbf{x}, t, \lambda)$$

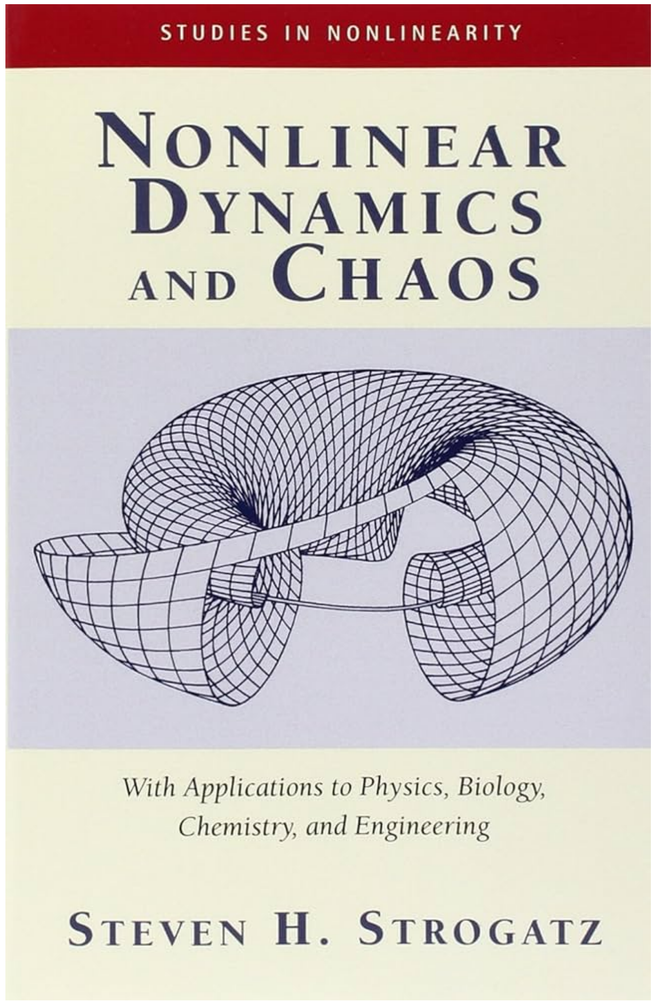
state vector $\mathbf{x} \in \mathbb{R}^d$; d : dimension

t : time λ : parameter

vector field $\mathbf{f}(\mathbf{x}, t, \lambda)$

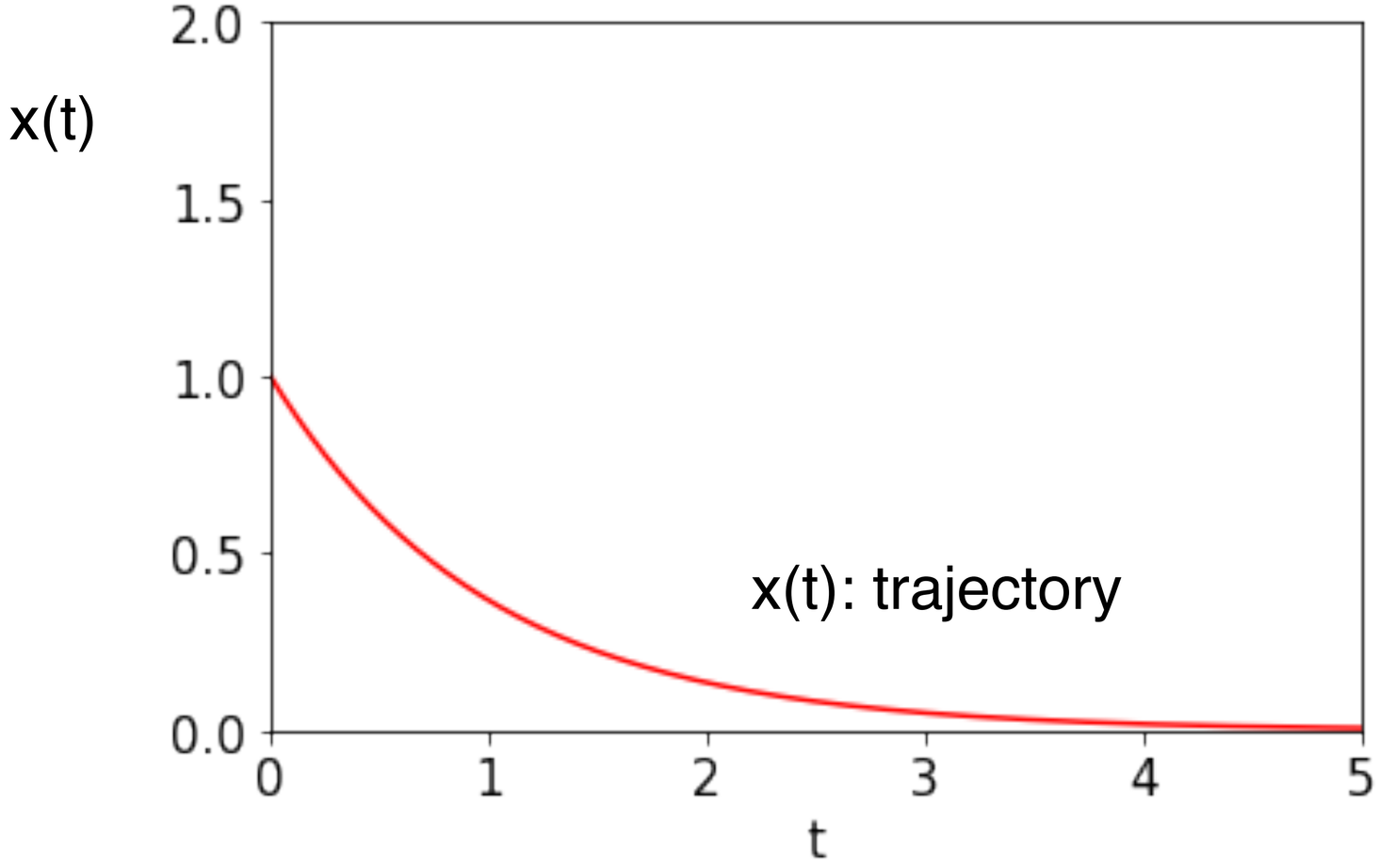
non-autonomous $\mathbf{f}(\mathbf{x}, t, \lambda)$

autonomous $\mathbf{f}(\mathbf{x}, \lambda)$



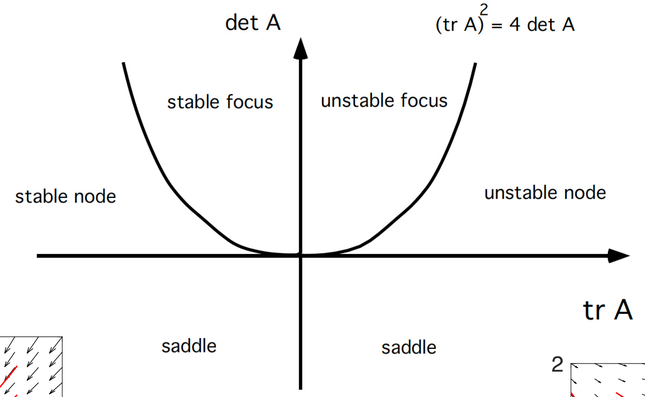
Example: linear system, d = 1

$$\frac{dx}{dt} = -x$$

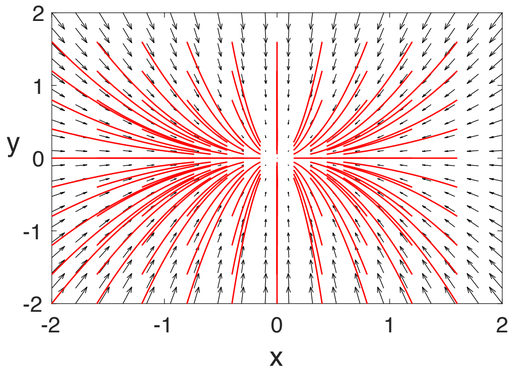


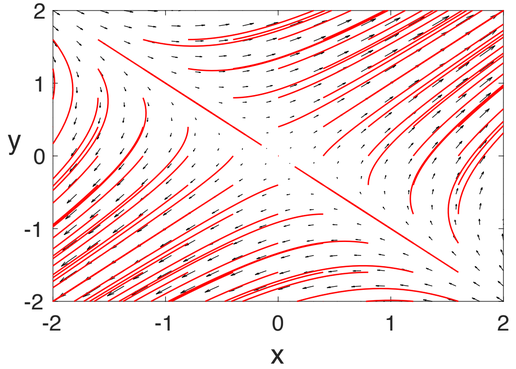
Example: linear systems, d = 2

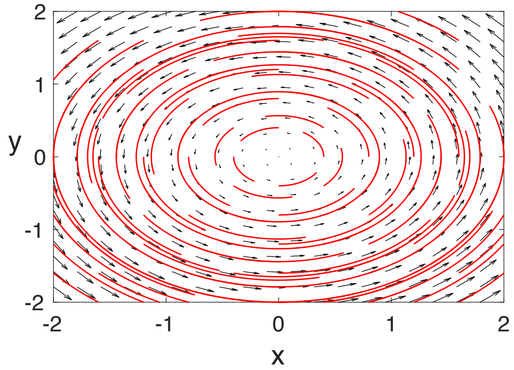
$$\frac{d\mathbf{x}}{dt} = A\mathbf{x}$$

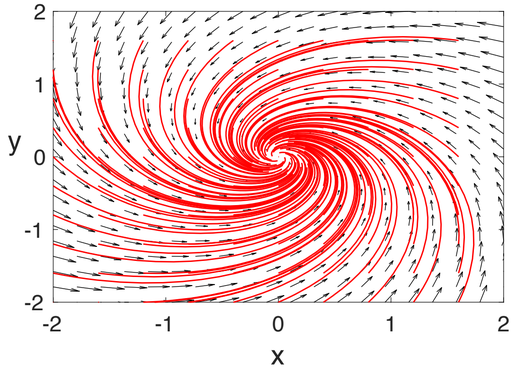


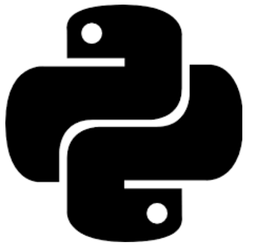
$$A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$





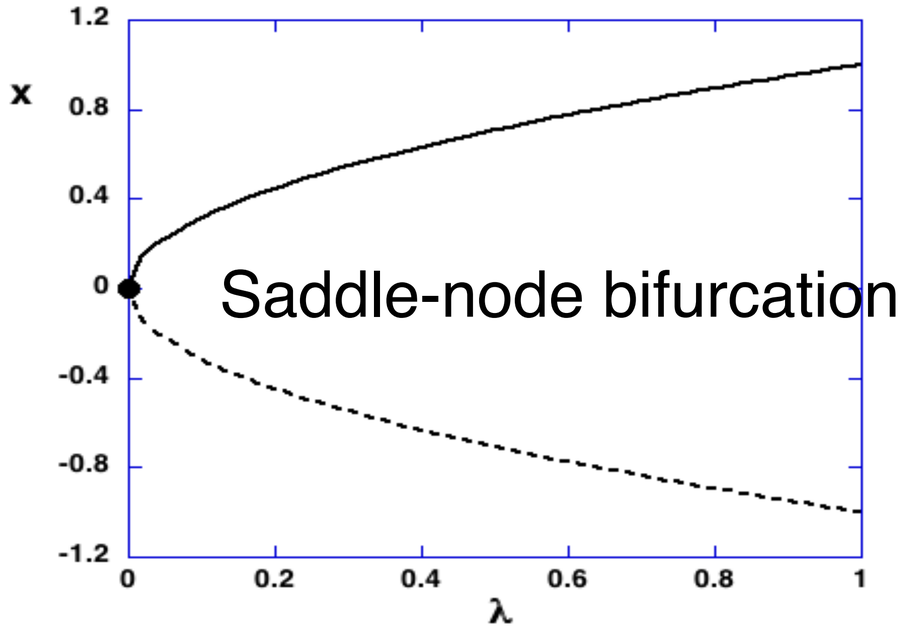




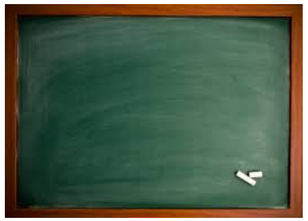


Example: nonlinear system, d = 1

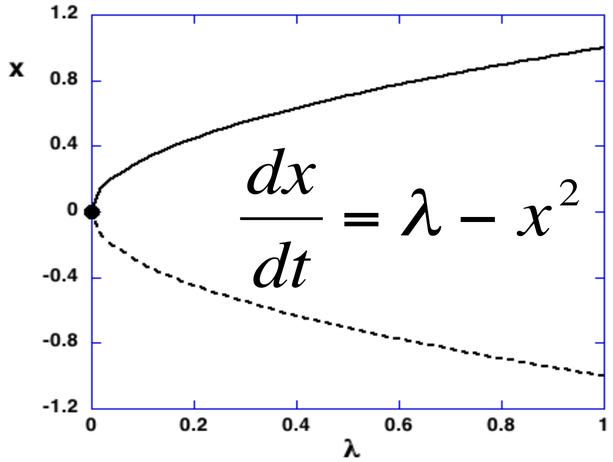
$$\frac{dx}{dt} = \lambda - x^2$$



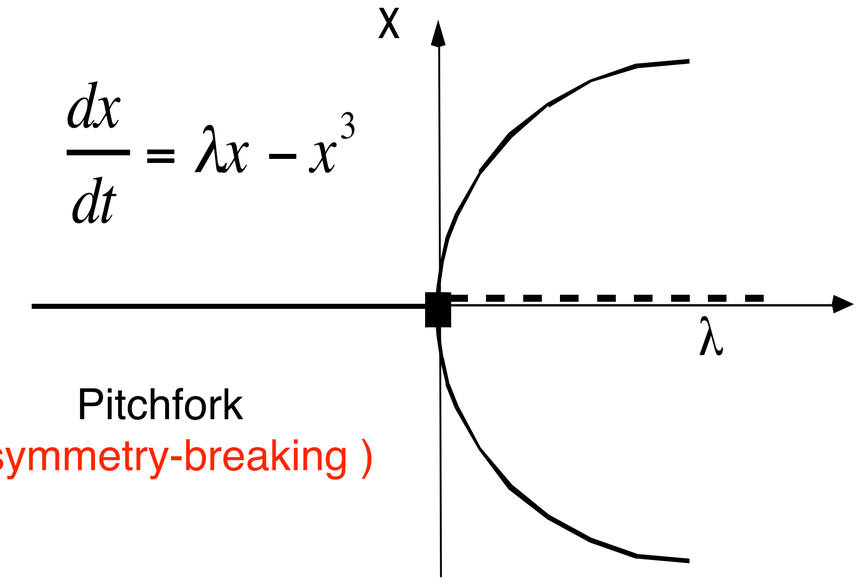
Saddle-node bifurcation



Elementary bifurcations, d = 1

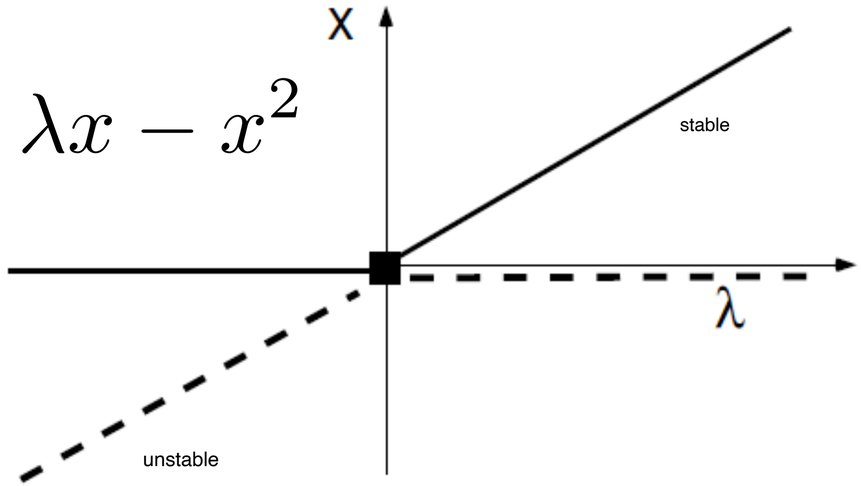


Saddle-node (non-existence)



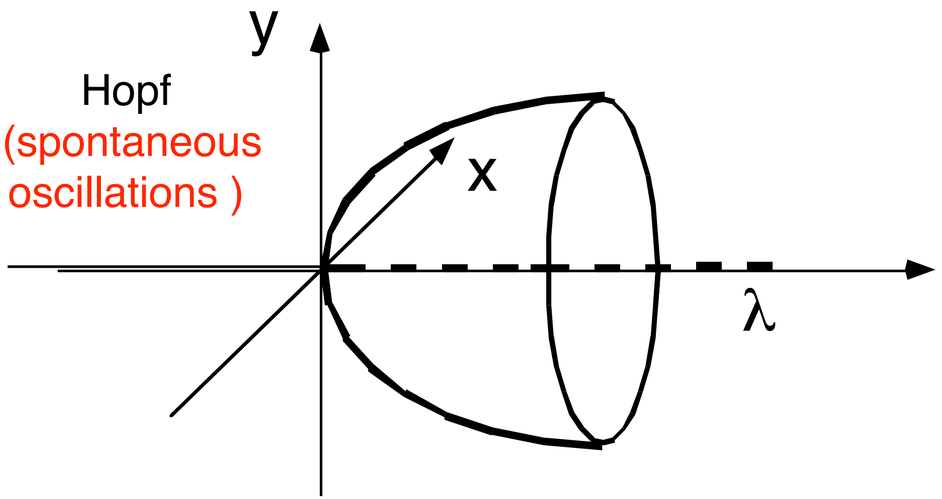
Pitchfork
(symmetry-breaking)

$$\frac{dx}{dt} = \lambda x - x^2$$



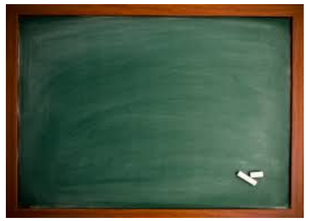
Transcritical (exchange of stability)

Elementary bifurcations, d = 2



$$\dot{x} = \lambda x - \omega y - x(x^2 + y^2)$$

$$\dot{y} = \lambda y + \omega x - y(x^2 + y^2)$$



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Exercises!