Placing our CCUS Work in Context: Lessons from Public Lectures

Jeff Reimer
UC Berkeley

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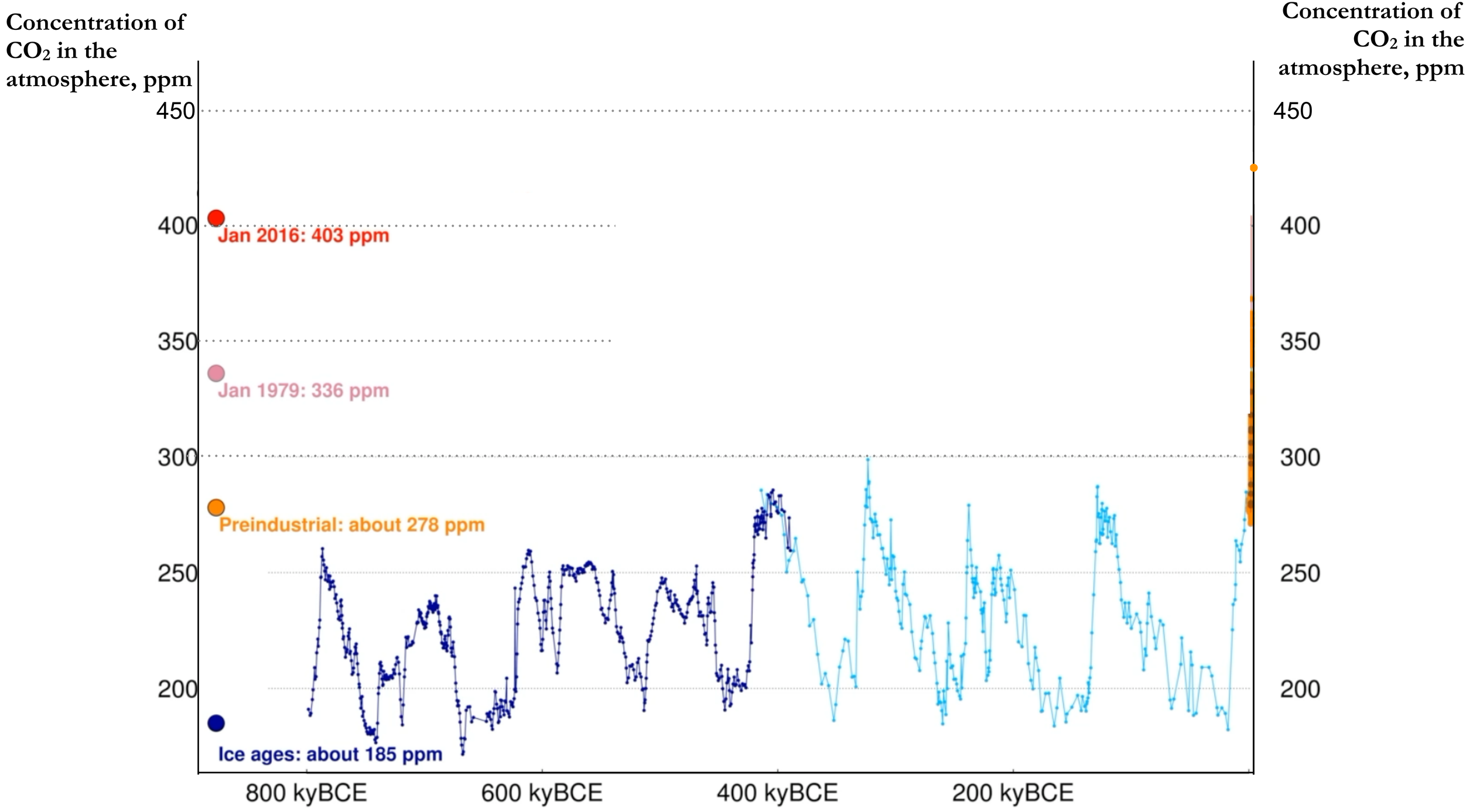
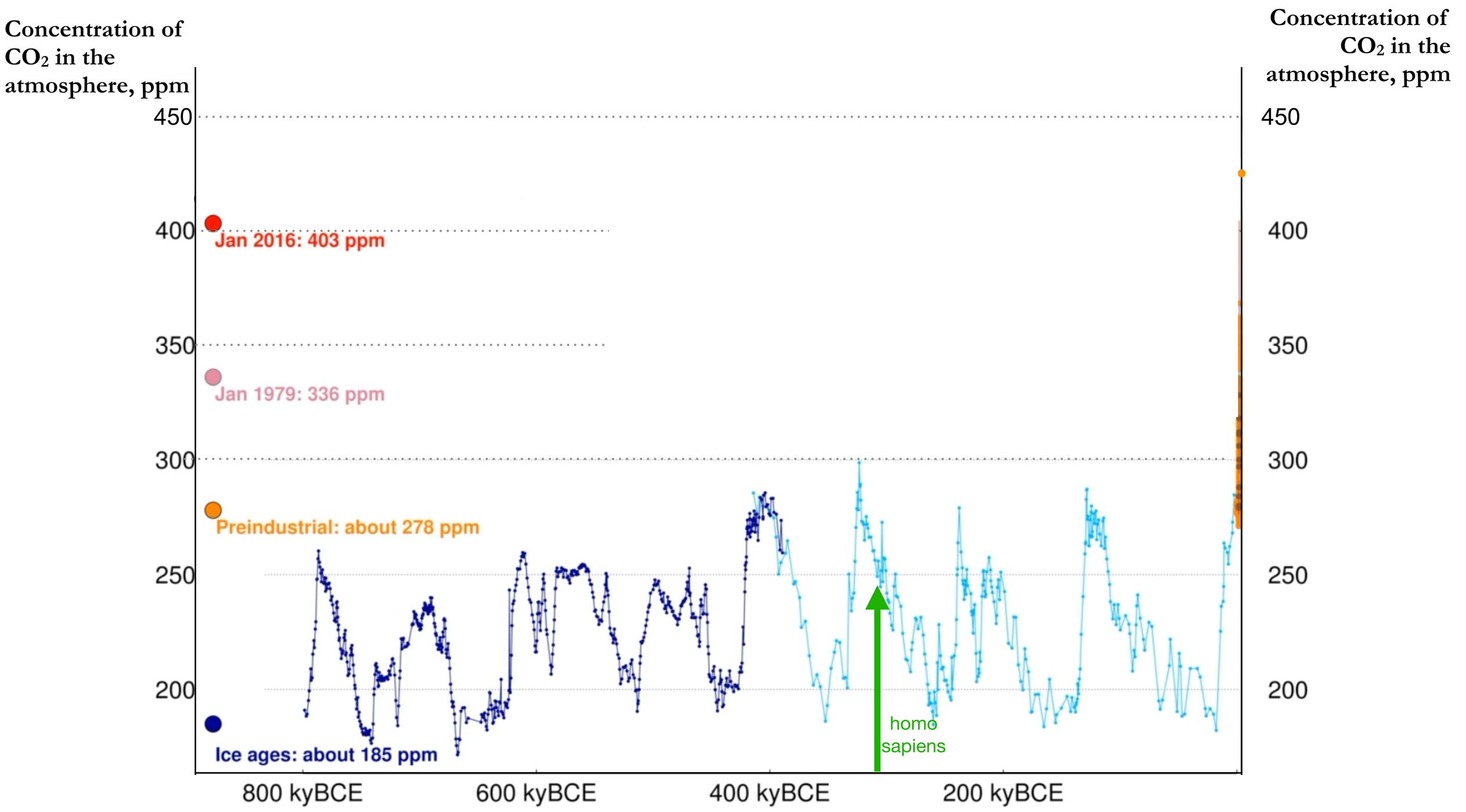


http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html



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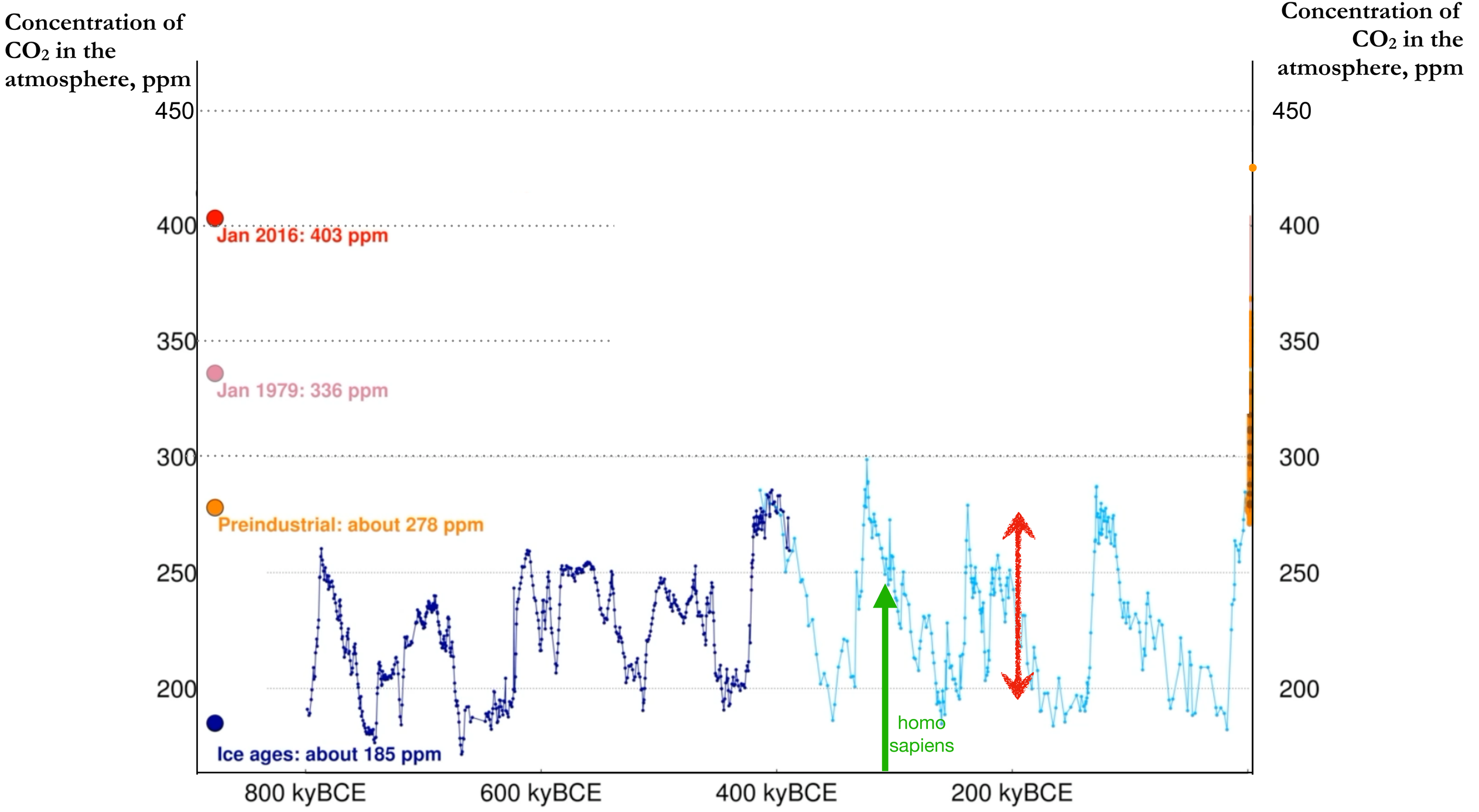

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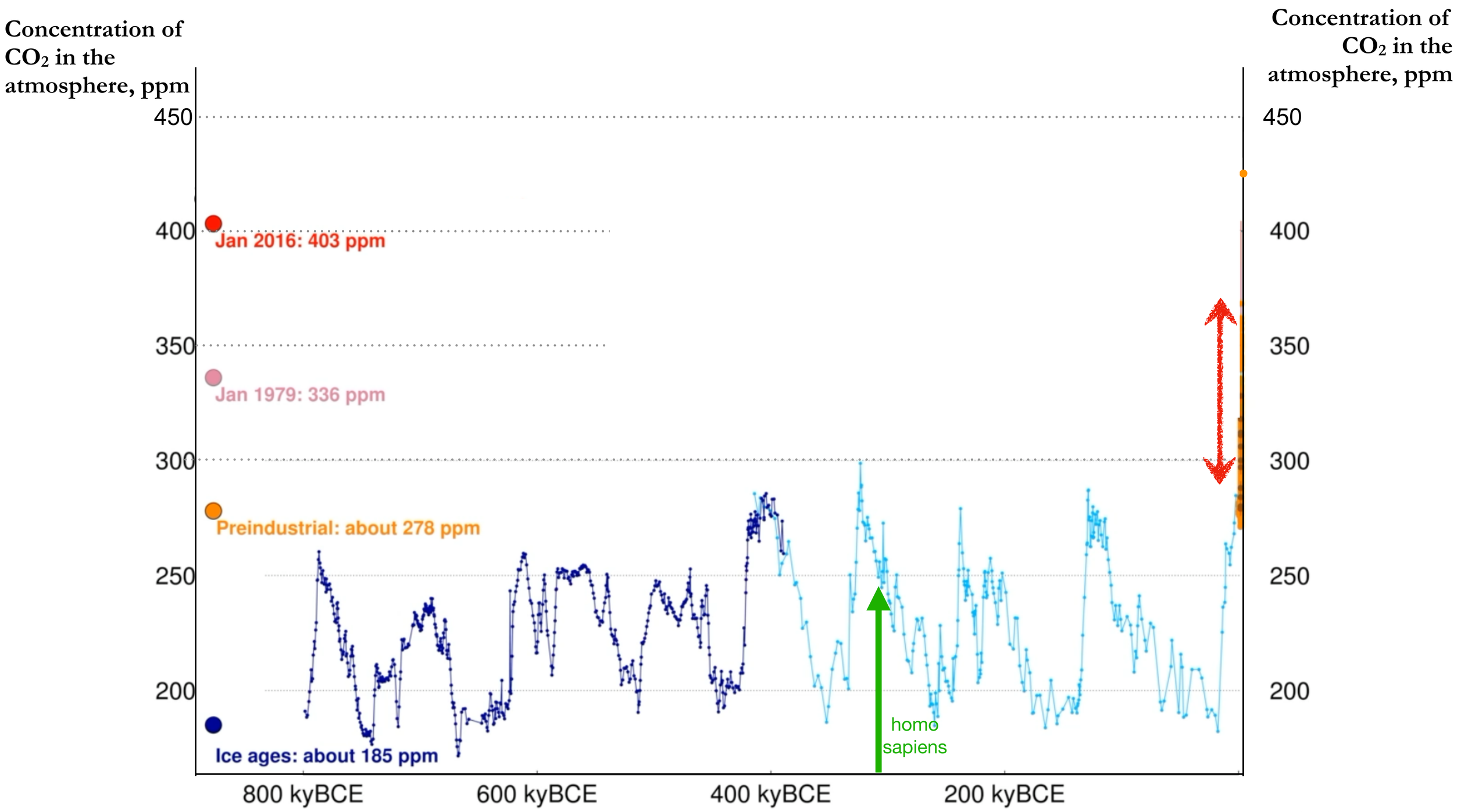

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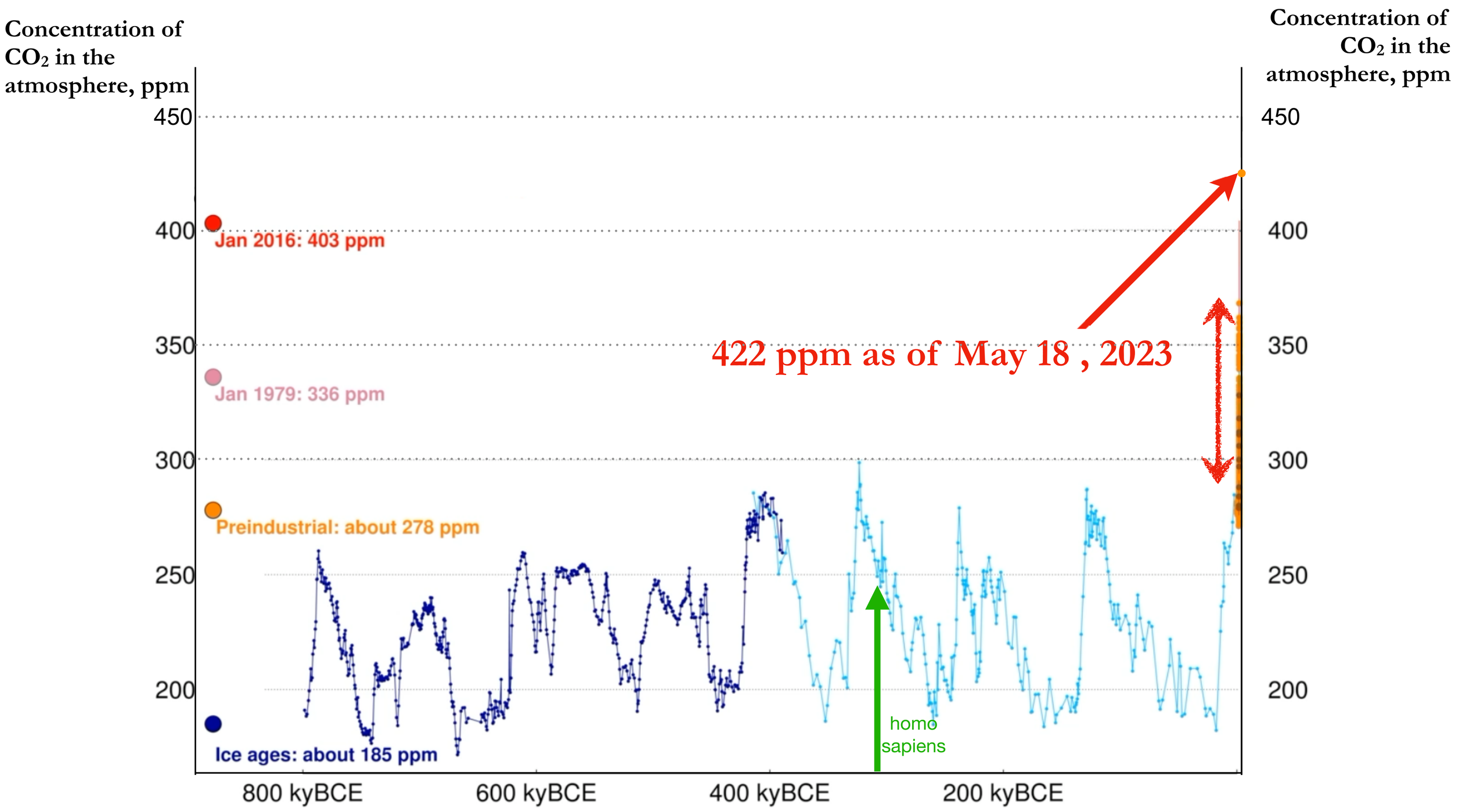


http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html

1400 million tons
of CO_2 emitted worldwide
from coal plants in 2017*

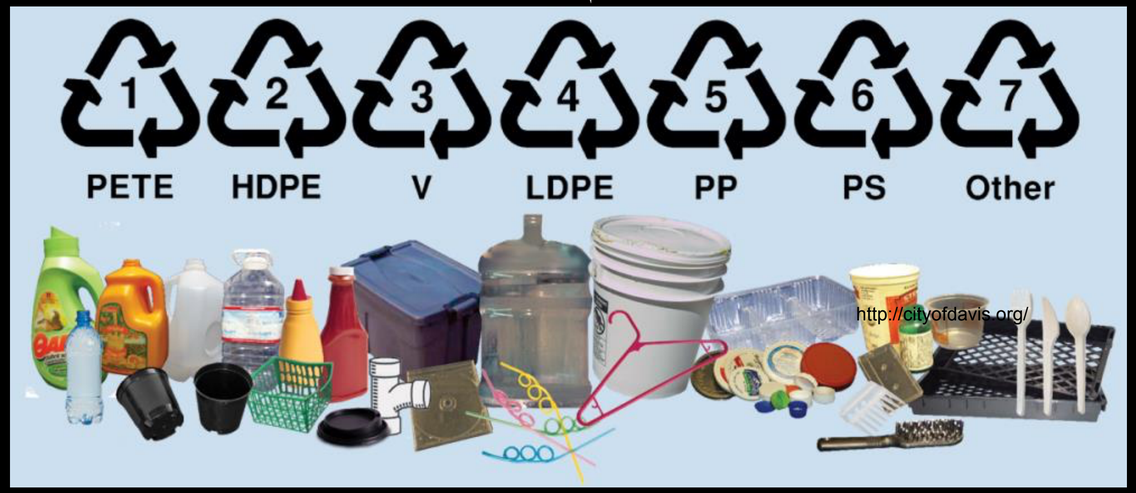
*USEIA

1400 million tons
of CO_2 emitted worldwide
from coal plants in 2017*

*USEIA

worldwide plastics
production in 2017:
344 million tons*

*Association of Plastics Manufacturers

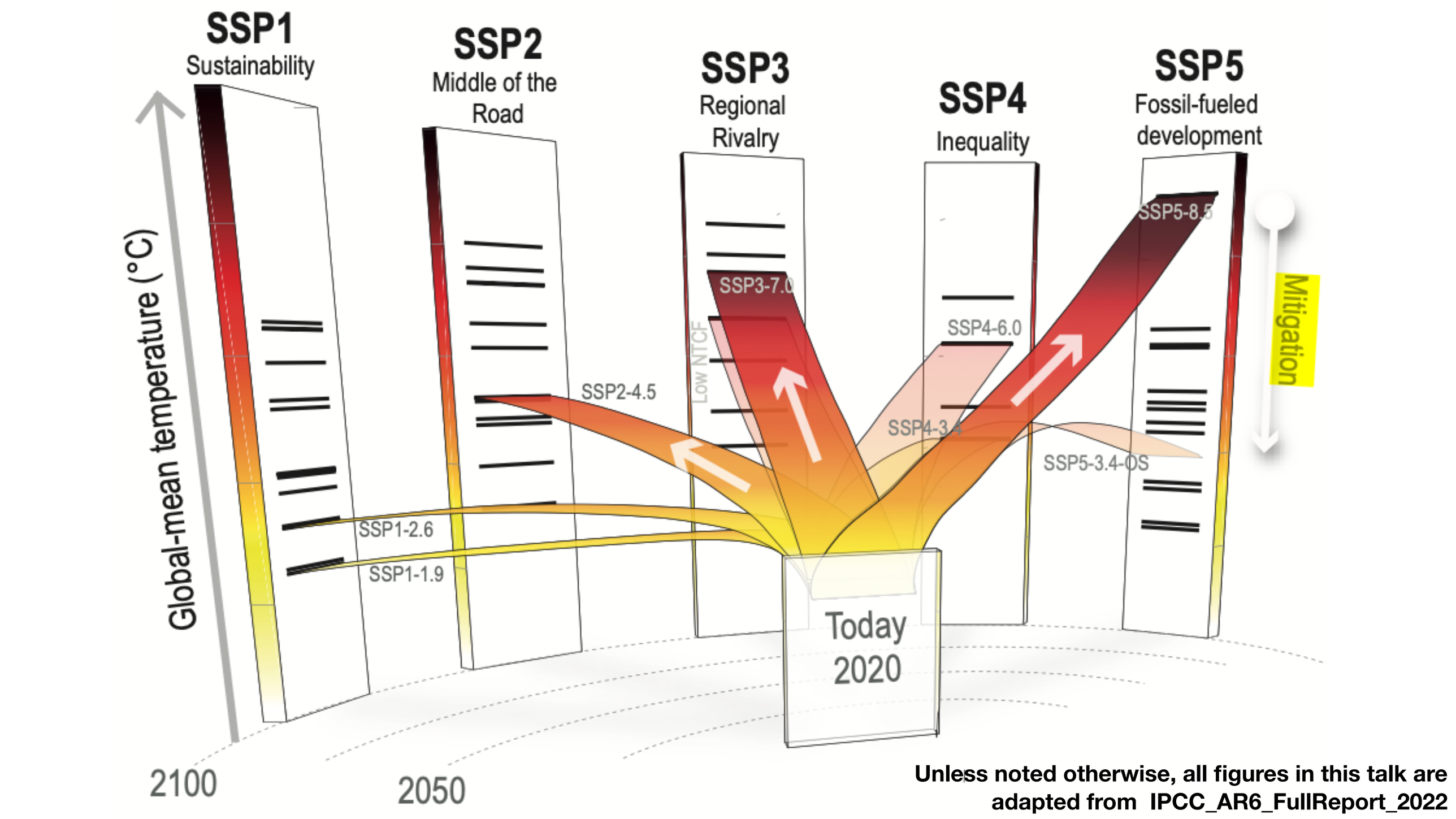



https://www.worldometers.info/
https://blog.ricksteves.com/blog/palio-crowds/


Mass of 8.10 billion people:
5.11 x 10^11 kilograms,
0.51 gigatons
https://www.worldometers.info/
https://blog.ricksteves.com/blog/palio-crowds/


Mass of 8.10 billion people:
5.11 x 10^11 kilograms,
0.51 gigatons
https://www.worldometers.info/
In 2021 humans emitted
36.4 gigatons of carbon
https://www.statista.com/statistics/276629/global-co2-emissions/
https://blog.ricksteves.com/blog/palio-crowds/

CO_2 in the future:
our choices



Unless noted otherwise, all figures in this talk are adapted from IPCC_AR6_FullReport_2022

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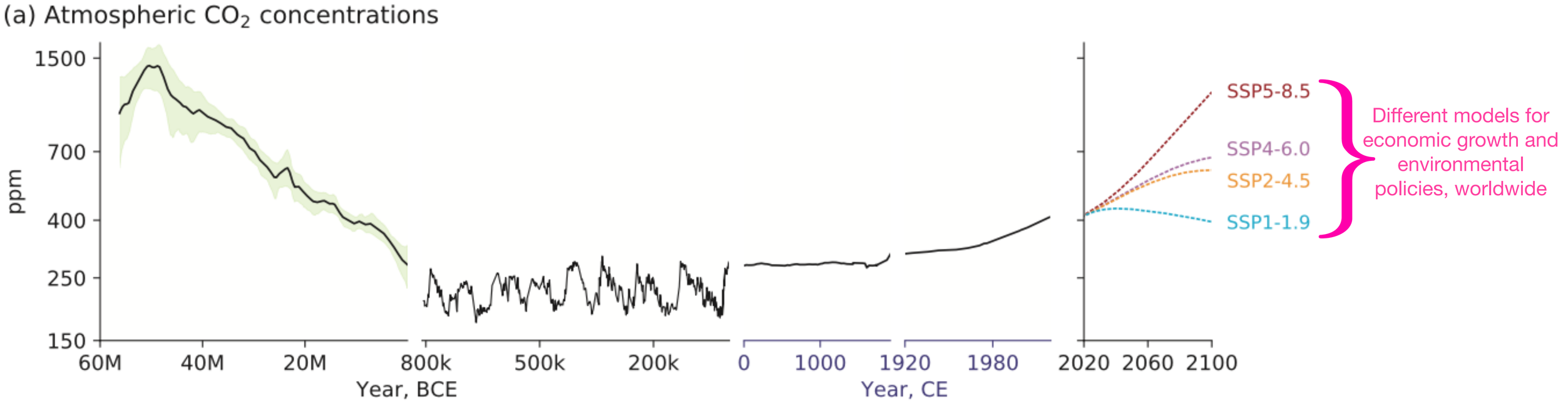
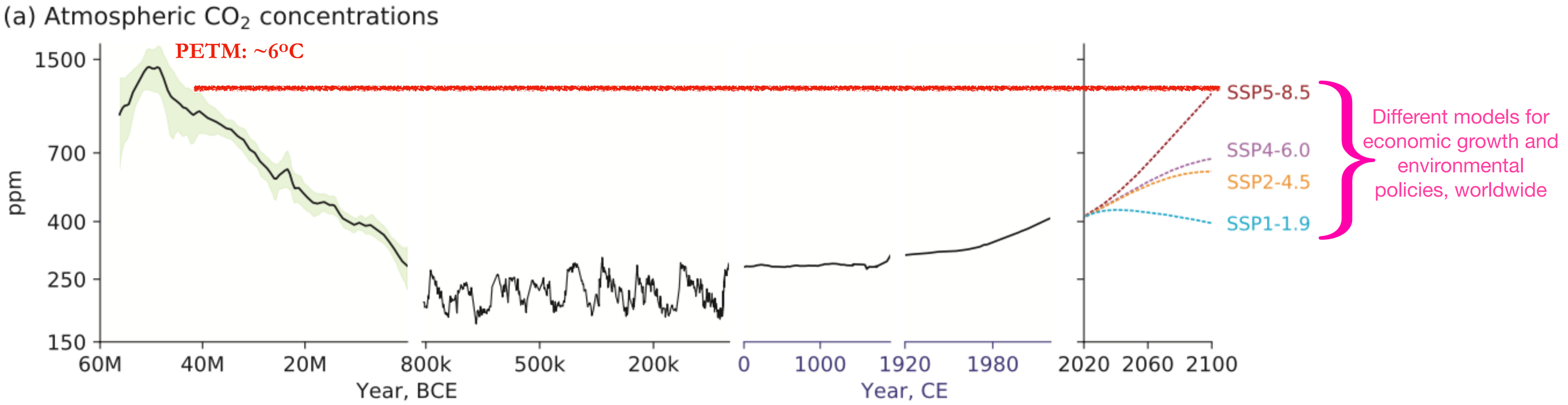

(a) Atmospheric CO_2 concentrations
1500
700
400
250
150
ppm
60M
40M
20M
800k
500k
200k
0
1000
1920
1980
2020
2060
2100
Year, BCE
Year, CE
SSP5-8.5
SSP4-6.0
SSP2-4.5
SSP1-1.9
Different models for economic growth and environmental policies, worldwide


(a) Atmospheric CO_2 concentrations
PETM: ~6ºC
1500
700
400
250
150
ppm
60M
40M
20M
800k
500k
200k
0
1000
1920
1980
2020
2060
2100
Year, BCE
Year, CE
SSP5-8.5
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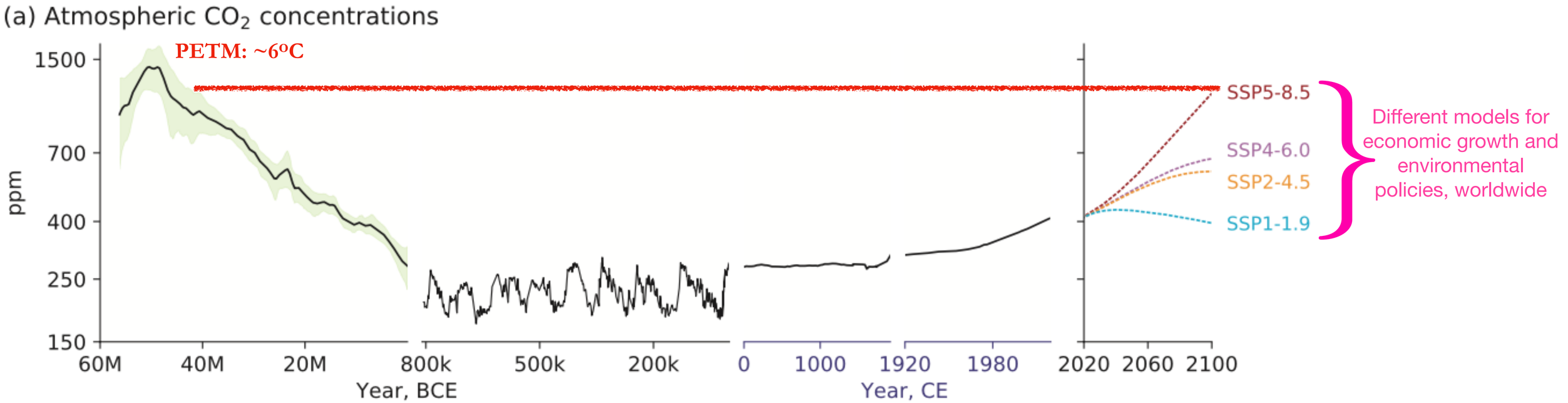
Different models for economic growth and environmental policies, worldwide


(a) Atmospheric CO_2 concentrations
PETM: ~6°C
1500
700
400
250
150
ppm
60M
40M
20M
800k
500k
200k
0
1000
1920
1980
2020
2060
2100
Year, BCE
Year, CE
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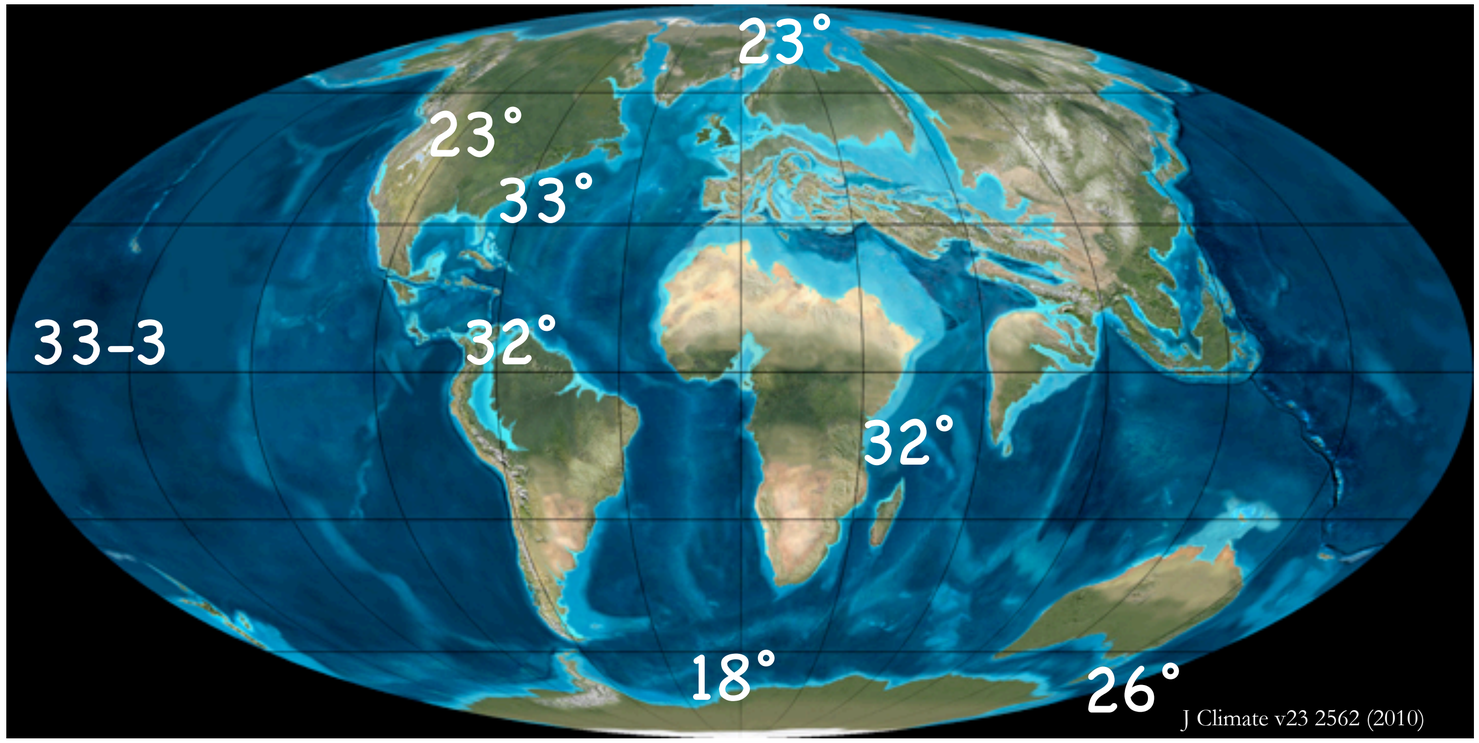
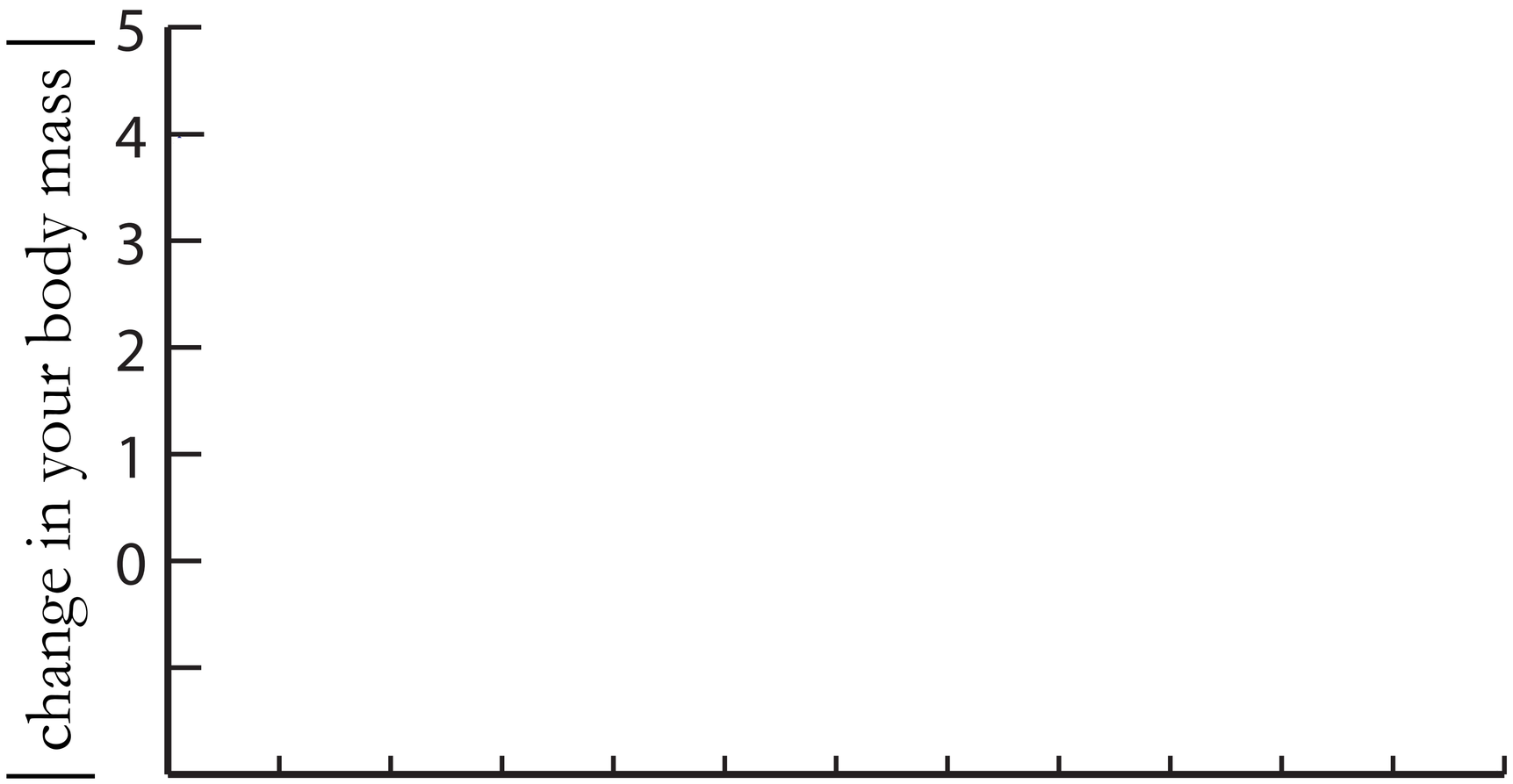
Different models for economic growth and environmental policies, worldwide


23°
23°
33°
33–3
32°
32°
18°
26°
J Climate v23 2562 (2010)

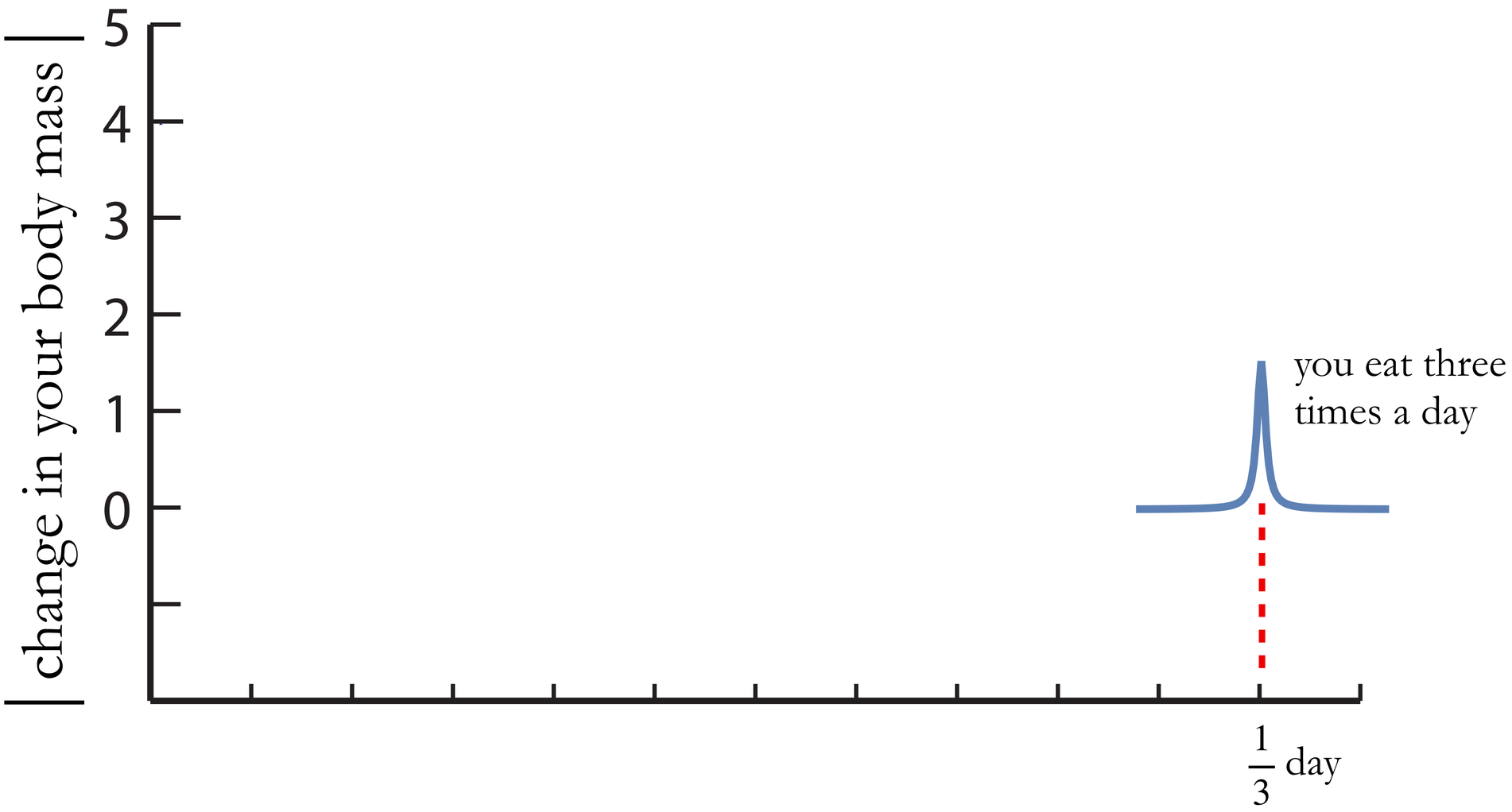
How does the Earth cope with CO_2?

“variance spectrum for your body mass”

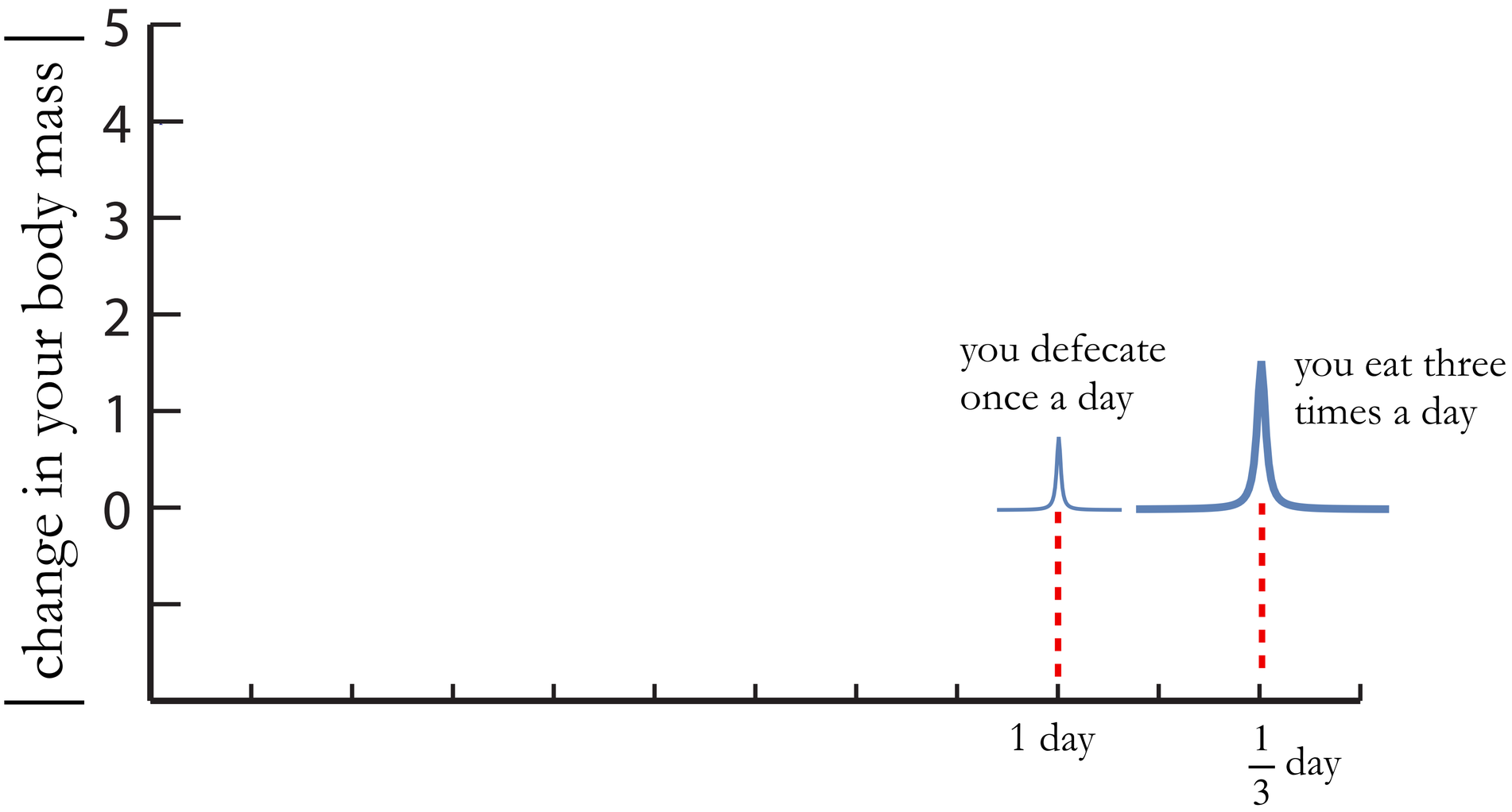


timescale of the event

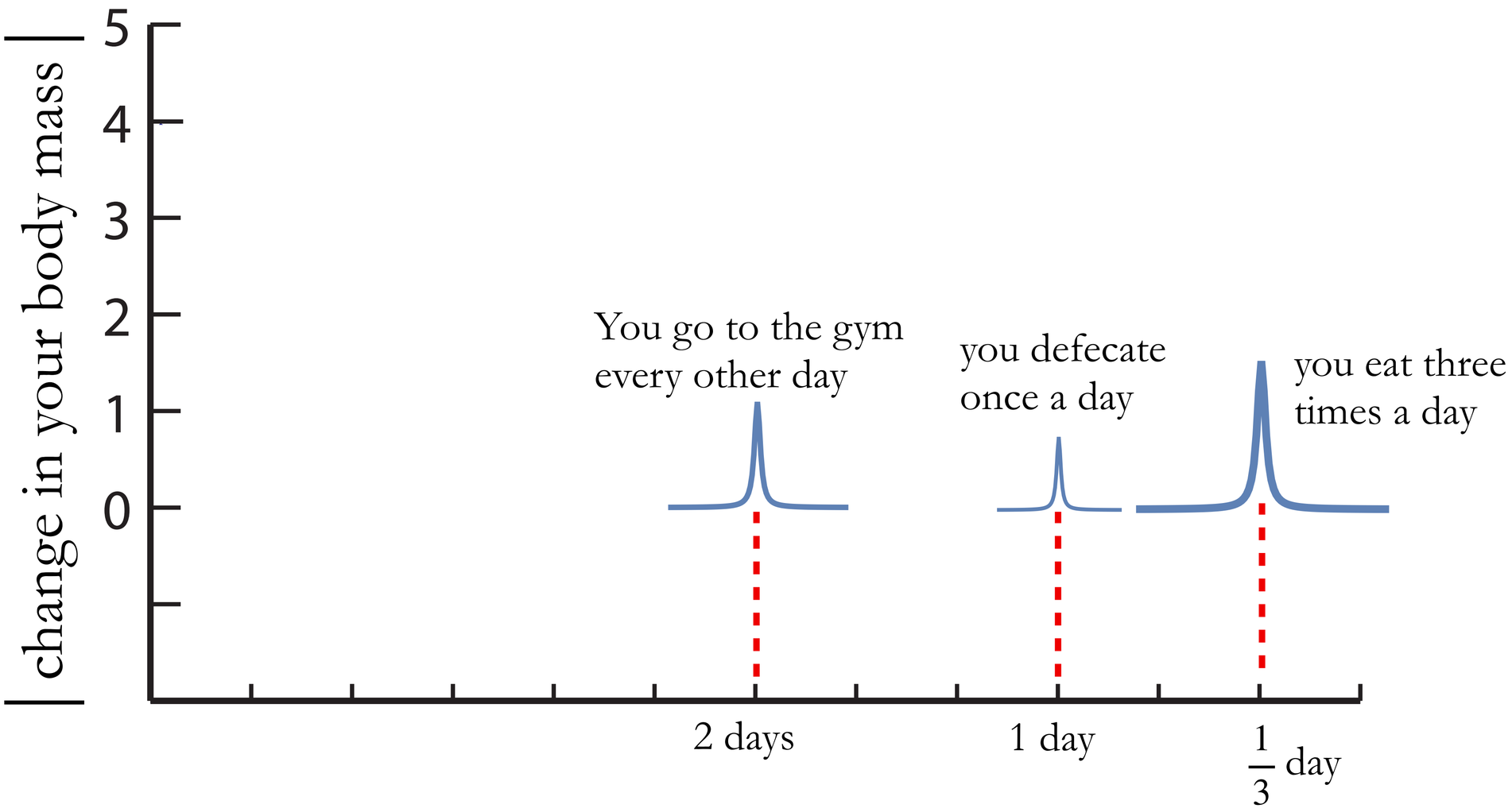
“variance spectrum for your body mass”



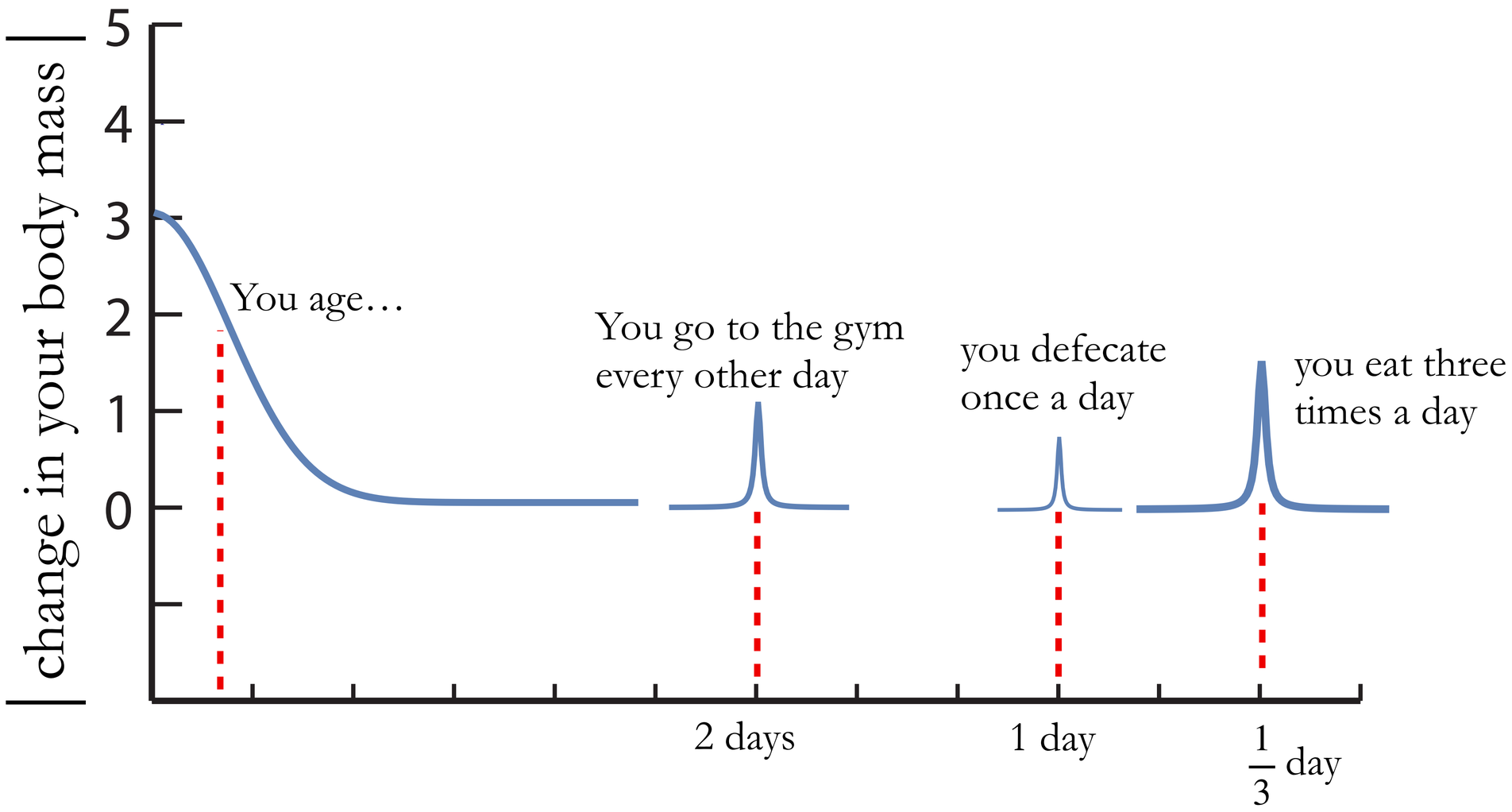
“variance spectrum for your body mass”



“variance spectrum for your body mass”

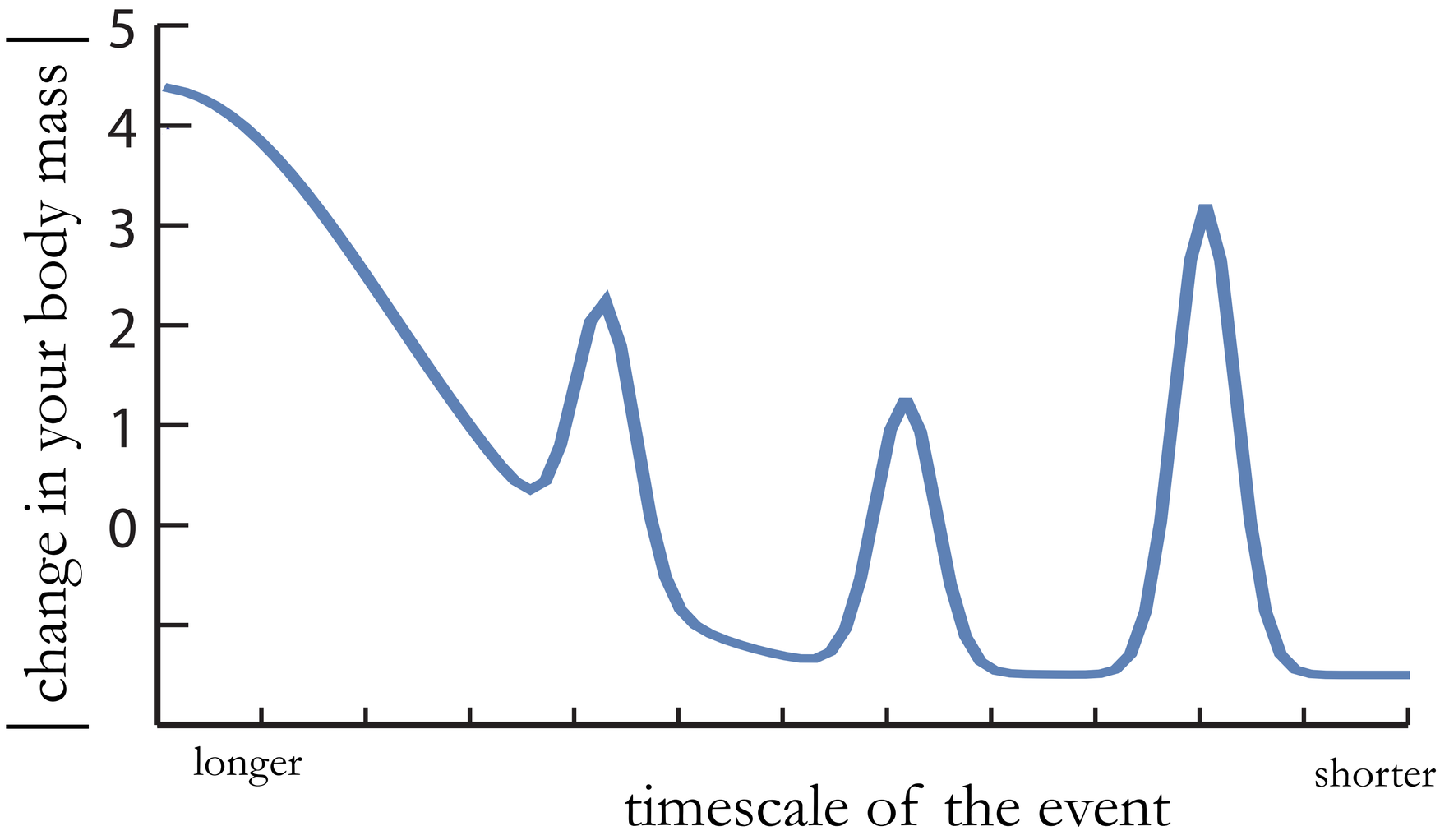


“variance spectrum for your body mass”

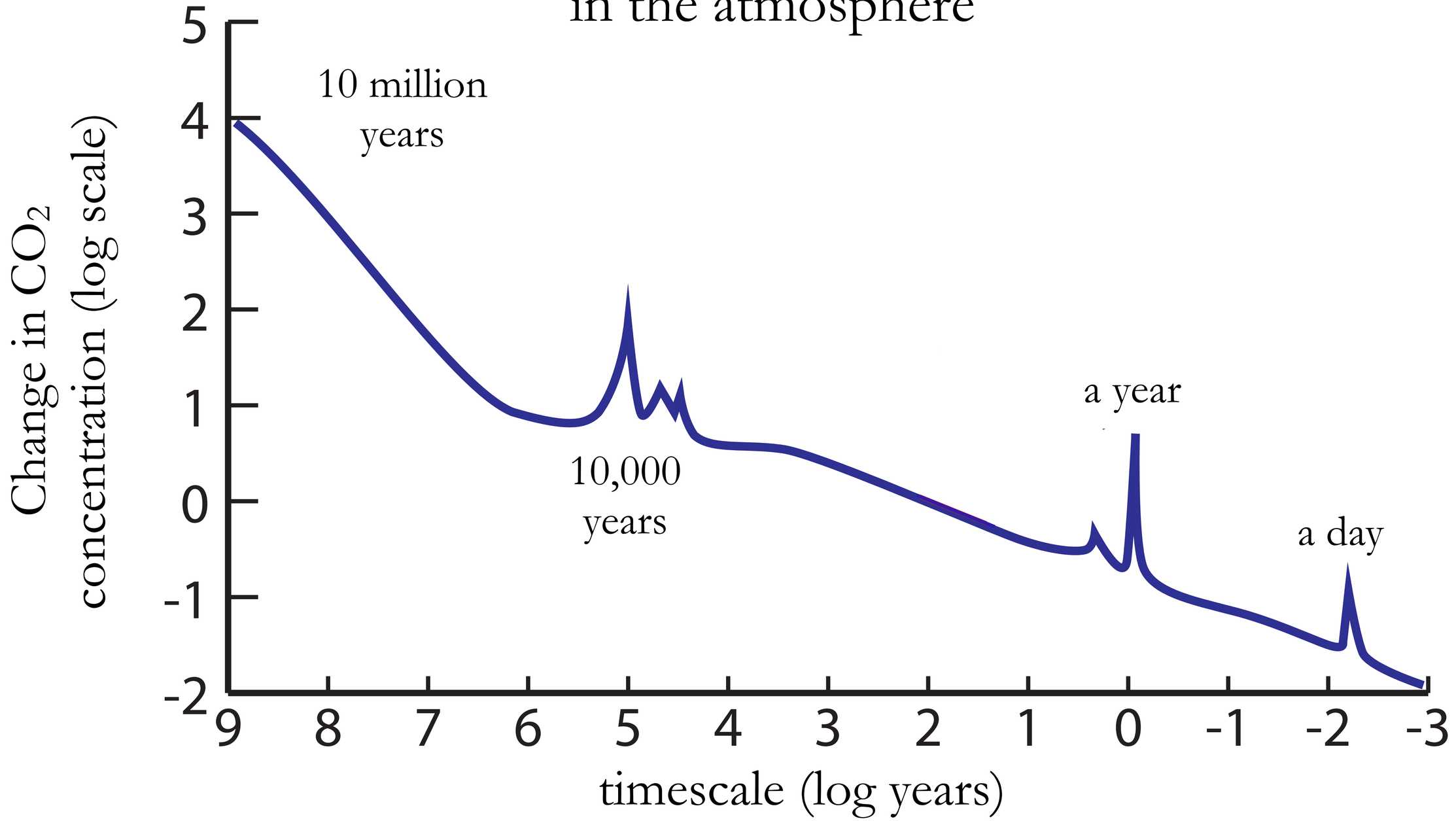


timescale of the event

variance spectrum for human body mass



variance "spectrum" for the fluctuations of the CO_2 levels in the atmosphere



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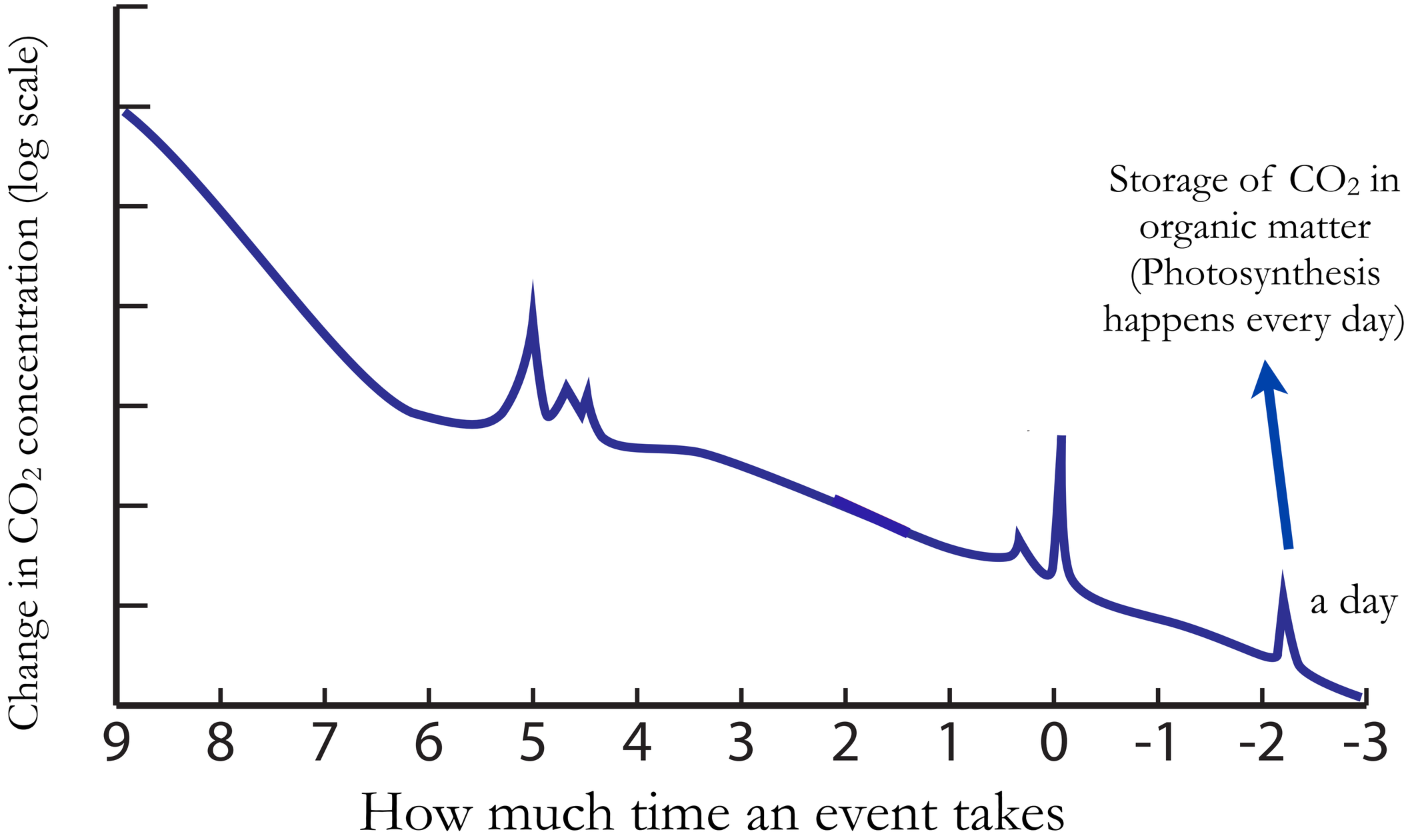
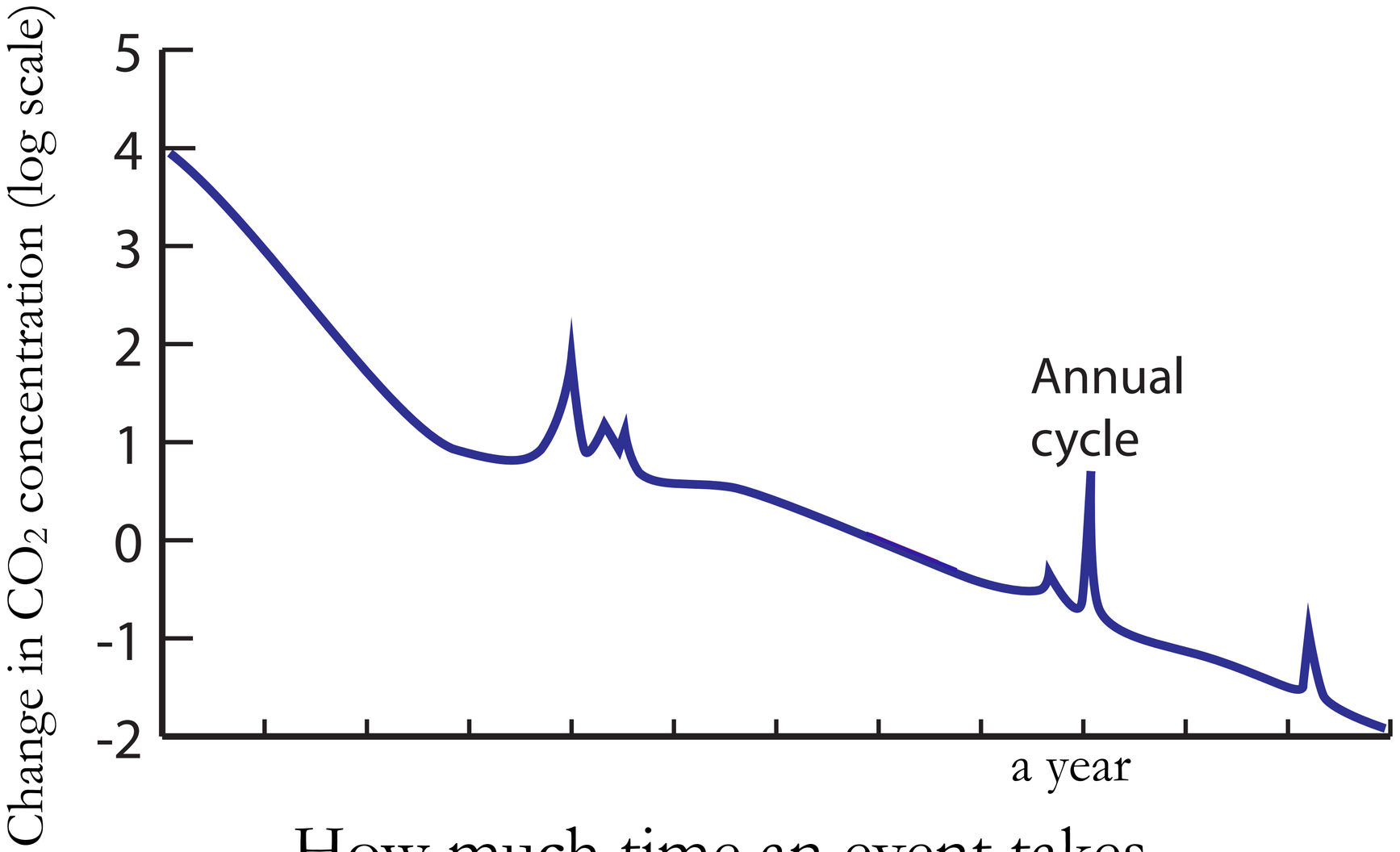
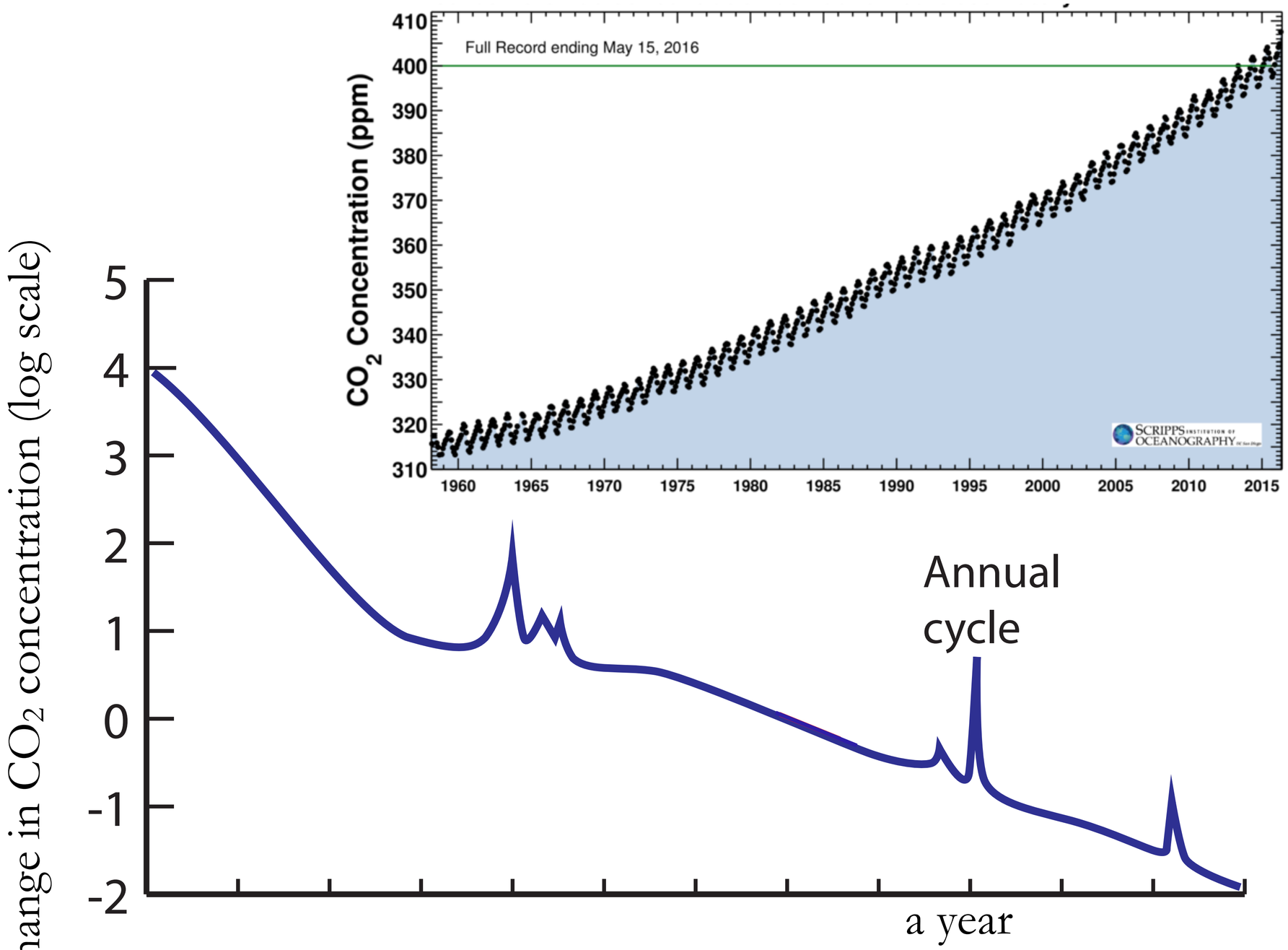
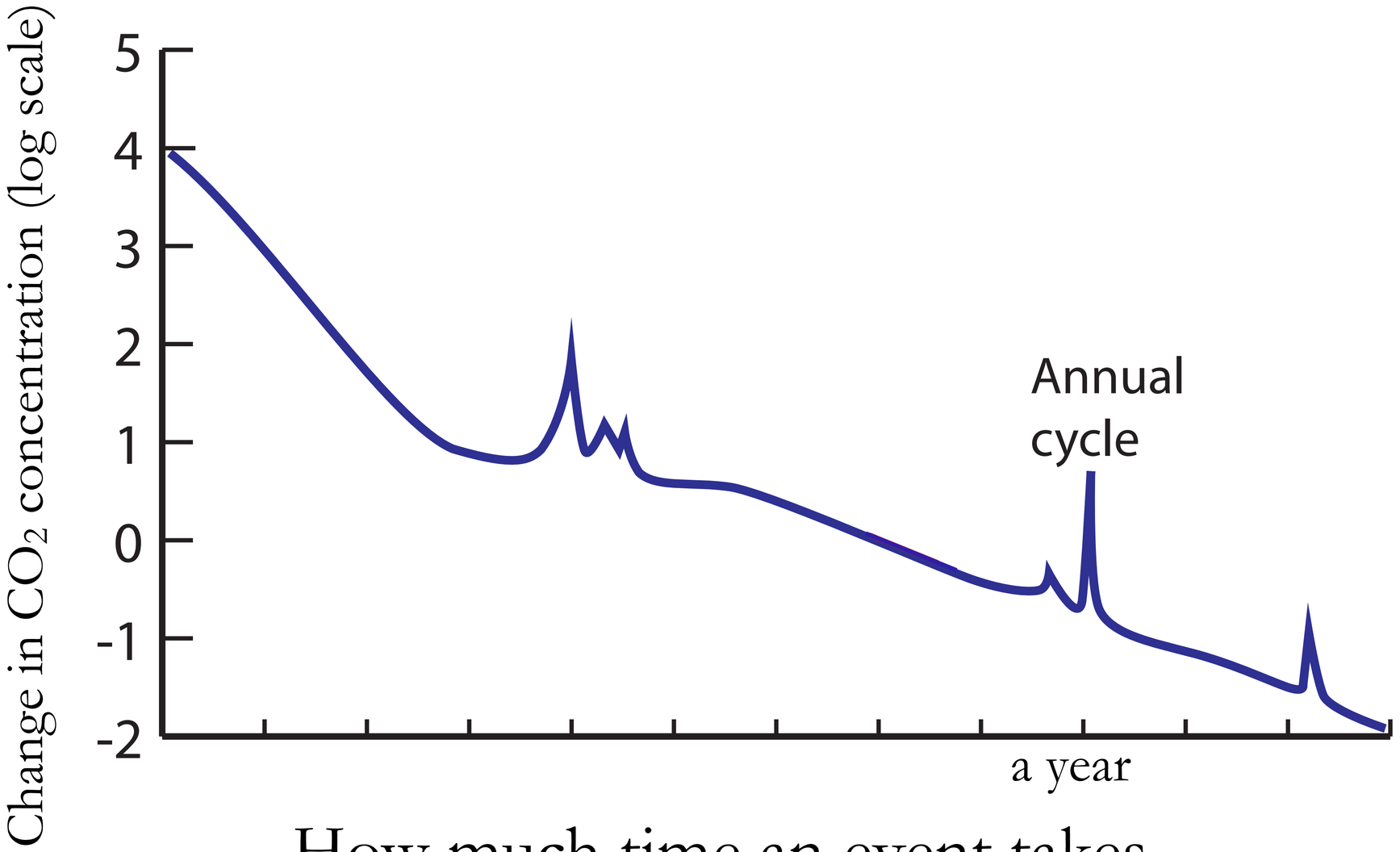

Change in CO_2 concentration (log scale)
Storage of CO_2 in organic matter (Photosynthesis happens every day)
a day
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
How much time an event takes



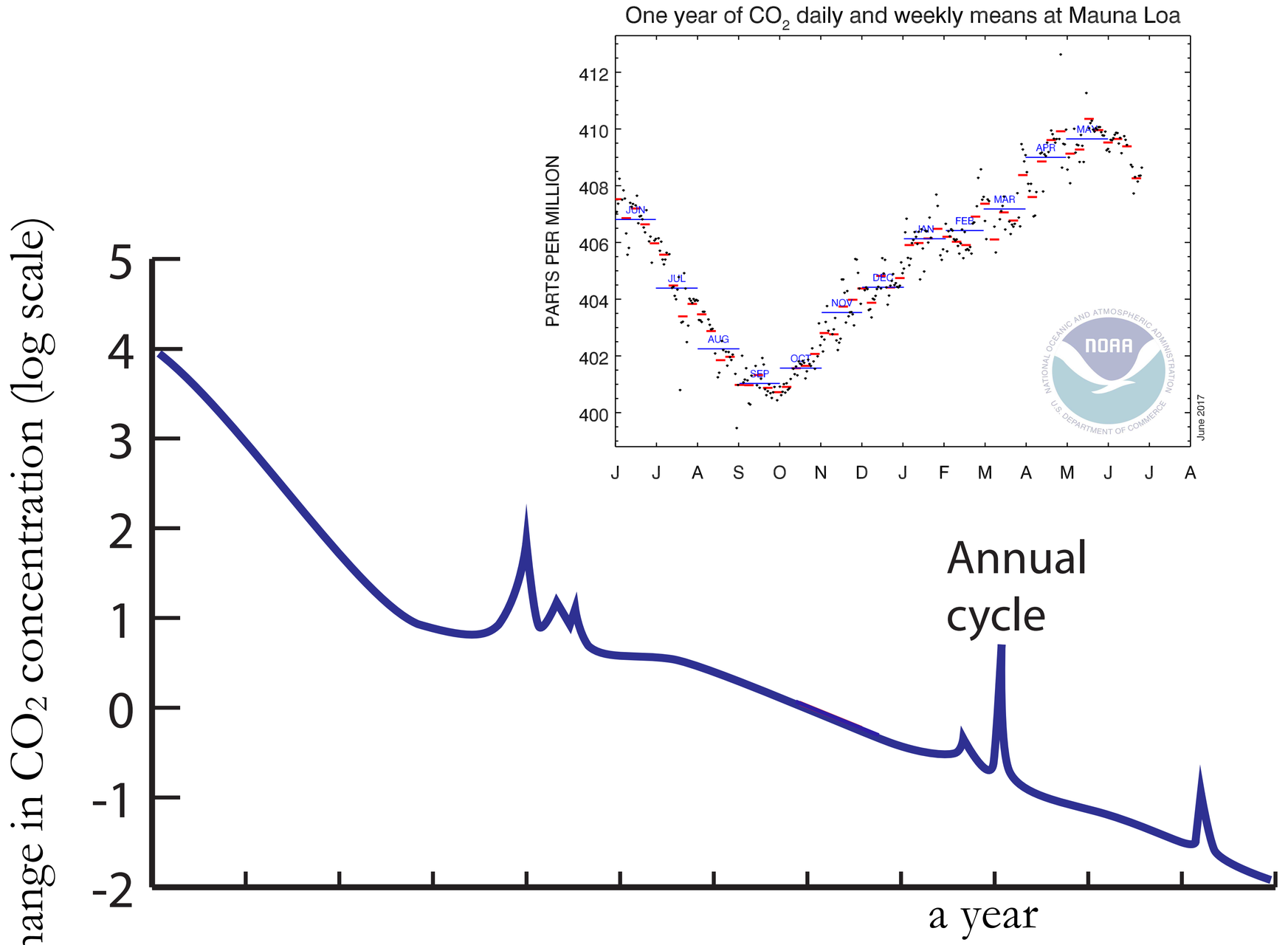
How much time an event takes

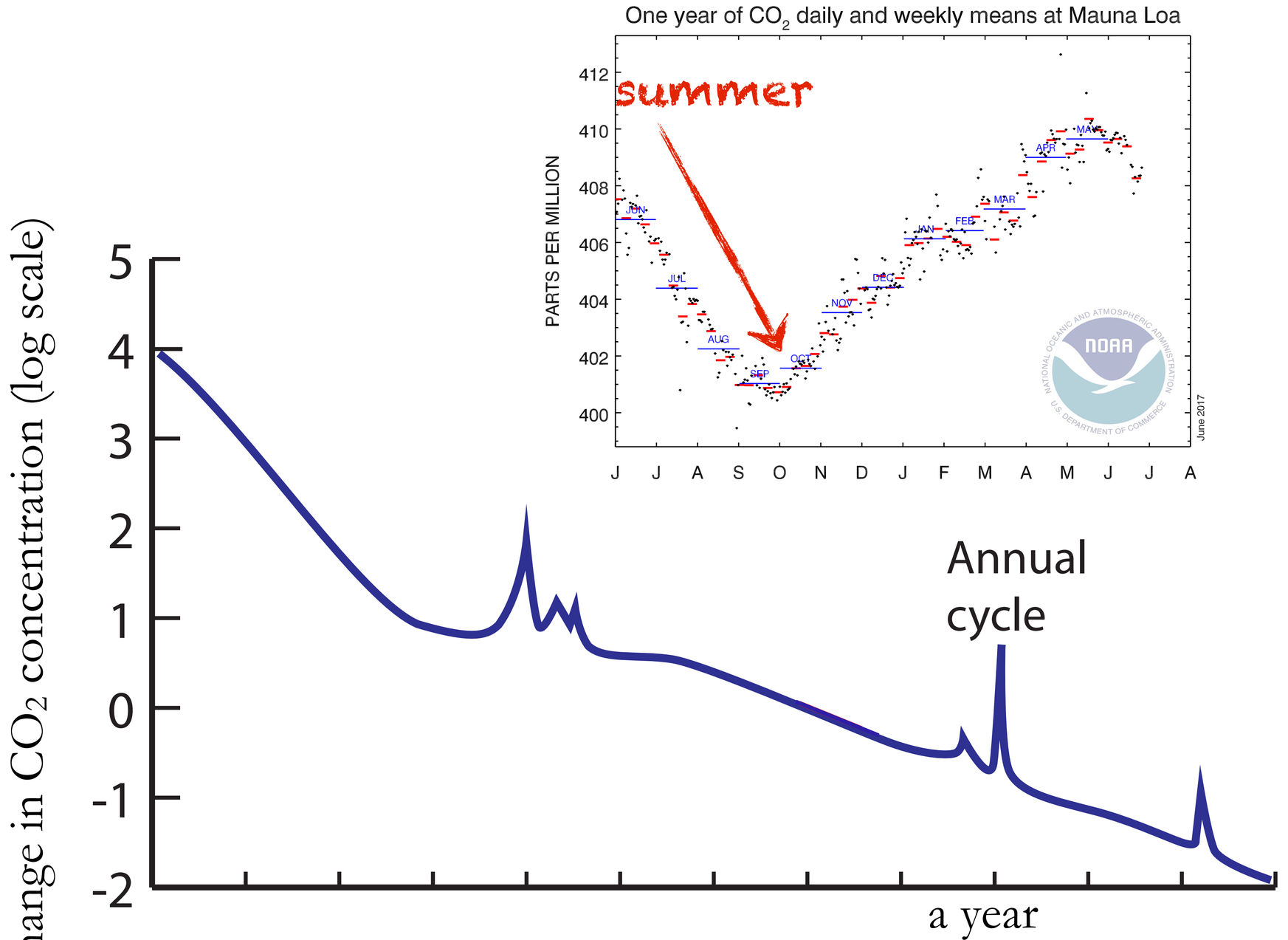


How much time an event takes



How much time an event takes


One year of CO_2 daily and weekly means at Mauna Loa
PARTS PER MILLION
412
410
408
406
404
402
400
J J A S O N D J F M A M J J A
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE
June 2017
Change in CO_2 concentration (log scale)
5
4
3
2
1
0
-1
-2
Annual cycle
a year
How much time an event takes


One year of CO_2 daily and weekly means at Mauna Loa
summer
PARTS PER MILLION
412
410
408
406
404
402
400
J J A S O N D J F M A M J J A
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
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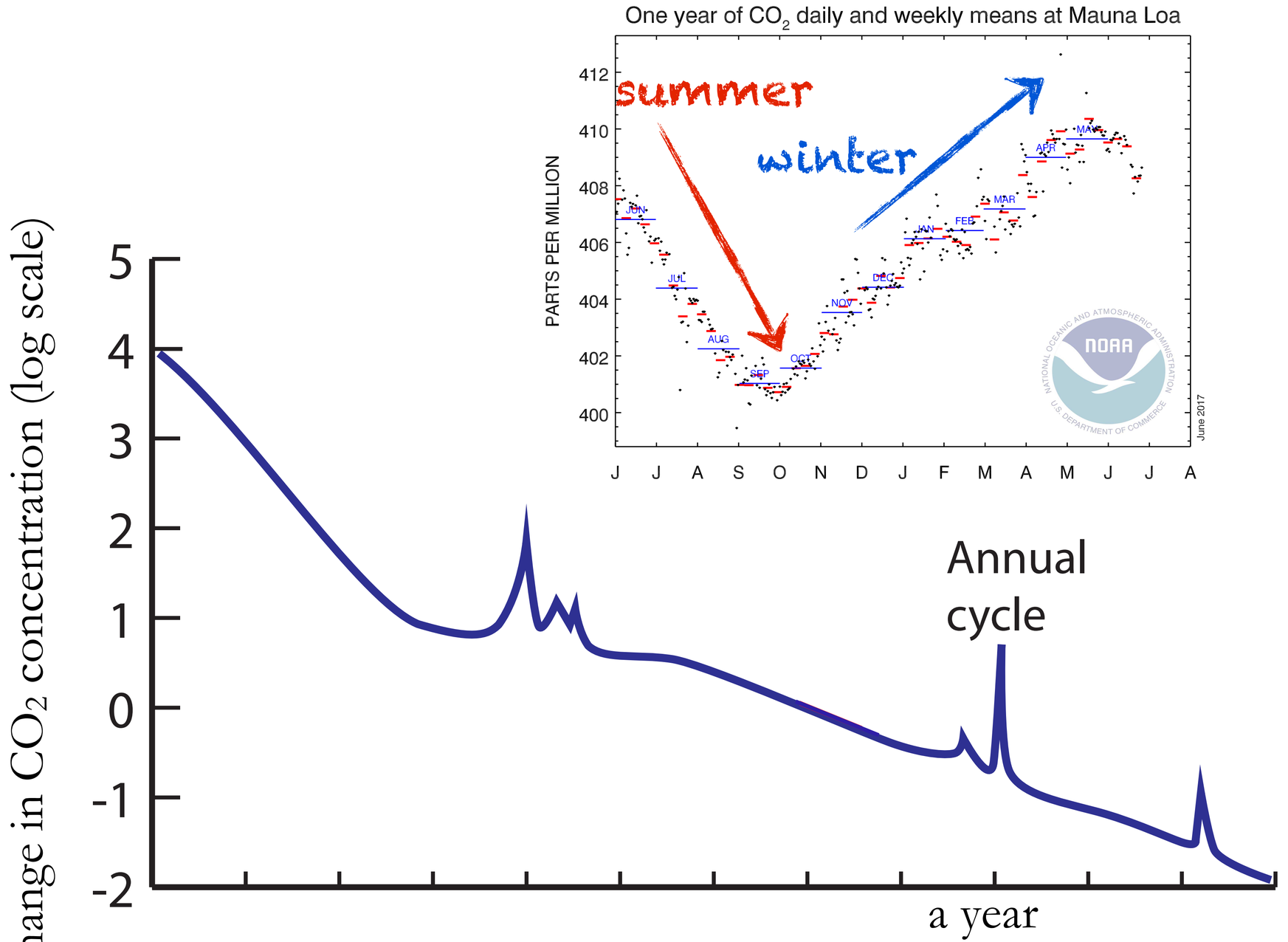
June 2017
Change in CO_2 concentration (log scale)
5
4
3
2
1
0
-1
-2
Annual cycle
a year
How much time an event takes


One year of CO_2 daily and weekly means at Mauna Loa
summer
winter
PARTS PER MILLION
412
410
408
406
404
402
400
J J A S O N D J F M A M J J A
JAN
FEB
MAR
APR
MAY
JUN
JUL
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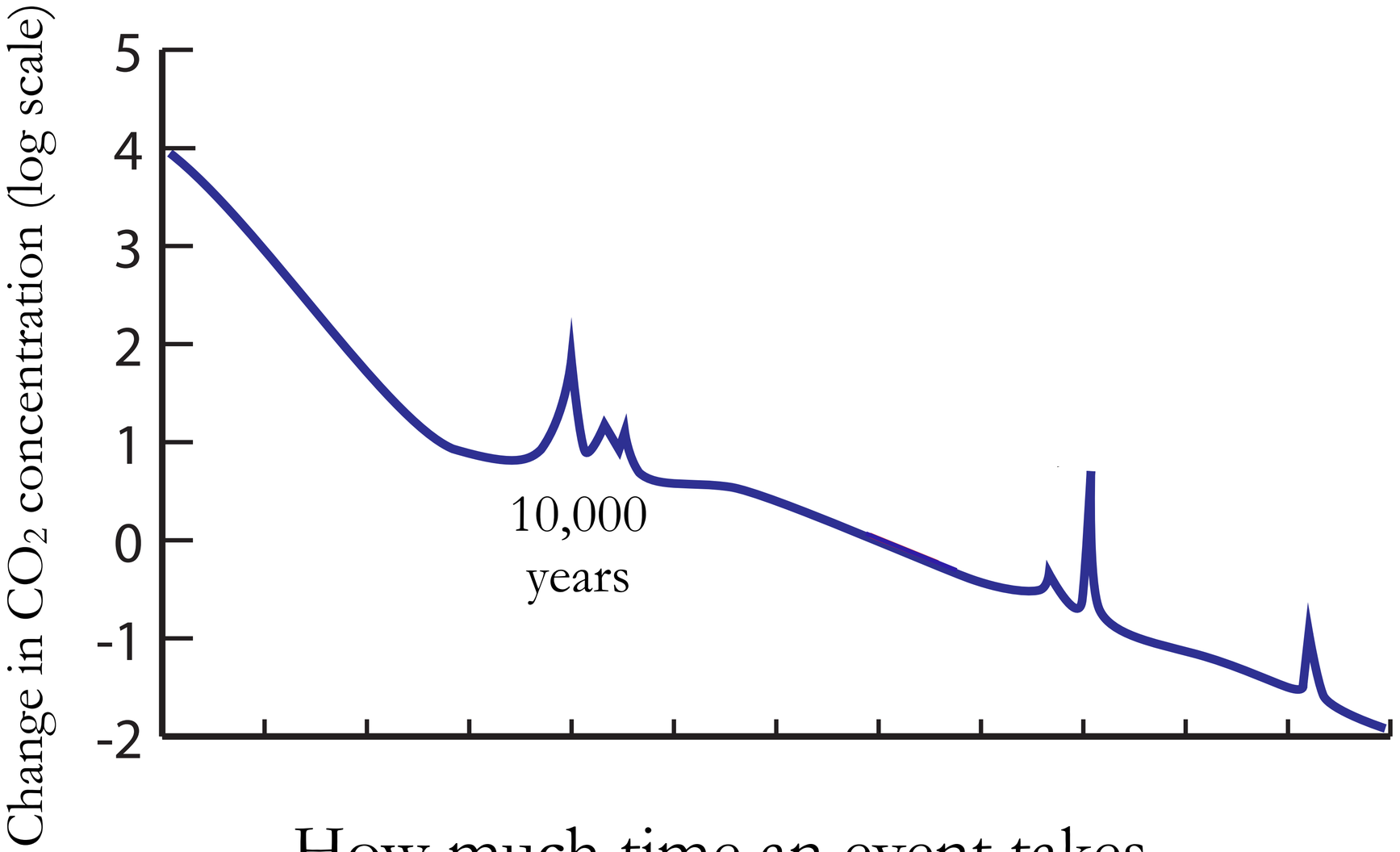
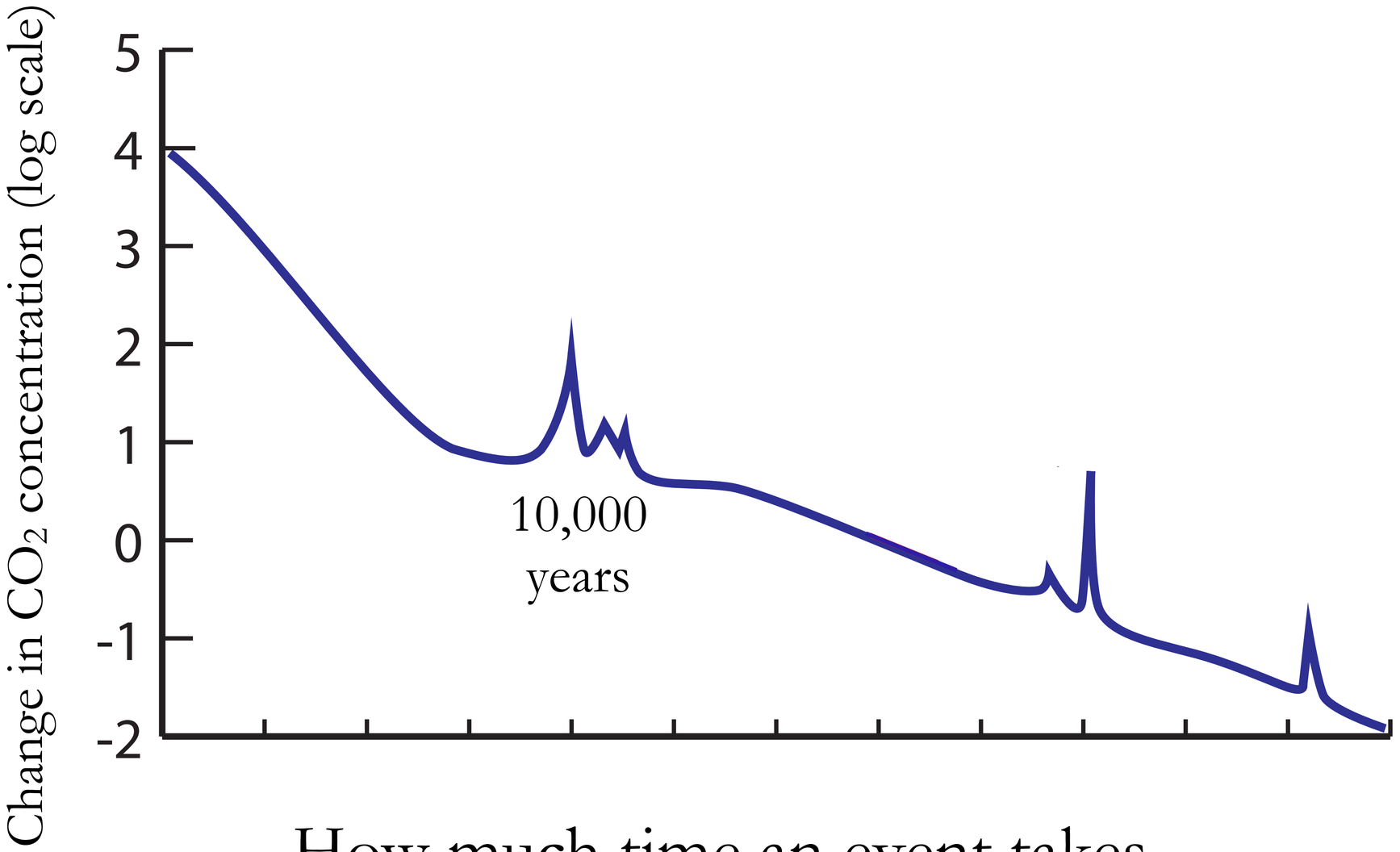
June 2017
Change in CO_2 concentration (log scale)
5
4
3
2
1
0
-1
-2
Annual cycle
a year
How much time an event takes

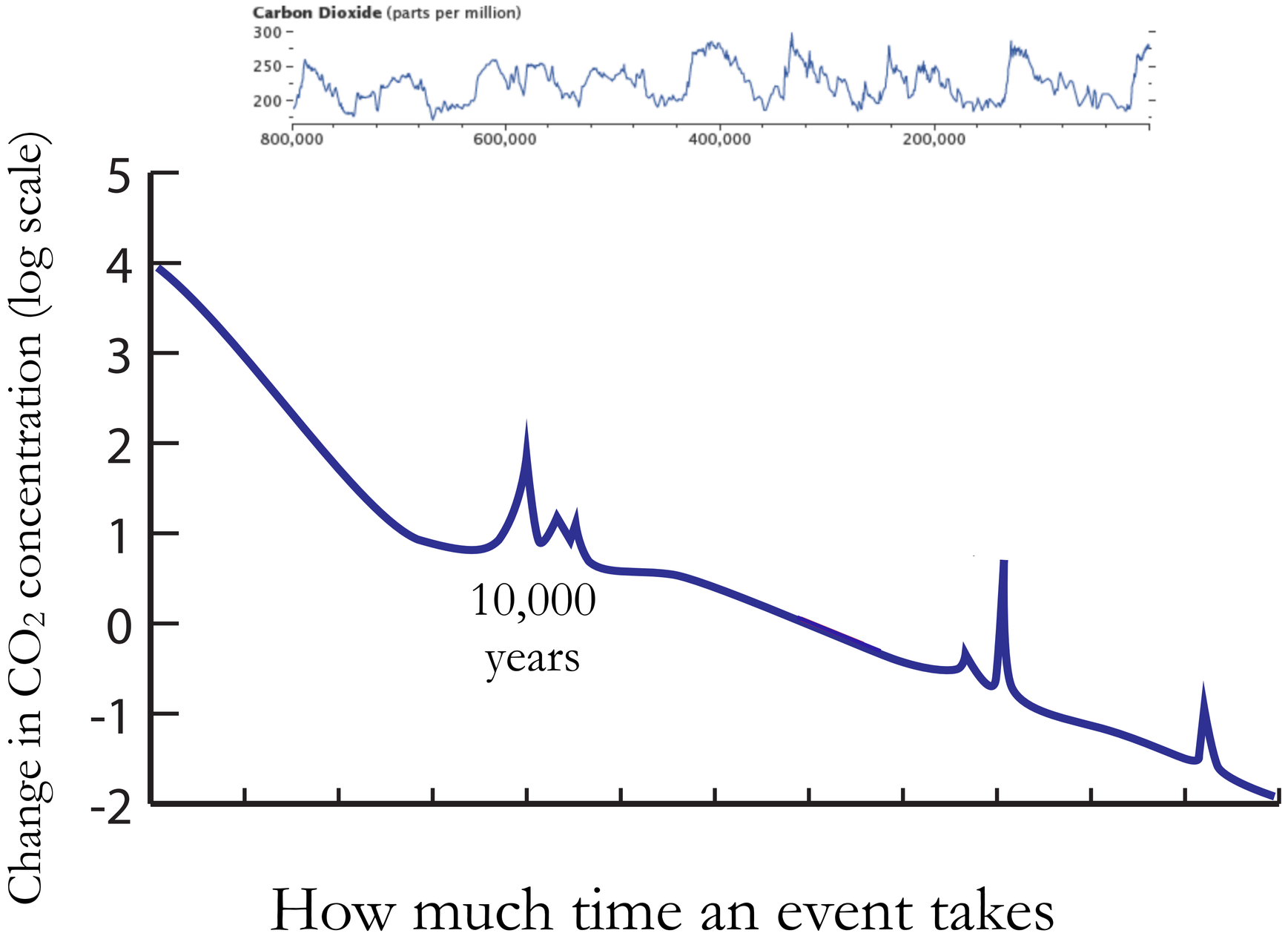


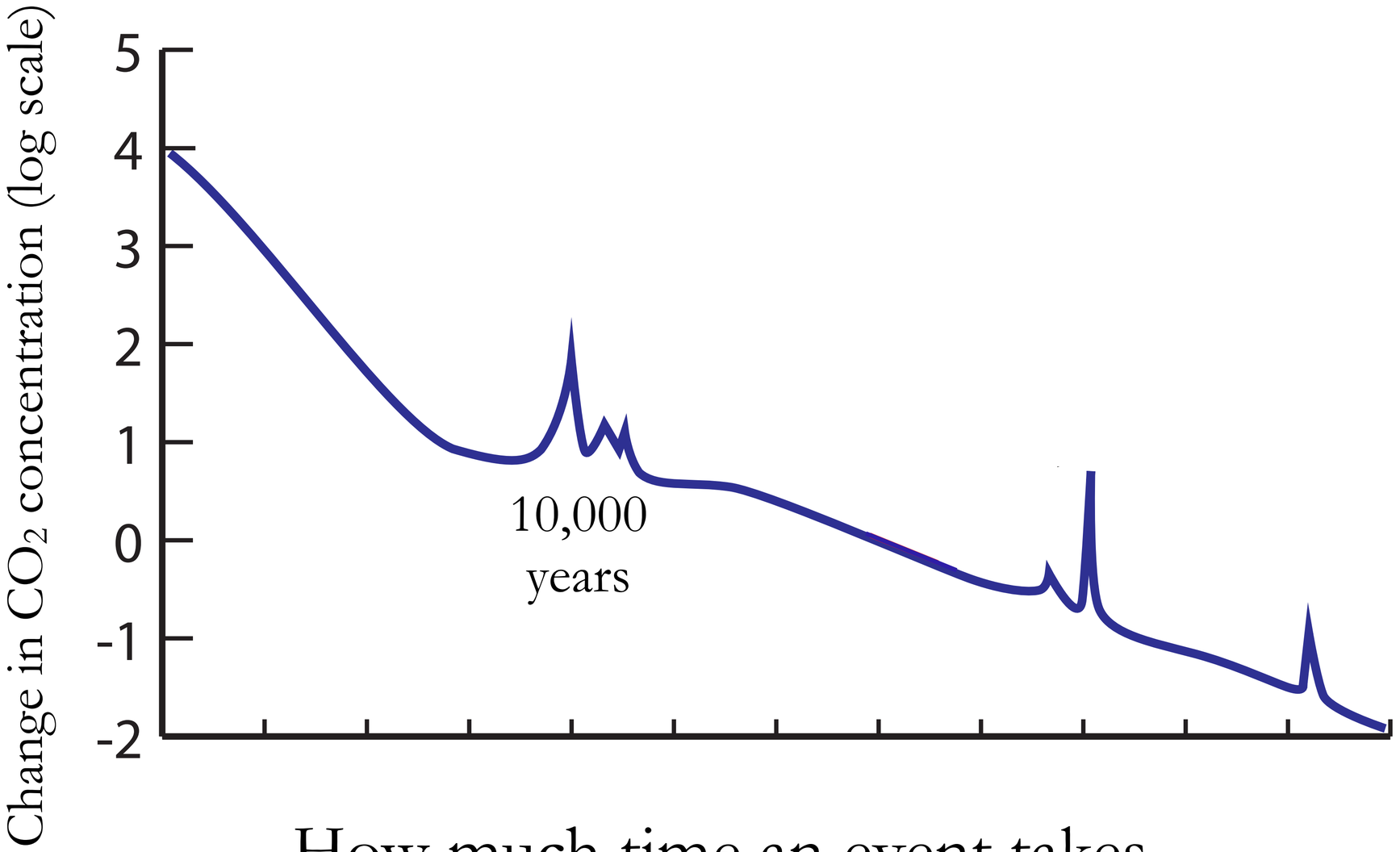
How much time an event takes

Change in CO_2 concentration (log scale)
5
4
3
2
1
0
-1
-2
10,000
years
How much time an event takes

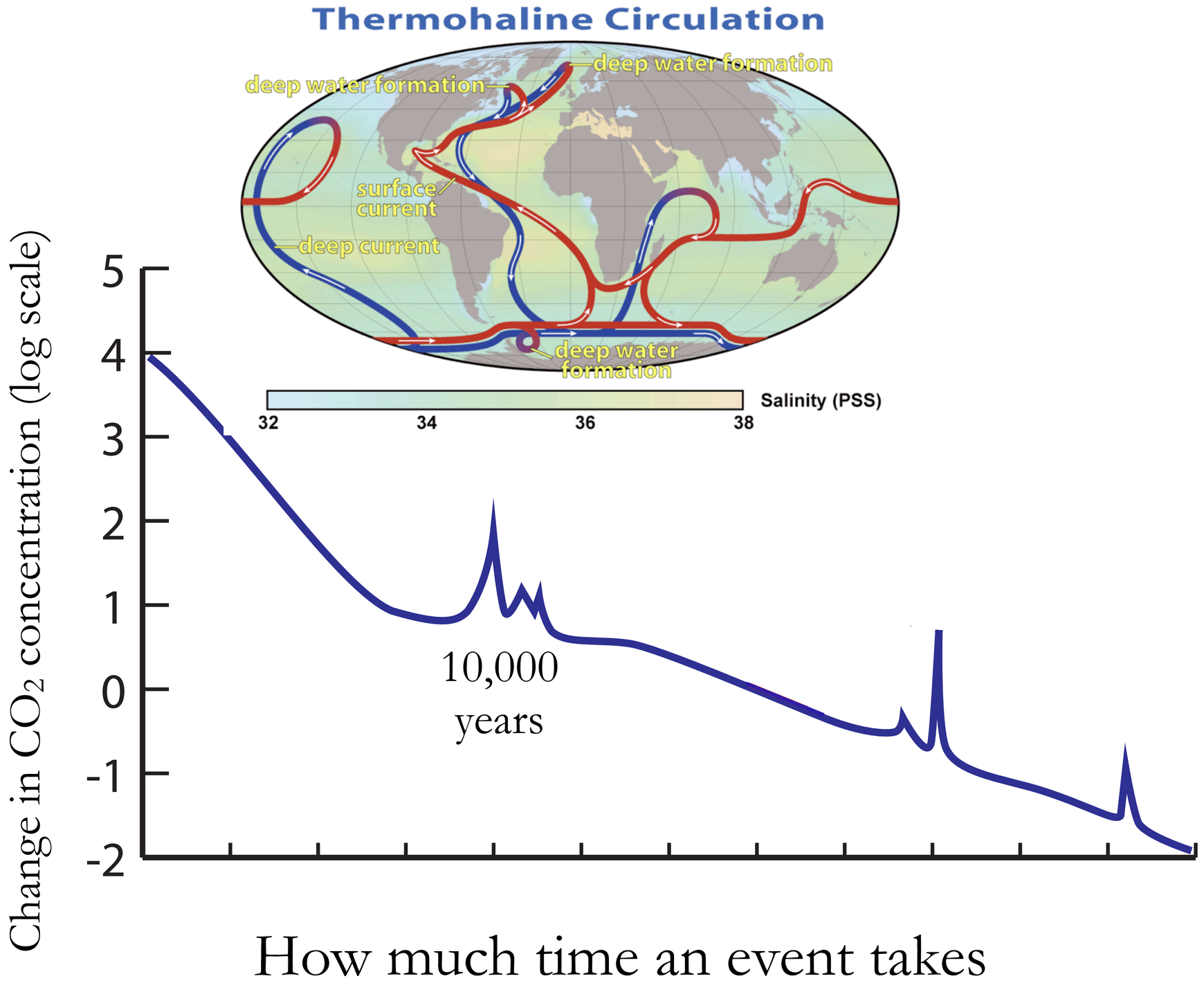


How much time an event takes

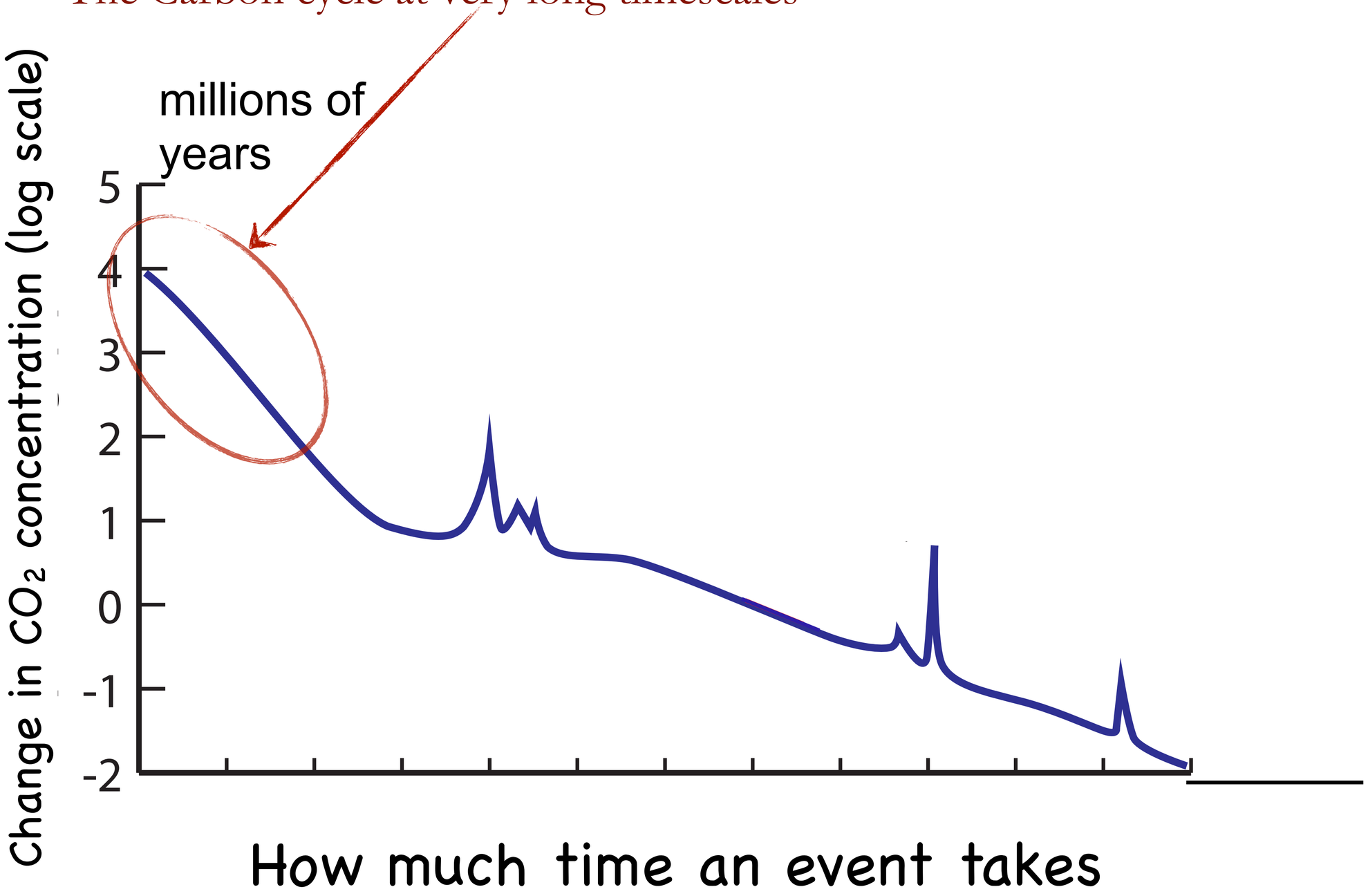

Carbon Dioxide (parts per million)
300
250
200
800,000
600,000
400,000
200,000
Change in CO_2 concentration (log scale)
5
4
3
2
1
0
-1
-2
10,000
years
How much time an event takes



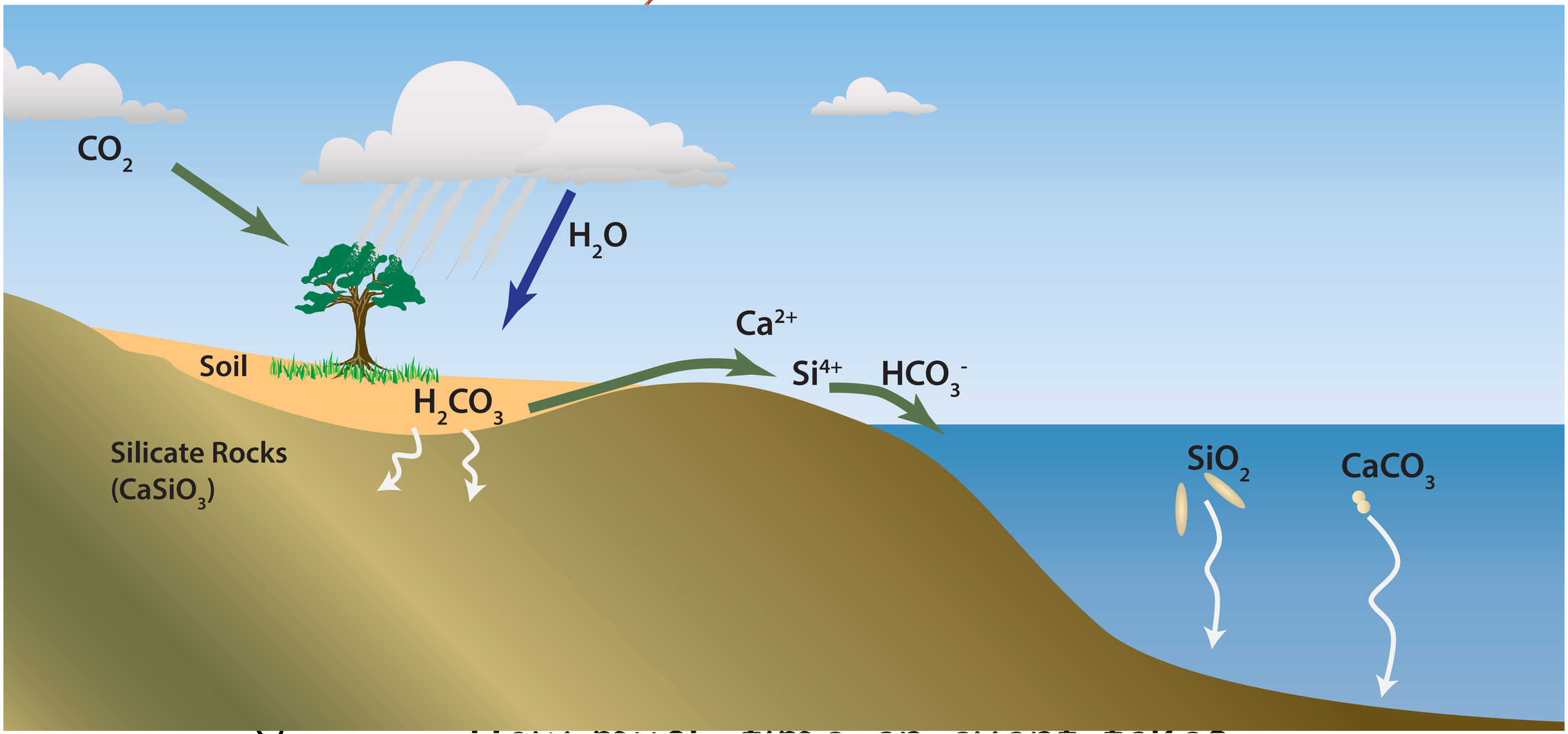
How much time an event takes

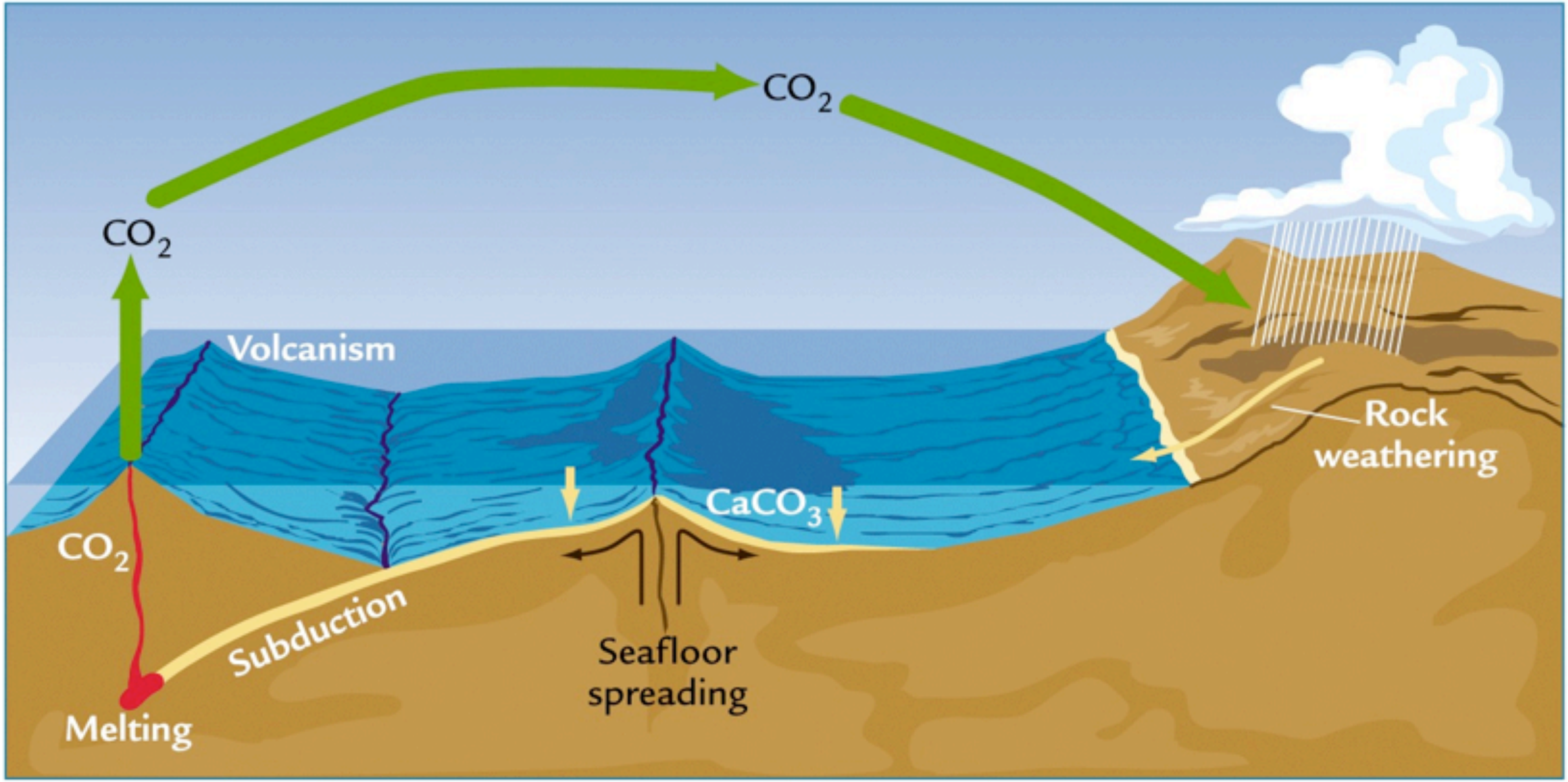

Thermohaline Circulation
deep water formation
deep water formation
surface current
deep current
deep water formation
Salinity (PSS)
32
34
36
38
Change in CO_2 concentration (log scale)
5
4
3
2
1
0
-1
-2
10,000 years
How much time an event takes

- The Carbon cycle at very long timescales

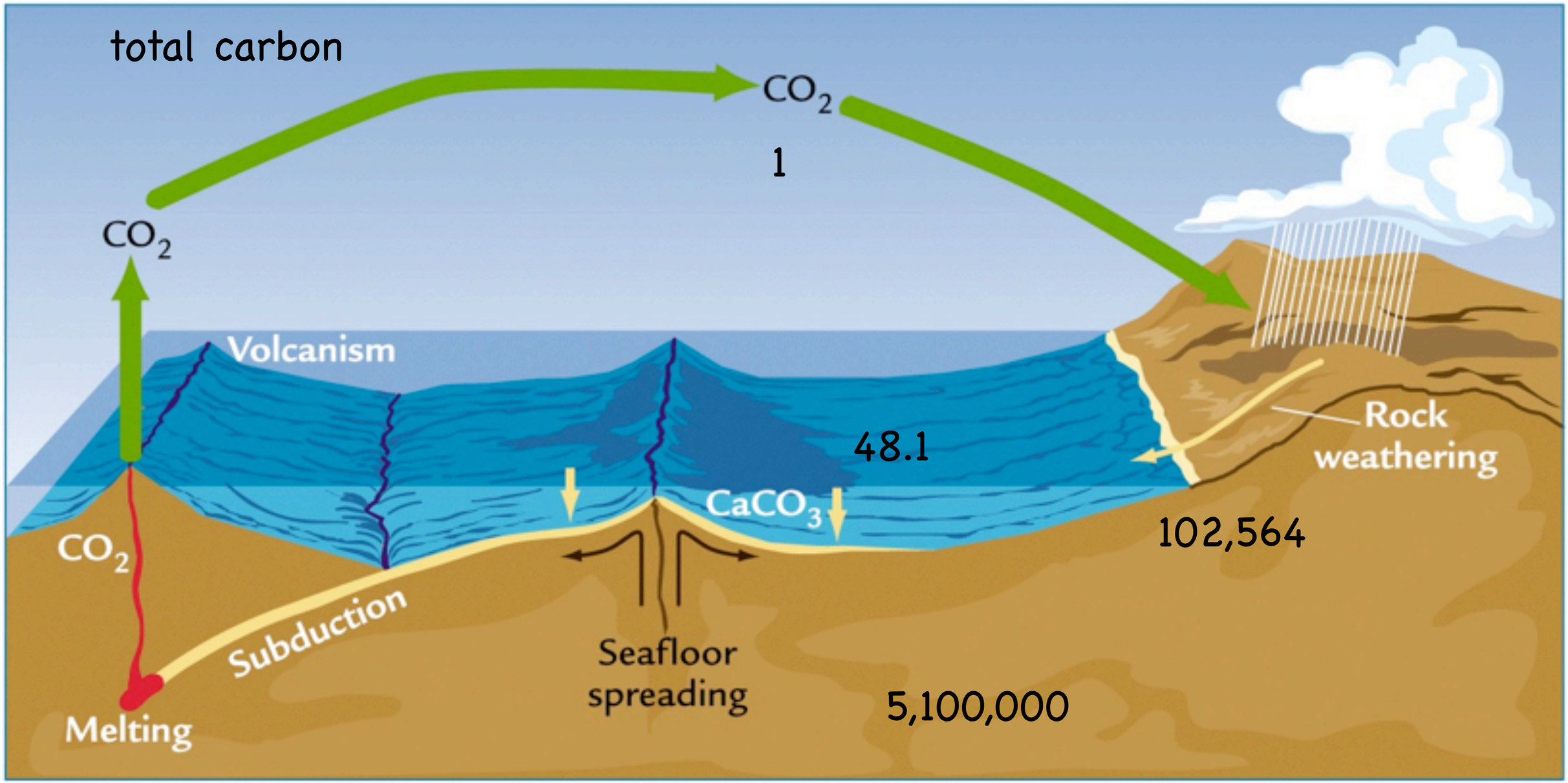


- The Carbon cycle at very long timescales





Carbon Capture and Sequestration (JAR with Berend Smit, Curt Oldenburg, Ian Bourg), World Scientific Press, 2013.



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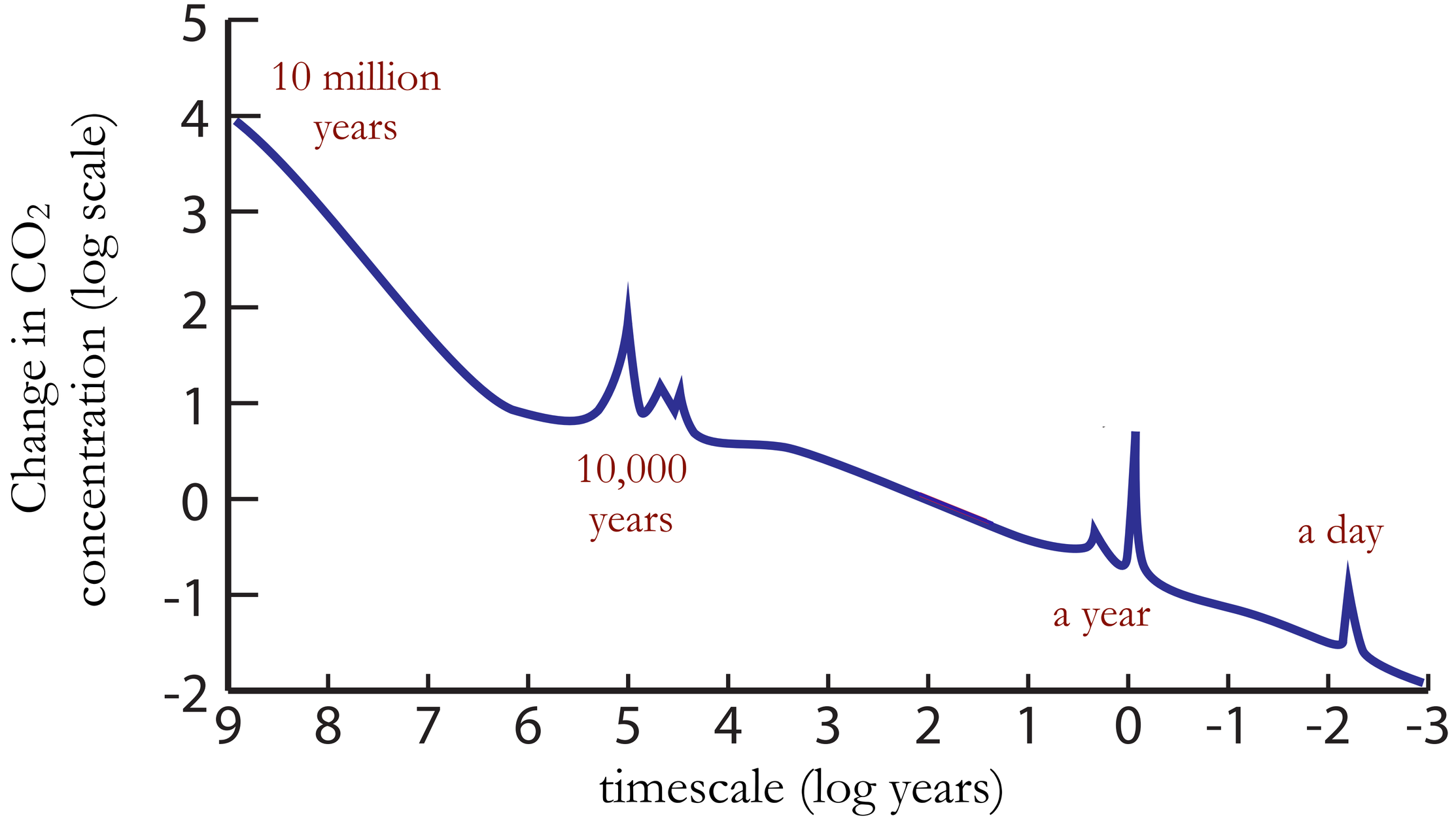
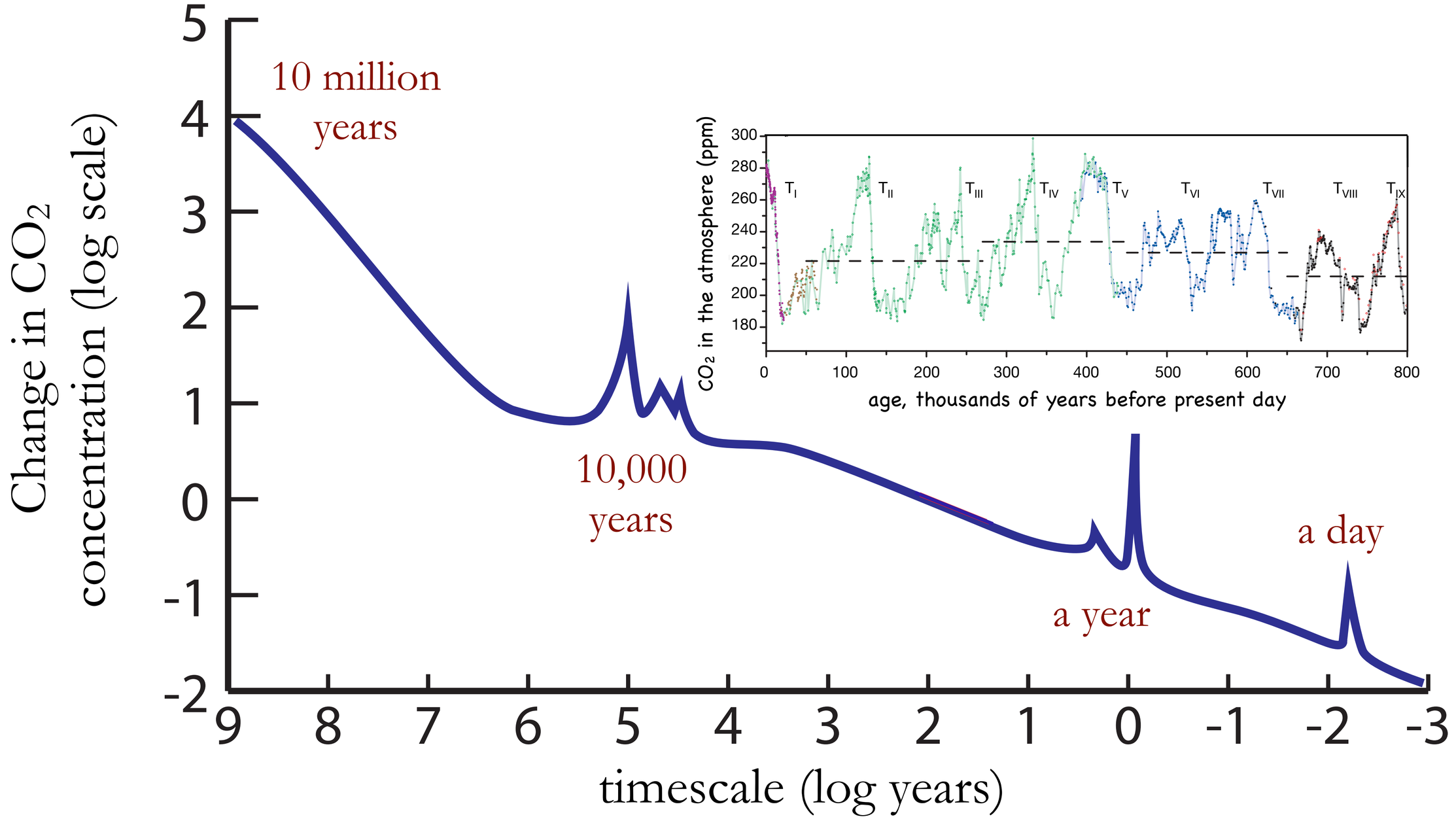
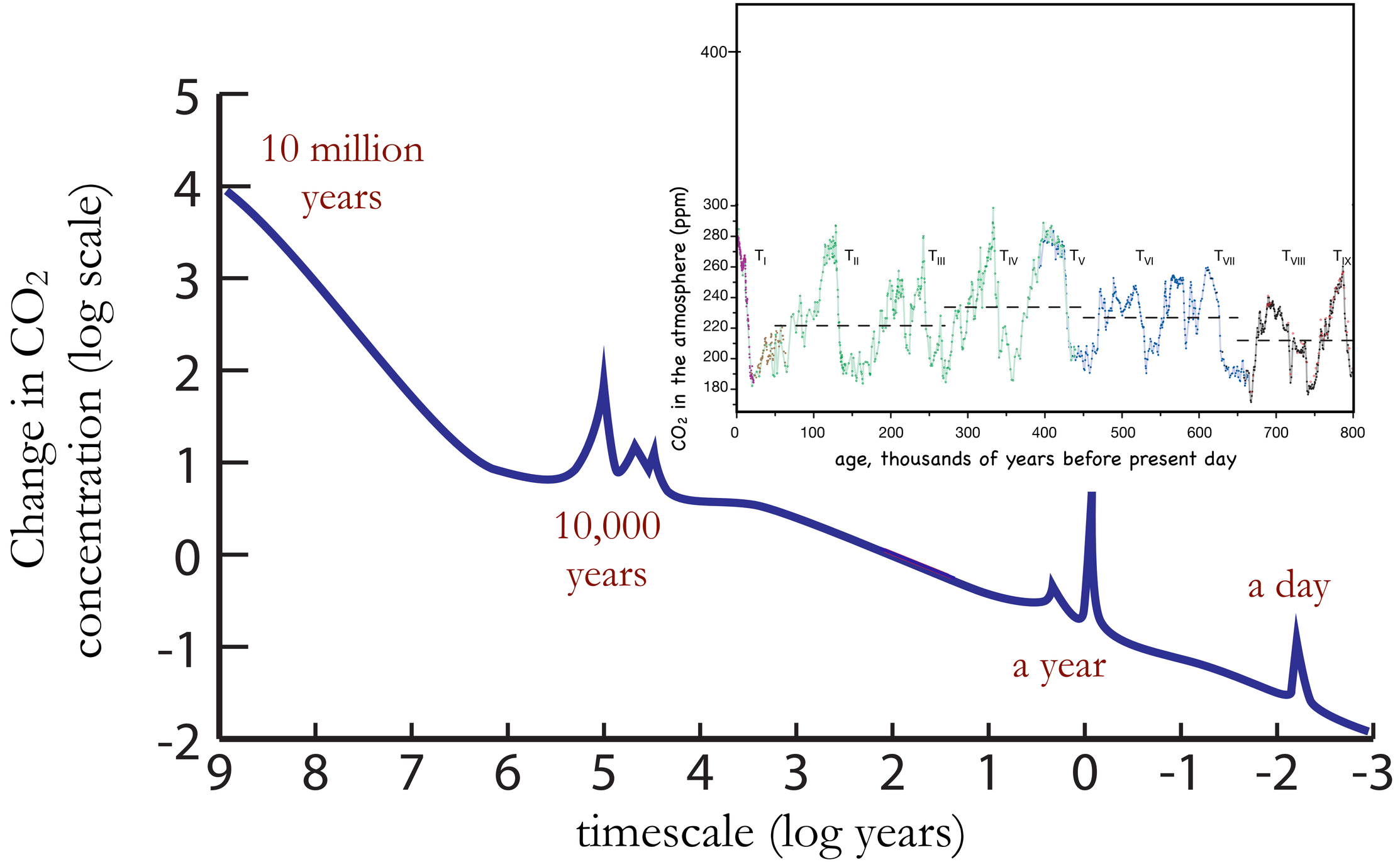
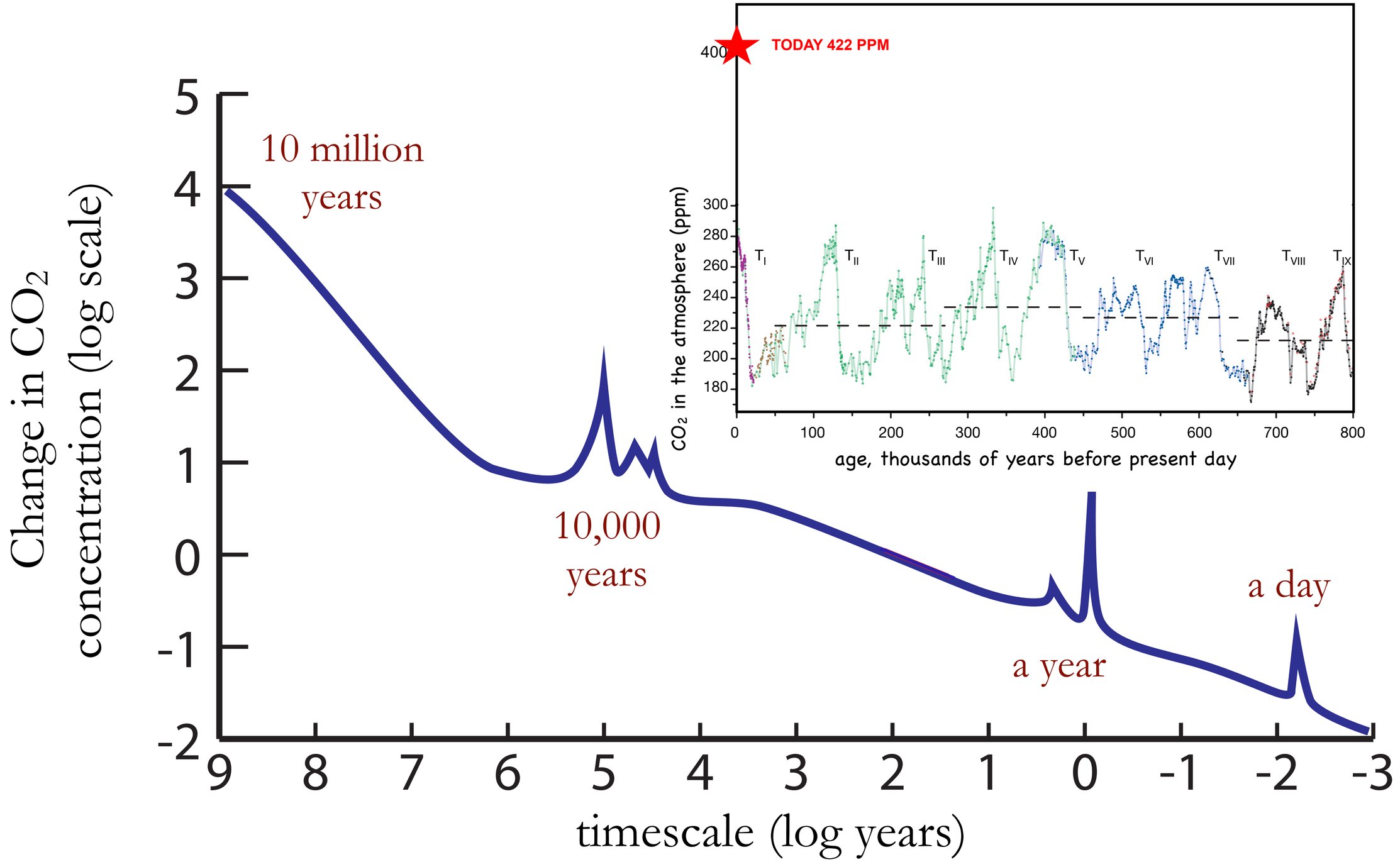
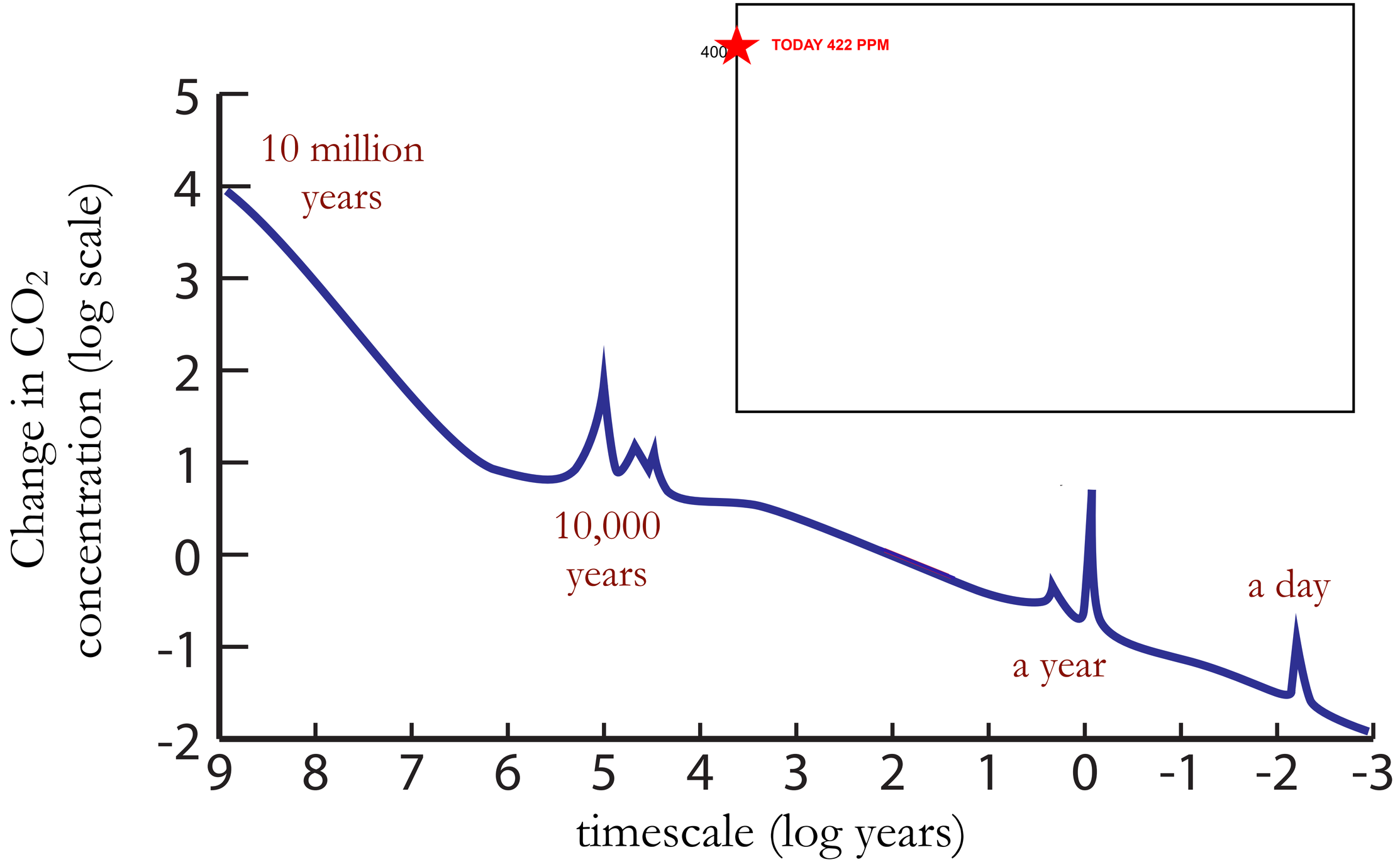

Change in CO_2 concentration (log scale)
5
4
3
2
1
0
-1
-2
10 million years
10,000 years
a year
a day
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
timescale (log years)


Change in CO_2 concentration (log scale)
5
4
3
2
1
0
-1
-2
10 million years
10,000 years
a year
a day
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
timescale (log years)
CO_2 in the atmosphere (ppm)
300
280
260
240
220
200
180
T_I
T_{II}
T_{III}
T_{IV}
T_V
T_{VI}
T_{VII}
T_{VIII}
T_{IX}
0
100
200
300
400
500
600
700
800
age, thousands of years before present day


Change in CO_2 concentration (log scale)
5
4
3
2
1
0
-1
-2
10 million years
10,000 years
a year
a day
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
timescale (log years)
CO_2 in the atmosphere (ppm)
400
300
280
260
240
220
200
180
T_I
T_{II}
T_{III}
T_{IV}
T_V
T_{VI}
T_{VII}
T_{VIII}
T_{IX}
0
100
200
300
400
500
600
700
800
age, thousands of years before present day


TODAY 422 PPM
400
300
280
260
240
220
200
180
CO_2 in the atmosphere (ppm)
T_I
T_{II}
T_{III}
T_{IV}
T_V
T_{VI}
T_{VII}
T_{VIII}
T_{IX}
0
100
200
300
400
500
600
700
800
age, thousands of years before present day
10 million years
10,000 years
a year
a day
Change in CO_2 concentration (log scale)
5
4
3
2
1
0
-1
-2
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
timescale (log years)



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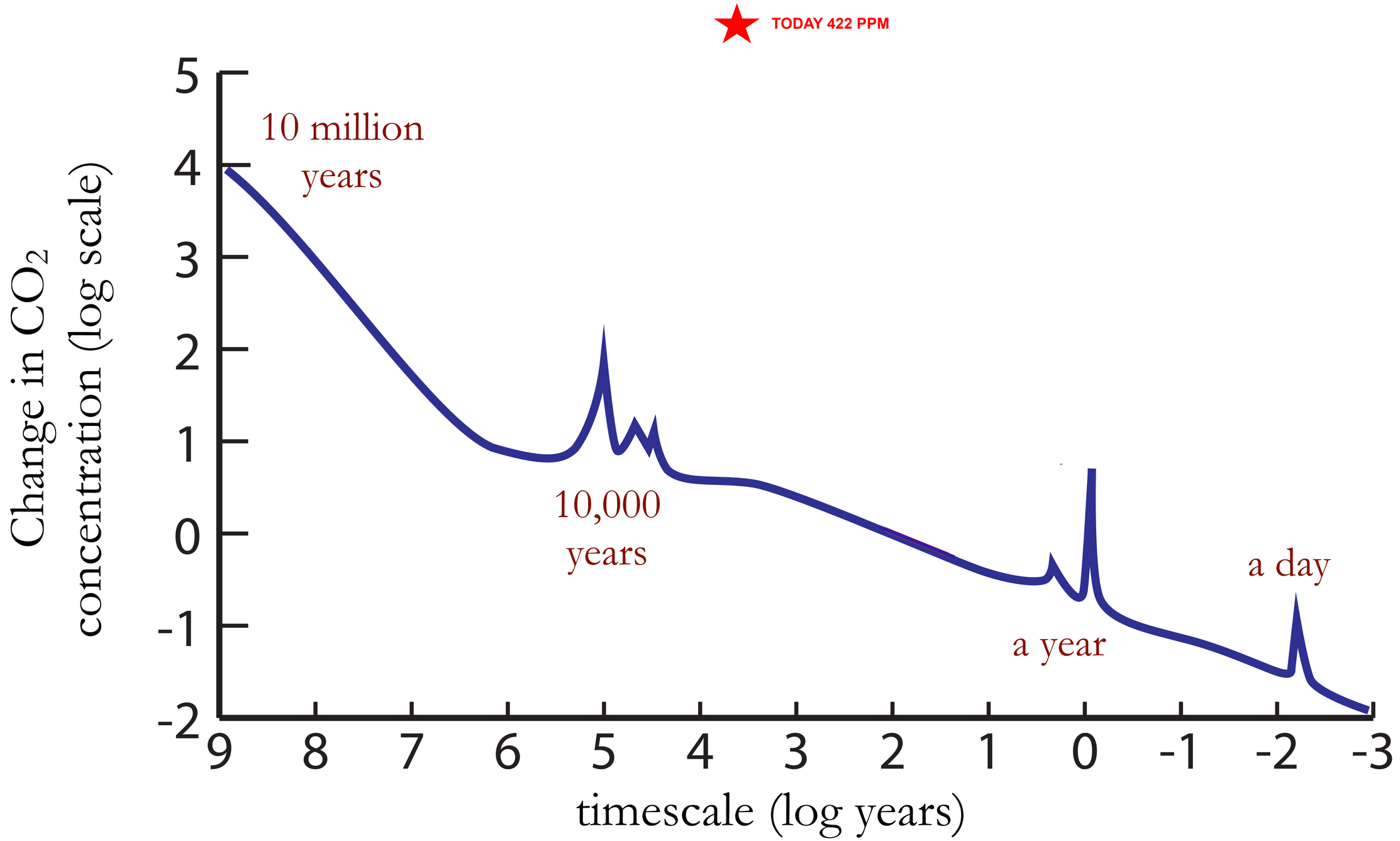
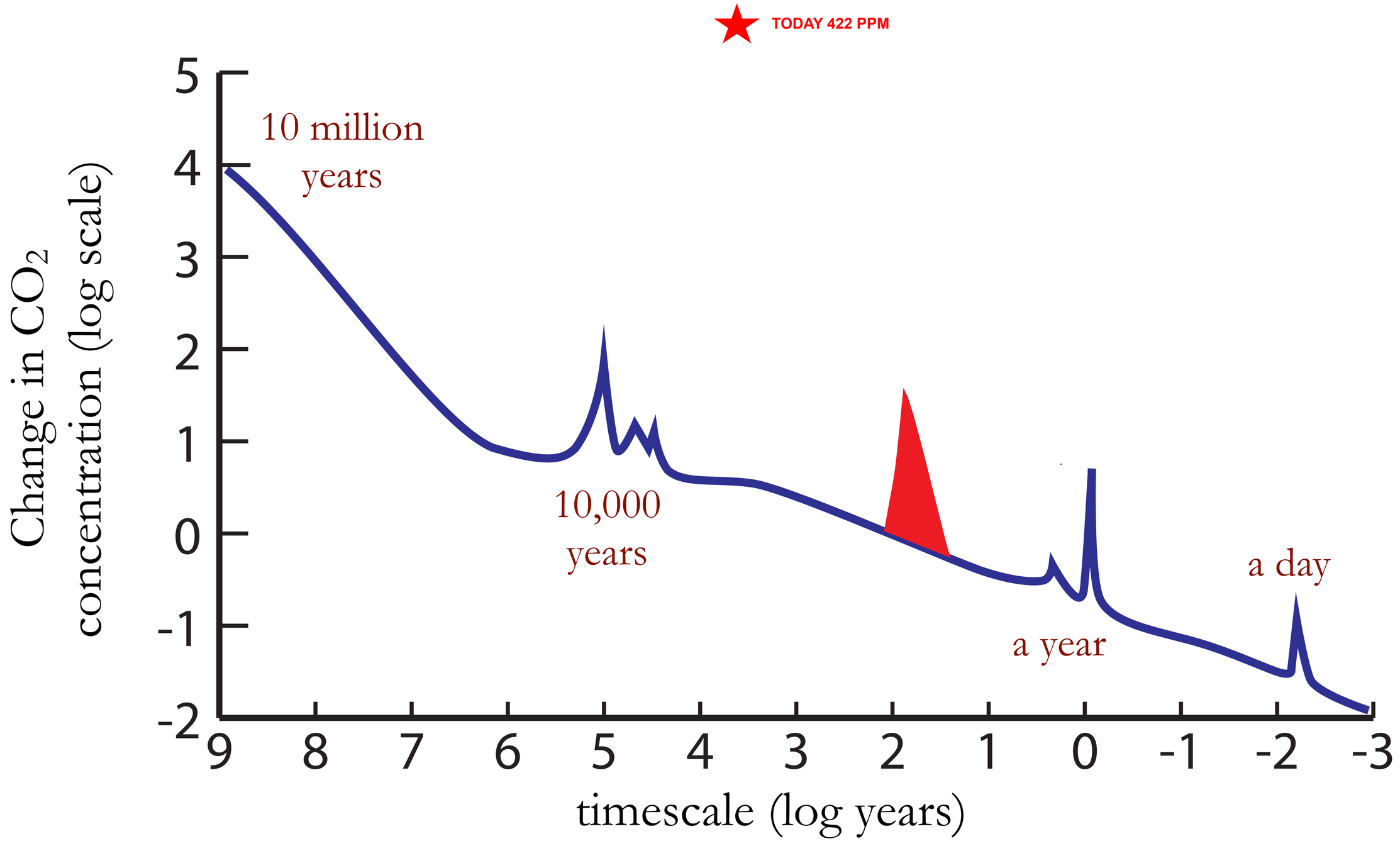
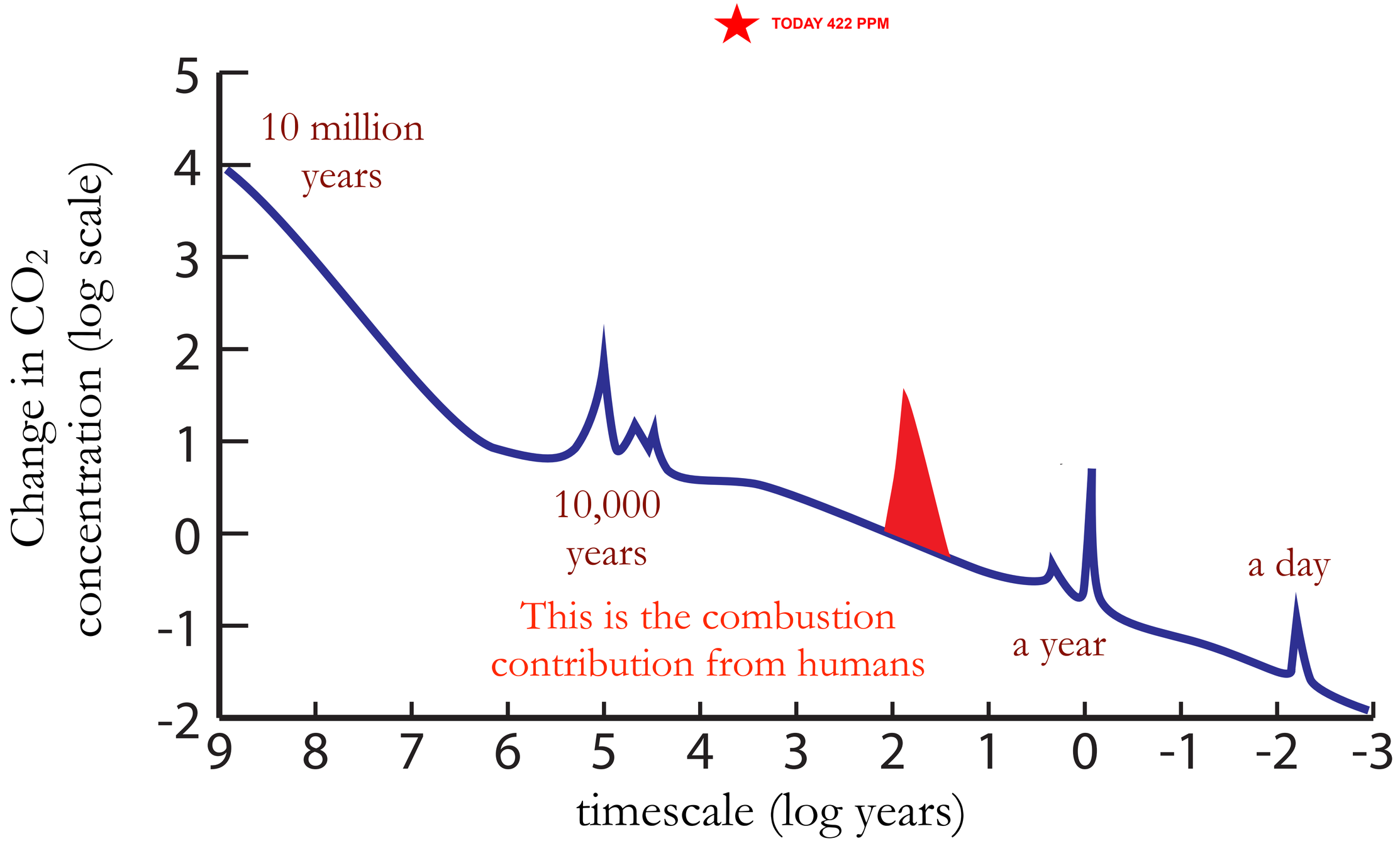


SCIENCE VOL 290 13 OCTOBER 2000

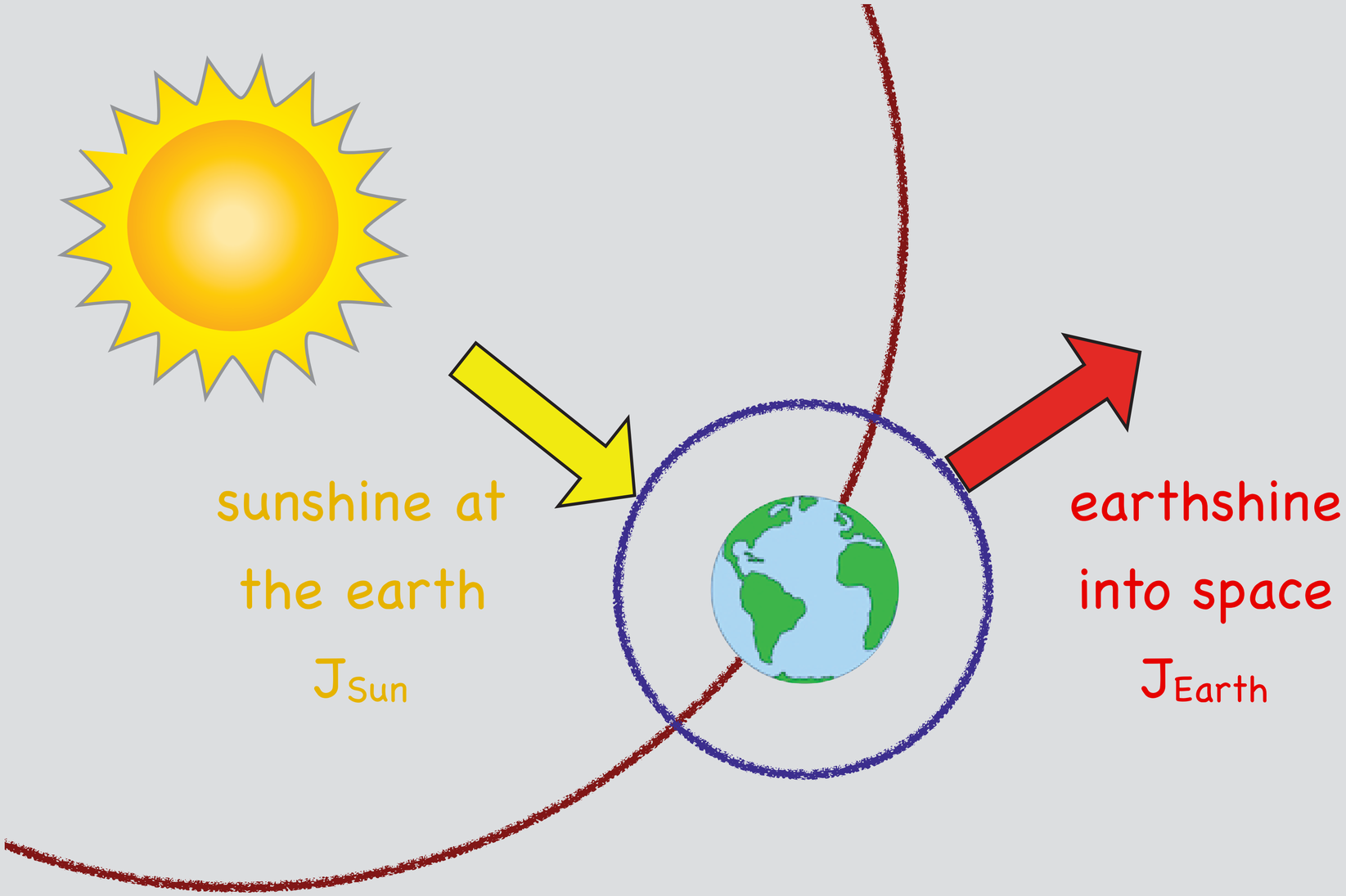

TODAY 422 PPM
10 million years
10,000 years
a year
a day
Change in CO_2 concentration (log scale)
timescale (log years)
5
4
3
2
1
0
-1
-2
9
8
7
6
5
4
3
2
1
0
-1
-2
-3



SCIENCE VOL 290 13 OCTOBER 2000

Radiative forcing

Radiative forcing



Carbon Capture and Sequestration (JAR with Berend Smit, Curt Oldenburg, Ian Bourg), World Scientific Press, 2013.

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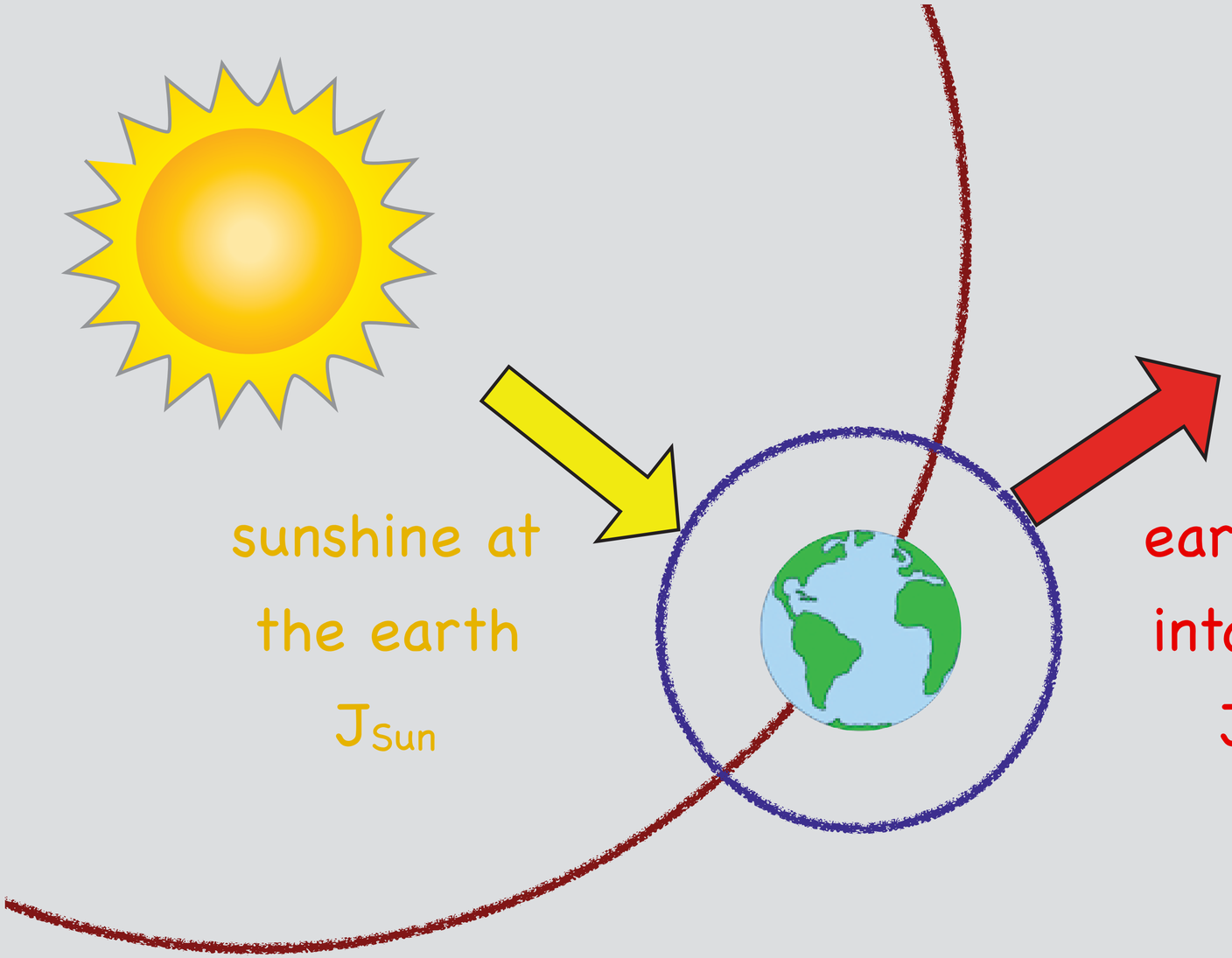

sunshine at the earth

J_{Sun}

earthshine into space

J_{Earth}

$$\mathrm{J}[=]\frac{energy}{area-time} \quad \mathrm{e.g.,}\frac{joules}{m^2-sec}=\frac{watts}{m^2}$$

$$=\sigma \mathrm{T}^4$$

"black body radiation"

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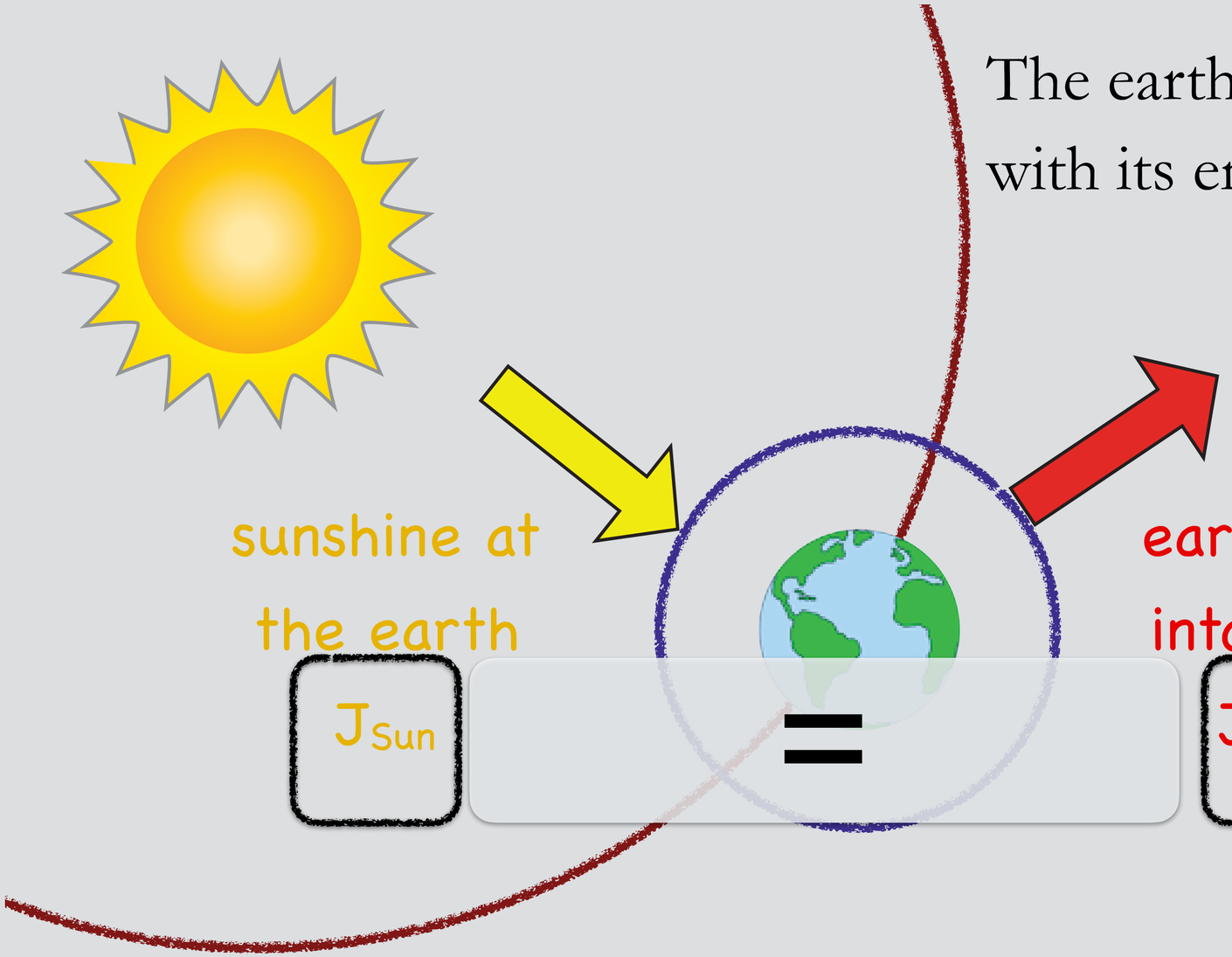
Radiative forcing



The earth **equilibrates** with its environment

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$$=\sigma \mathrm{T}^4$$

"black body radiation"

sunshine at the earth

earthshine into space

J_{Sun} = J_{Earth}

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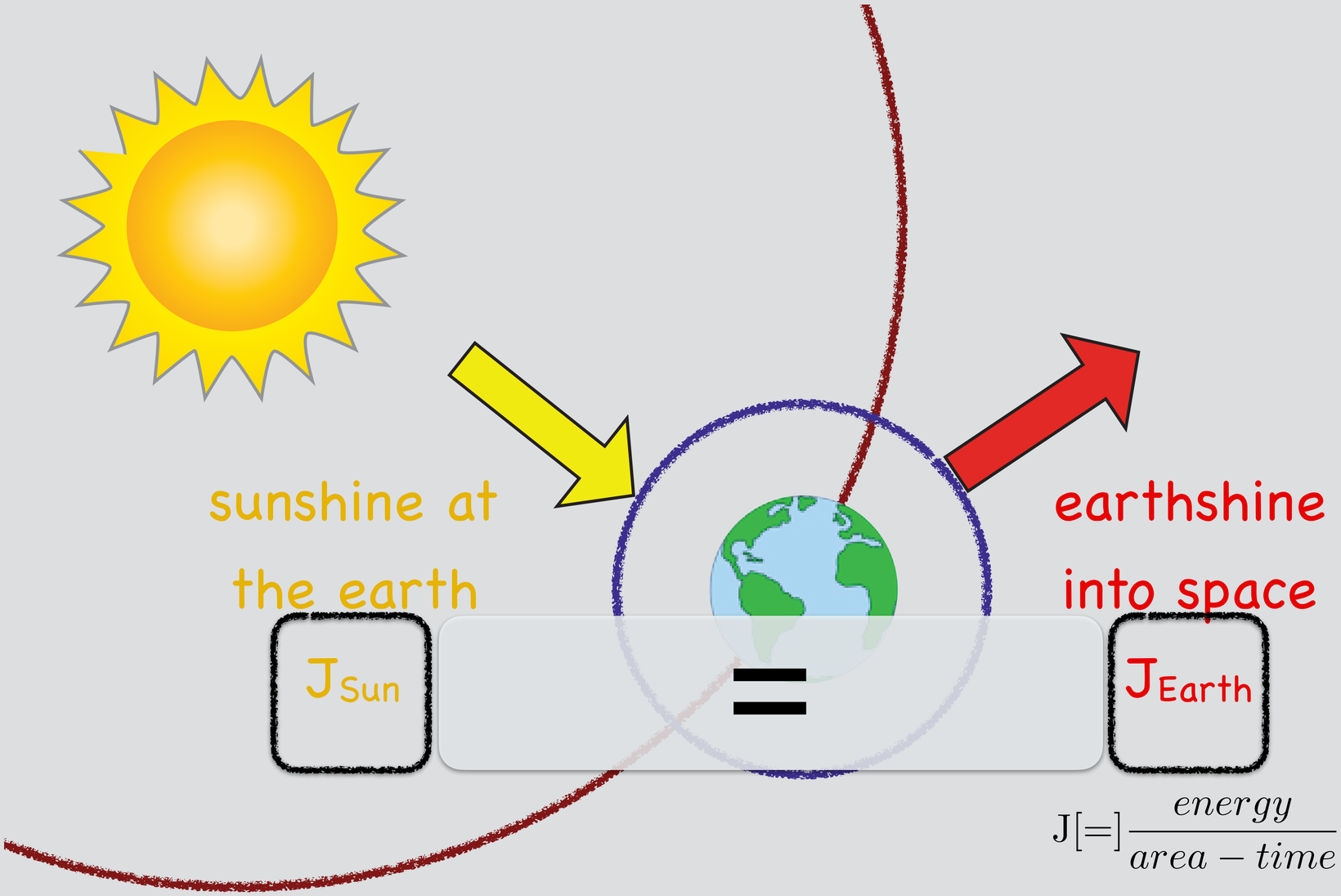

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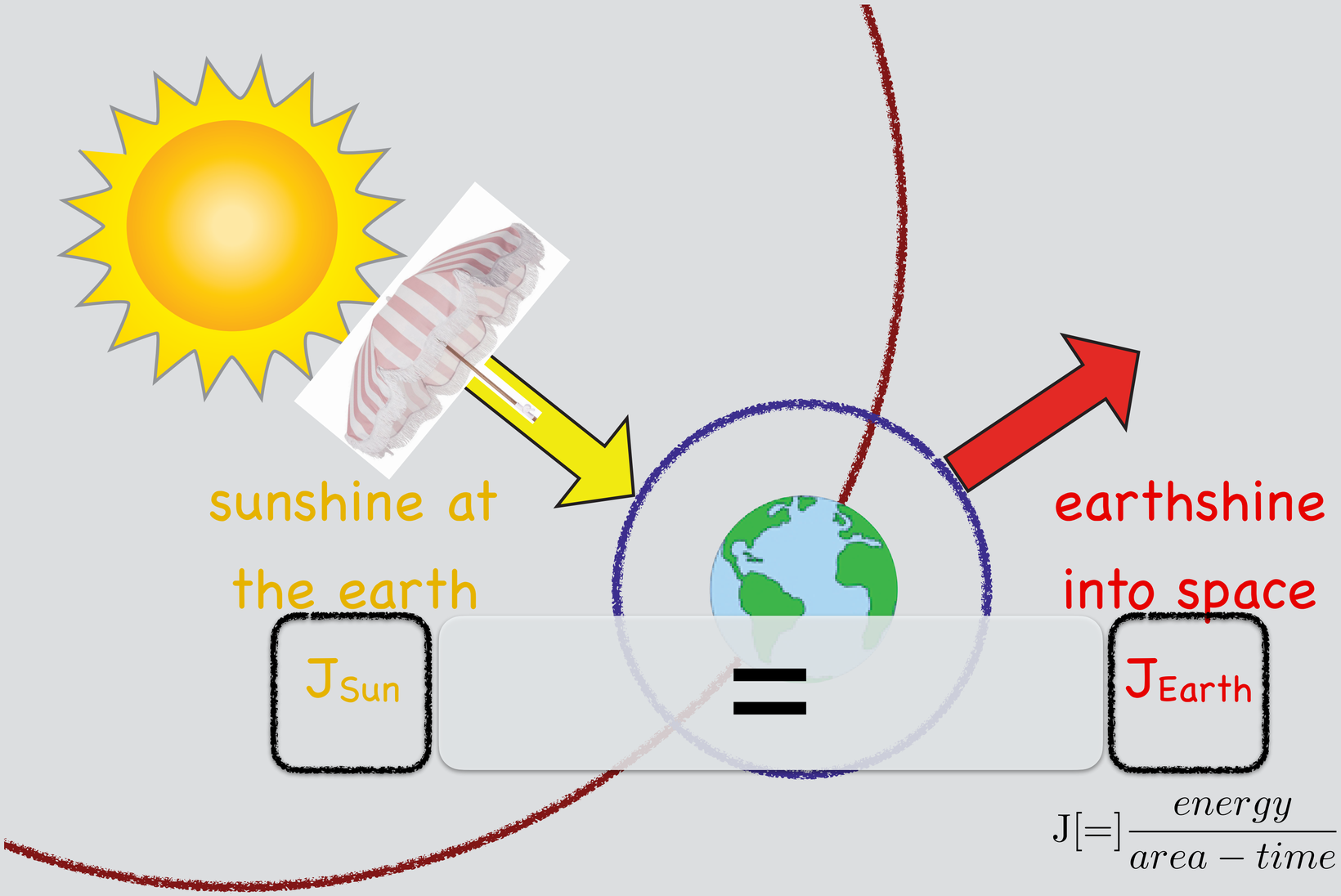

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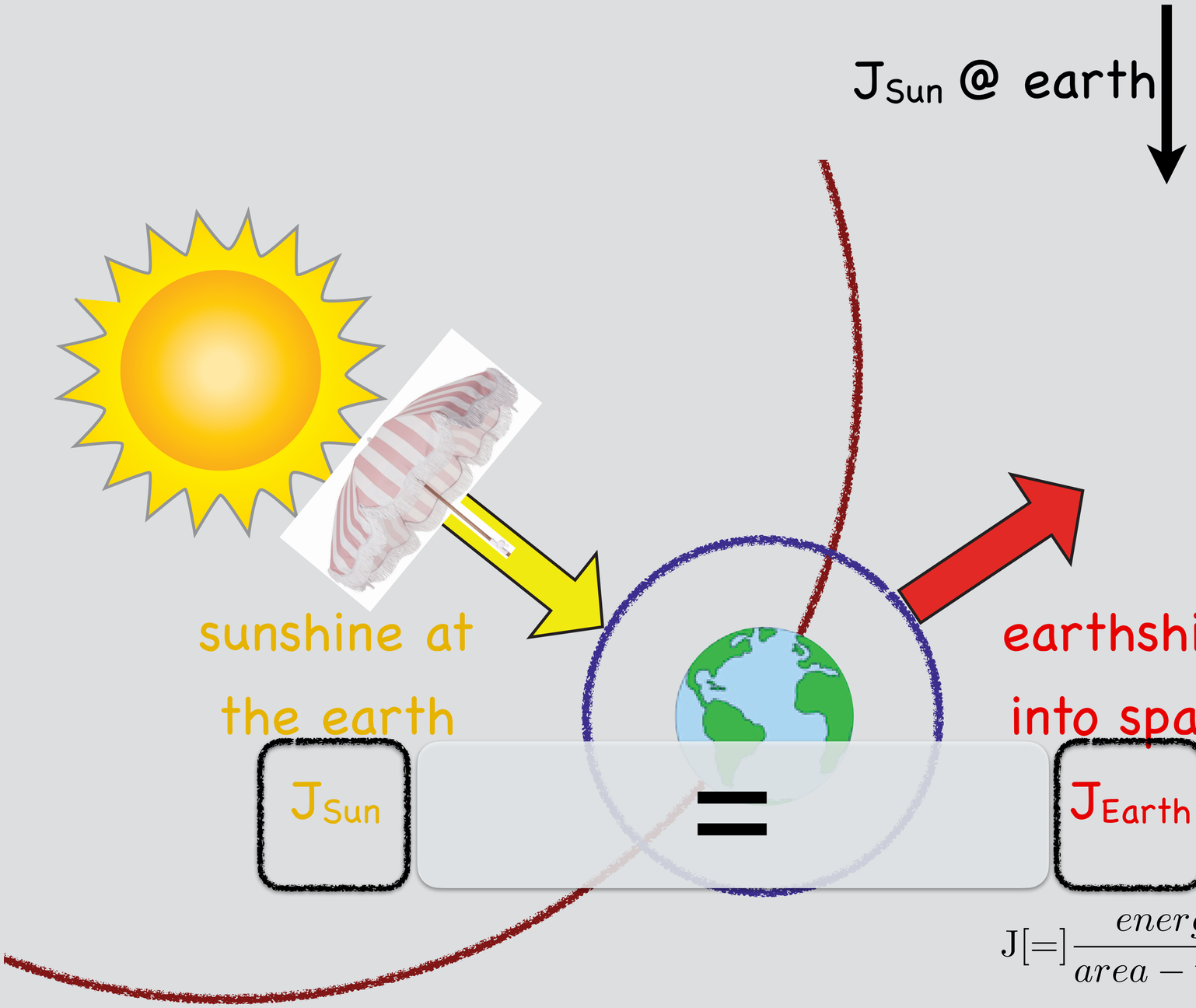

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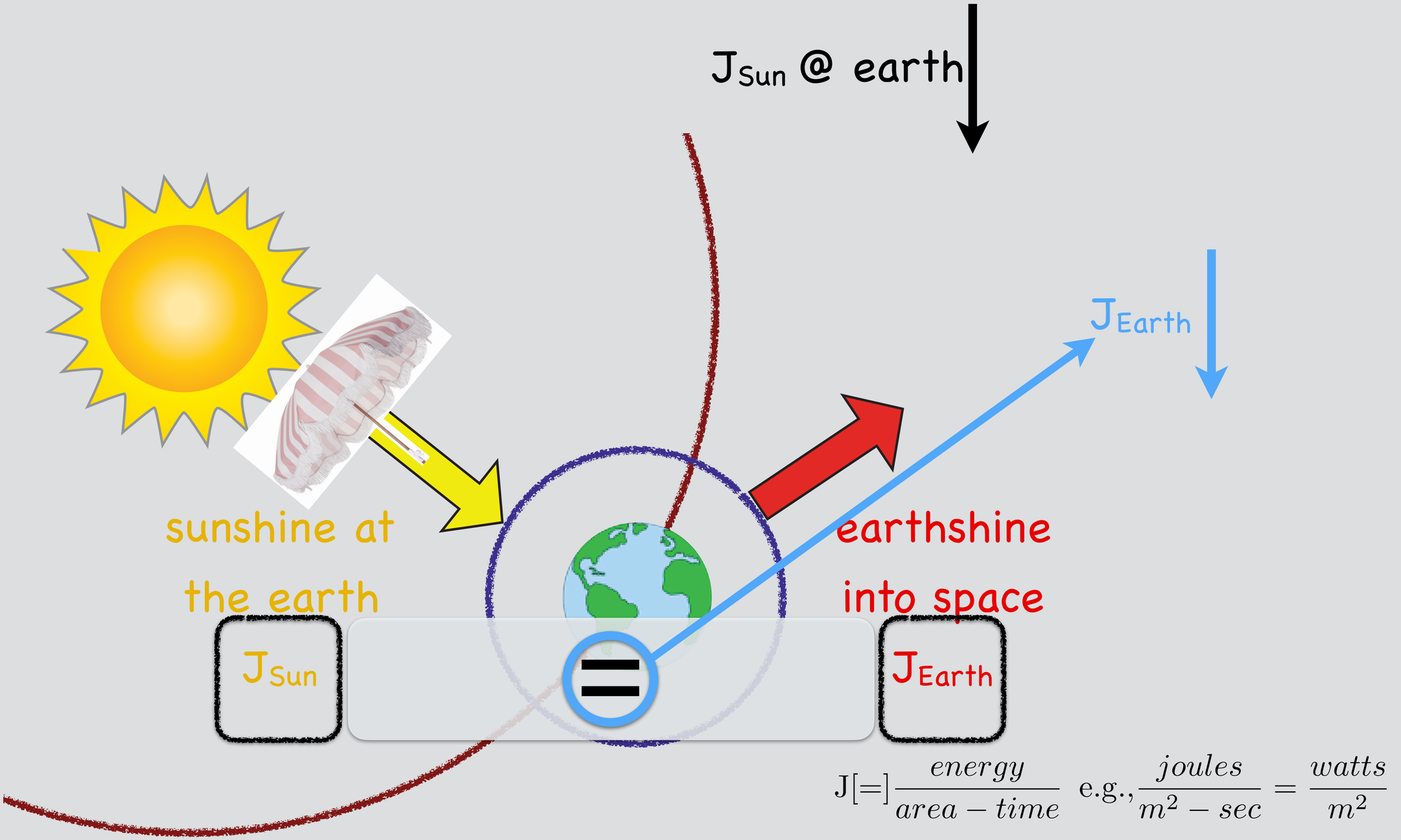

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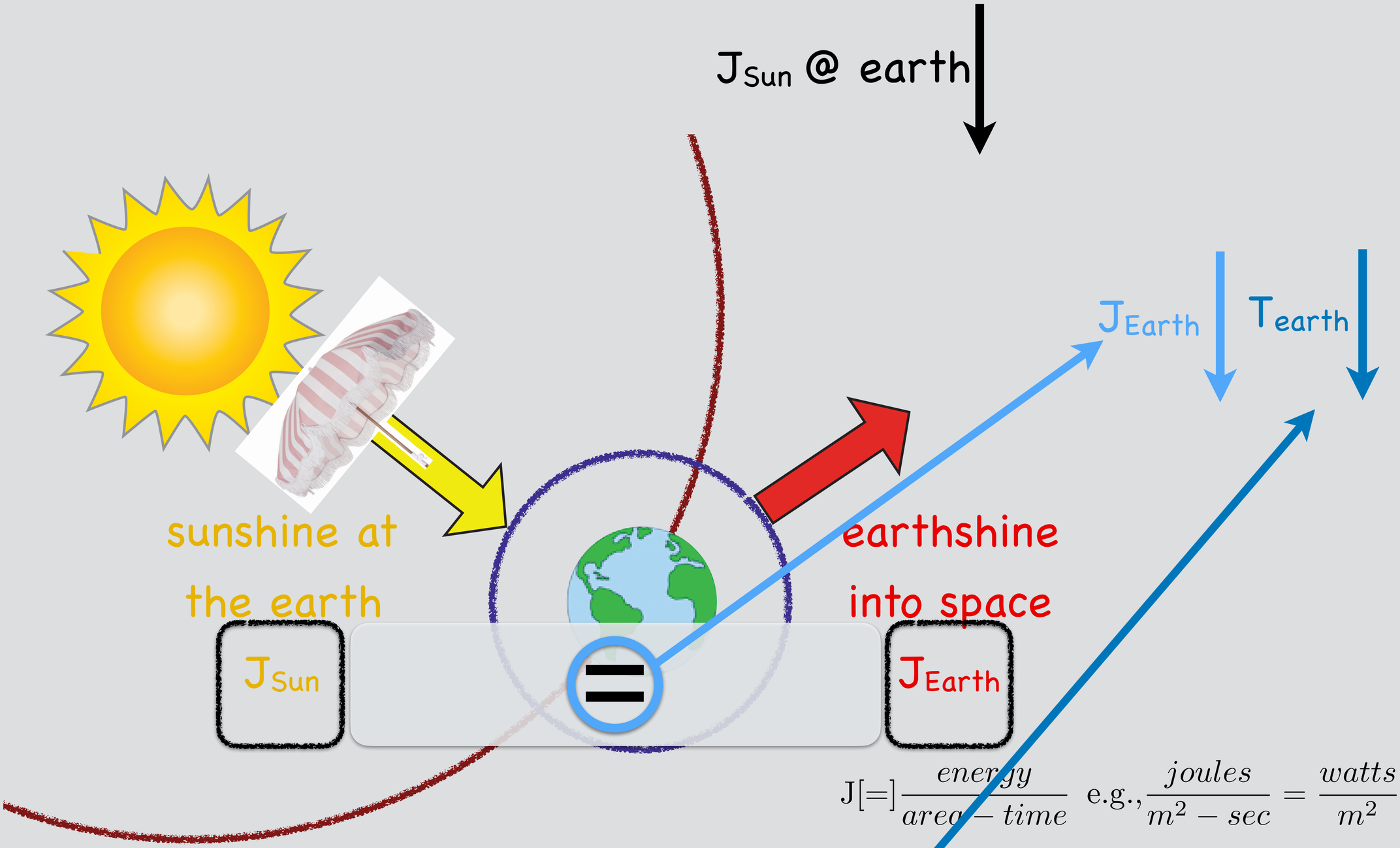
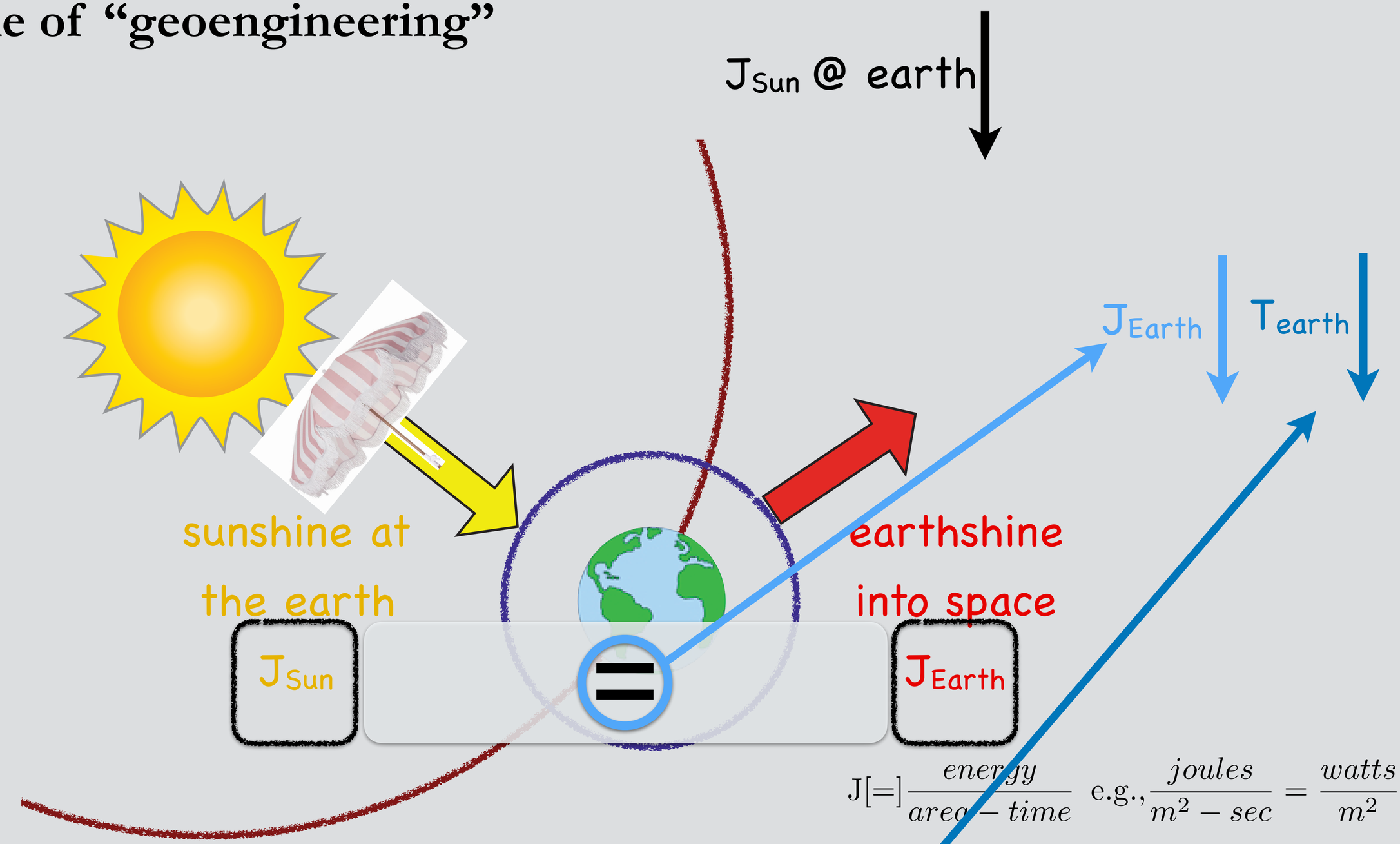


$$J[=]\frac{energy}{area-time} \quad \text{e.g.,} \frac{joules}{m^2-sec} = \frac{watts}{m^2}$$

$$= \sigma T^4$$

an example of “geoengineering”



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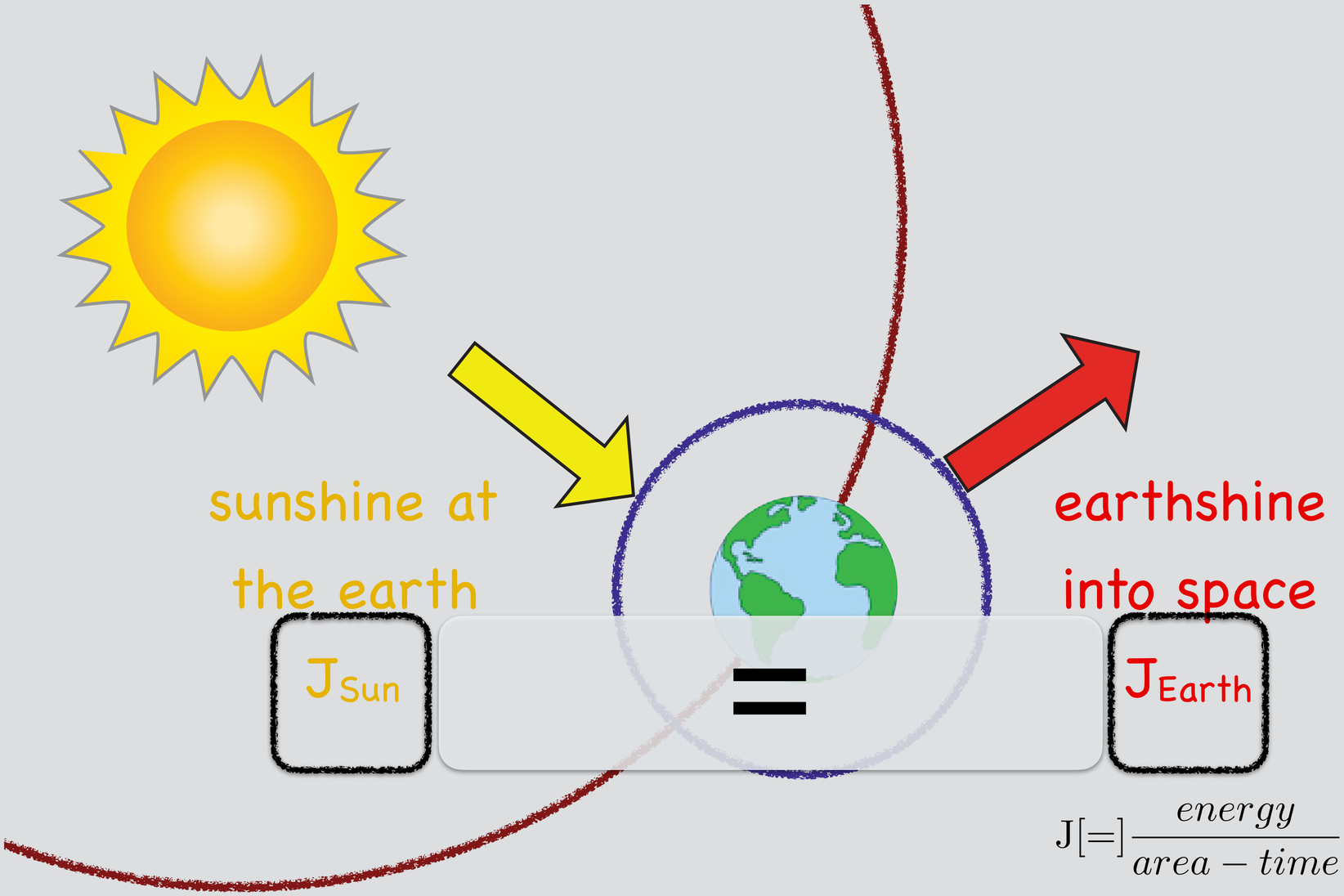
$$= \sigma T^4$$



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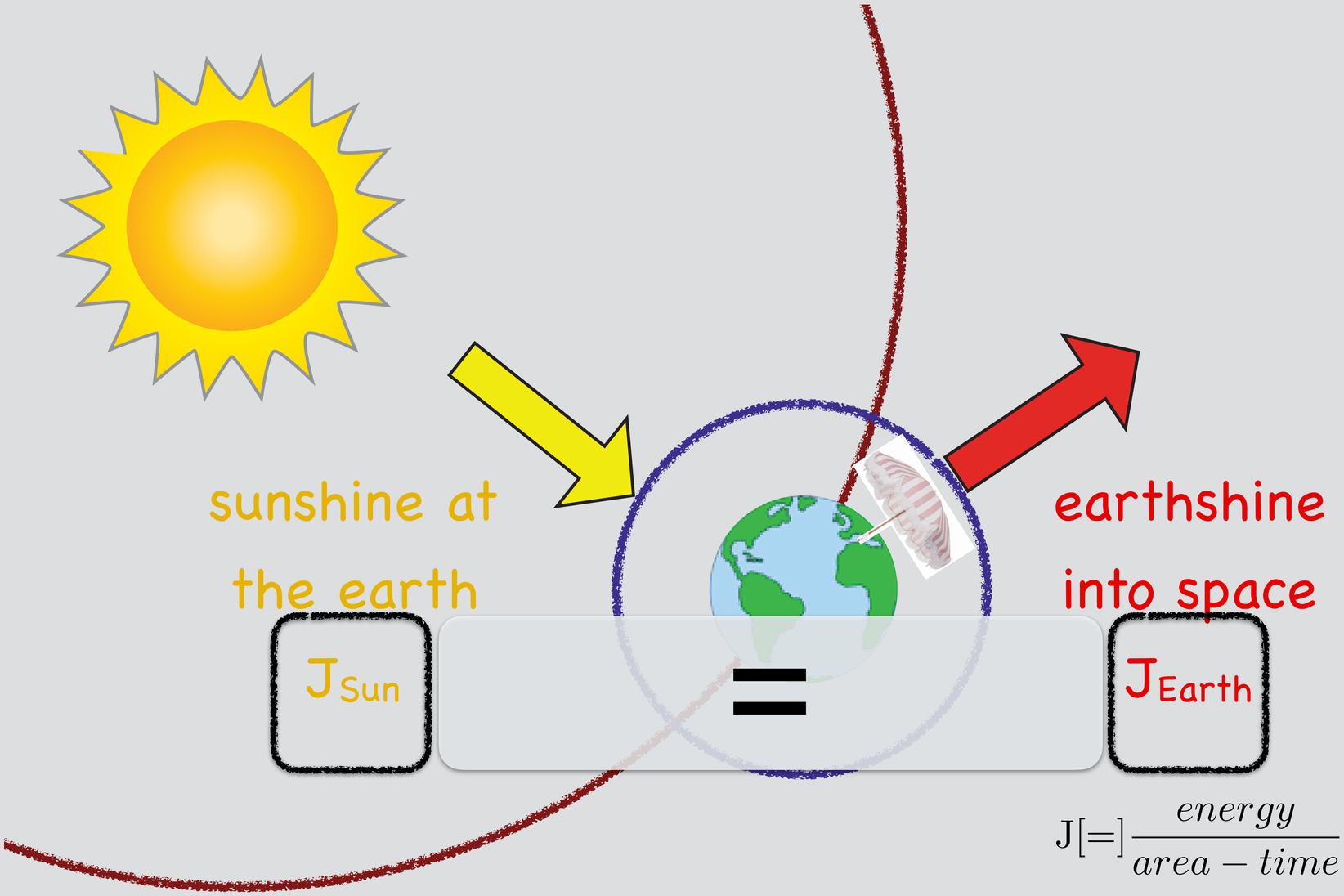

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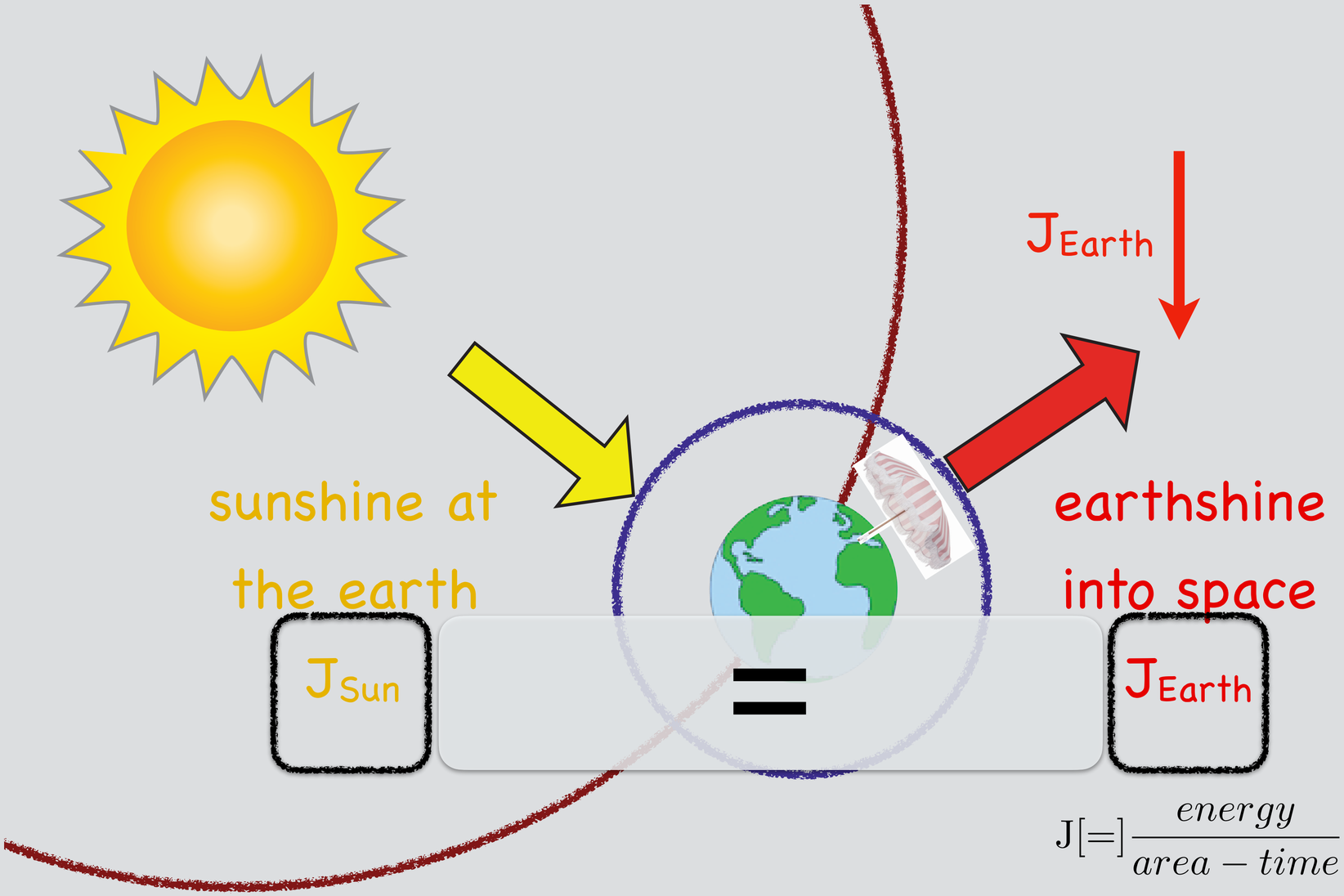

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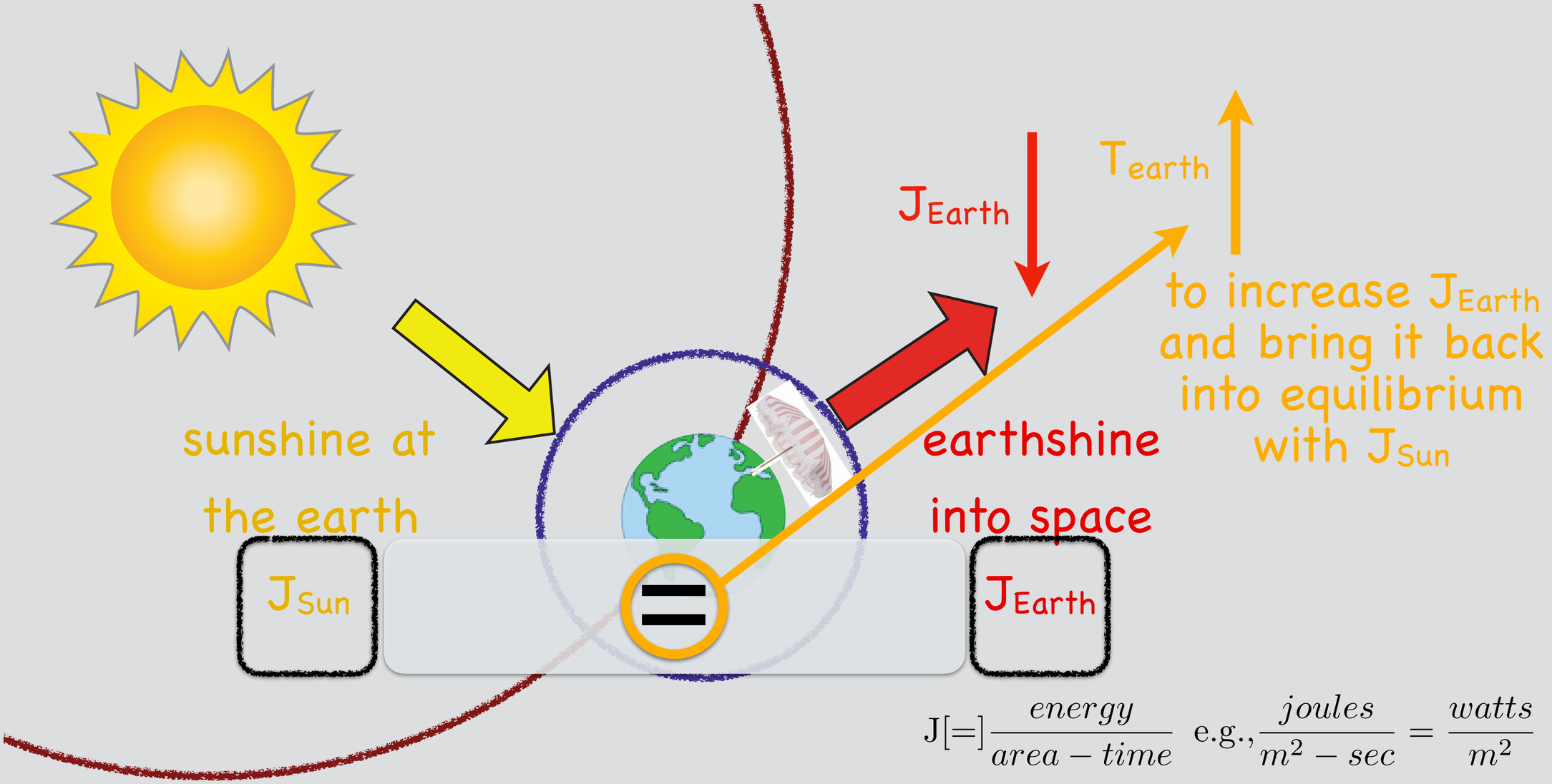

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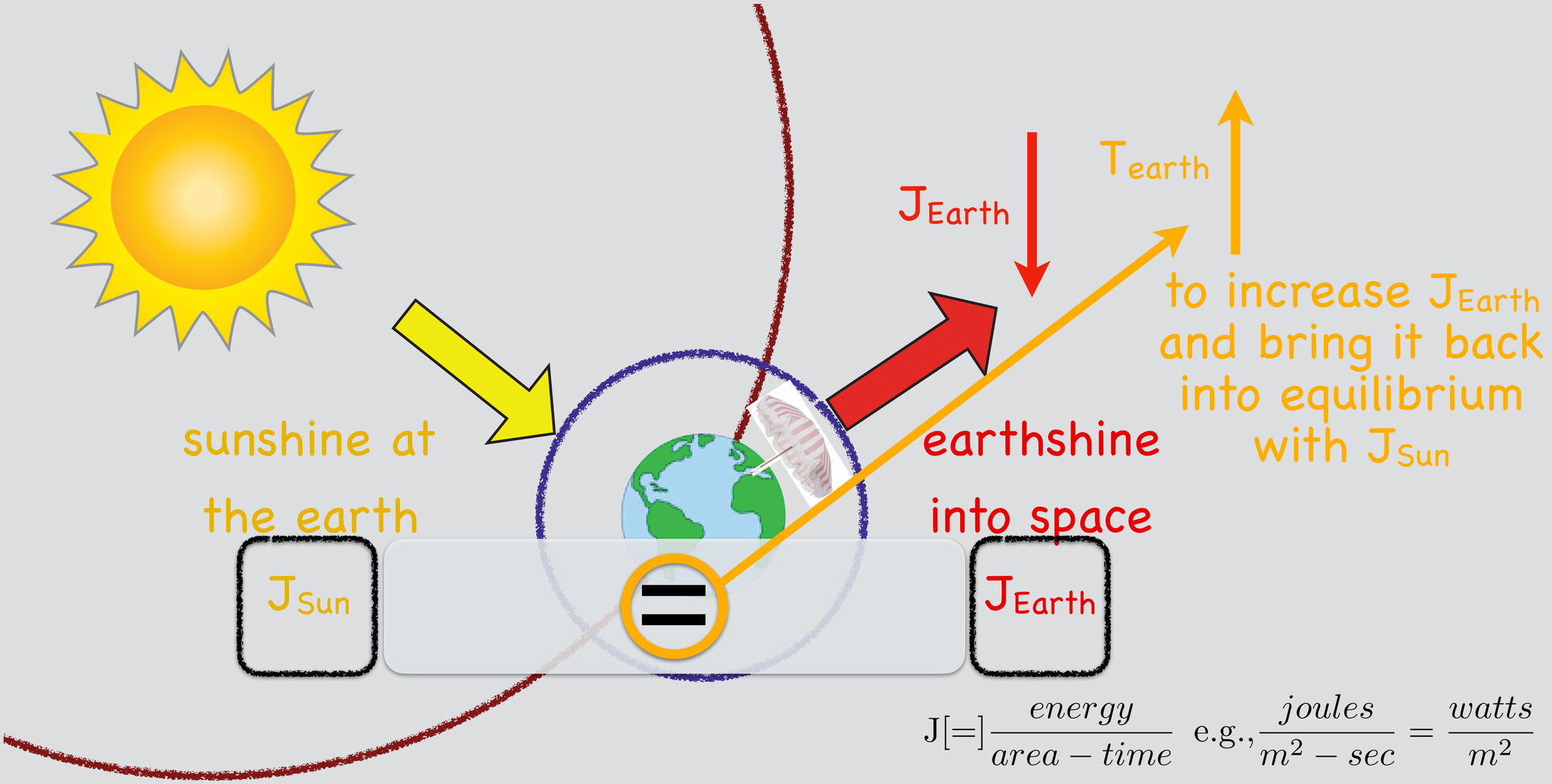
Umbrella@Earth is an example of changes in "radiative forcing"



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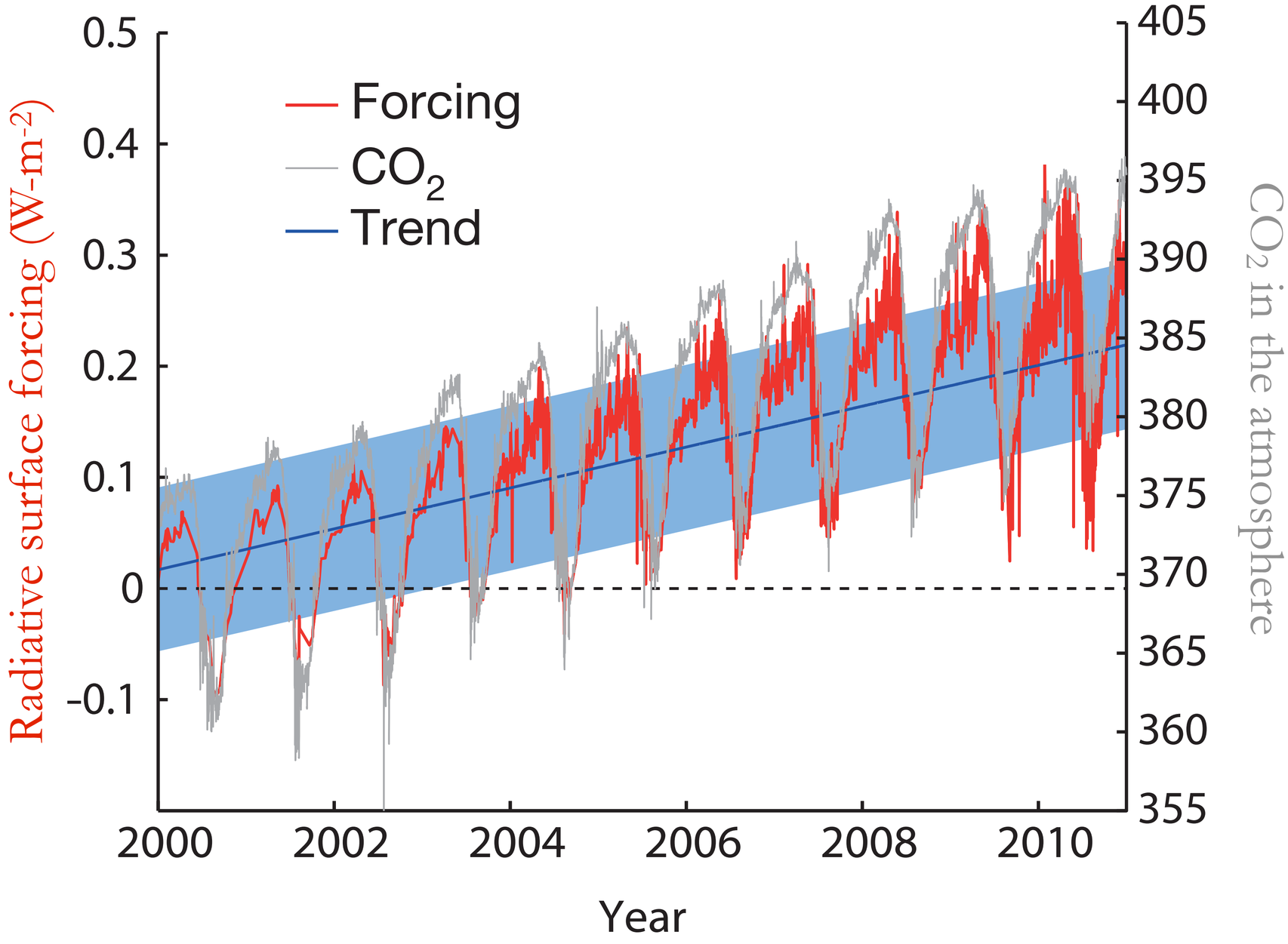
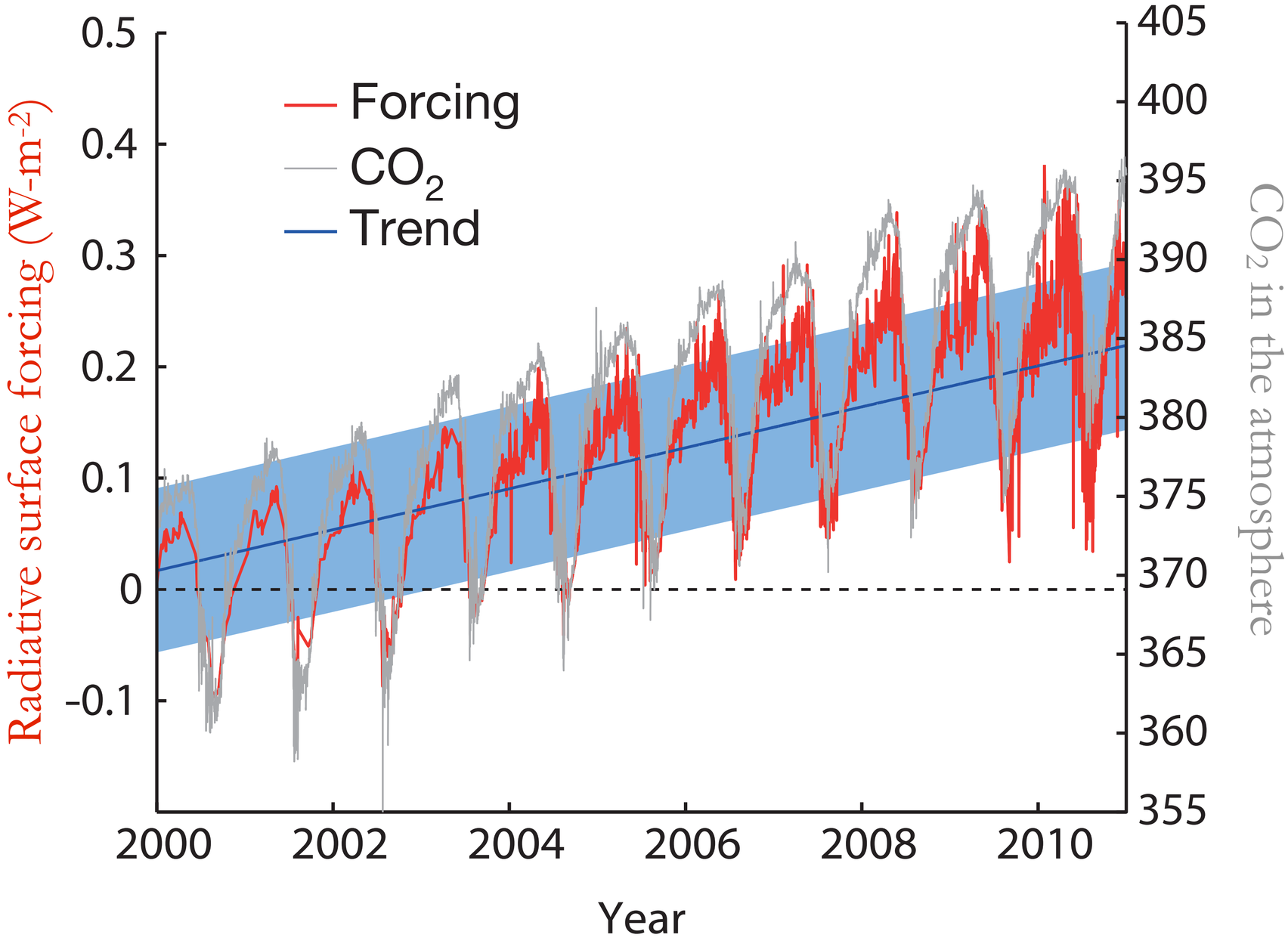


Feldman, D.R., Collins, W.D., Gero, P.J., Torn, M.S., Mlawer, E.J., and Shippert, T. R., Nature, 2015

Our CO_2 waste is **warming** the planet by radiative forcing



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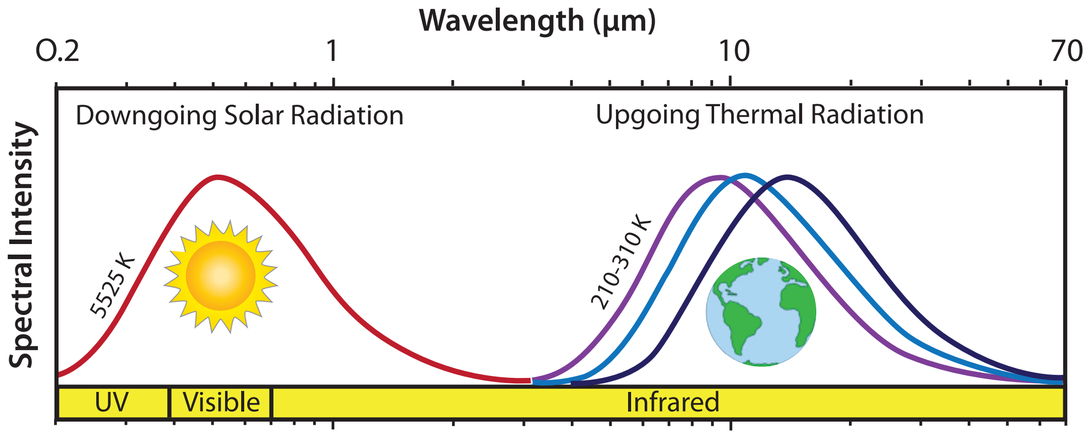

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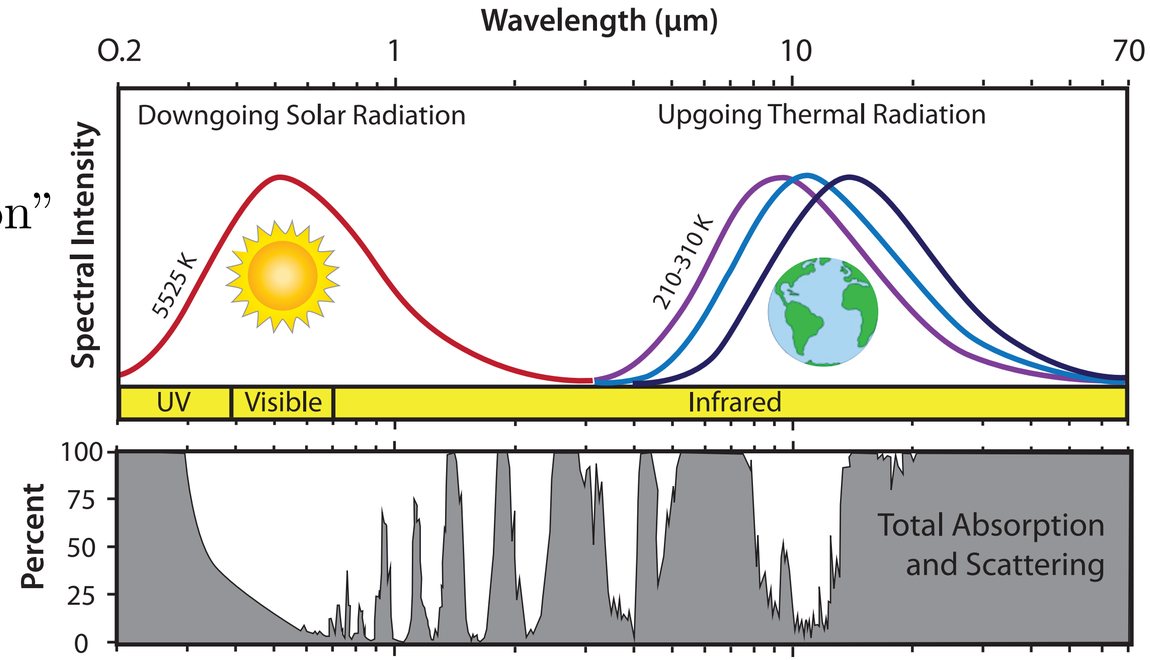

The role of our atmosphere:
absorb incoming sunshine…
and
absorb outgoing earthshine

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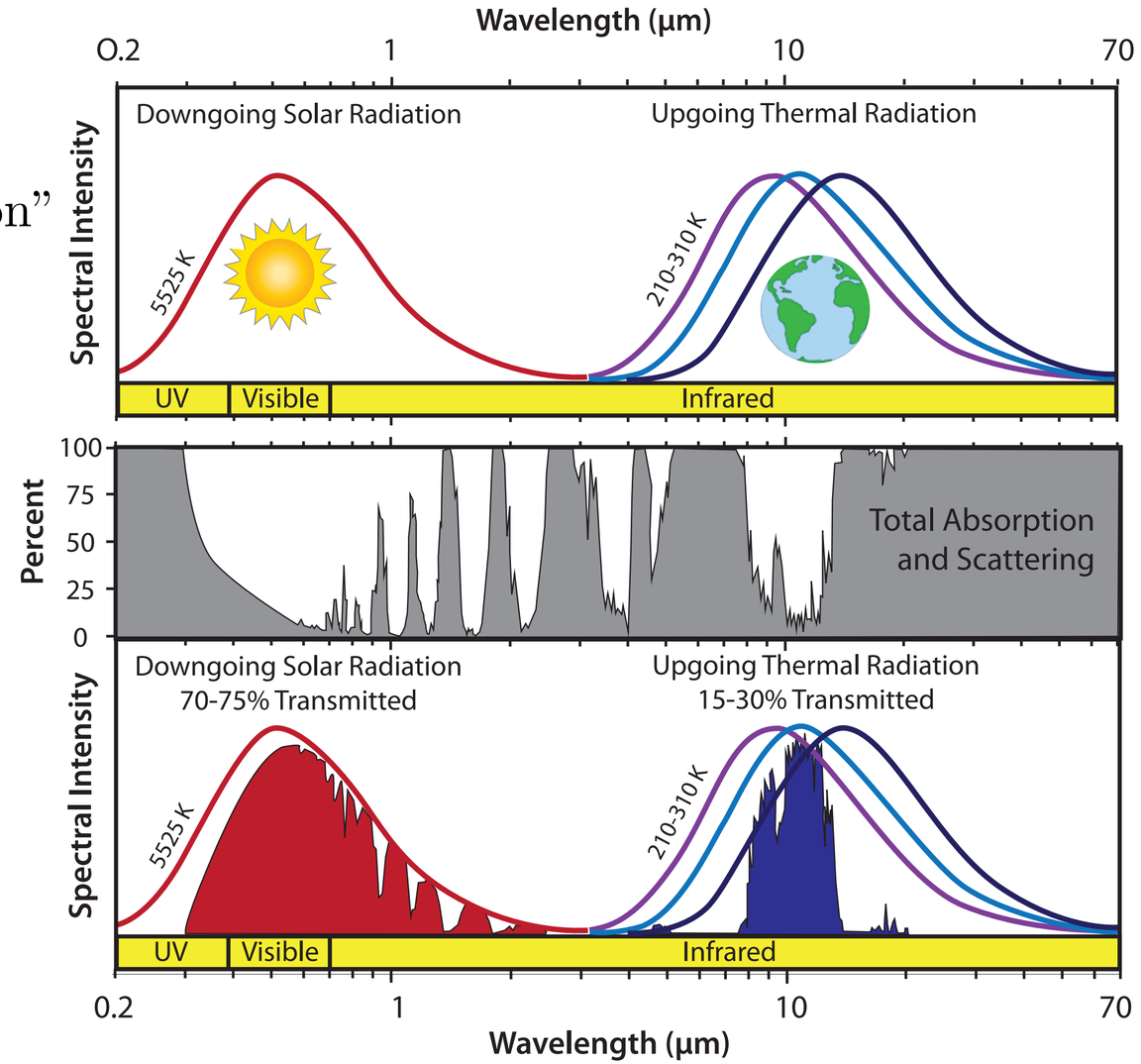

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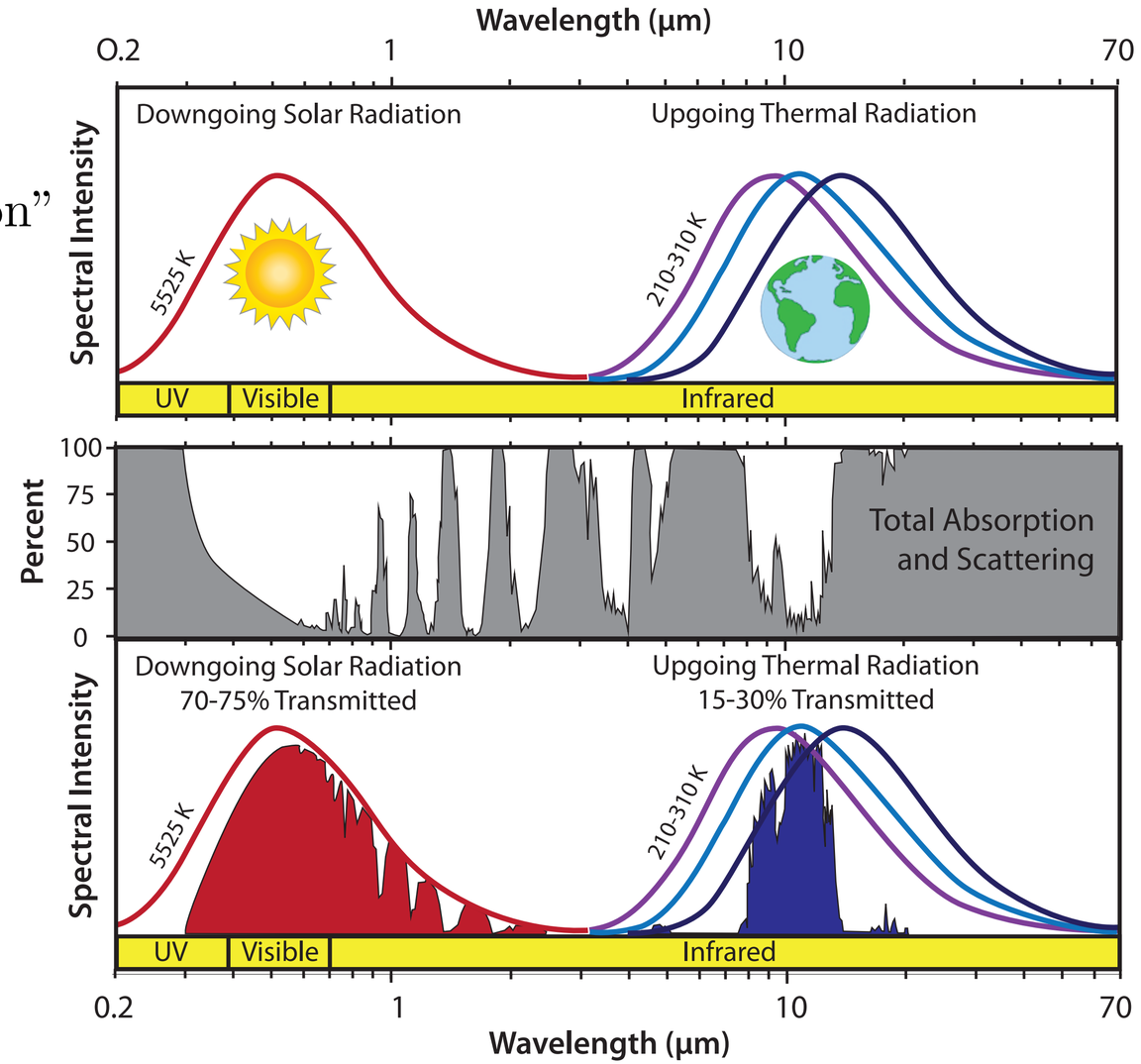

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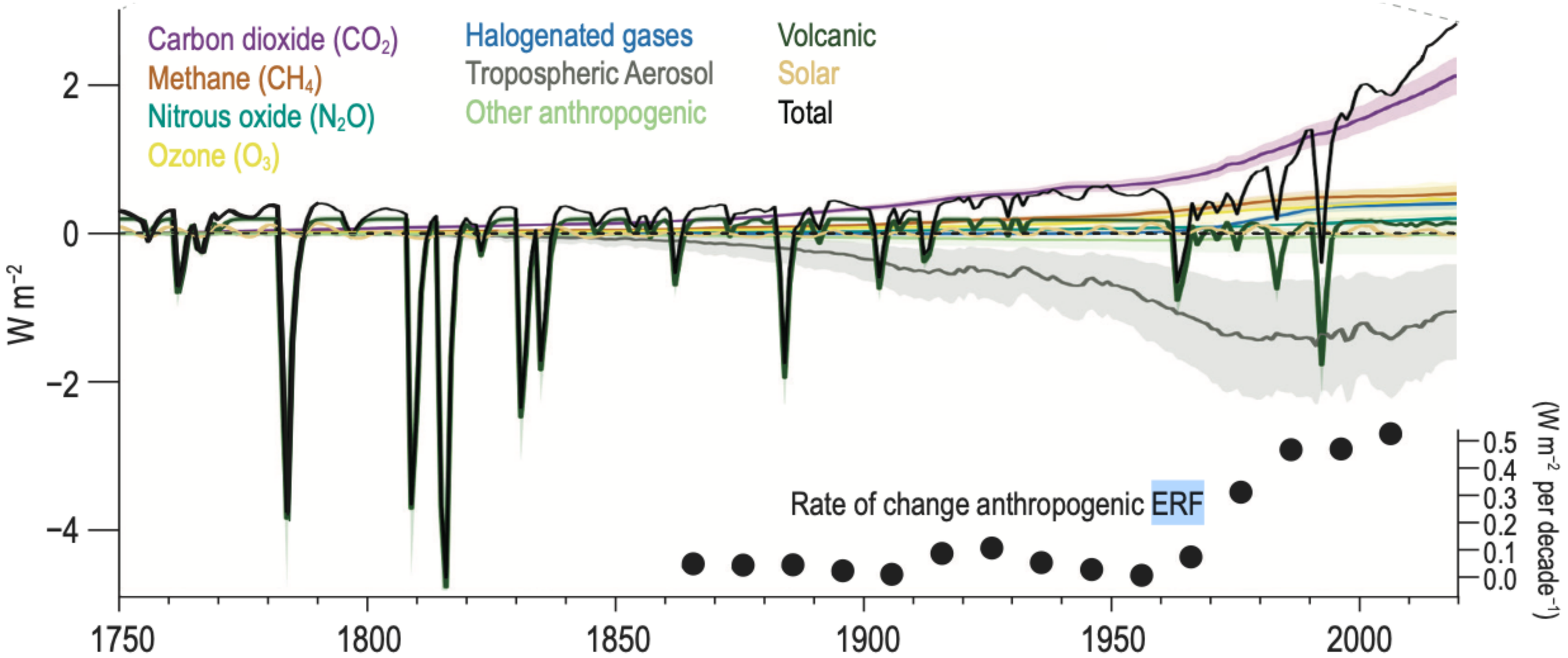
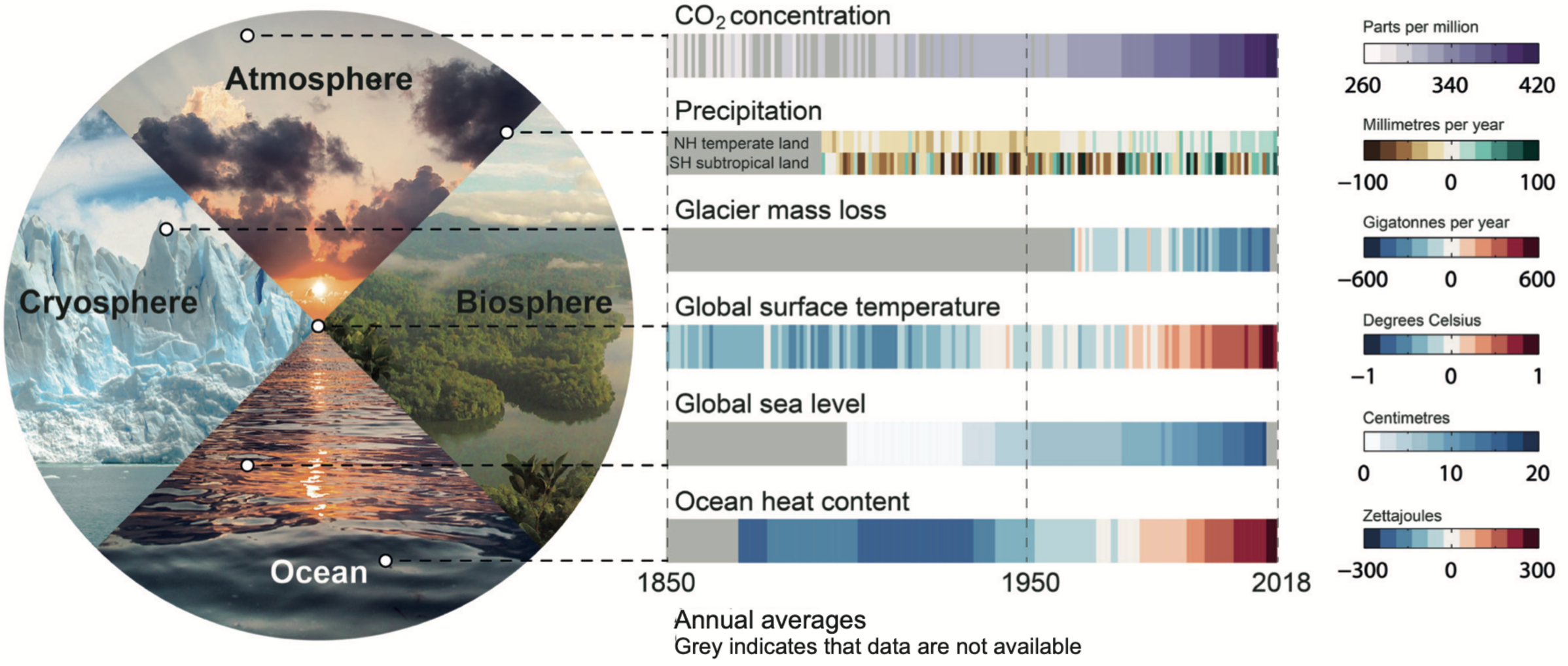
Changes in radiative forcing with time from various sources



Consequences


Atmosphere
Cryosphere
Biosphere
Ocean
CO_2 concentration
Parts per million
260
340
420
Precipitation
NH temperate land
SH subtropical land
Millimetres per year
−100
0
100
Glacier mass loss
Gigatonnes per year
−600
0
600
Global surface temperature
Degrees Celsius
−1
0
1
Global sea level
Centimetres
0
10
20
Ocean heat content
Zettajoules
−300
0
300
1850
1950
2018
Annual averages
Grey indicates that data are not available

Global warming has increased global economic inequality

Noah S. Diffenbaugh[a,b,1] and Marshall Burke[a,c,d]

9808–9813 | PNAS | May 14, 2019 | vol. 116 | no. 20

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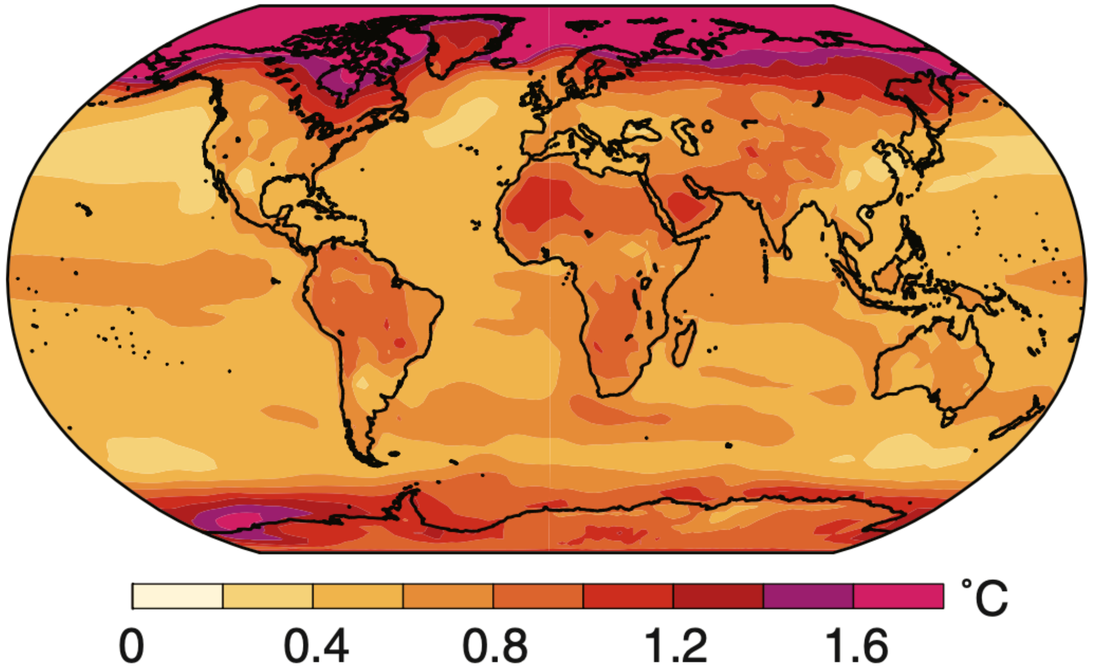
change in temperature from anthropogenic forcing



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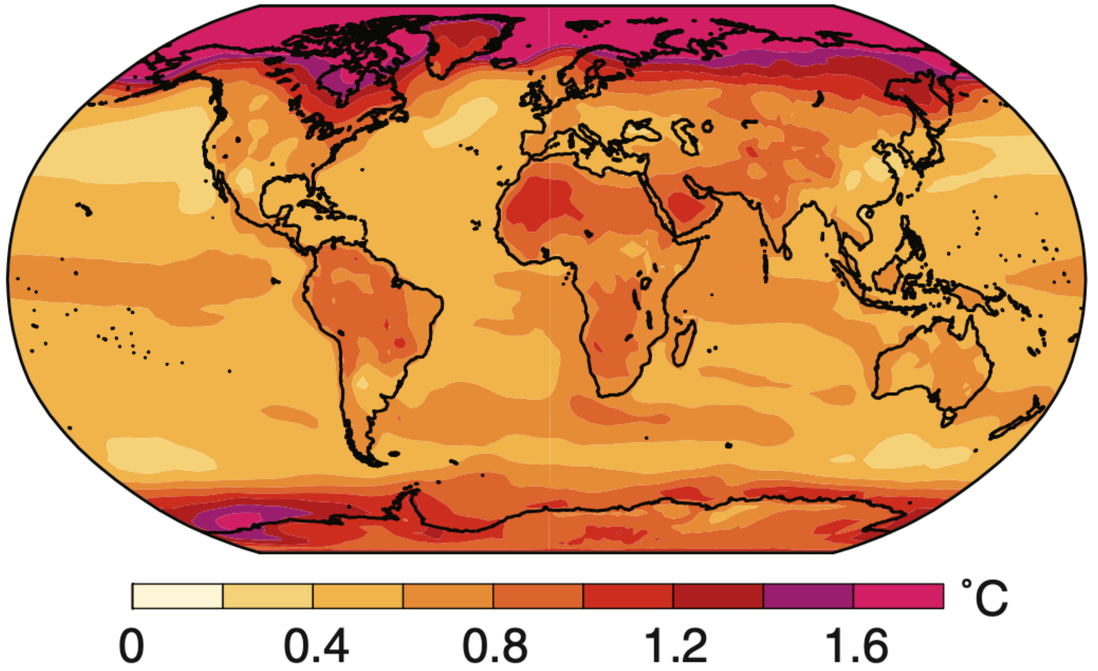

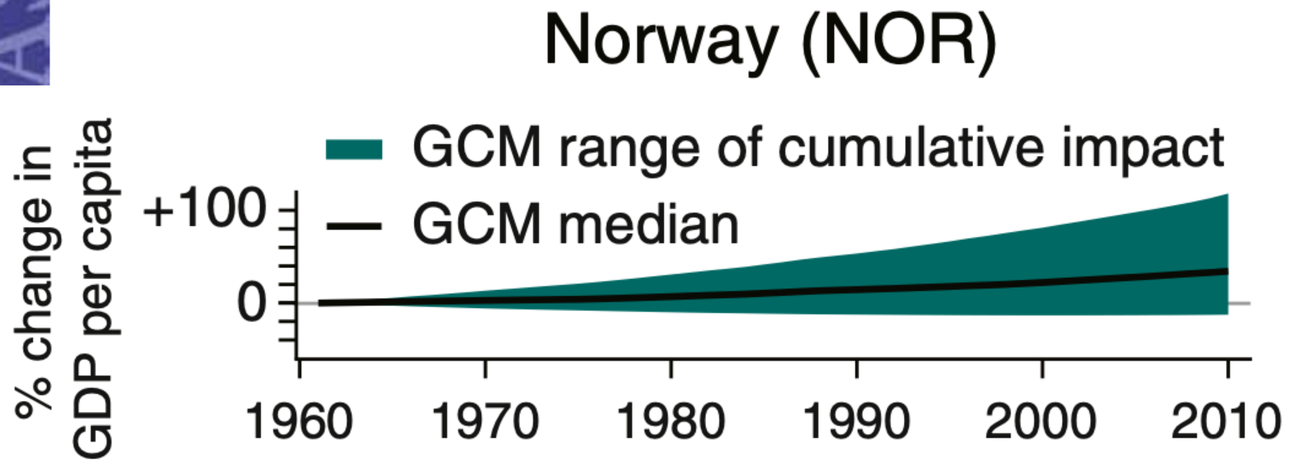

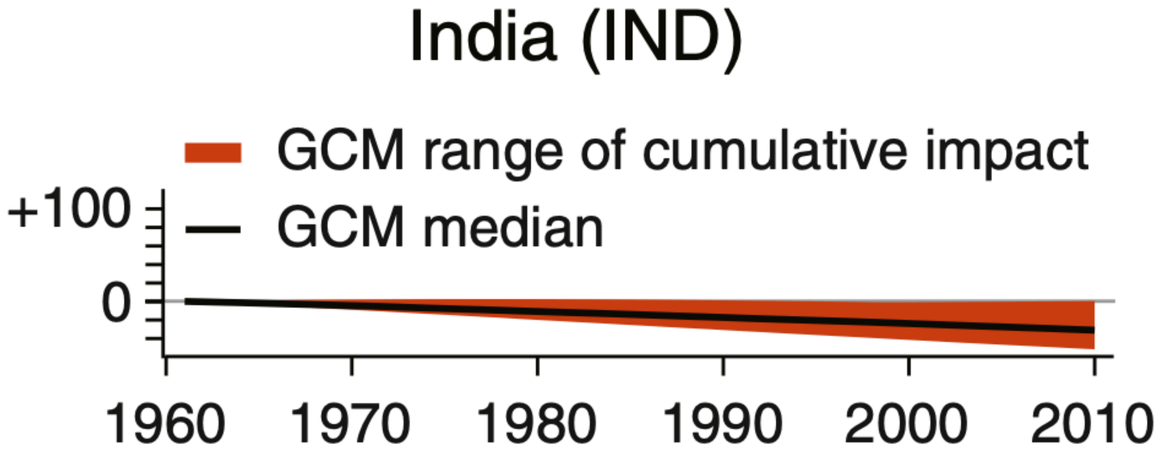

"Cool" countries benefit economically with warming

"Warm" countries experience cumulative losses with warming

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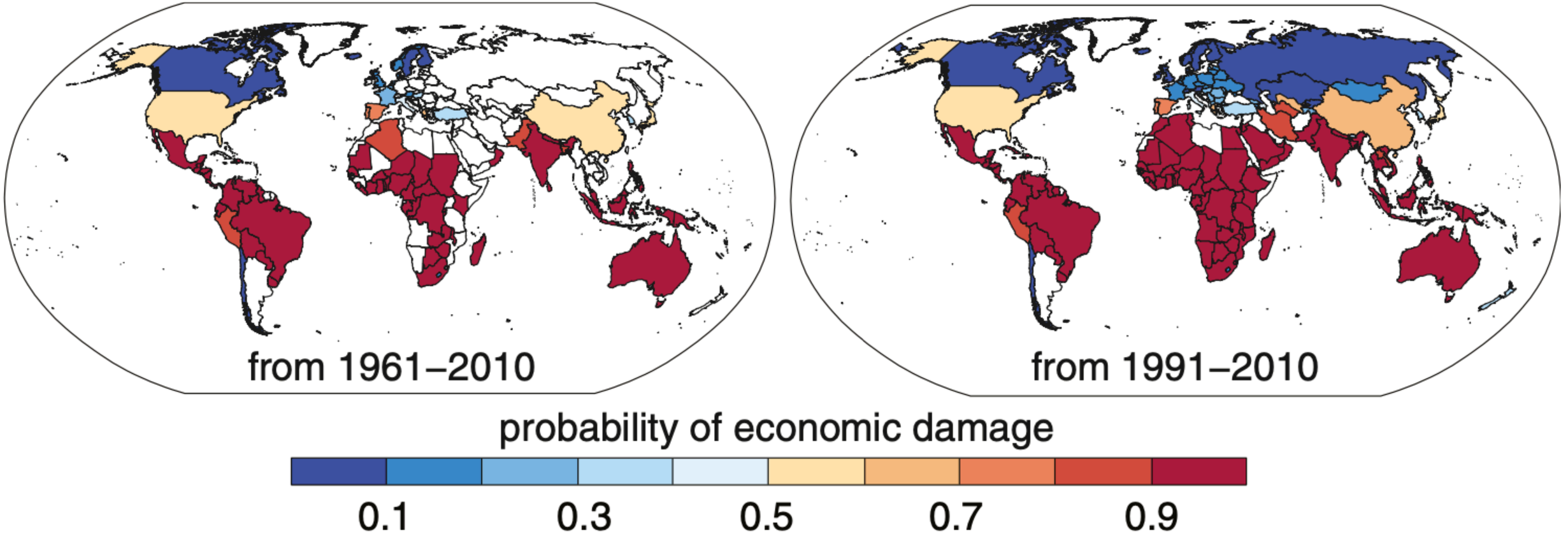

What are the FUTURE consequences?

nature climate change

NATURE CLIMATE CHANGE | VOL 8 | AUGUST 2018 | 723–729 |

ARTICLES

https://doi.org/10.1038/s41558-018-0222-x

Higher temperatures increase suicide rates in the United States and Mexico USA, Chile, Canada

Marshall Burke[1,2,3*], Felipe González[4], Patrick Baylis[5], Sam Heft-Neal[2], Ceren Baysan[6], Sanjay Basu[7] and Solomon Hsiang[3,8]

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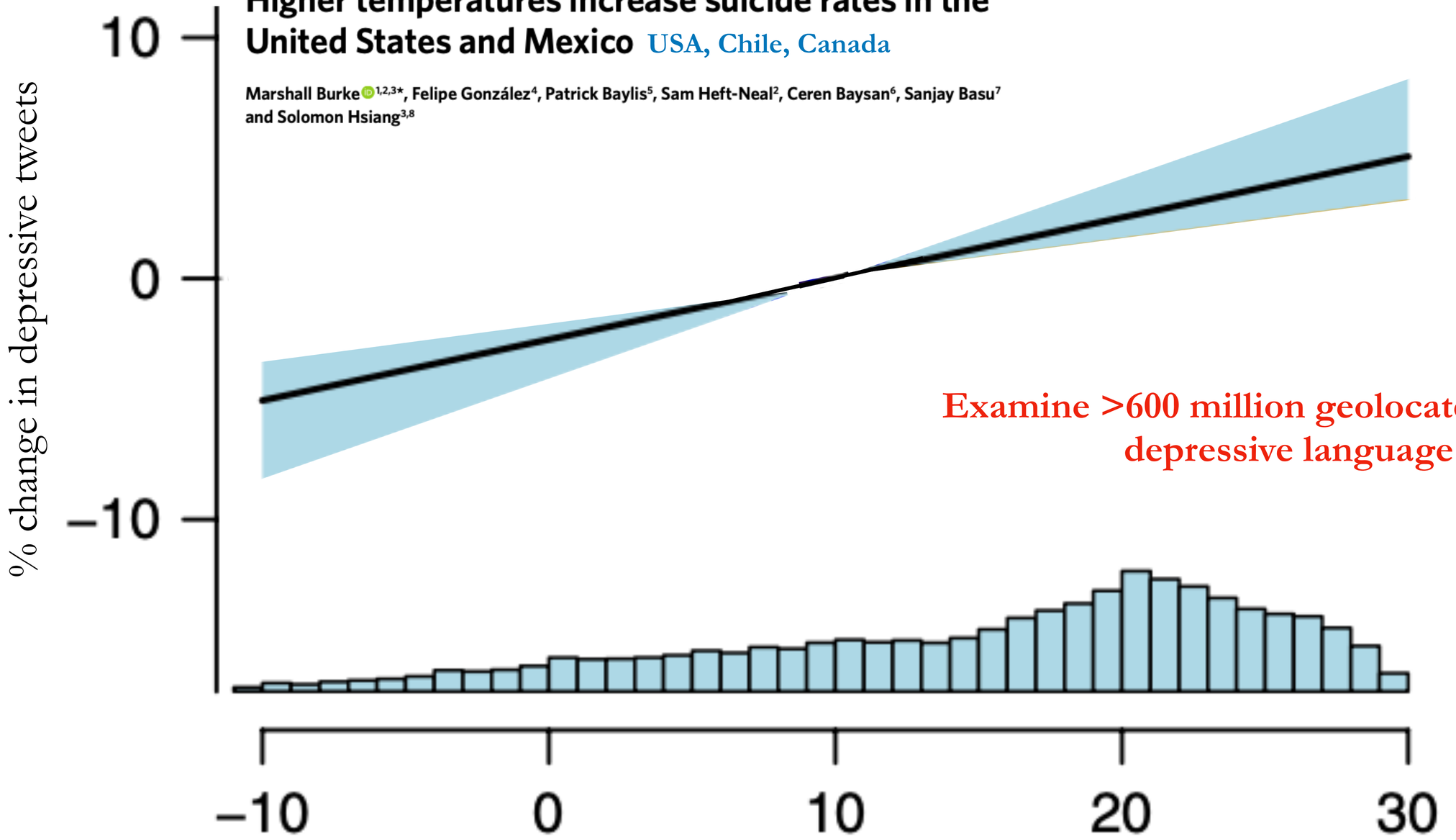

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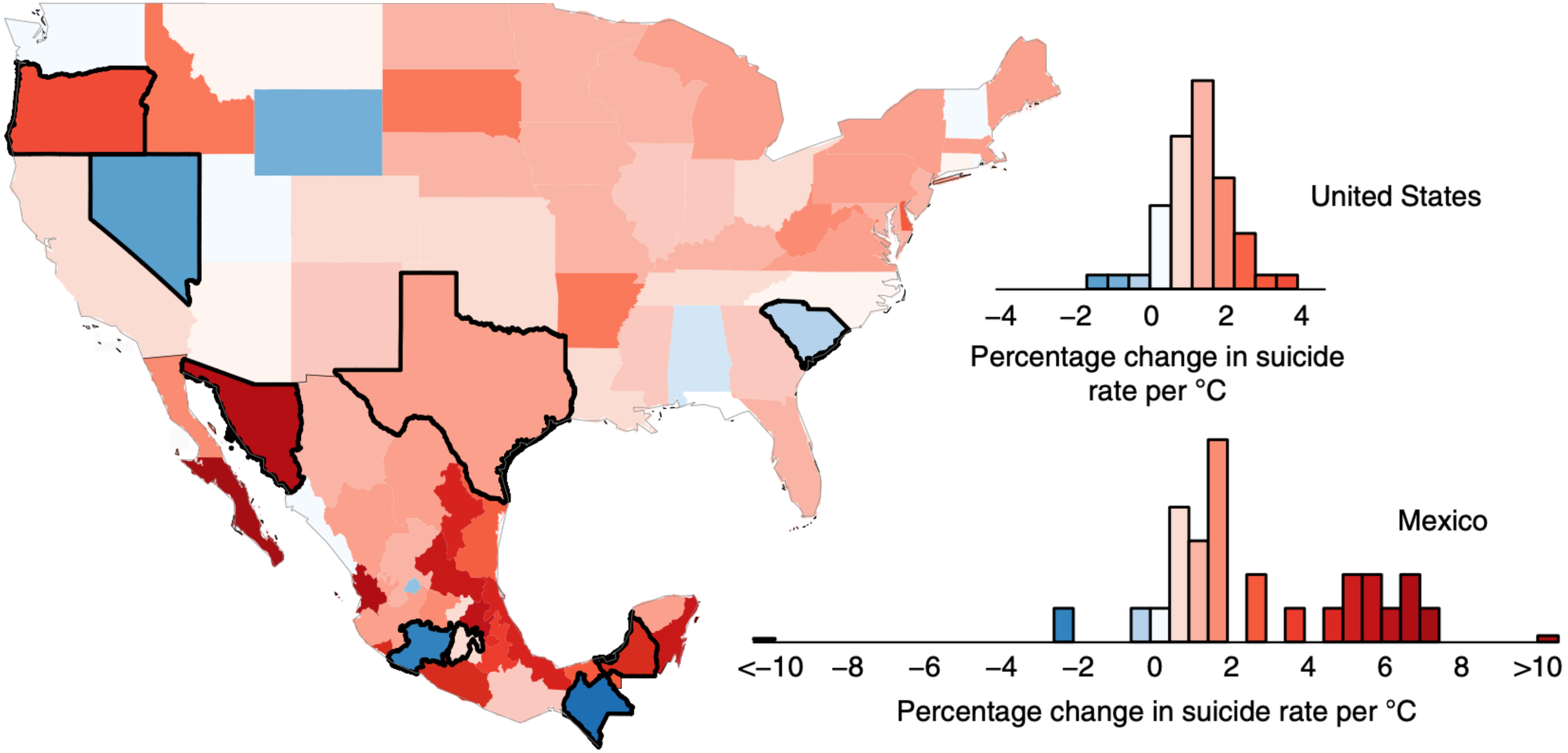
We are more likely to commit suicide when it is hot…



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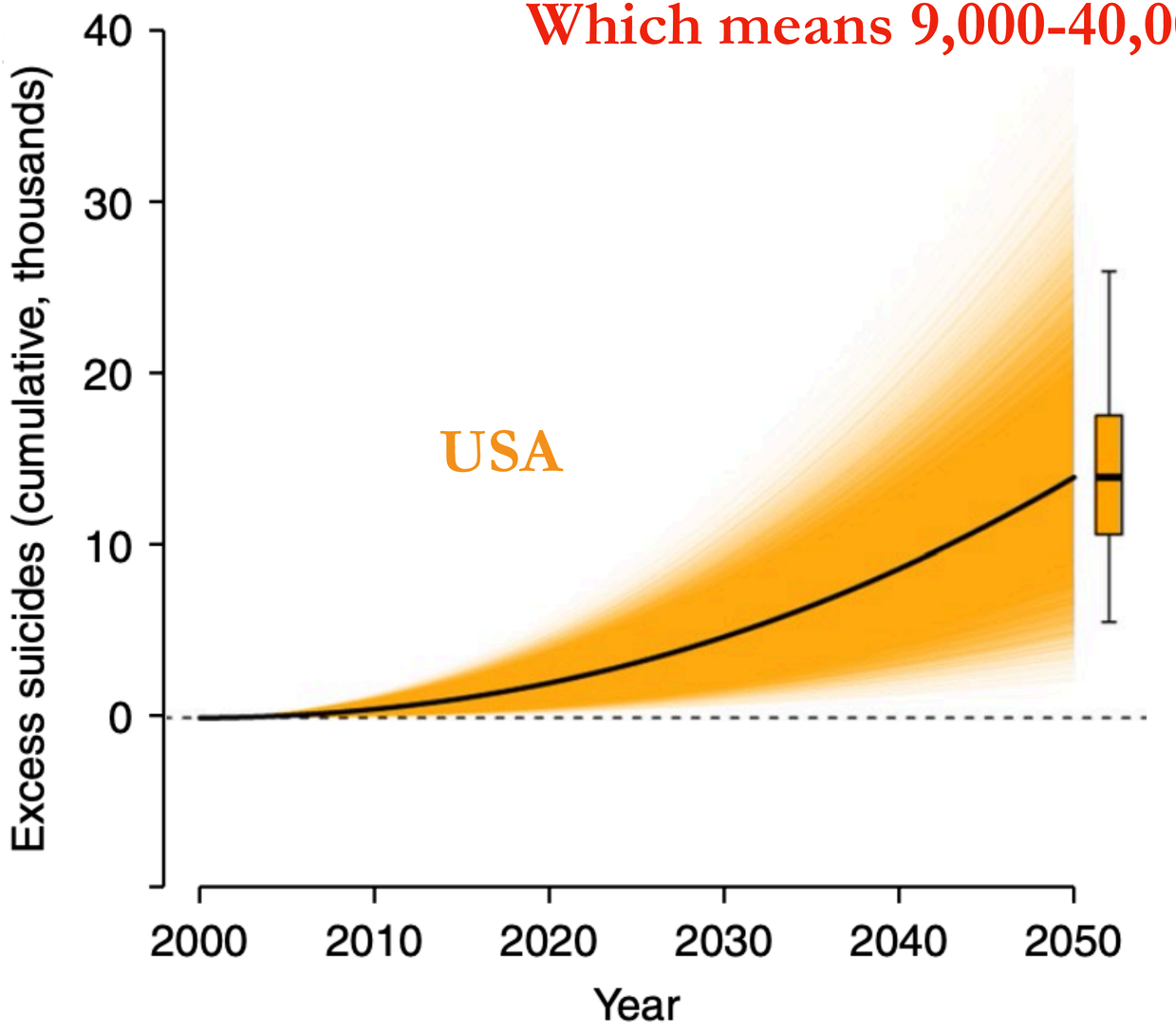
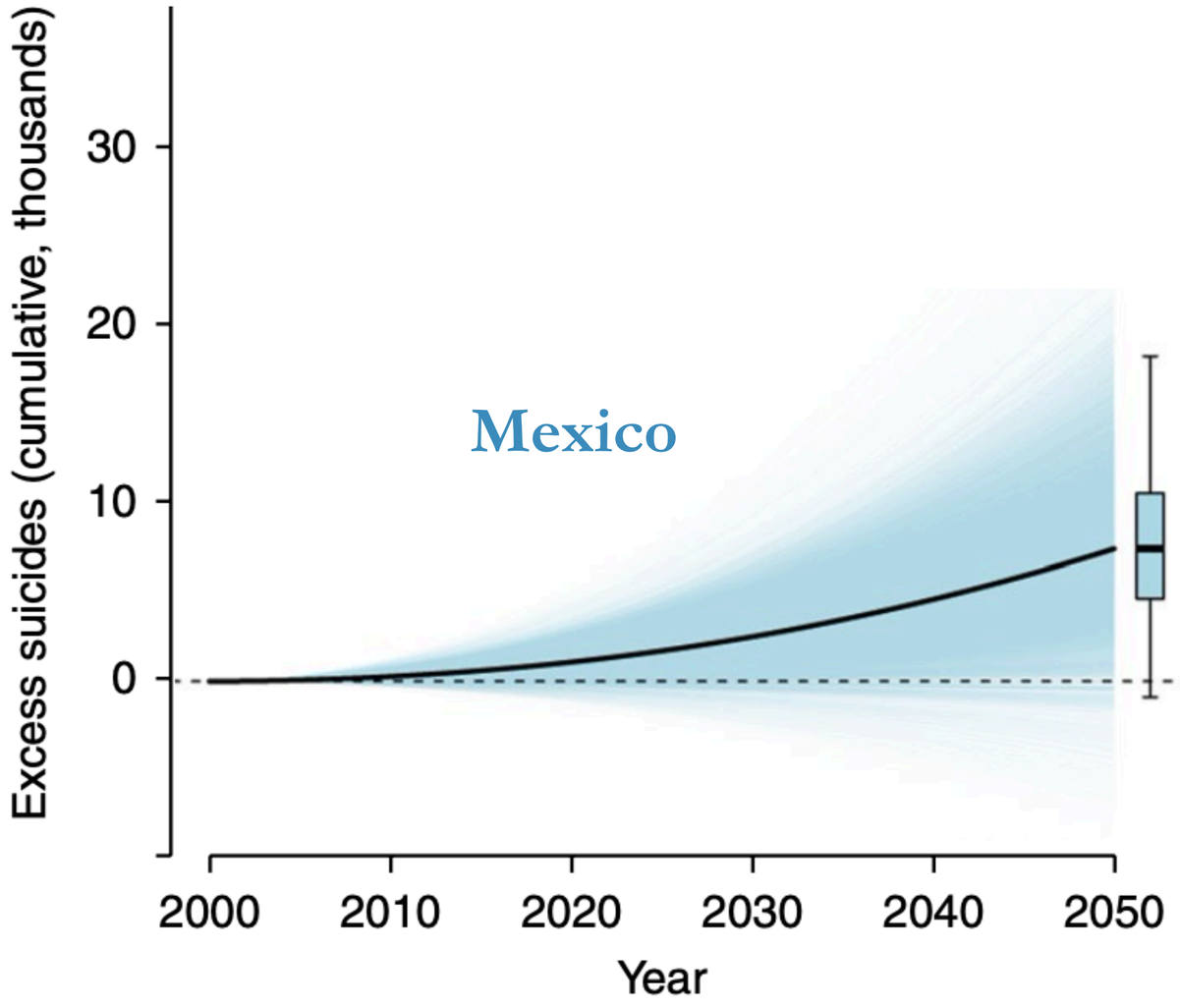
Higher temperatures increase suicide rates in the United States and Mexico

Which means 9,000-40,000 additional suicides





SCIENTIFIC REPORTS

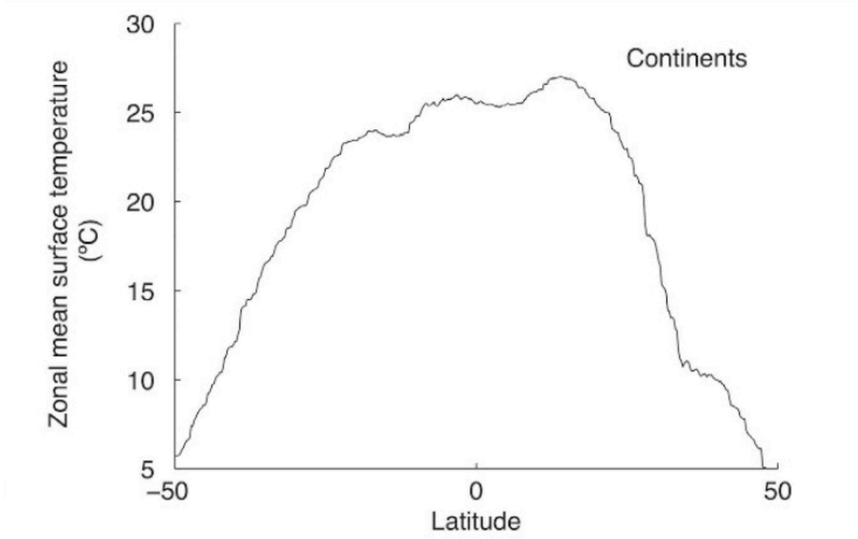
OPEN

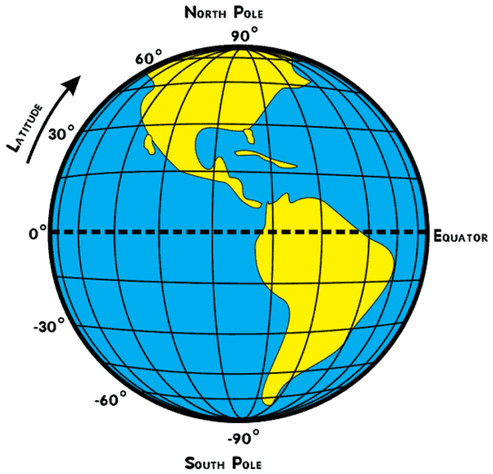
Potentially Extreme Population Displacement and Concentration in the Tropics Under Non-Extreme Warming 2 degrees C

Received: 16 December 2015
Accepted: 21 April 2016
Published: 09 June 2016

Solomon M. Hsiang[1,2] & Adam H. Sobel[3,4,5]

2 degree C scenario





https://www.geographyrealm.com/latitude-longitude/

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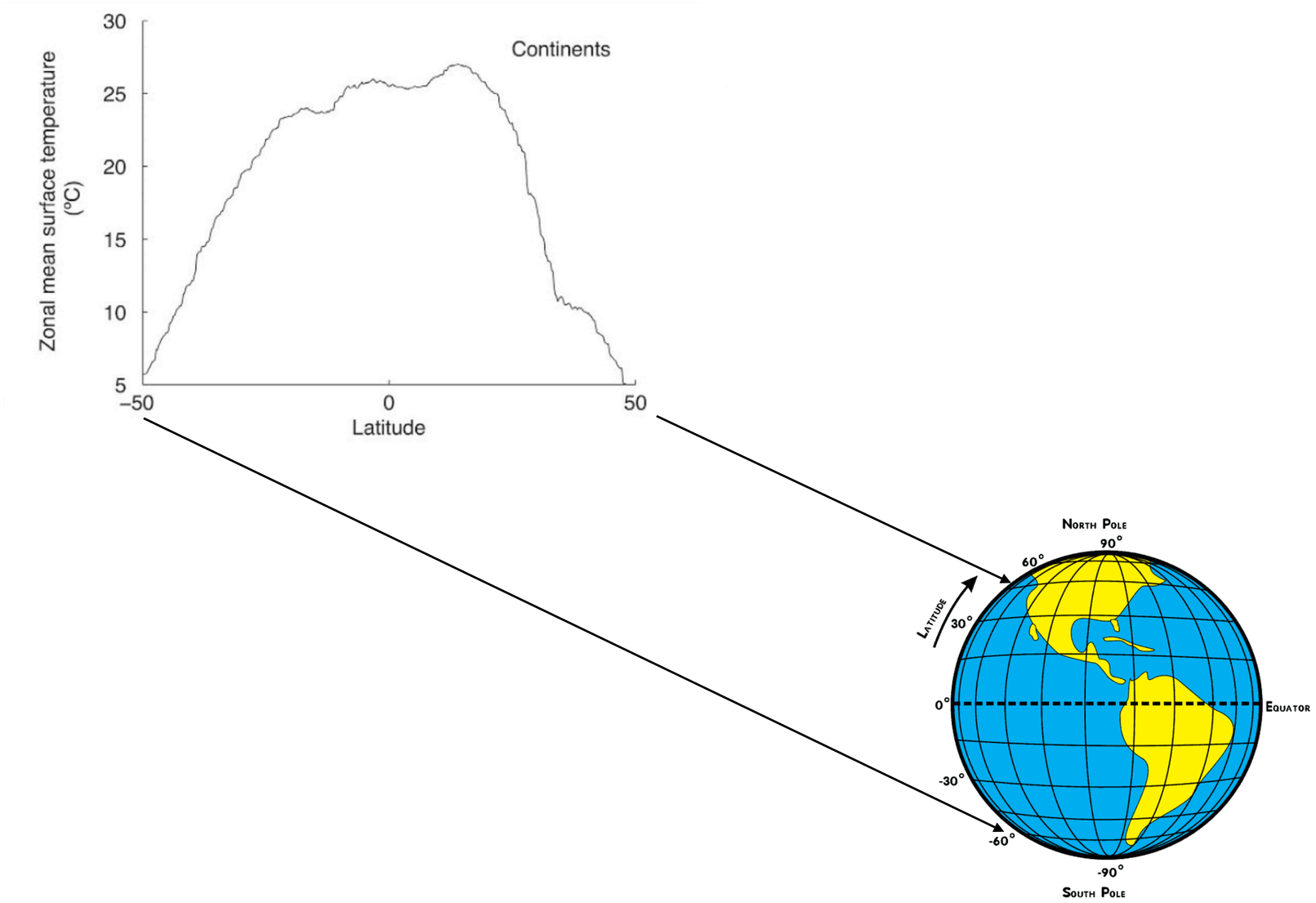

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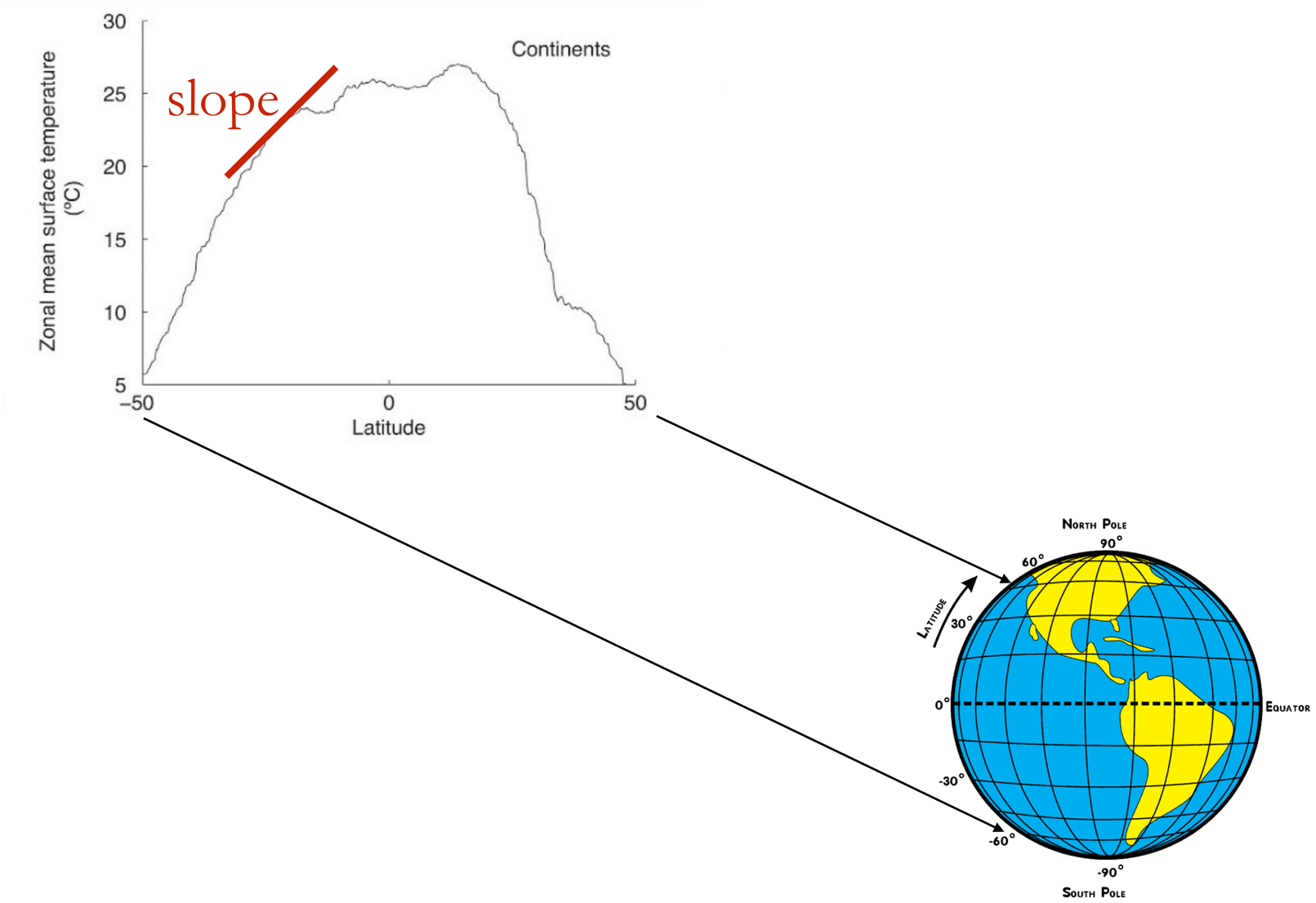

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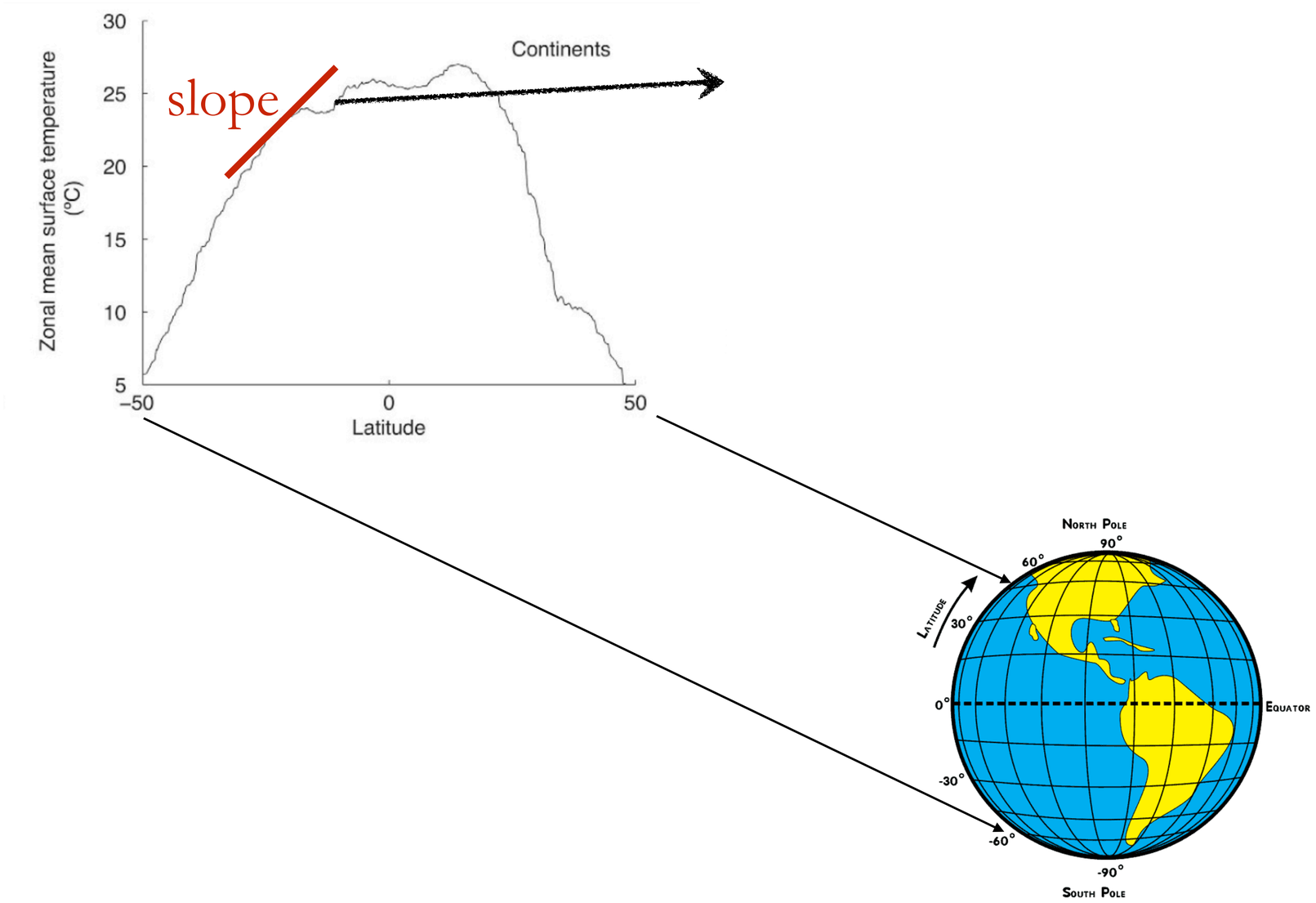

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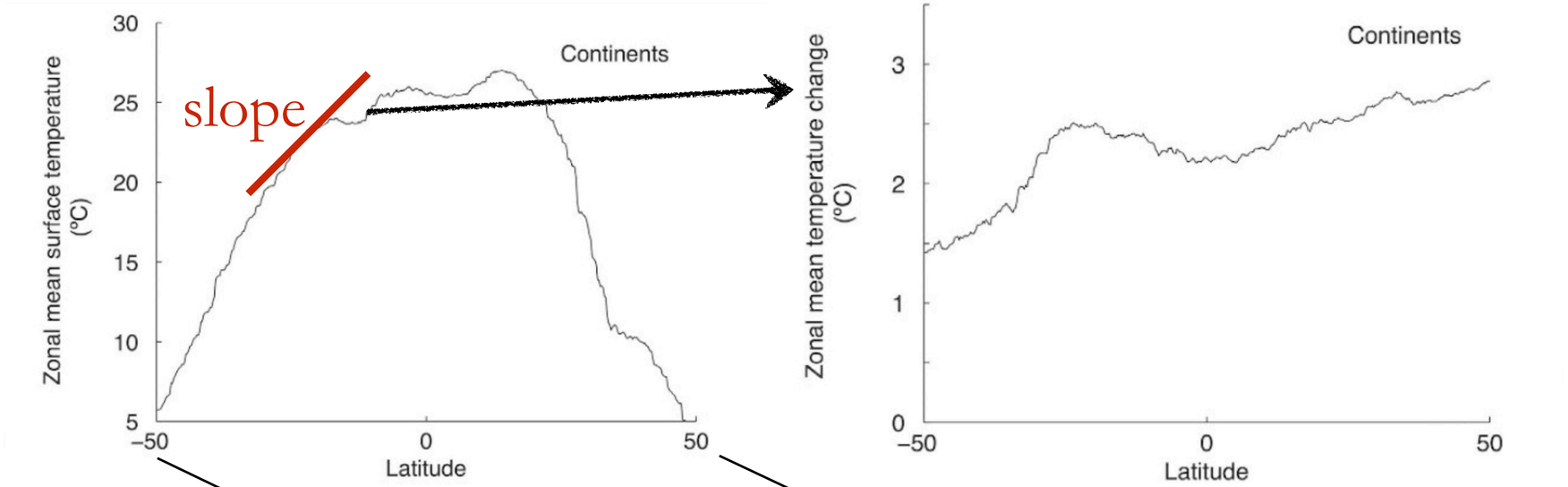

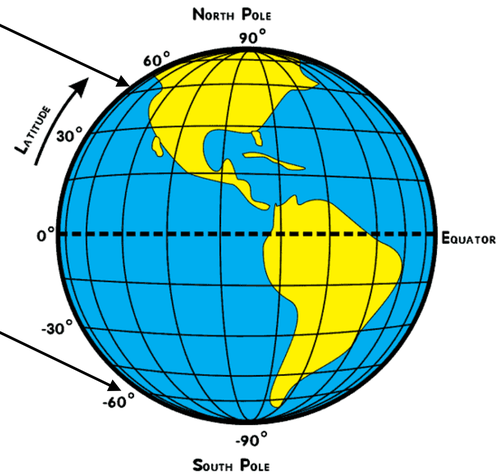

https://www.geographyrealm.com/latitude-longitude/

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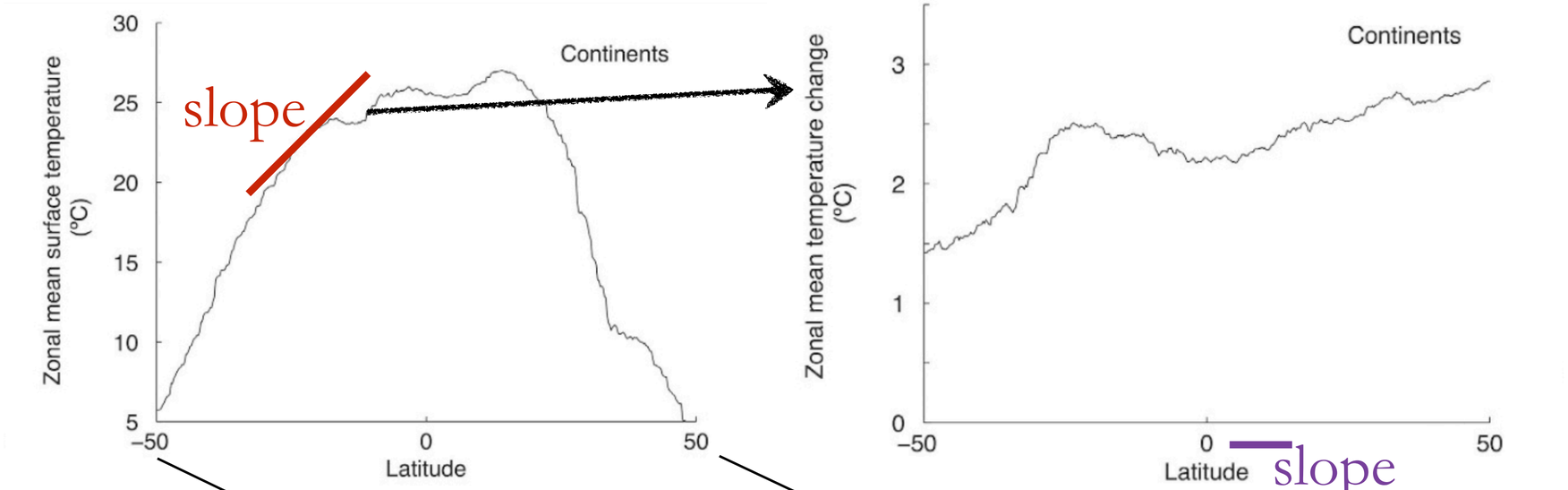

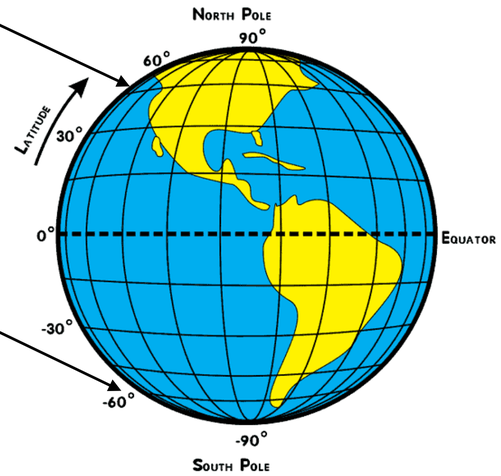

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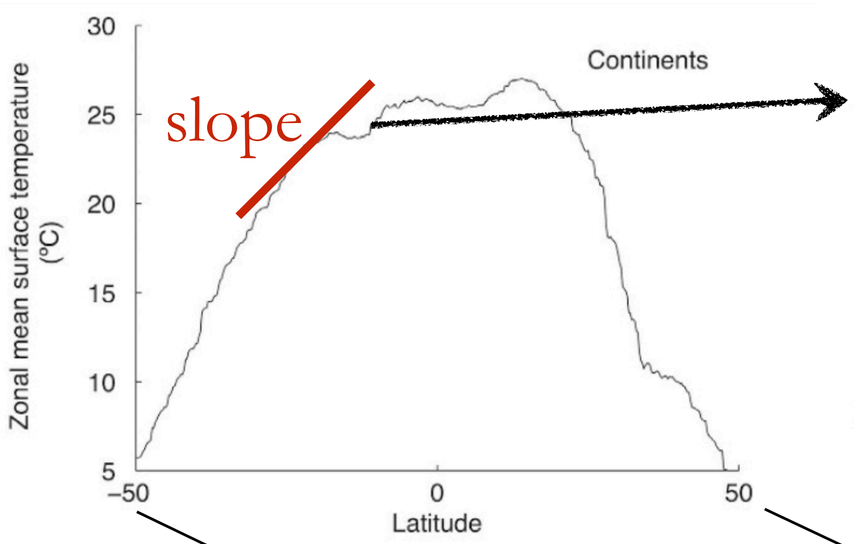

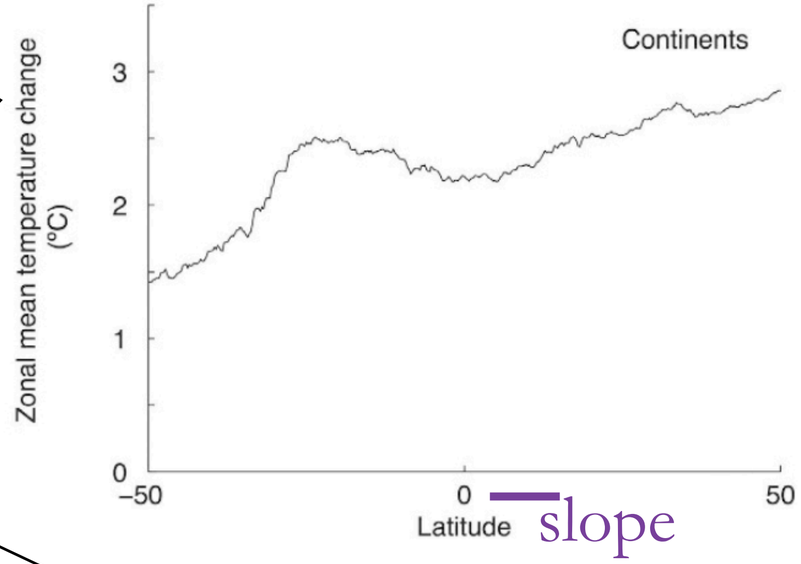

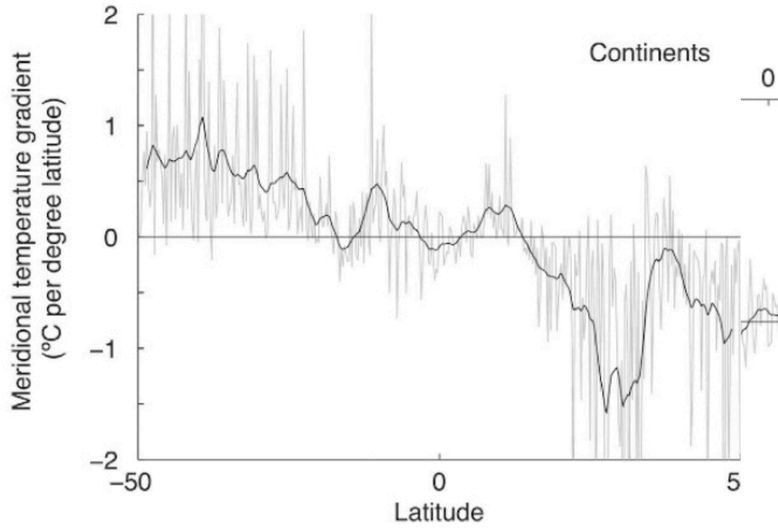

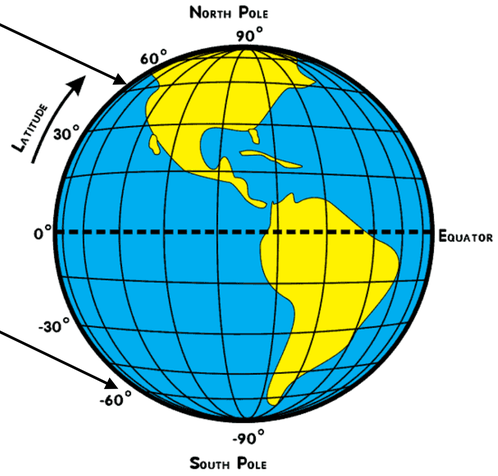

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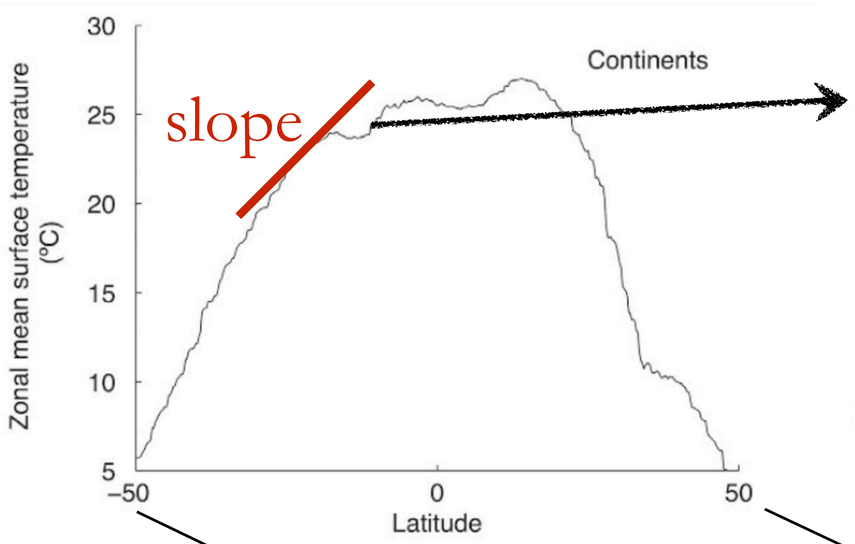

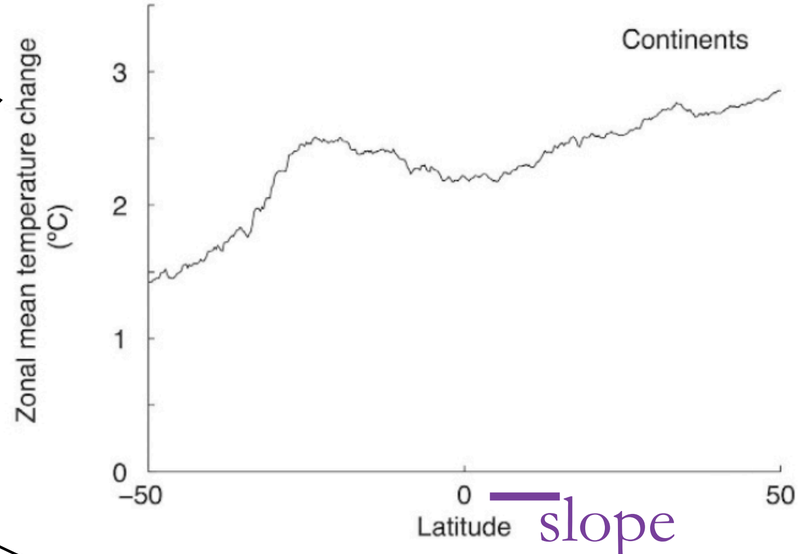

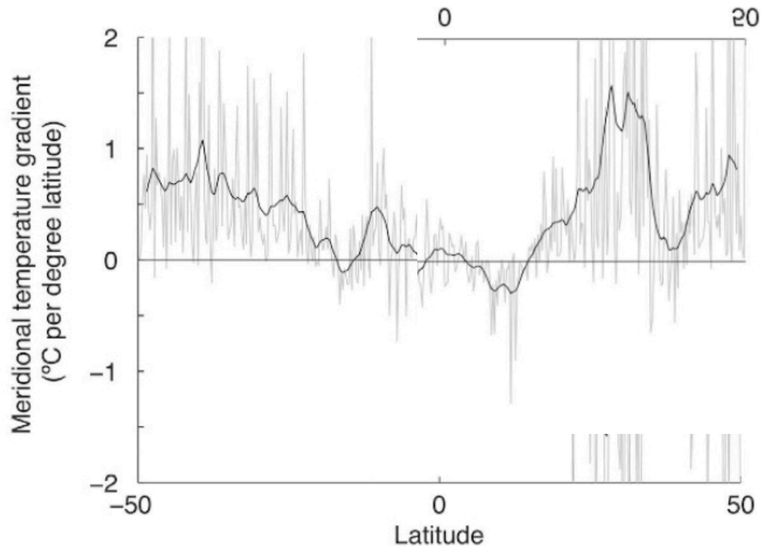

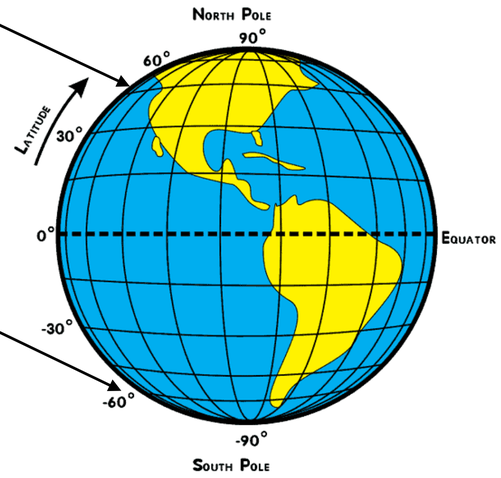

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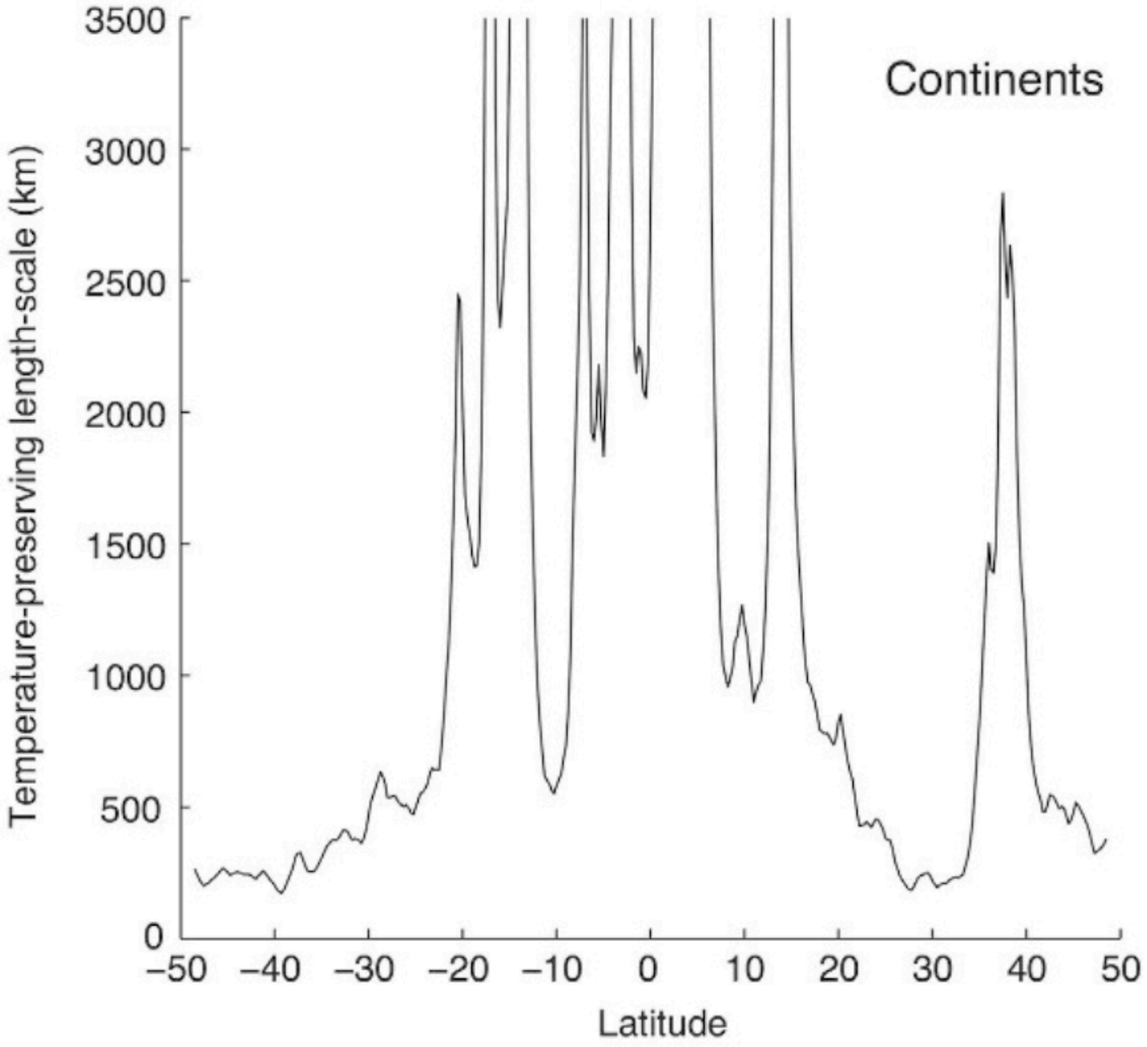
SCIENTIFIC REPORTS

OPEN

Potentially Extreme Population Displacement and Concentration in the Tropics Under Non-Extreme Warming 2 degrees C

Received: 16 December 2015
Accepted: 21 April 2016
Published: 09 June 2016

Solomon M. Hsiang[1,2] & Adam H. Sobel[3,4,5]



Migration distance to keep the same median temperature (IF we keep to 2C rise globally)

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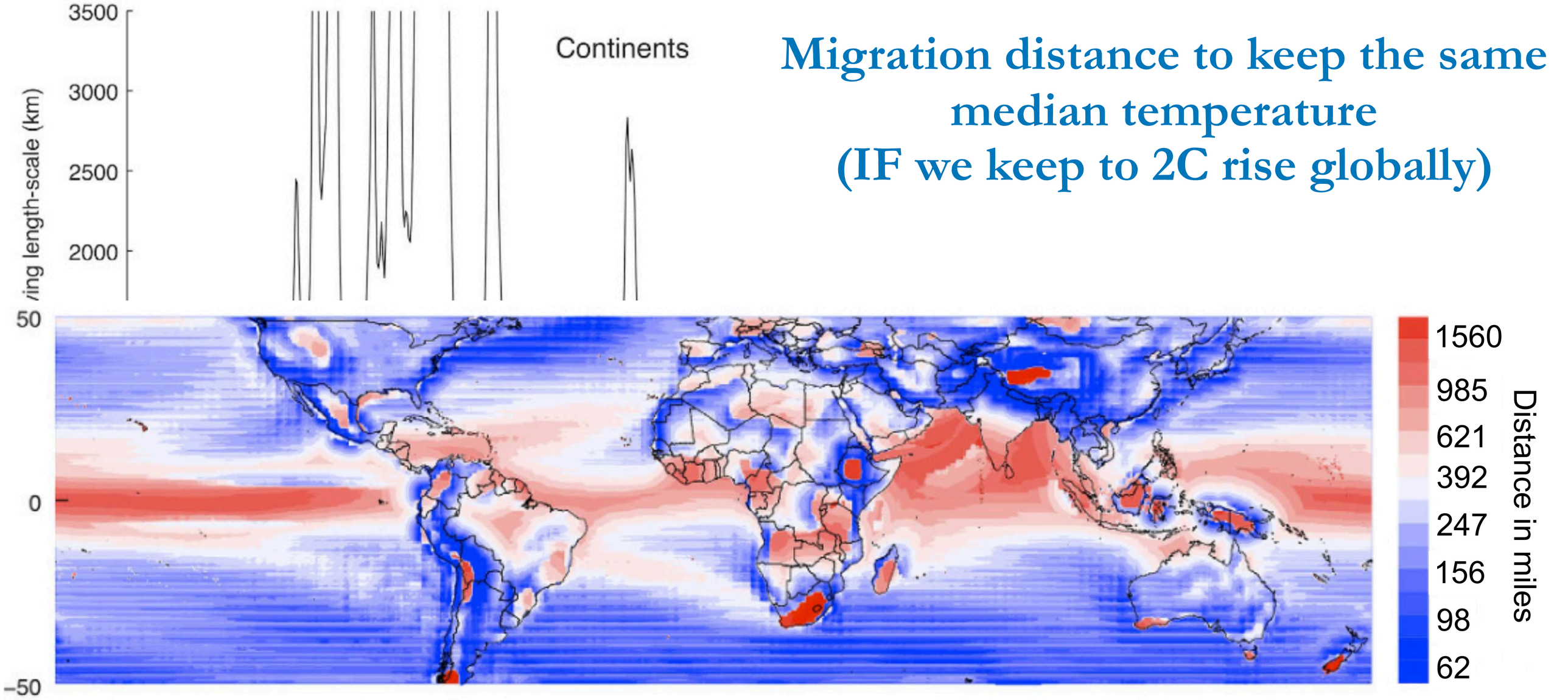
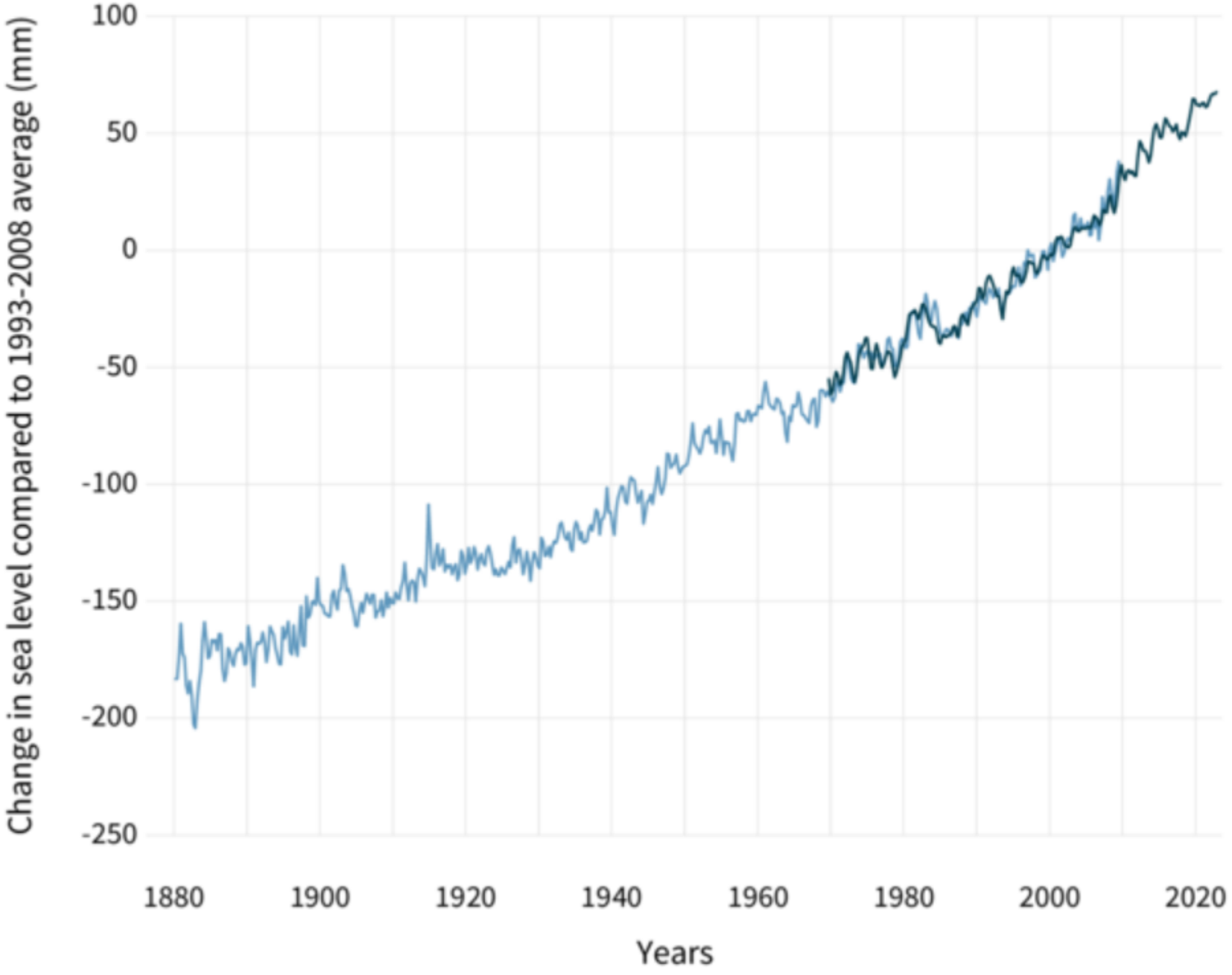


Reference: Zurich to Les Diablerets = 191.1 km; 118.7 miles

GLOBAL SEA LEVEL



PUBLISHED APRIL 19, 2022

Land underwater at high tide ■ Buildings

Old projection for 2050

The New York Times

By Denise Lu and Christopher Flavelle Oct. 29, 2019

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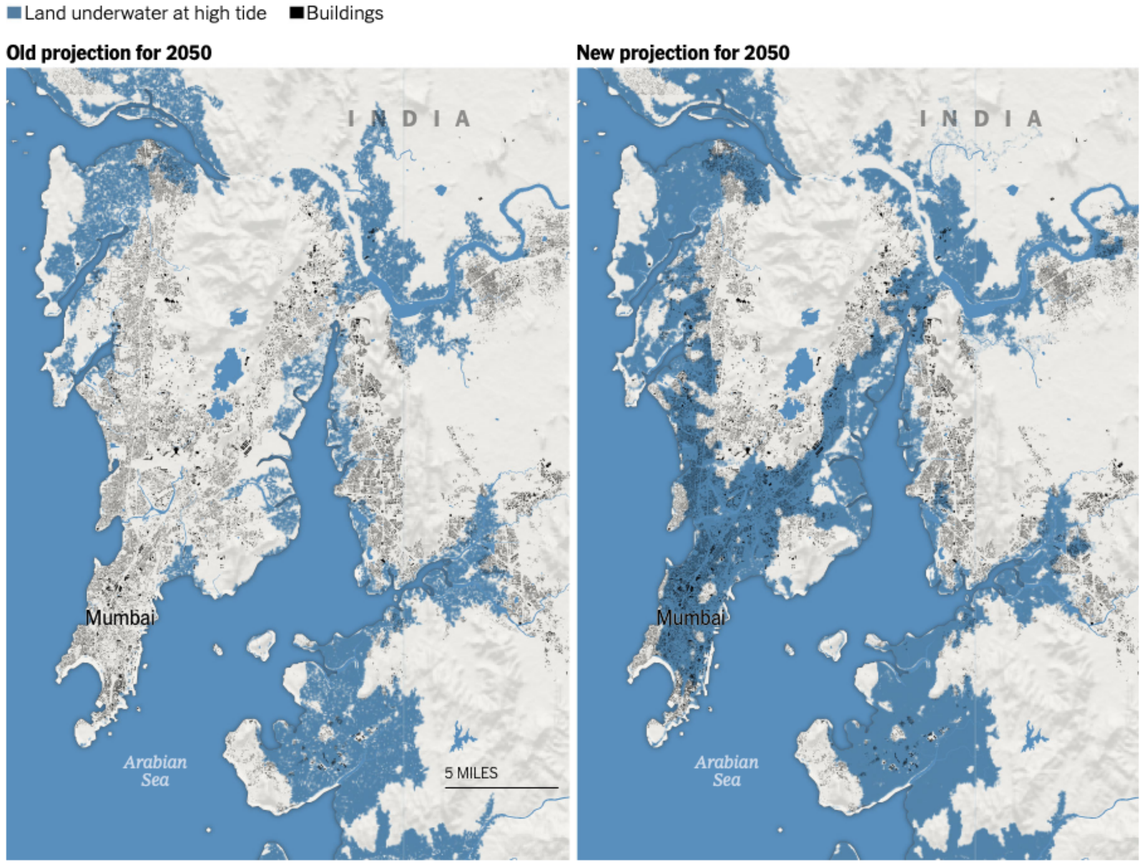

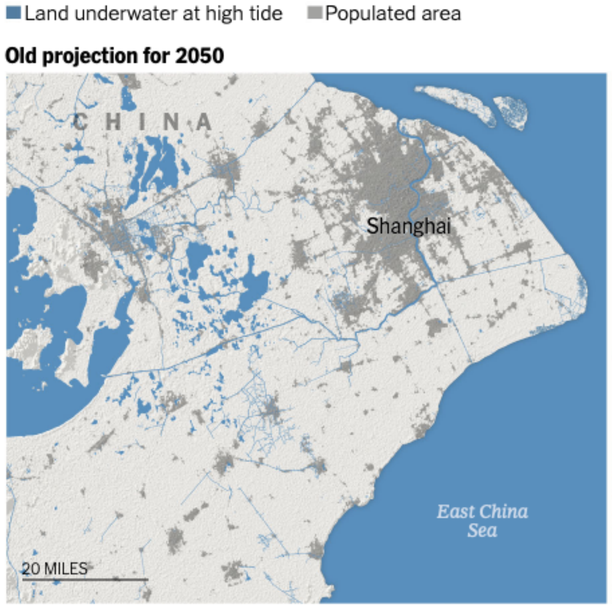

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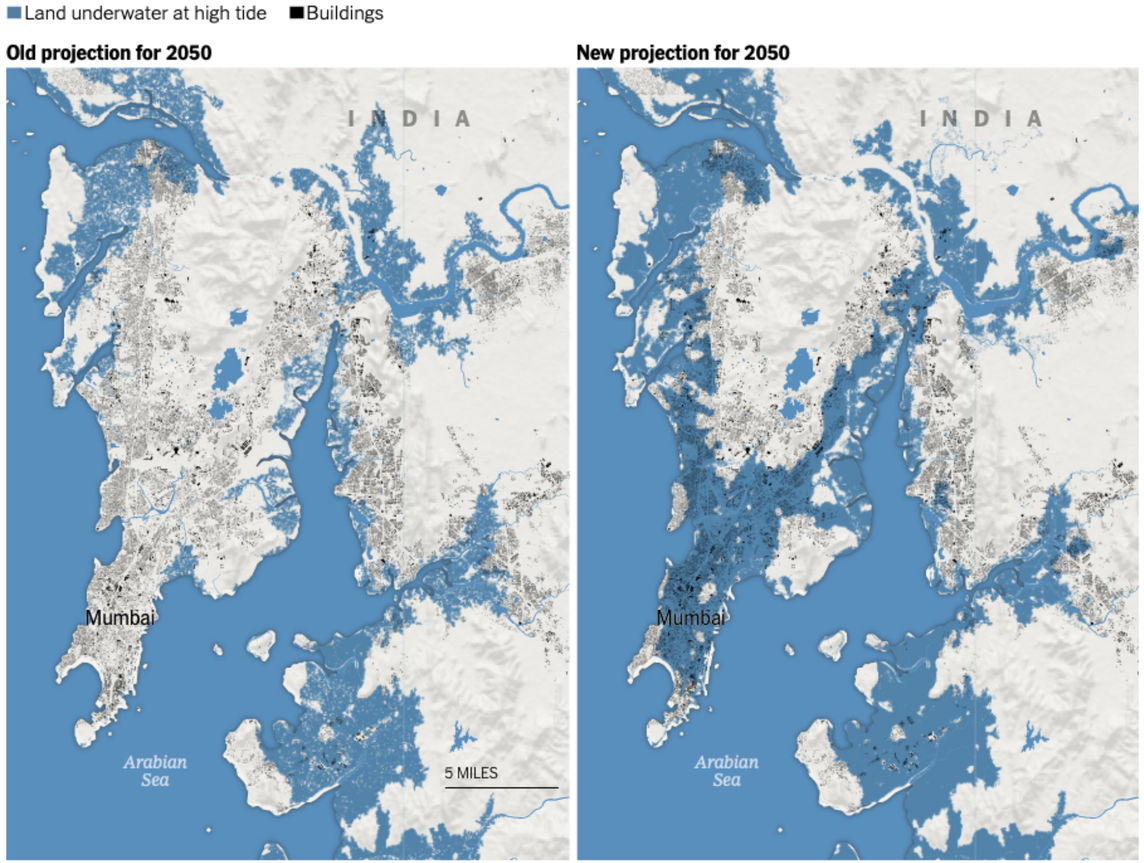

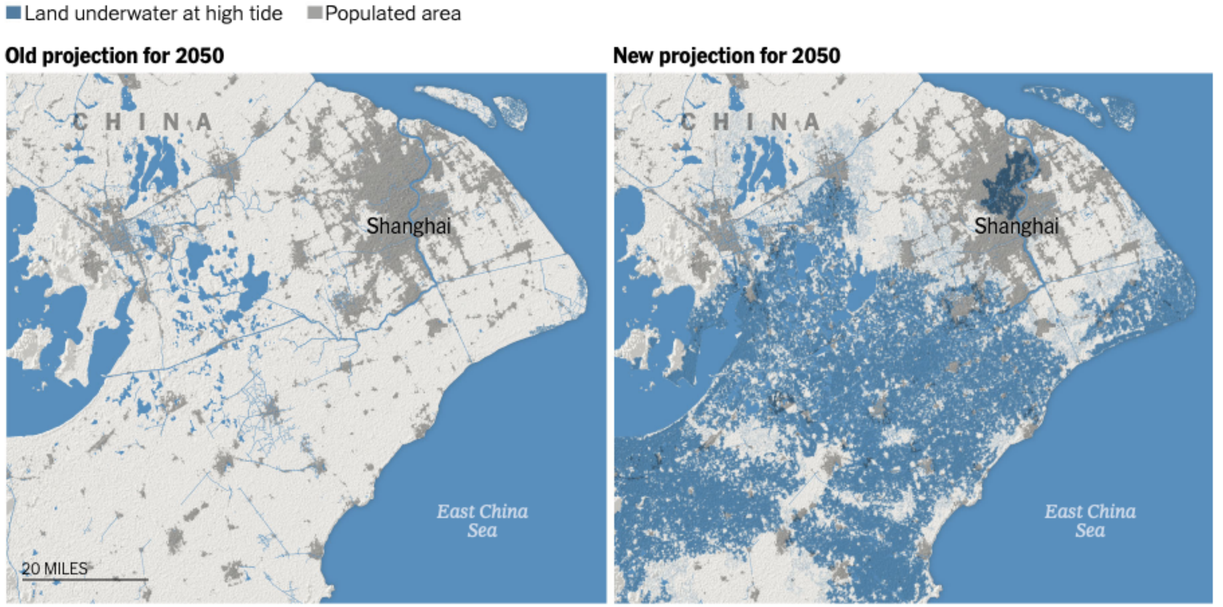

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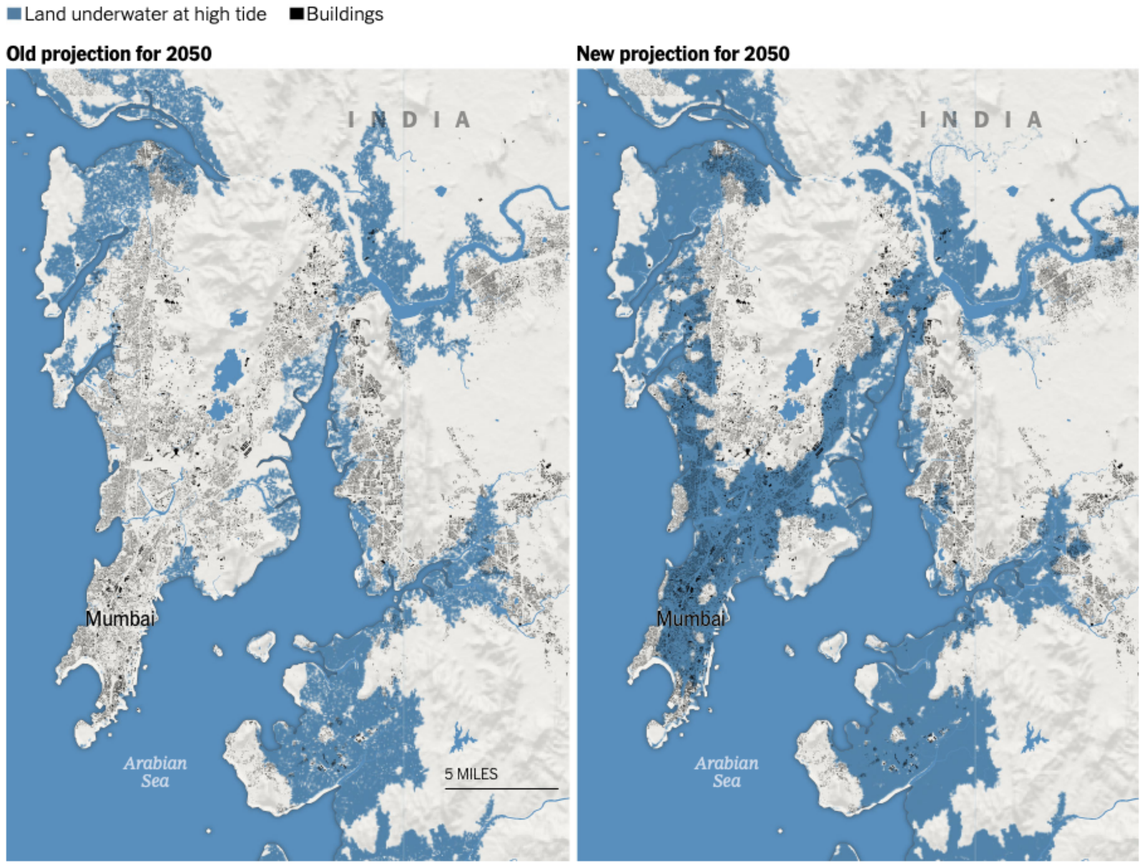

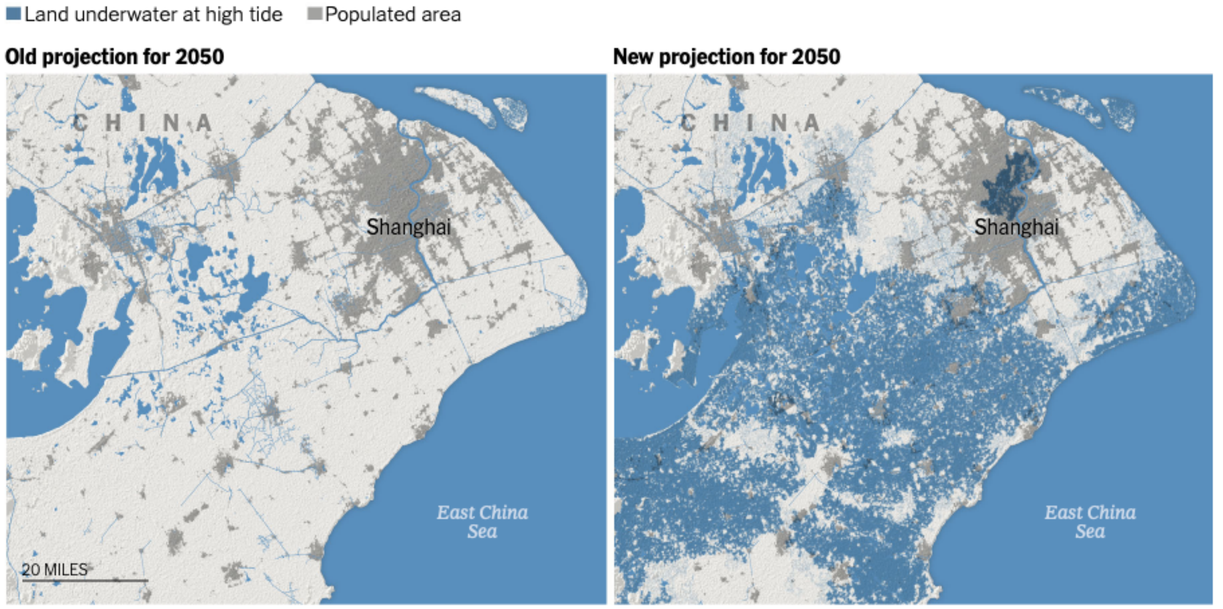

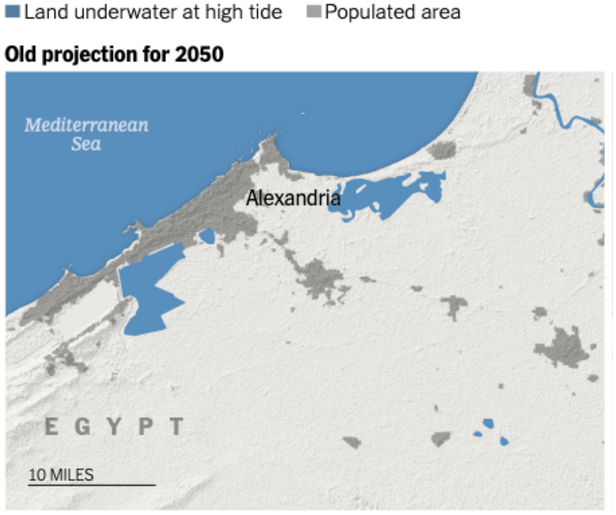

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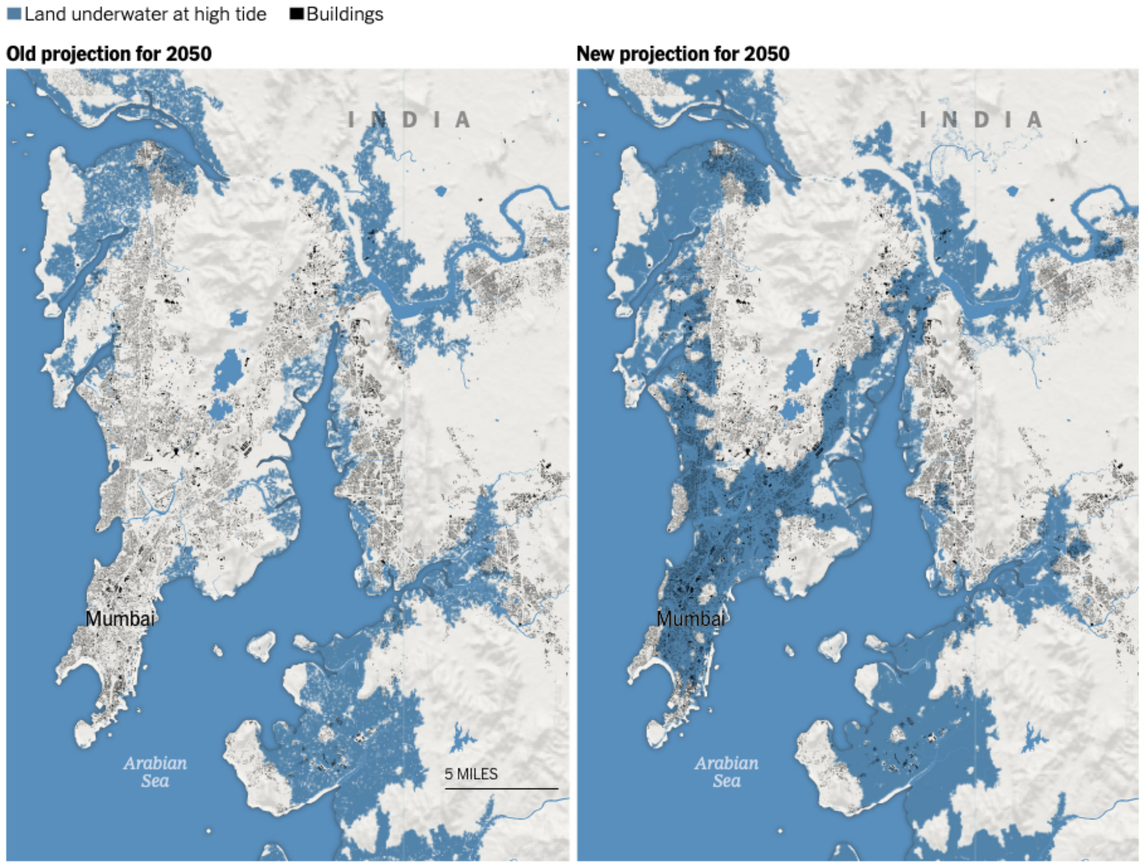

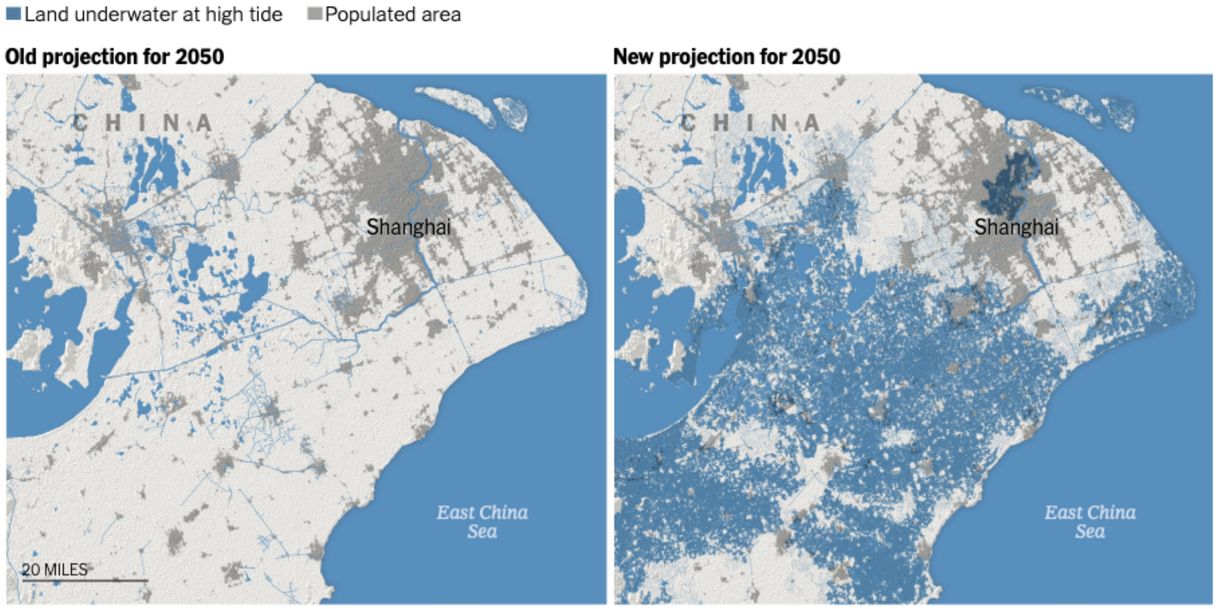

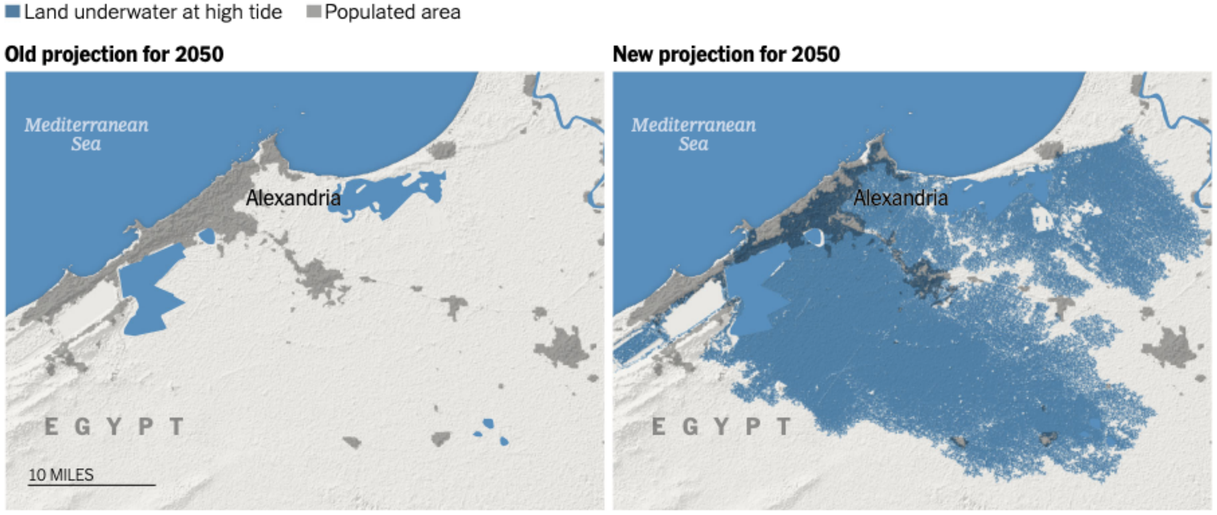

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Scott A. Kulp[1*] & Benjamin H. Strauss[1]

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- Mathematical models connect the atmosphere to our future changing climate and its consequences

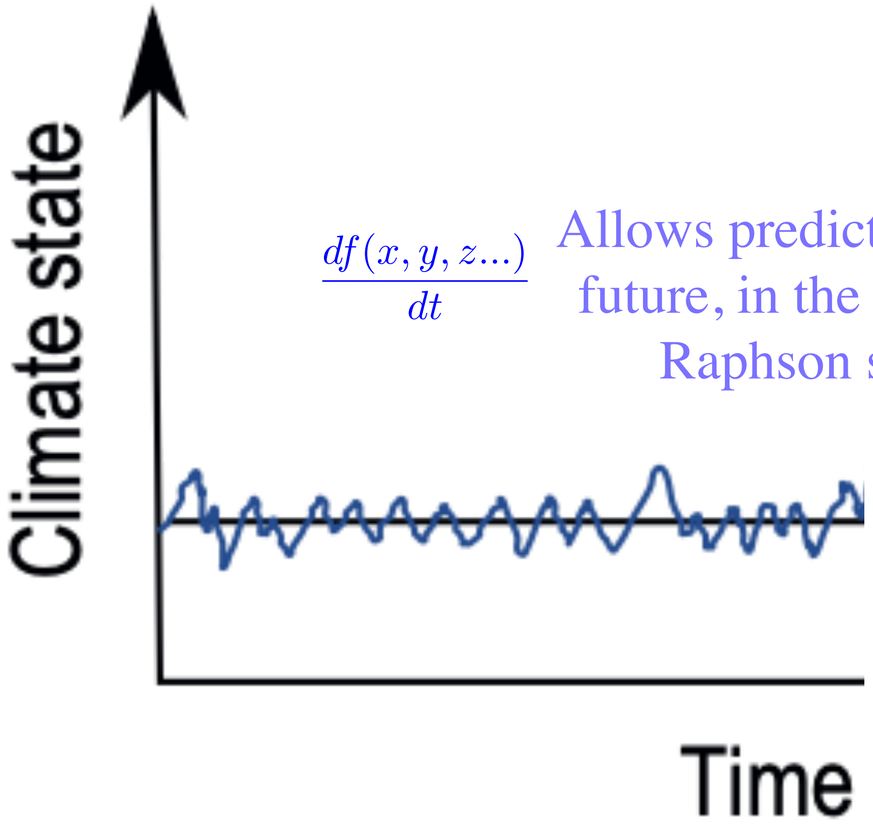
“What keeps you up at night?”

….

calculus,

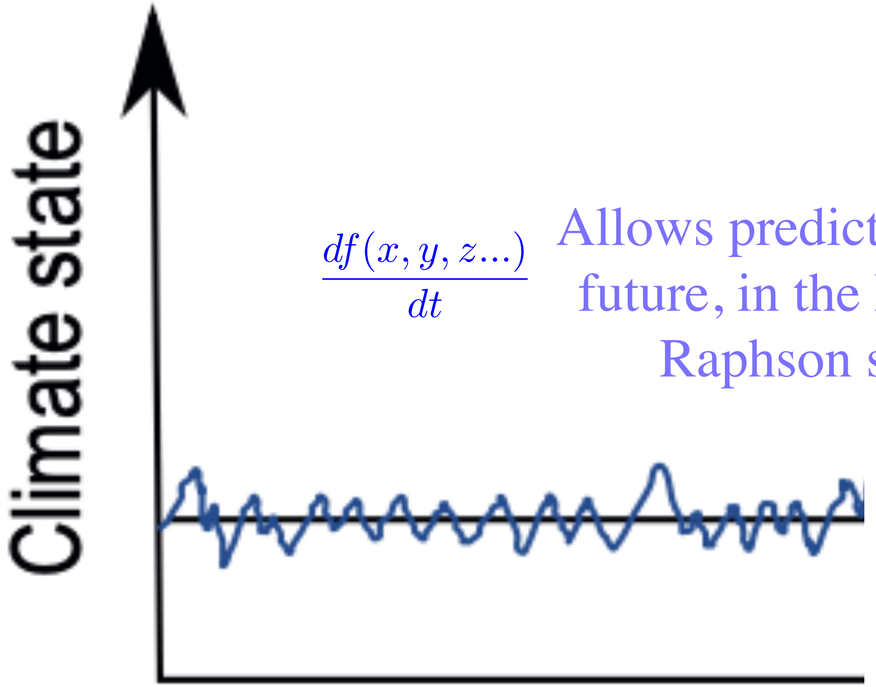
and

….



$\frac{df(x,y,z...)}{dt}$

Allows prediction in the future, in the Newton-Raphson sense



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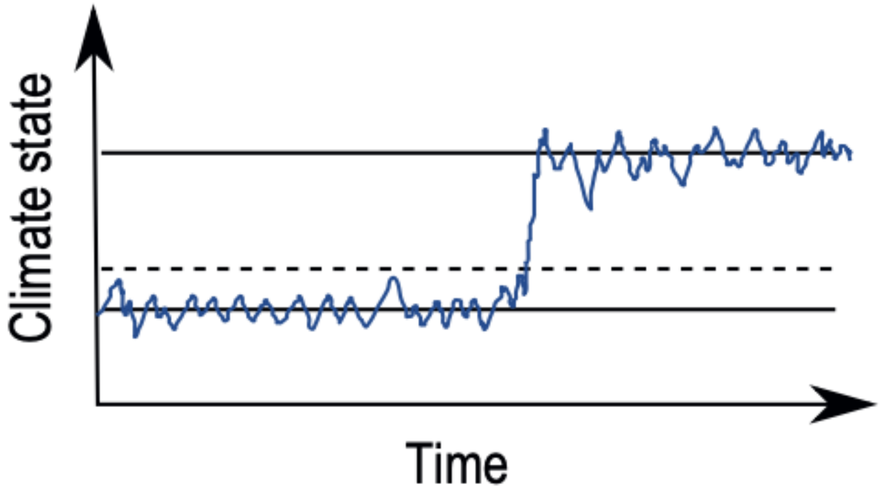
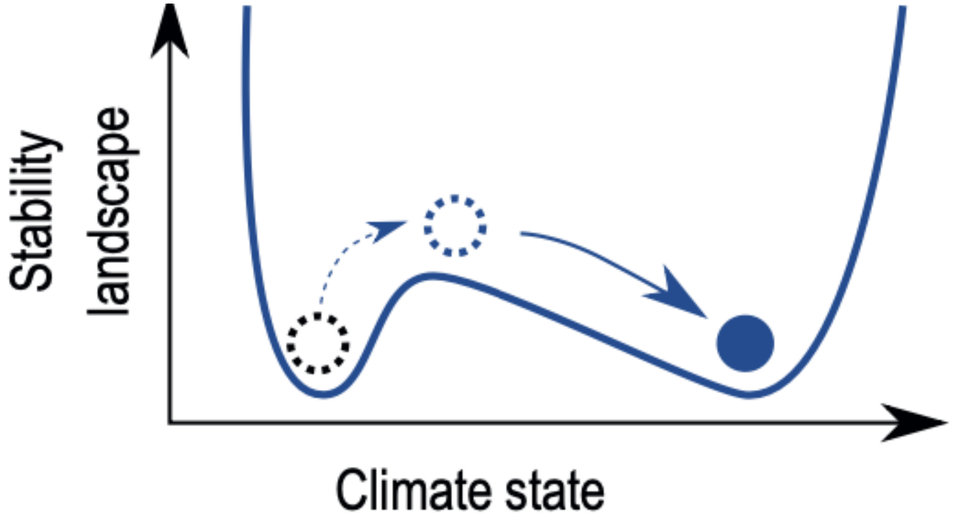
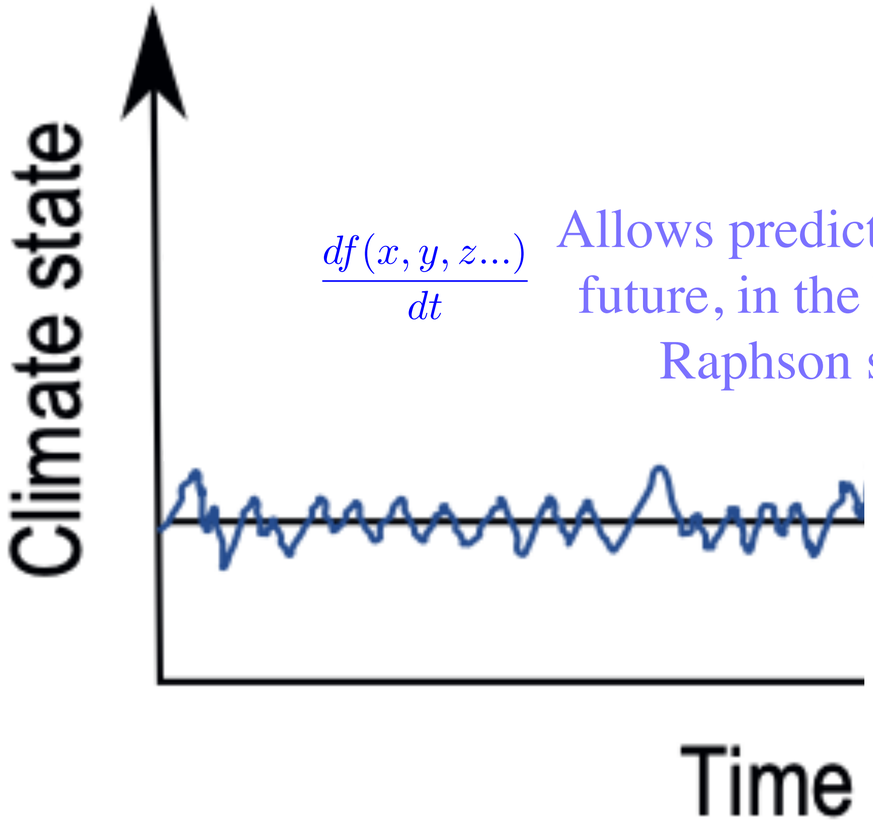
noise-induced tipping events… for instance drought events causing sudden dieback of the Amazon rainforest….







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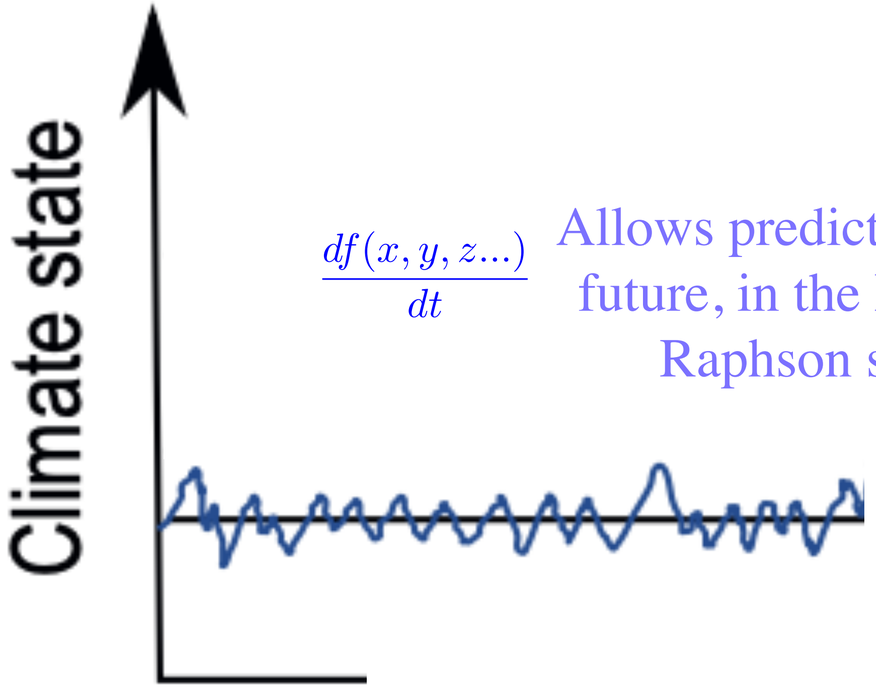

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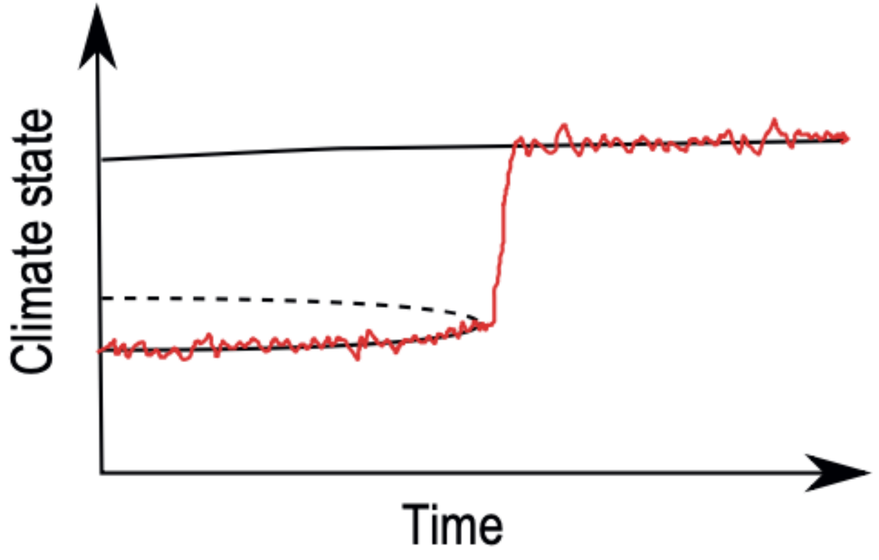
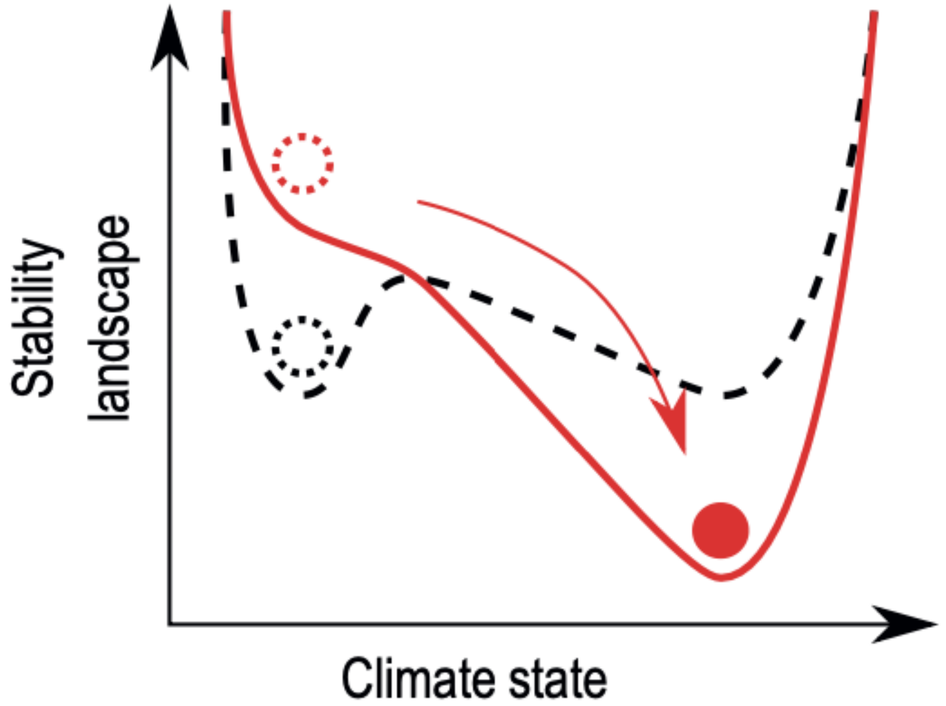
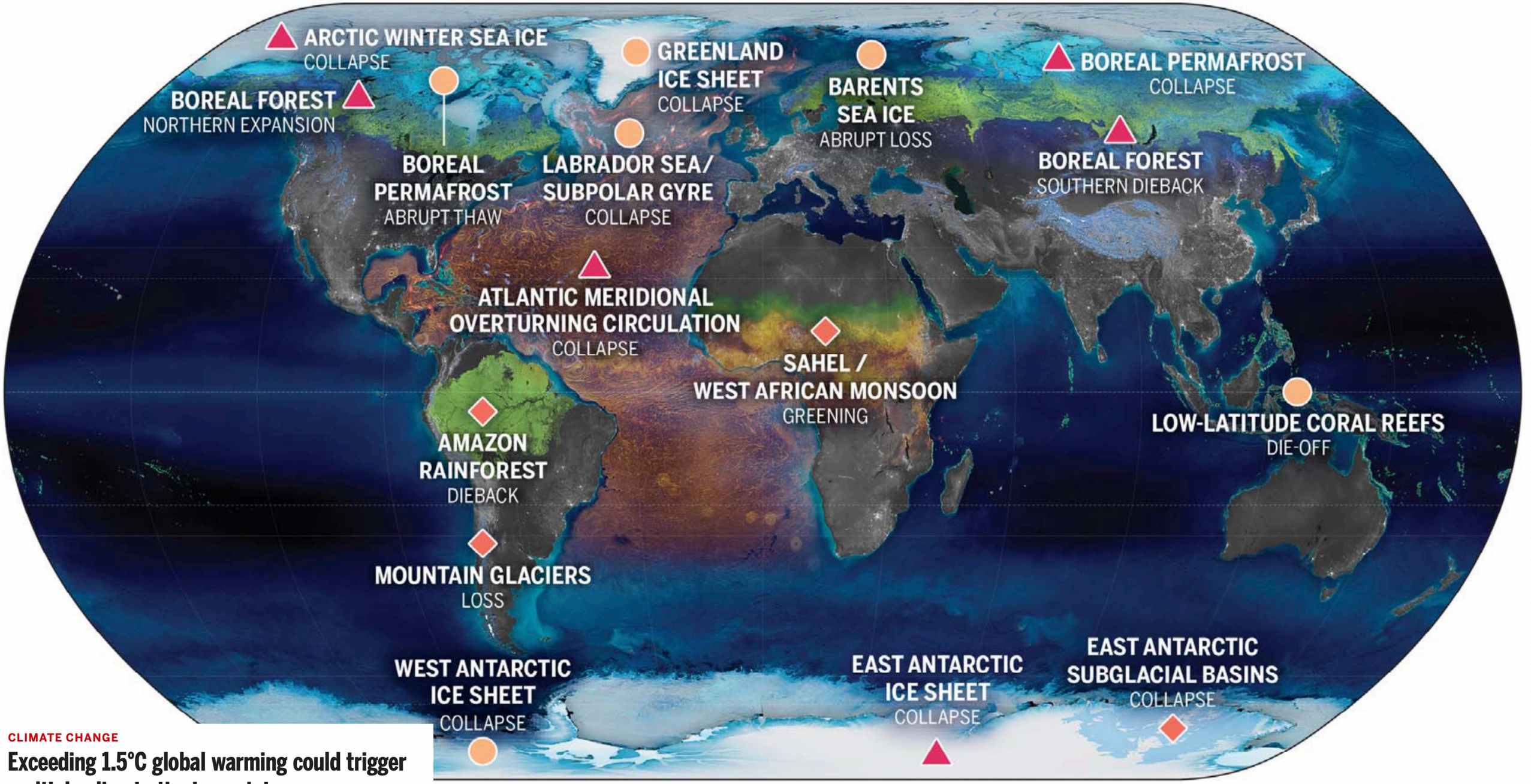
bifurcation tipping events

e.g., collapse of the thermohaline circulation in the Atlantic Ocean

…a critical level in the forcing is reached.







CLIMATE CHANGE

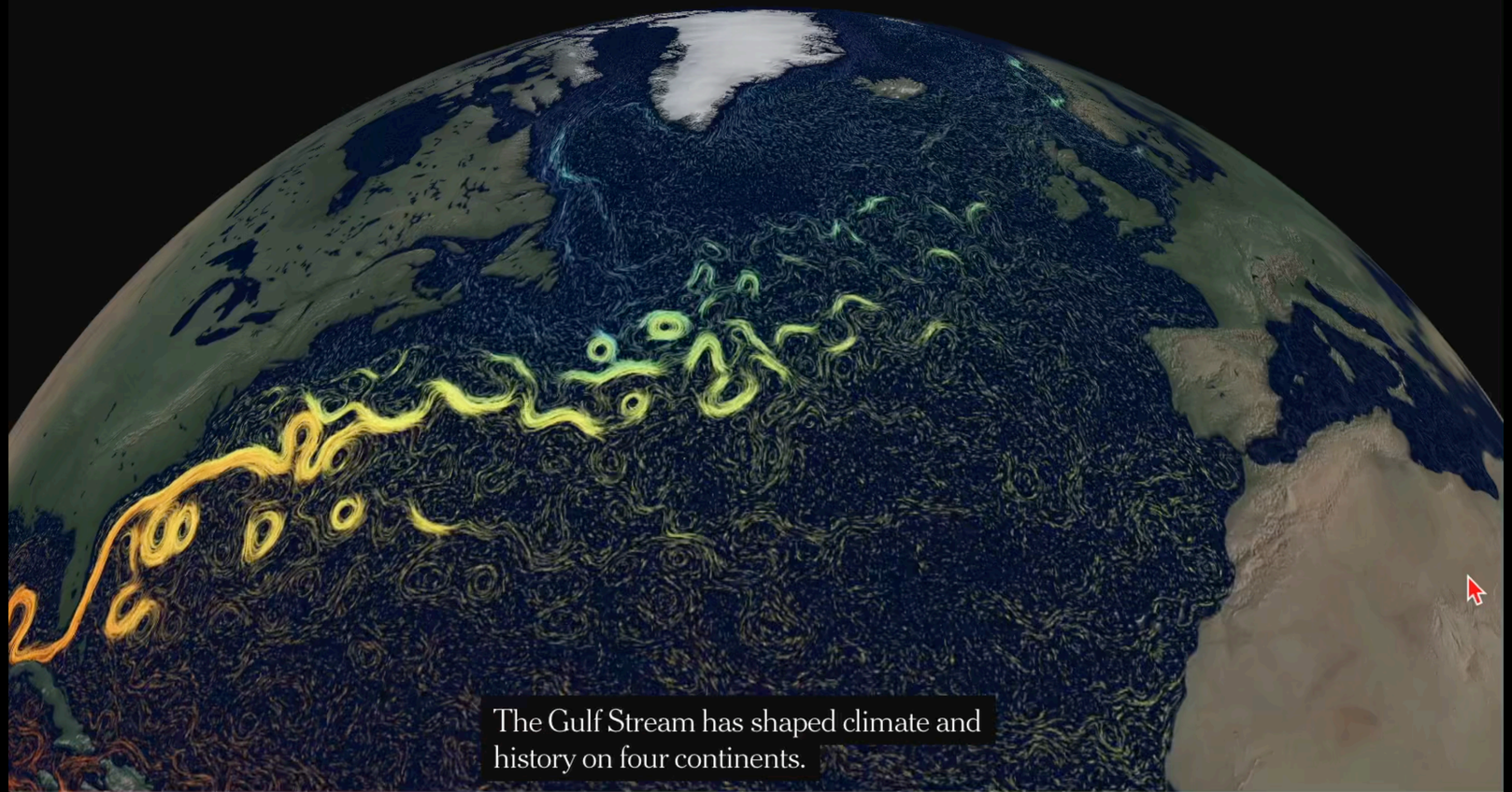
Exceeding 1.5°C global warming could trigger multiple climate tipping points

David I. Armstrong McKay[1,2,3,4]*, Arie Staal[1,2,5], Jesse F. Abrams[3], Ricarda Winkelmann[6], Boris Sakschewski[6], Sina Loriani[6], Ingo Fetzer[1,2], Sarah E. Cornell[1,2], Johan Rockström[1,6], Timothy M. Lenton[3]*

In the Atlantic Ocean, Subtle Shifts Hint at Dramatic Dangers

The warming atmosphere is causing an arm of the powerful Gulf Stream to weaken, some scientists fear.

By MOISES VELASQUEZ-MANOFF and JEREMY WHITE



The Gulf Stream has shaped climate and history on four continents.

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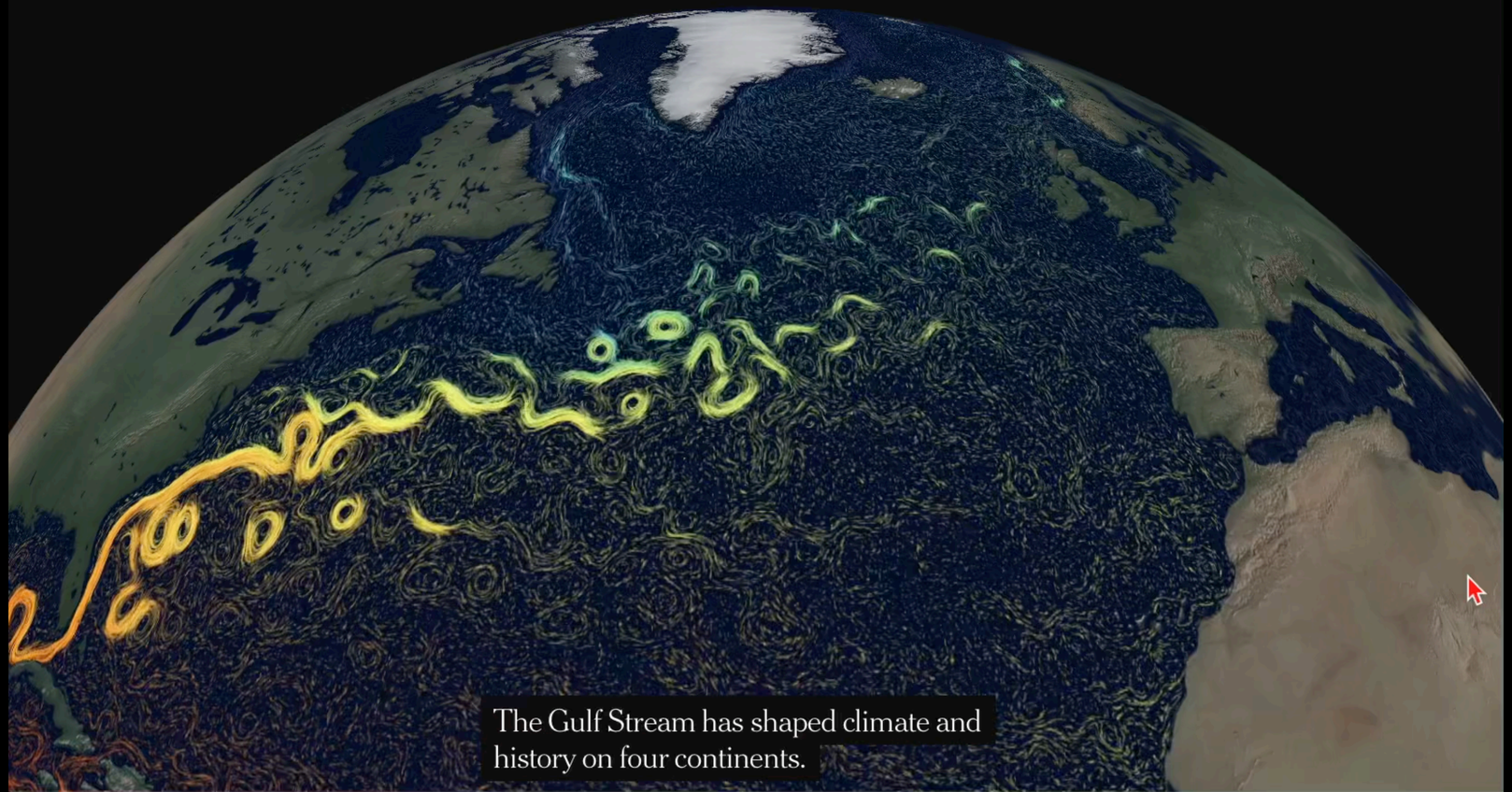

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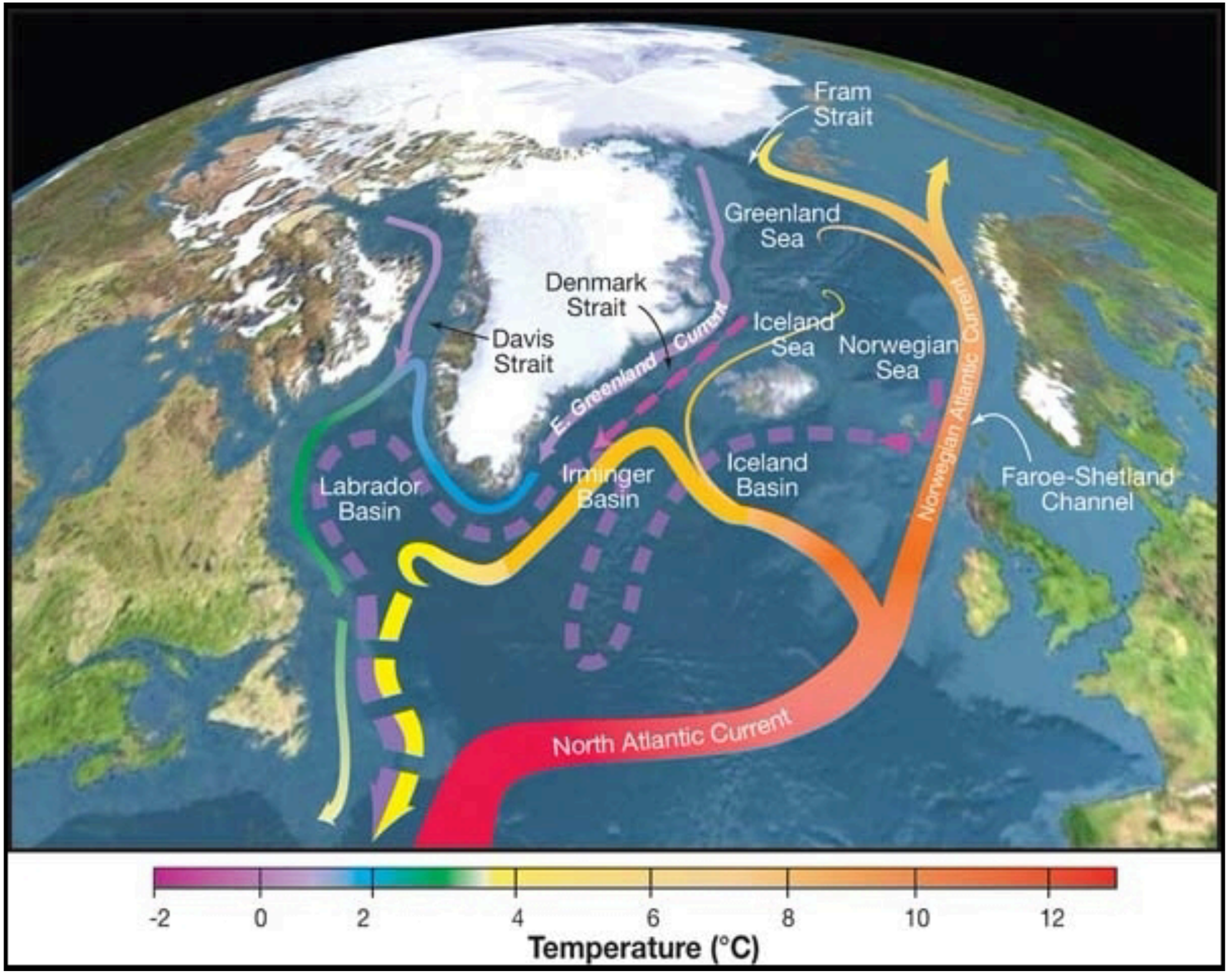
Atlantic Meridional Overturning Circulation



https://science.howstuffworks.com/environmental/earth/oceanography/amoc-news.htm

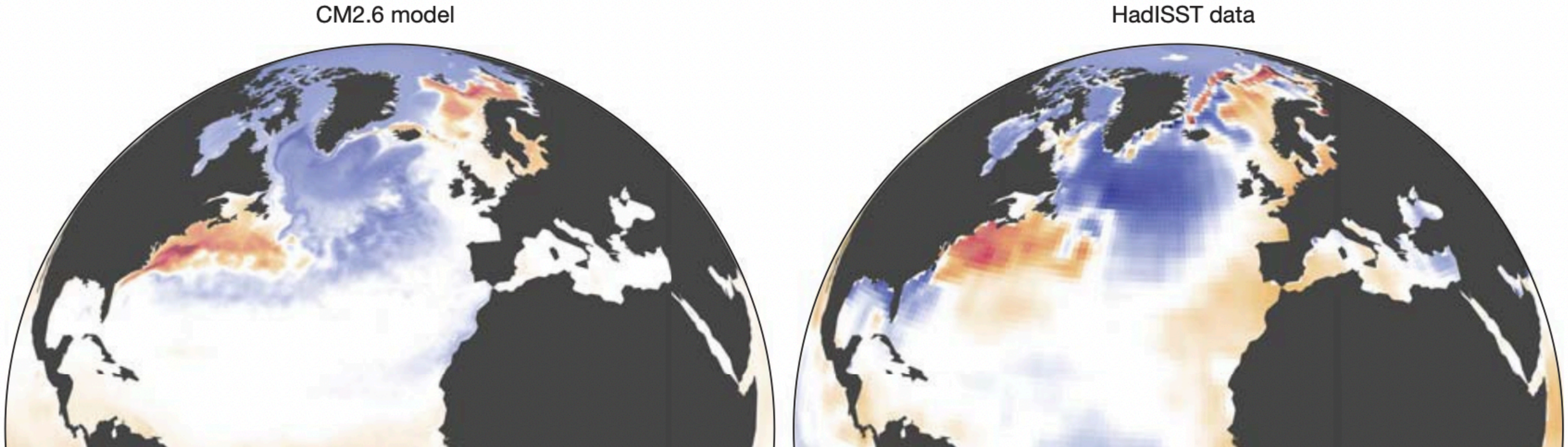
ARTICLE nature

https://doi.org/10.1038/s41586-018-0006-5

12 APRIL 2018 | VOL 556 | NATURE | 191

Observed fingerprint of a weakening Atlantic Ocean overturning circulation

L. Caesar[1,2]*, S. Rahmstorf[1,2]*, A. Robinson[1,3,4,5], G. Feulner[1] & V. Saba[6]



ARTICLES
https://doi.org/10.1038/s41558-021-01097-4
nature climate change
Check for updates

Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation

NATURE CLIMATE CHANGE | VOL 11 | AUGUST 2021 | 680–688 |

Niklas Boers [1,2,3] ✉

BRIEF COMMUNICATION
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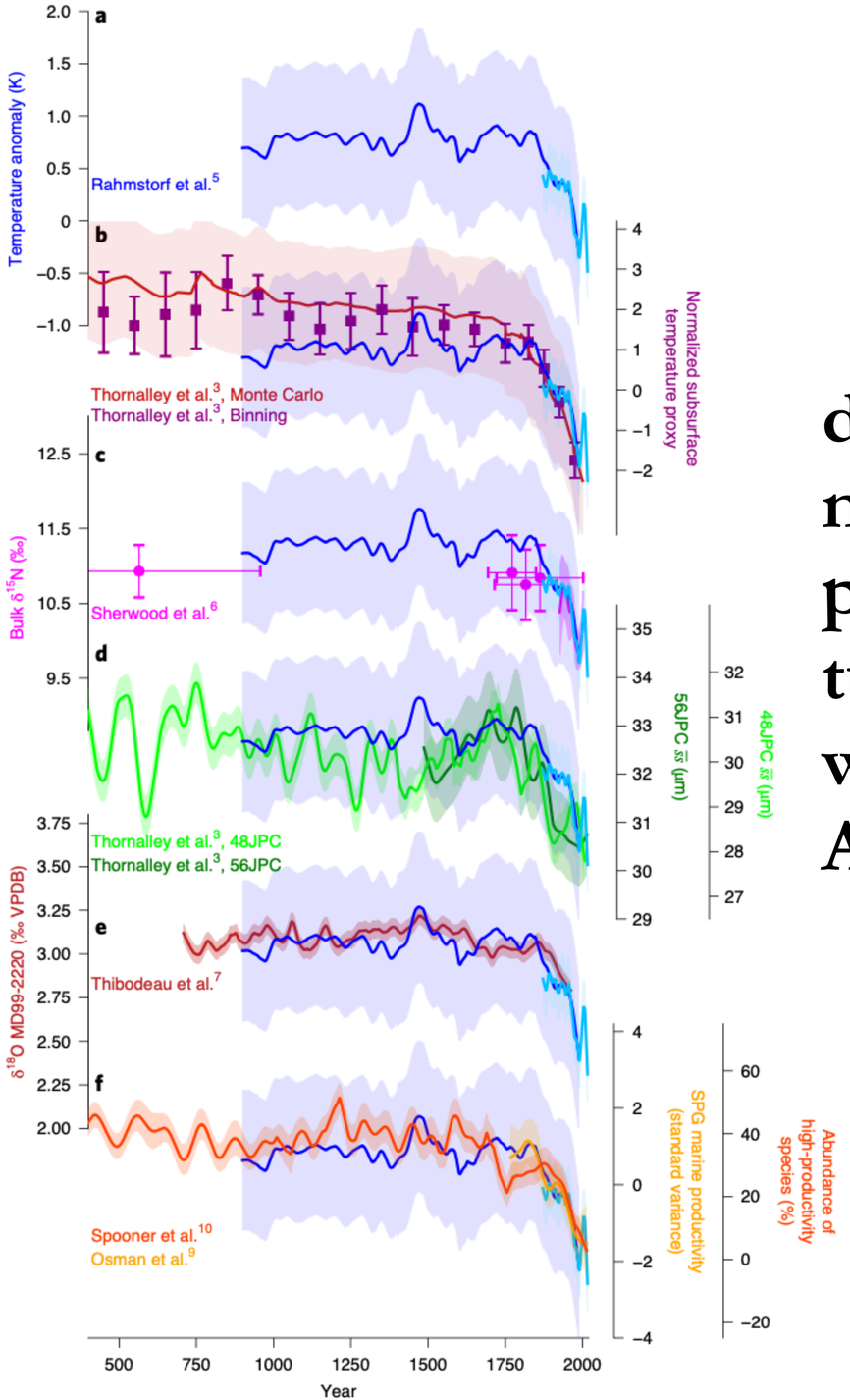
Current Atlantic Meridional Overturning Circulation weakest in last millennium

L. Caesar [1,2] ✉, G. D. McCarthy [1], D. J. R. Thornalley [3], N. Cahill [4] and S. Rahmstorf [2,5]

NATURE GEOSCIENCE | VOL 14 | MARCH 2021 | 118–120 | www.nature.com/naturegeoscience



data..NOT model… proxies for turnover of water in the AMOC

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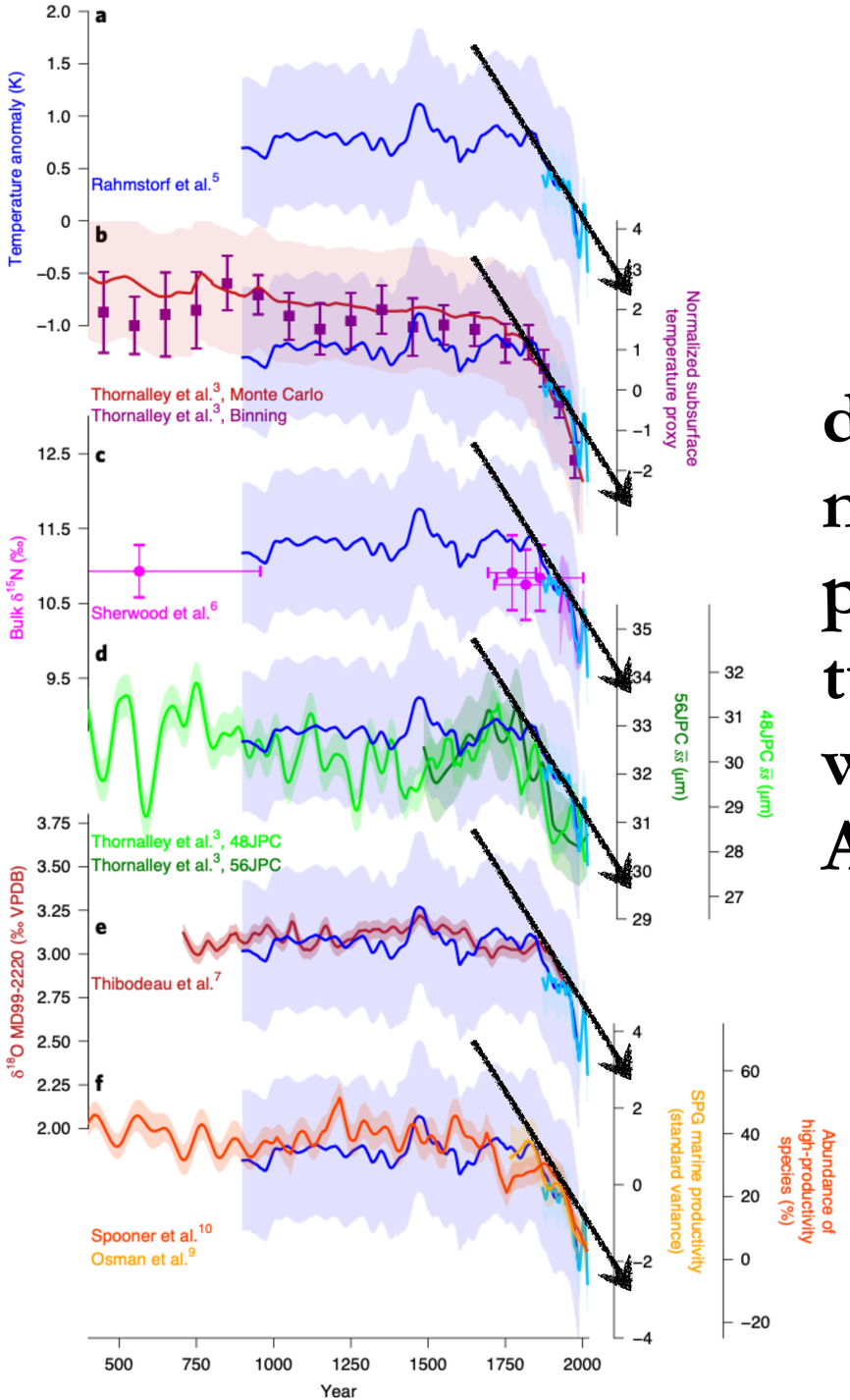

data..NOT model… proxies for turnover of water in the AMOC

The evolution of the North Atlantic Meridional Overturning Circulation since 1980

Laura C. Jackson[1]✉, Arne Biastoch[2,3], Martha W. Buckley[4], Damien G. Desbruyères[5], Eleanor Frajka-Williams[6], Ben Moat[6] and Jon Robson[7]

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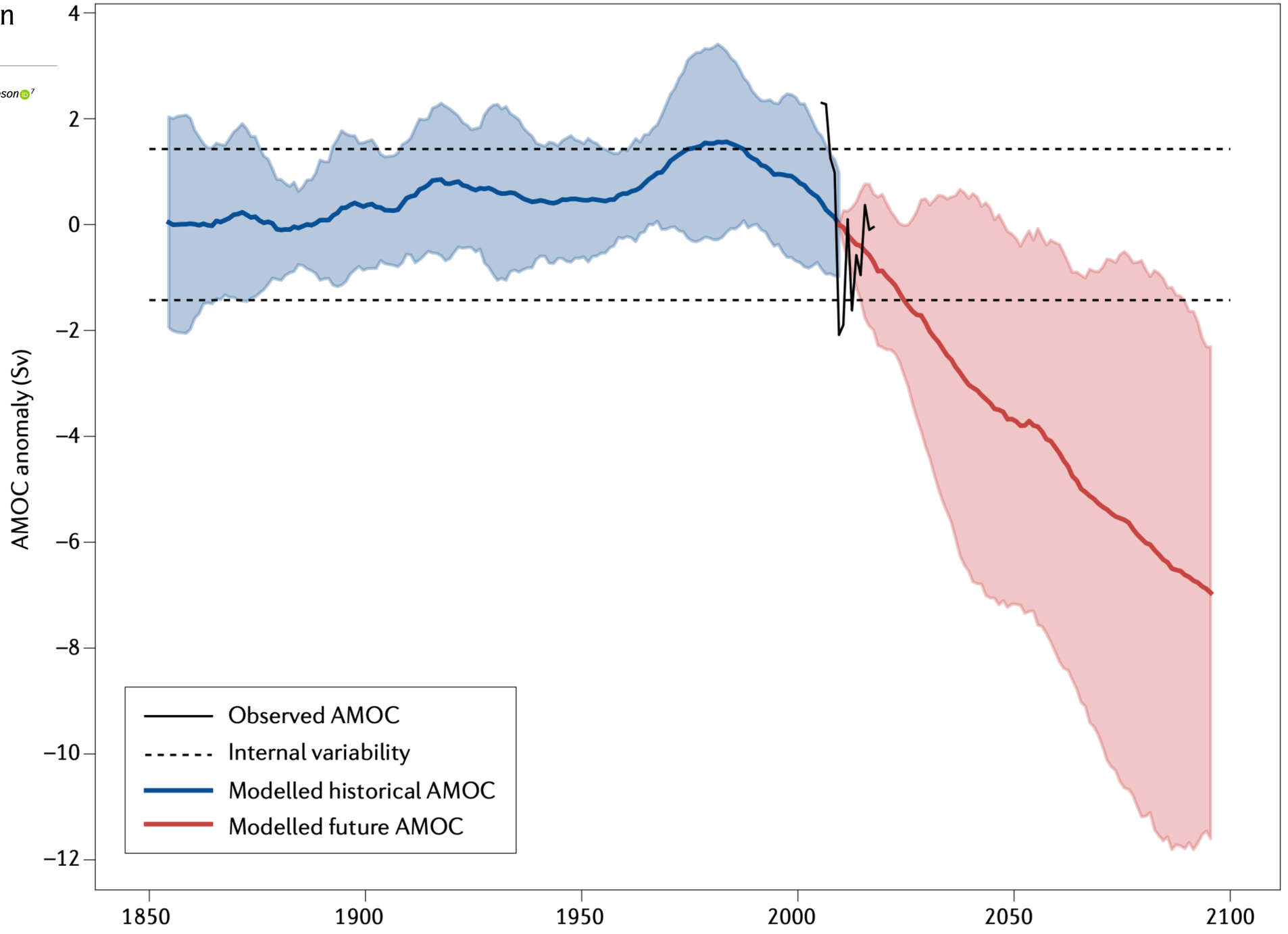
VOLUME 3 | APRIL 2022 | 241



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Answer:
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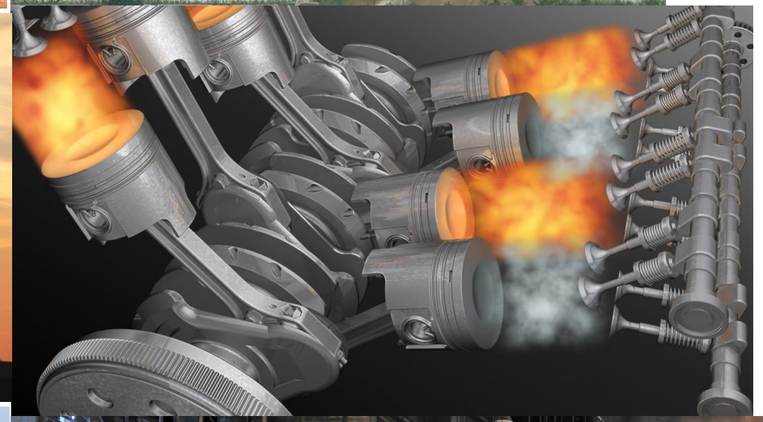
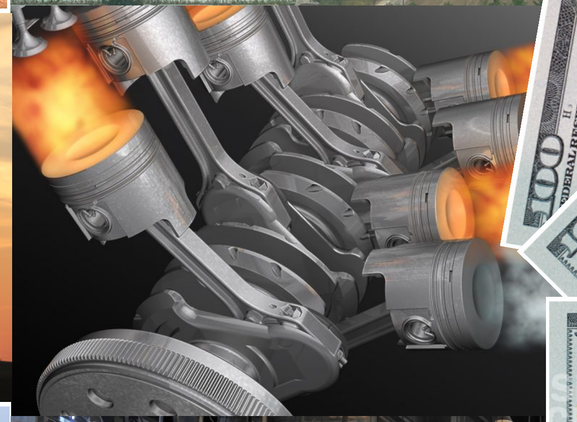
justice

extraction



extraction

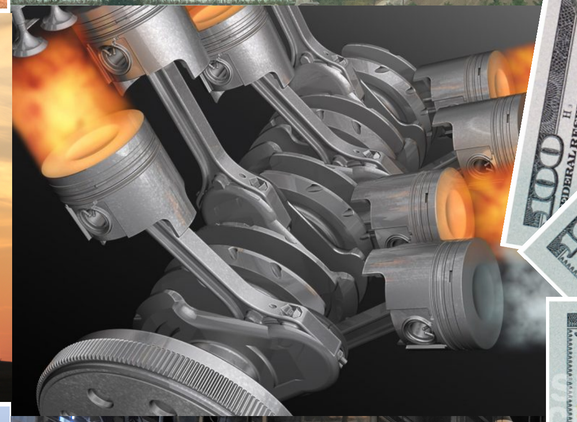
burn



extraction

burn

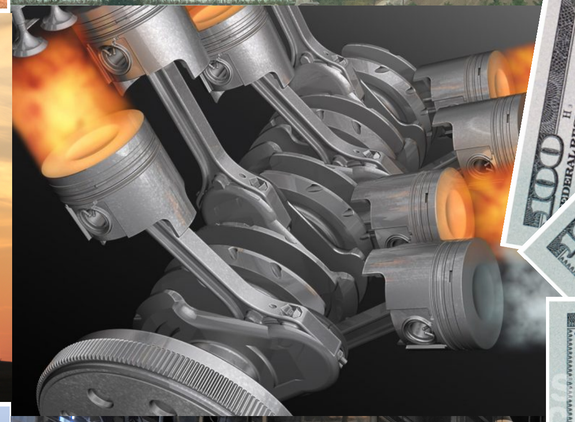
profit



extraction

burn

profit - environmental justice

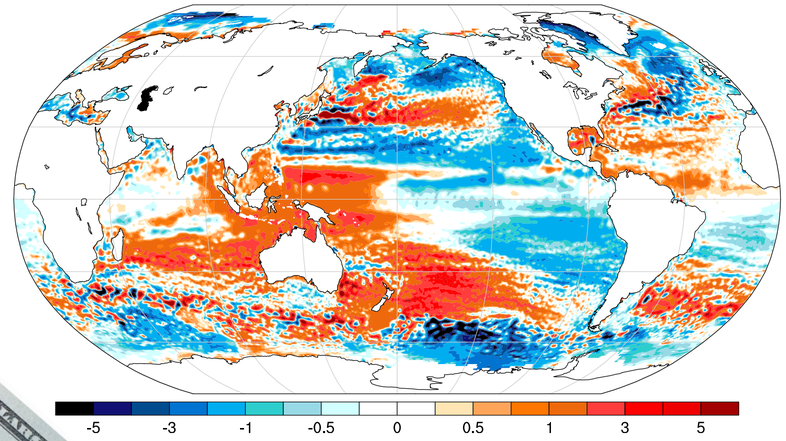


extraction

burn

profit - environmental justice

consequences



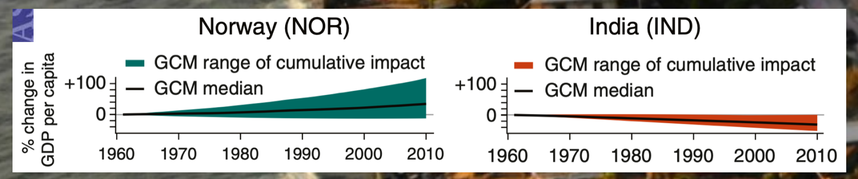
extraction

burn

profit - environmental justice

consequences

consequences
are not shared
equally…



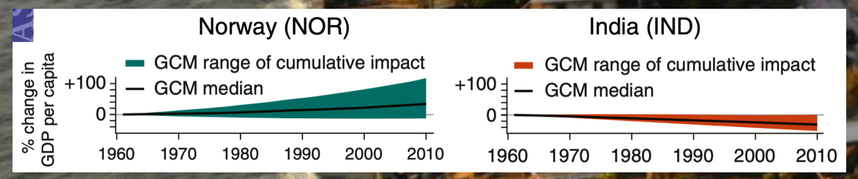
extraction

burn

profit - environmental justice

consequences - climate justice

consequences
are not shared
equally…



What are we going to do?