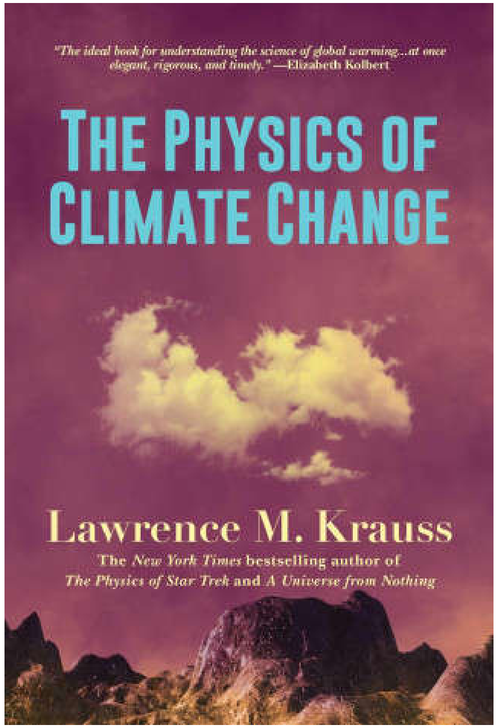
# Fizyka i chemia atmosfery
# Wykład VII
# „Zmiany klimatyczne AD 2023”

Grzegorz Karwasz
Instytut Fizyki UMK




„The Physics of Climate Change”
Lawrence M. Krauss
A Post Hill Press Book, 2023

# Recenzje (1)

**The first book to briefly and clearly present the science of climate change in a way that is accessible to laypeople, providing the perspective needed to understand and assess the foundations and predictions of climate change.**

"Brilliant and fundamental, this is the necessary book about our prime global emergency. Here you'll find the facts, the processes, the physics of our complex and changing climate, but delivered with eloquence and urgency. Lawrence Krauss writes with a clarity that transcends mere politics. Prose and poetry were never better bedfellows." --Ian McEwan
"The ideal book for understanding the science of global warming..at once elegant, rigorous, and timely." --Elizabeth Kolbert, Pulitzer Prizewinning author of *The Sixth Extinction*

"A brief, brilliant, and charming summary of what physicists know about climate change and how they learned it." --Sheldon Glashow, Nobel Laureate in Physics, Metcalf Distinguished Professor Emeritus, Boston University

"The distinguished scientist Lawrence Krauss turns his penetrating gaze on the most pressing existential threat facing our world: climate change. It is brimming with information lucidly analysed. Such hope as there is lies in science, and a physicist of Dr. Krauss's imaginative versatility is unusually qualified to offer it." --Richard Dawkins, author of *The Blind Watchmaker* and *Science in the Soul*

# Recenzje (1)

Pierwsza książka, która krótko i jasno przedstawia naukę o zmianach klimatu w sposób przystępny dla laików, zapewniając perspektywę potrzebną do zrozumienia i oceny podstaw i prognoz zmian klimatu.

"Błyskotliwa i fundamentalna, jest to niezbędna książka o naszym głównym globalnym kryzysie. Znajdziesz tu fakty, procesy, fizykę naszego złożonego i zmieniającego się klimatu, ale przedstawione z elokwencją i pilnością. Lawrence Krauss pisze z jasnością, która wykracza poza zwykłą politykę. Proza i poezja nigdy nie były lepszymi towarzyszami." – Ian McEwan
"Idealna książka do zrozumienia nauki o globalnym ociepleniu. jednocześnie elegancka, rygorystyczna i aktualna" – Elizabeth Kolbert, laureatka Nagrody Pulitzera, autorka książki "Szóste wymieranie„

"Krótkie, błyskotliwe i urocze podsumowanie tego, co fizycy wiedzą o zmianach klimatycznych i jak się tego nauczyli." --Sheldon Glashow, laureat Nagrody Nobla w dziedzinie fizyki, Metcalf Distinguished Professor Emeritus, Boston University

"Wybitny naukowiec Lawrence Krauss kieruje swoje przenikliwe spojrzenie na najbardziej palące egzystencjalne zagrożenie, przed którym stoi nasz świat: zmiany klimatyczne. Jest pełen informacji, które zostały przejrzyście przeanalizowane. Taka nadzieja, jaka istnieje, leży w nauce, a fizyk o wszechstronności wyobraźni dr Kraussa ma niezwykłe kwalifikacje, aby ją zaoferować" – Richard Dawkins, autor książek "Ślepy zegarmistrz" i "Nauka w duszy"

"Lucid and gripping, this study of the most severe challenge humans have ever faced leads the reader from the basic physics of climate change to recognition of the damage that humans have already caused and on to the prospects that lie ahead if we do not change course soon." --Noam Chomsky, Laureate Professor, University of Arizona, author of *Internationalism or Extinction?*

"Lawrence Krauss tells the story of climate change with erudition, urgency, and passion. It is our great good luck that one of our most brilliant scientists is also such a gifted writer. This book will change the way we think about the future." --Jennifer Finney Boylan, author of *Good Boy* and *She's Not There*

"Everything on climate change that I've seen is either dumbed down and bossy or written for other climate scientists. I've been looking for a book that can let me, a layperson, understand the science. This book does just what I was looking for. It is important." --Penn Jillette, Magician, author of *Presto!* and *God, No!*

"The renowned physicist Lawrence Krauss makes the science behind one of the most important issues of our time accessible to all." --Richard C. J. Somerville, Distinguished Professor Emeritus, Scripps Institution of Oceanography, University of California, San Diego

"Lawrence Krauss is a fine physicist, a talented writer, and a scientist deeply engaged with public affairs. His book deserves wide readership. The book's eloquent exposition of the science and the threats should enlighten all readers and motivate them to an urgent concern about our planet's future." --Lord Martin Rees, Astronomer Royal, former president of the Royal Society, author of *On the Future: Prospects for Humanity*

"To przejrzyste i porywające studium najpoważniejszego wyzwania, przed jakim kiedykolwiek stanęła ludzkość, prowadzi czytelnika od podstaw fizyki zmian klimatycznych do rozpoznania szkód, które ludzie już wyrządzili i do perspektyw, które stoją przed nami, jeśli wkrótce nie zmienimy kursu." – Noam Chomsky, profesor laureat, University of Arizona, autor książki Internacjonalizm czy wymieranie?
"Lawrence Krauss opowiada historię zmian klimatycznych z erudycją, pilnością i pasją. To nasze wielkie szczęście, że jeden z naszych najwybitniejszych naukowców jest również tak utalentowanym pisarzem. Ta książka zmieni sposób, w jaki myślimy o przyszłości" – Jennifer Finney Boylan, autorka książek "Good Boy" i "She's Not There"

"Wszystko, co widziałem na temat zmian klimatu, jest albo głupie i apodyktyczne, albo napisane dla innych klimatologów. Szukałem książki, która pozwoliłaby mi, laikowi, zrozumieć naukę. Ta książka robi dokładnie to, czego szukałem. To jest ważne." – Penn Jillette, iluzjonista, autor książki Presto! i Boże, nie!

"Znany fizyk Lawrence Krauss sprawia, że nauka stojąca za jednym z najważniejszych zagadnień naszych czasów jest dostępna dla wszystkich" – Richard C. J. Somerville, emerytowany profesor

"Lawrence Krauss jest znakomitym fizykiem, utalentowanym pisarzem i naukowcem głęboko zaangażowanym w sprawy publiczne. Jego książka zasługuje na szerokie grono czytelników. Elokwentne przedstawienie nauki i zagrożeń w tej książce powinno oświecić wszystkich czytelników i zmotywować ich do pilnej troski o przyszłość naszej planety." – Lord Martin Rees, Astronom Królewski, były prezes Towarzystwa Królewskiego, autor książki On the Future: Prospects for Humanity

# Wstęp

Motto: Im więcej zmian, tym bardziej jest to sama rzecz. J.-B. A. Karr, 1849

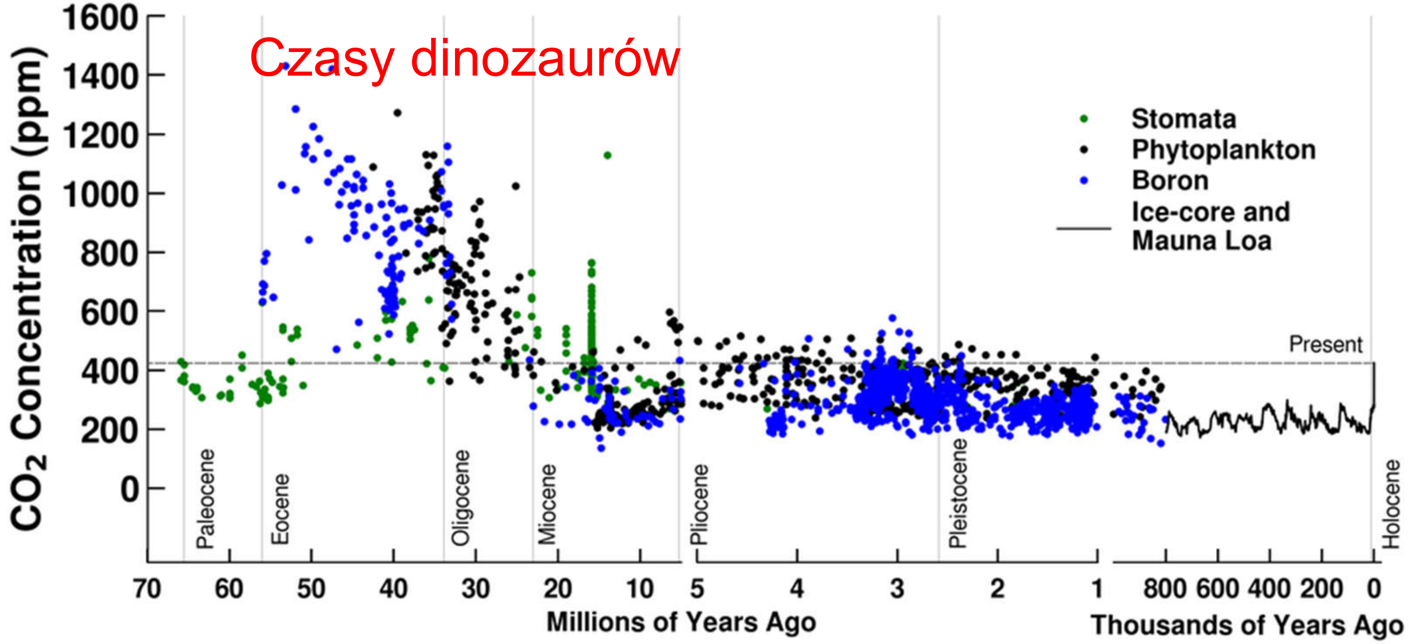
To już prawie dwadzieścia lat, kiedy *Fizyka klimatu* wyszła w twardej oprawie.

Przede wszystkim jest to książka o procesach fizycznych, które leżą u podstaw zmian klimatycznych.

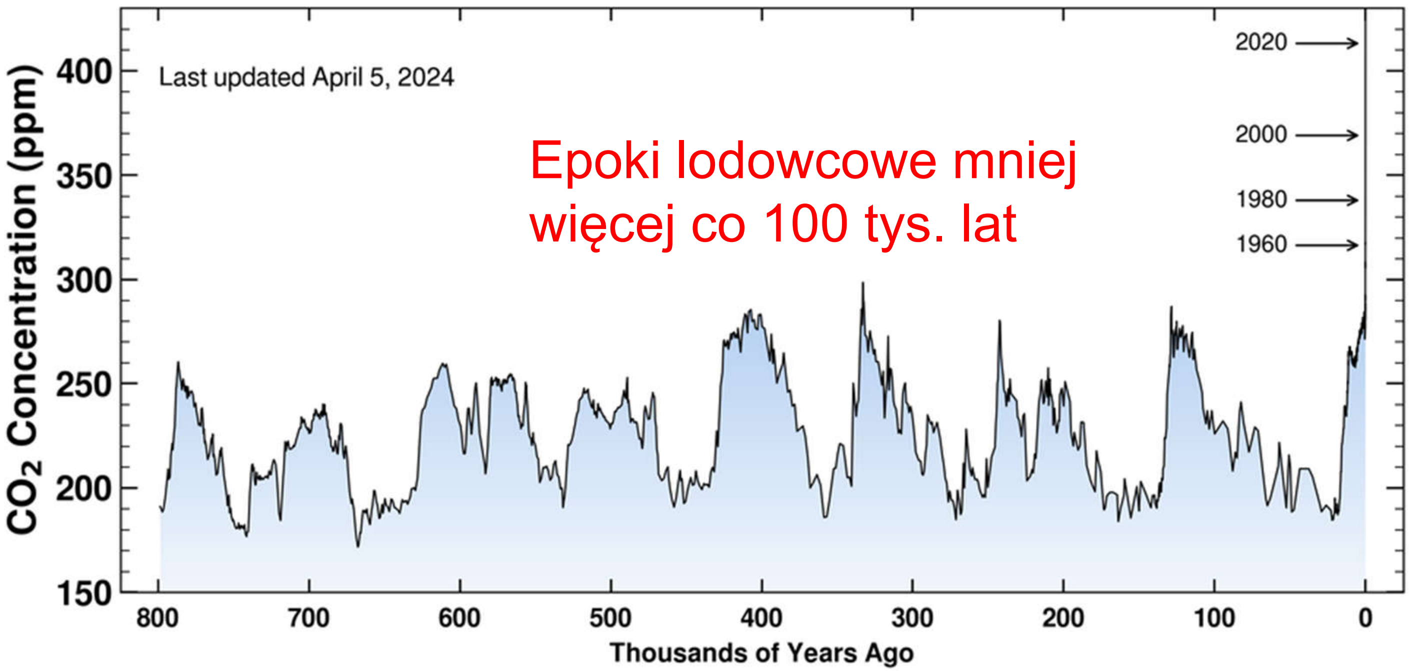
Można powiedzieć, że problem stał się jeszcze  bardziej palący po pandemii, kiedy ekonomia wróciła do stanu „buziness as usual", i w 2021 globalna emisja ze spalania paliw wyniosła 37,98 mld ton, przekraczając wartość sprzed pandemii z 2018 roku 36,86 mld ton, i wzrost $CO_2$ w atmosferze o 2,58 ppm był piątym największym rocznym wzrostem zanotowanym przez NOAA w ciągu ostatnich 60-ciu lat. Do stycznia 2023 poziom $CO_2$ wzrósł do 419,62 ppm.

W tym samym topnienie lodu na Grenlandii wyniosło 146 +- 64 mld ton w sezonie roztopów 2021-2022. (viii)

# Keeling's (czyli $CO_2$) curves




https://keelingcurve.ucsd.edu/

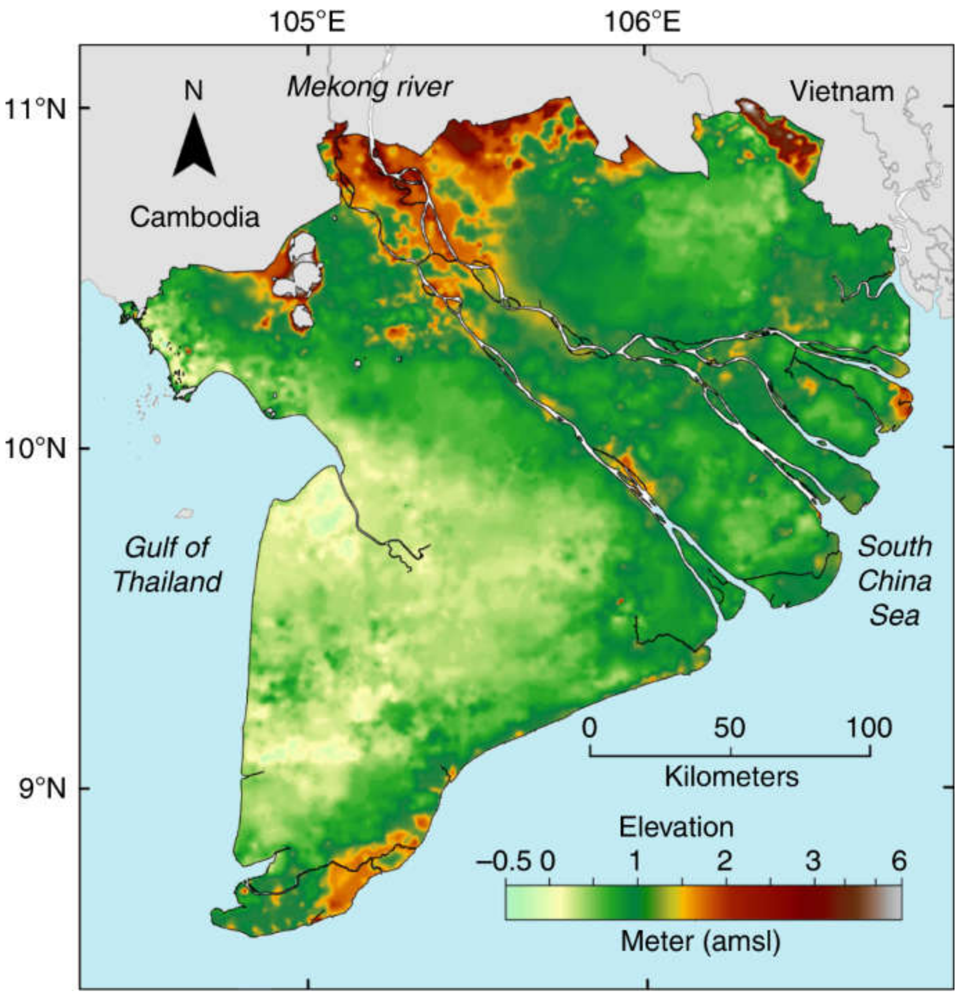


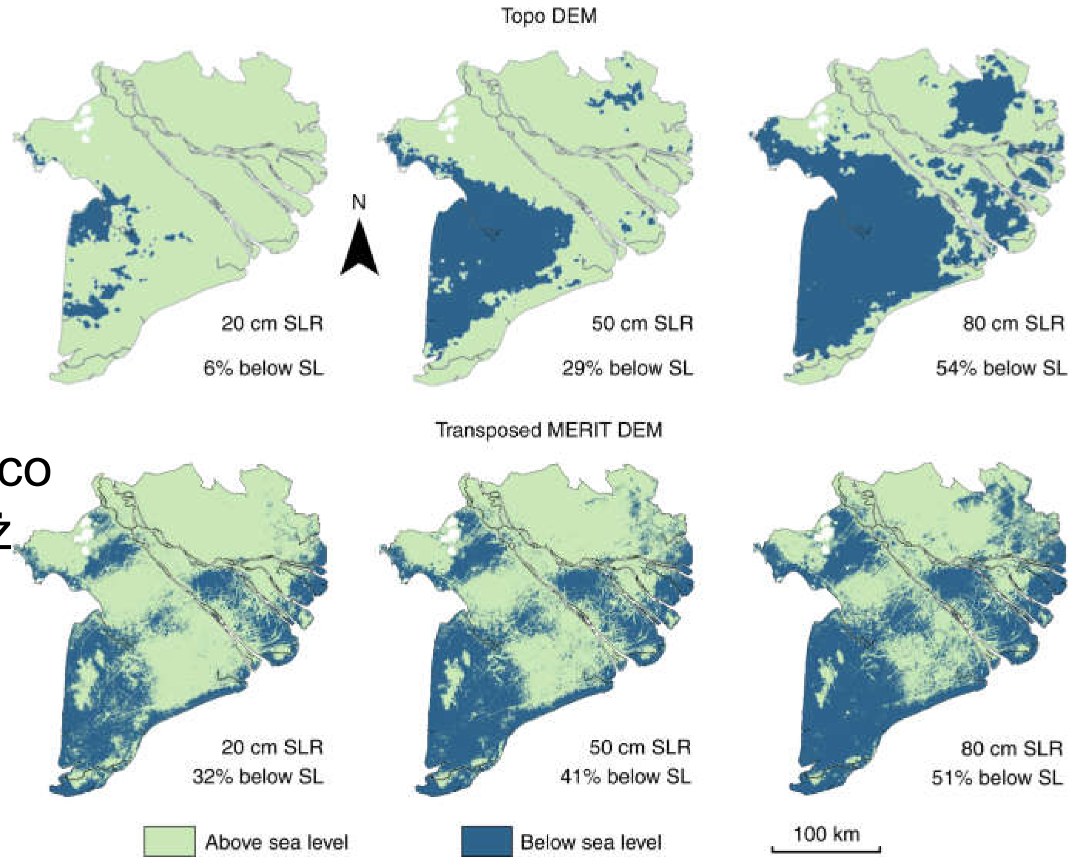
# A river like no other: Delta Mekongu

Podróż w dół rzeki Mekongu aż do jej delty jest przeżyciem jakich niewiele. Niespławna w większości swego biegu 2,800 mil, jest najdłuższą rzeką w Południowo-wschodniej Azji i dwunastą z najdłuższych na świecie. Po przepłynięciu przez Phnom Penh w Kambodży, kieruje się do Wietnamu a płaskie ukształtowanie terenu umożliwia jej rozlanie się na wielu oddzielnych gałęzi. Basen Mekongu pokrywa powierzchnię równoważną Francji i Niemiec razem wziętych. Średnio, rzeka jest szeroka na milę, ale w wielu punktach znacznie szersza. Wodospad Khom, na granicy między Laosem a Kambodżą jest najszerszy na świecie. Rzeka niesie 475 mld metrów sześciennych rocznie, i zapewnia wodę i żywność dla 60 milionów ludzi. (p.1)

Delta Mekongu charakteryzuje się największą gęstością ryb słodkowodnych na świecie, i jest domem dla ponad tysiąca gatunków. Bezpośrednio żywiąc 14 mln ludzi, daje więcej ryb niż wszystkie jeziora USA. Wylewy rzeki nawadniają pola ryżowe, czyniąc deltę największą ryżową miską świata.

# Obszary zalane

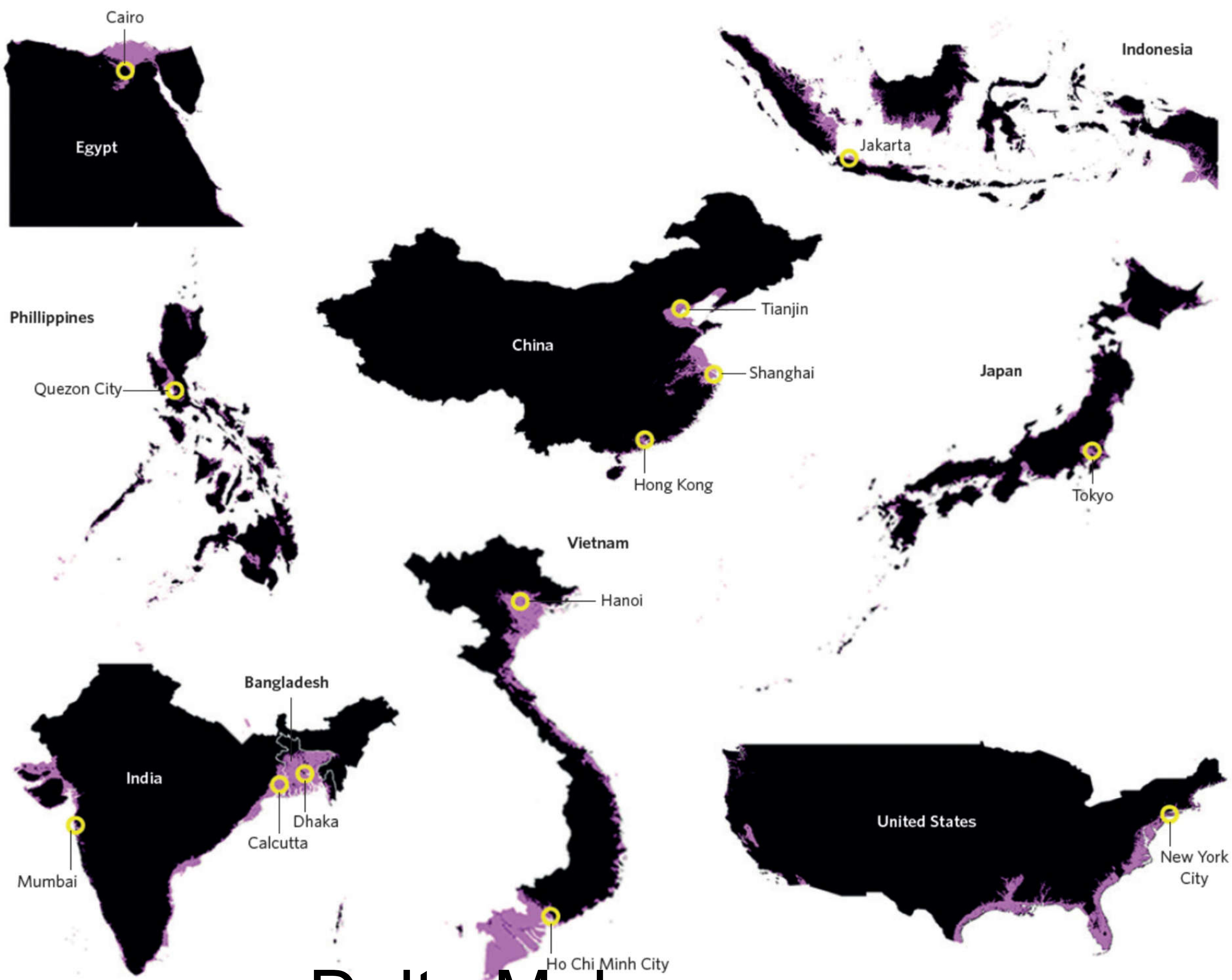



Sprawę pogarszają wysokie przepływy, co prawda raz na dzień, ale dochodzące aż do Phnom Penh. Wraz z podniesieniem się poziomu morza, żyzne pola ryżowe zamienią się w zarośla mangrowców.

P.S. Minderhoud et al., https://www.nature.com/articles/s41467-019-11602-1

NATURE CLIMATE CHANGE DOI: 10.1038/NCLIMATE2923




# Delta Mekongu

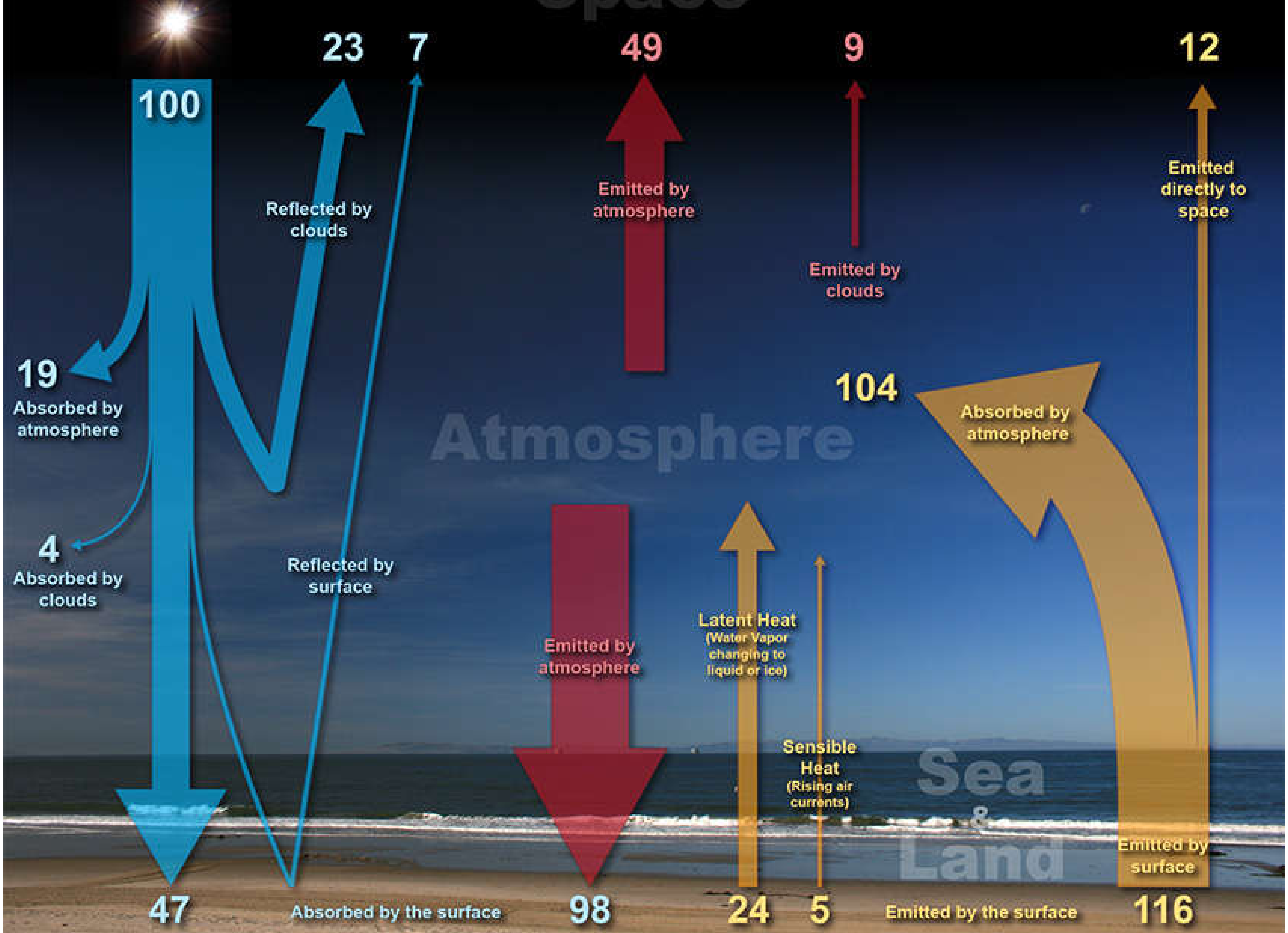
**Figure 6 | Projected submerged areas in heavily populated areas affected by sea-level rise.** The maps show areas of submergence for countries with at least 50 million people living on land affected by long-term sea-level projection based on the 1,280 Pg C emission scenario. Sea-level rise is based

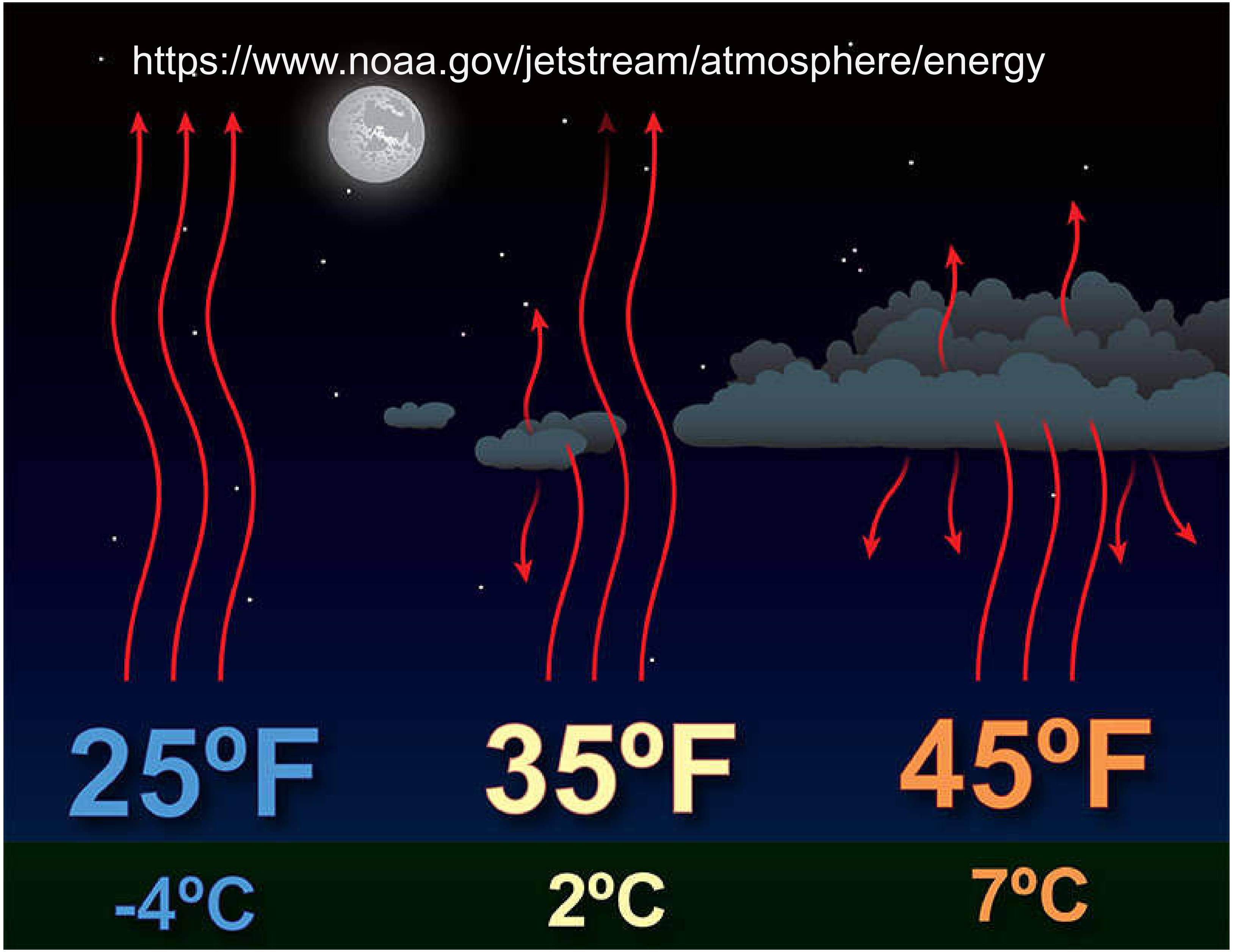
# Florida: everglades

# Mississippi estuarios


1993 – celowe uszkodzenie wałów zalało 57 km$^2$

https://www.noaa.gov/jetstream/atmosphere/energy




https://www.noaa.gov/jetstream/atmosphere/energy
25°F
35°F
45°F
-4°C
2°C
7°C

# Chapter 8. Forcing the issue

So far, we have established:

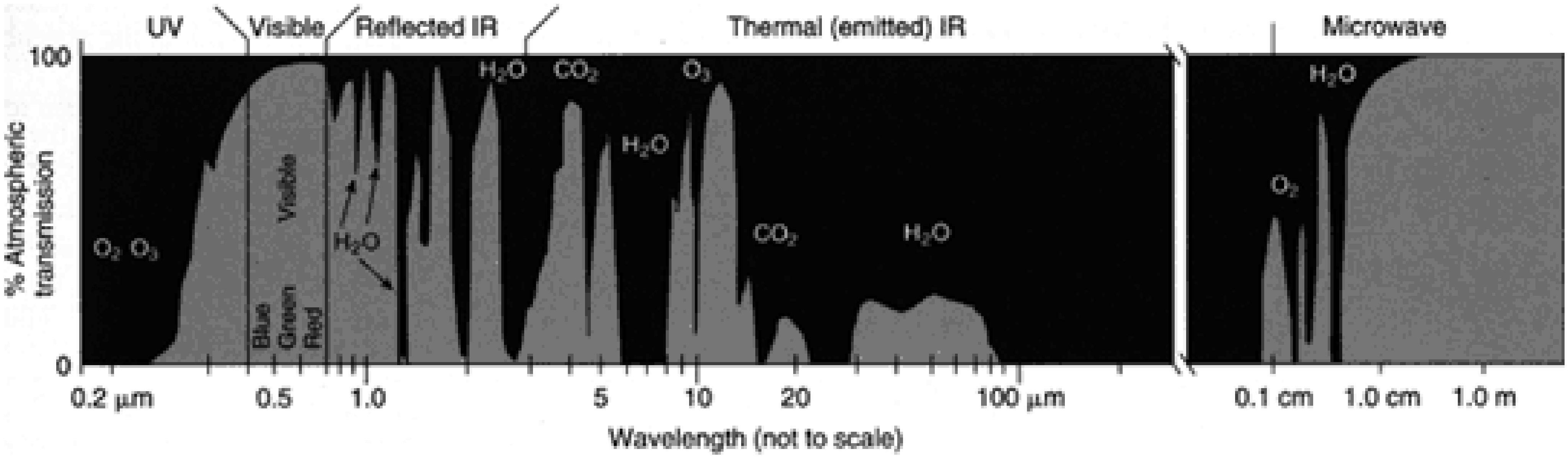
a) $CO_2$ level have been measured to be increasing yearly at a level consistent with emissions produced by human industrial activity. Current levels are unprecedented over the past one million years or so and more than 30 percent higher than at any other period during that time.

b) $CO_2$ is measured to be a greenhouse gas, in that it absorbs infrared radiation emitted by Earth's surface. Along with water vapor, it is quantitatively responsible for keeping Earth's surface temperature over its history, right up to the present.

c) Increasing the absorption in the atmosphere of outgoing radiation from Earth-s Surface increases the Surface temperature of the Earth. This is the original greenhouse effect, misnamed perhaps, but nevertheless the physics of which is well established both theoretically and experimentally.

These facts led to the conclusion that the increasing $CO_2$ concentration in our atmosphere should lead to further warming od the Earth's surface. The key question is how much? Was Svante Arrhenius correct in estimating 3ºC of warming if the $CO_2$ concentration hits 450 ppm, which, at current rates, will occur by 2050? And even if this were true, what impact would a 3ºC rise have on the globe? (Krauss, p.68)

# Absorption bands

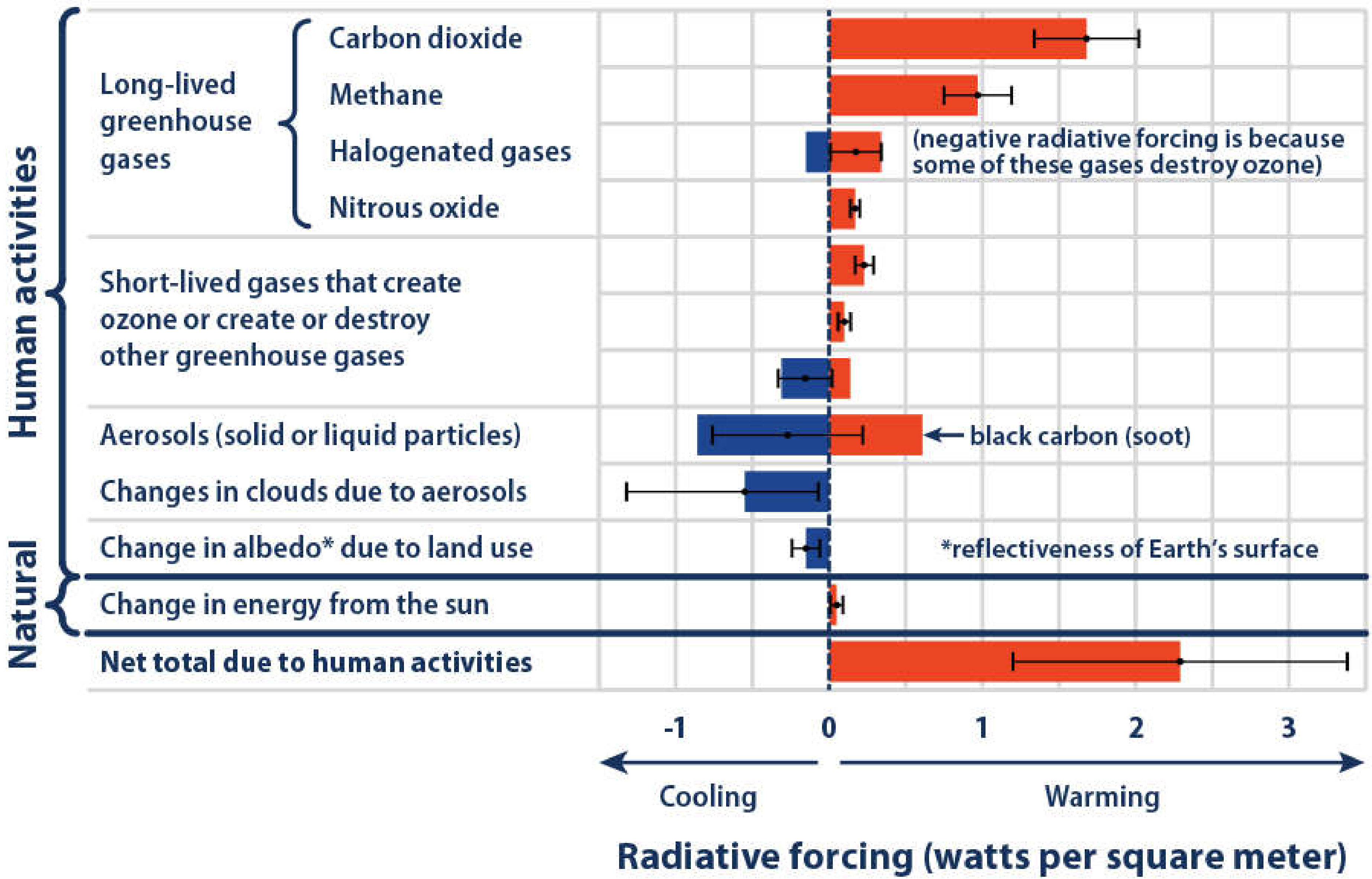



Some $H_2O$ and $CO_2$ absorption bands do overlap, so adding $CO_2$ will not increase the absorption?

Answer: the distribution of $H_2O$ and $CO_2$ in troposphere and stratosphere is different, so *complementary* trapping of IR can occur. (See the Lecture No. 3. on the vertical structure of the atmosphere).

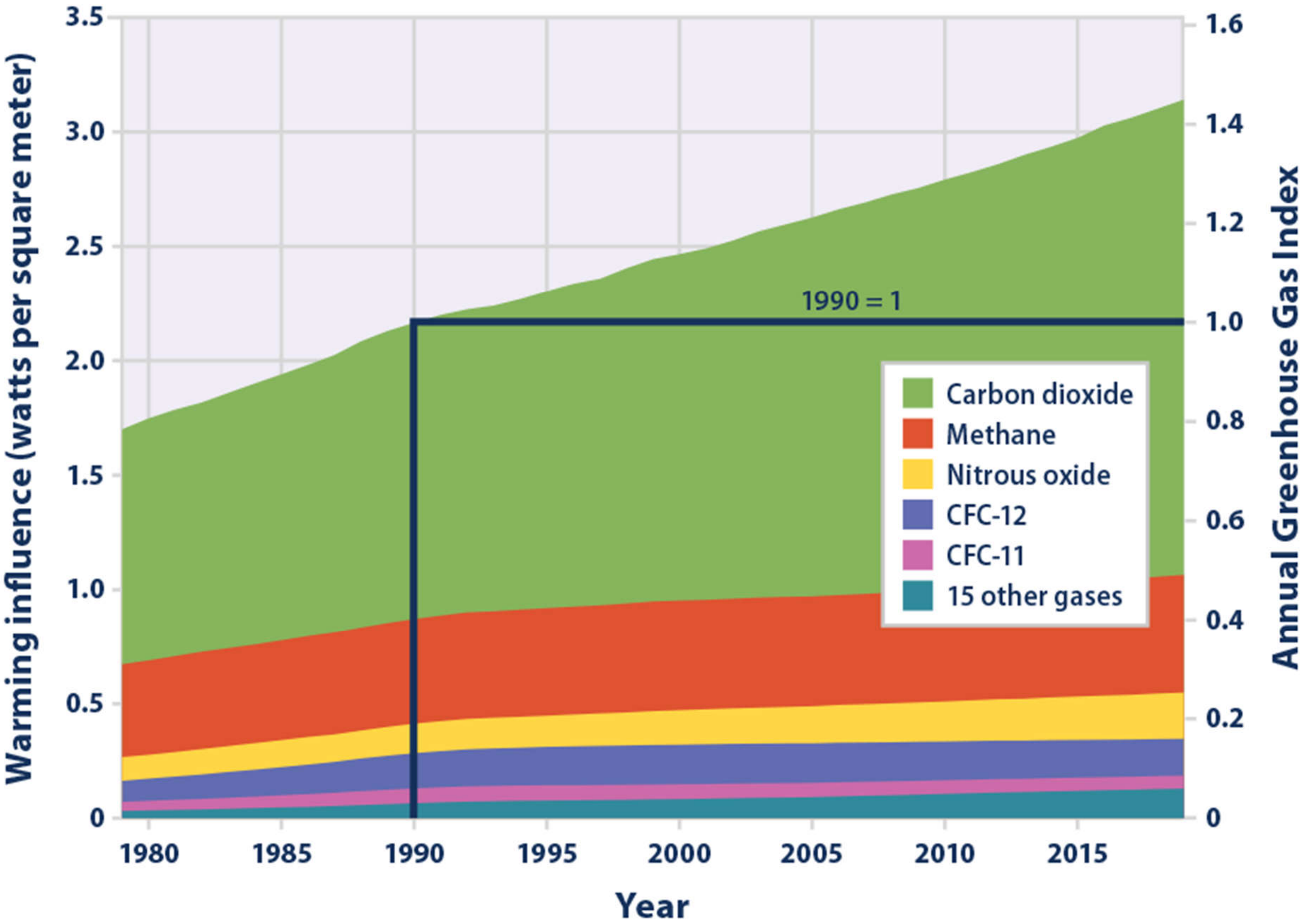
https://earthobservatory.nasa.gov/features/RemoteSensing/remote_04.php

# Radiative forcing




https://www.epa.gov/climate-indicators/climate-change-indicators-climate-forcing

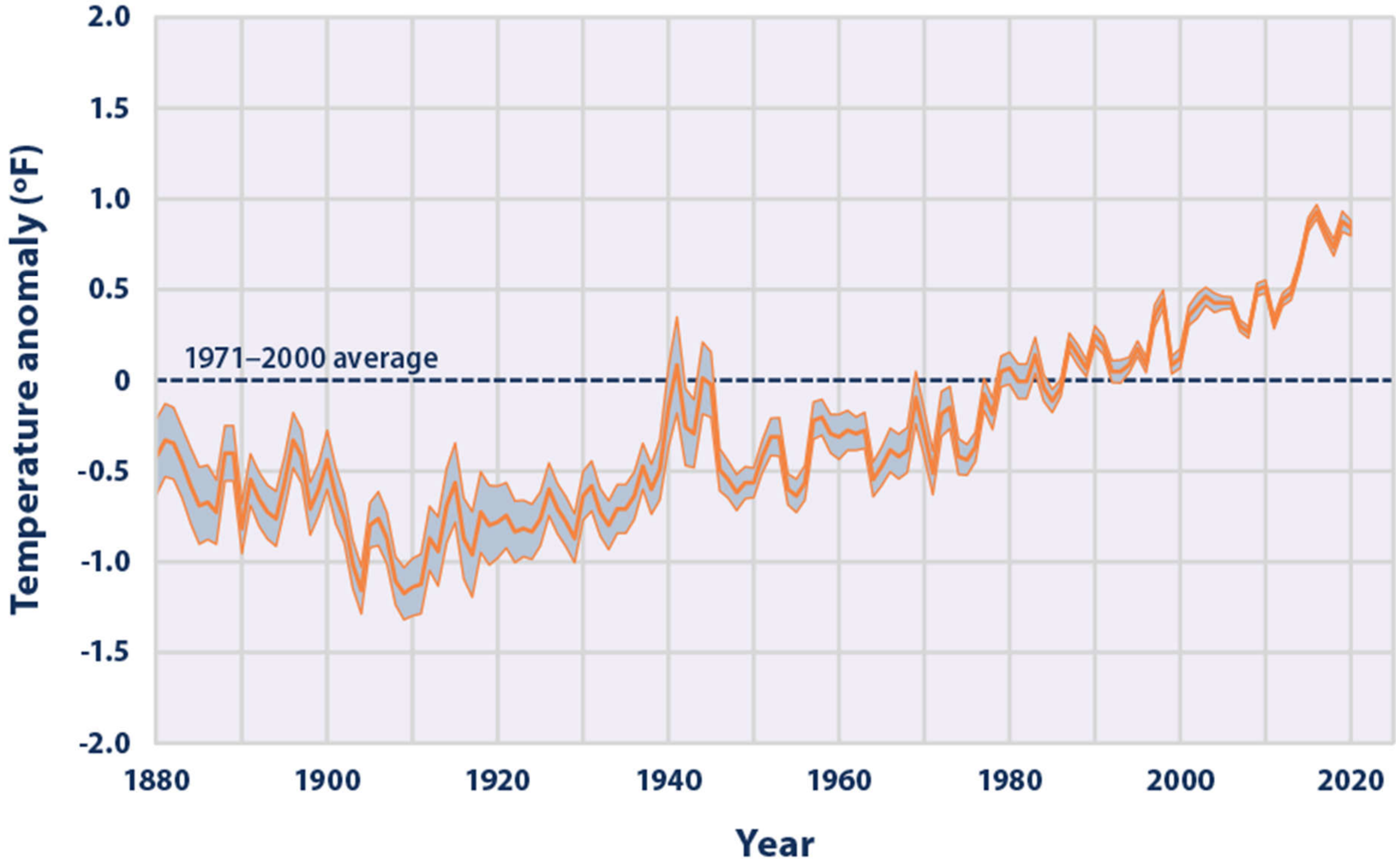
# Radiative forcing: gases




https://www.epa.gov/climate-indicators/climate-change-indicators-climate-forcing

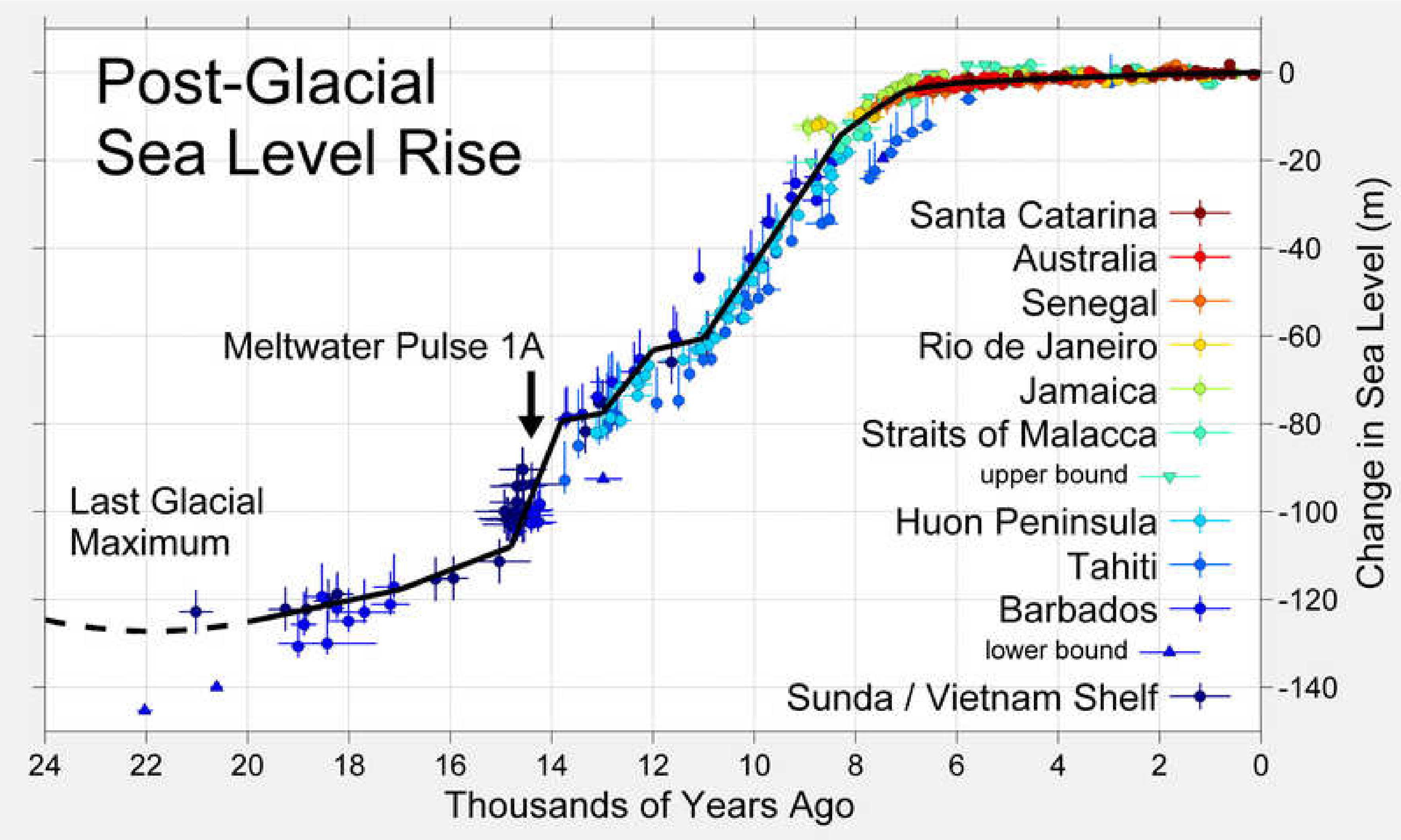
# Ocean temperature

**Figure 1.** Average Global Sea Surface Temperature, 1880–2020



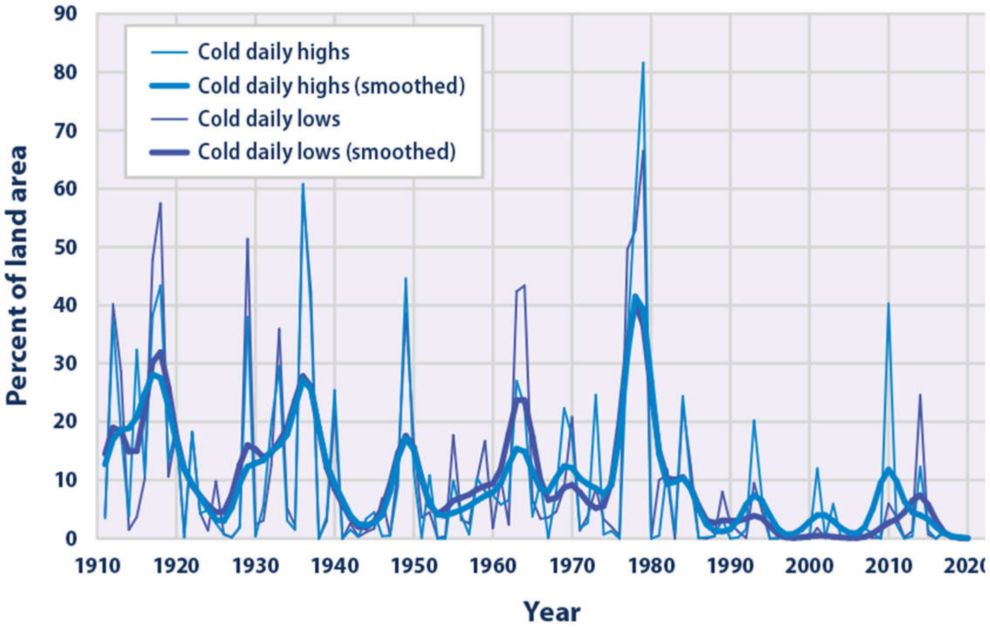

https://www.epa.gov/climate-indicators/climate-change-indicators-sea-surface-temperature

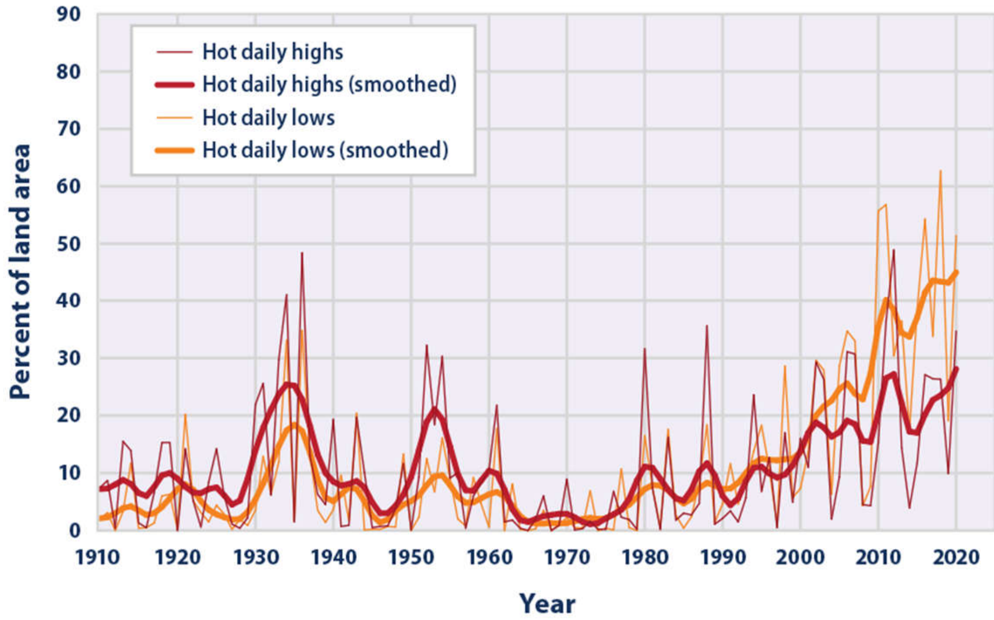
# Post-glacial melting




https://commons.wikimedia.org/wiki/File:Post-Glacial_Sea_Level.png
L.M. Krauss, The Physics of Climate Change, str. 128

# Anomalie temperatury



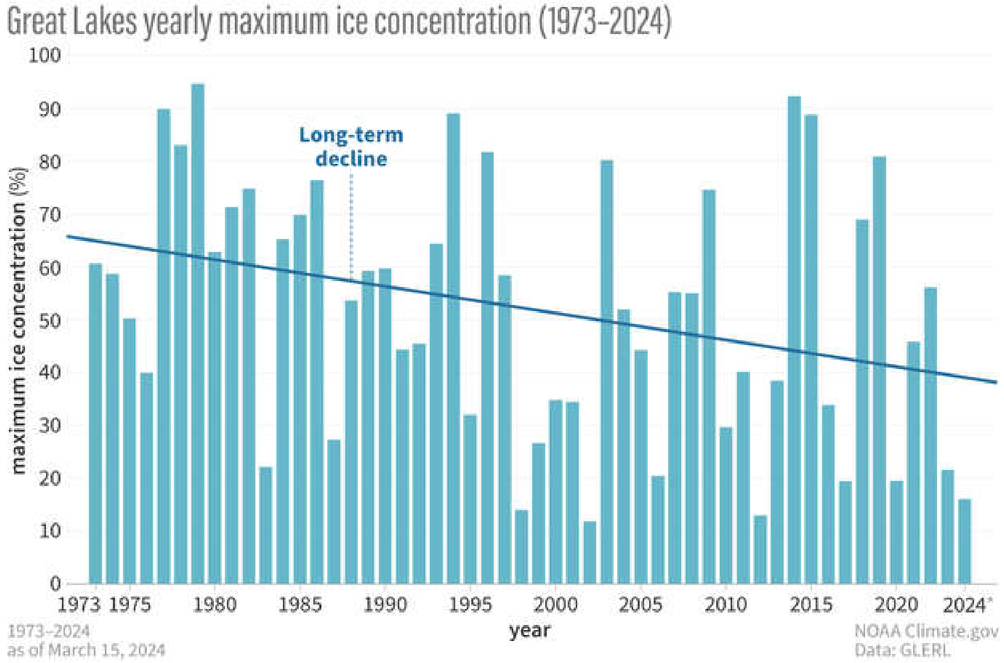

**Zimy coraz cieplejsze (widać cykl ok. 20 lat)**
**Latem – liczba gorących nocy rośnie bardziej niż liczba gorących dni**

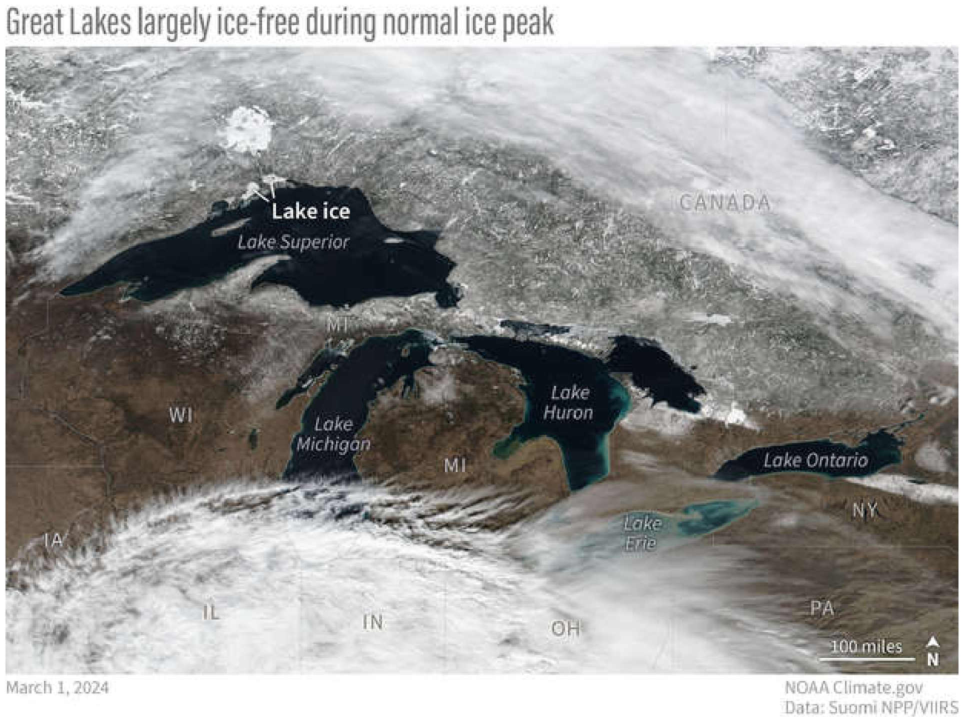
This graph shows the percentage of the land area of the contiguous 48 states with unusually cold daily high and low temperatures during the months of **December, January, and February**. The thin lines represent individual years, while the thick lines show a nine-year weighted average. Blue lines represent daily highs, while purple lines represent daily lows. The term "unusual" in this case is based on the long-term average conditions at each location.

This graph shows the percentage of the land area of the contiguous 48 states with unusually hot daily high and low temperatures during the months of **June, July, and August**. The thin lines represent individual years, while the thick lines show a nine-year weighted average. Red lines represent daily highs, while orange lines represent daily lows. The term "unusual" in this case is based on the long-term average conditions at each location.

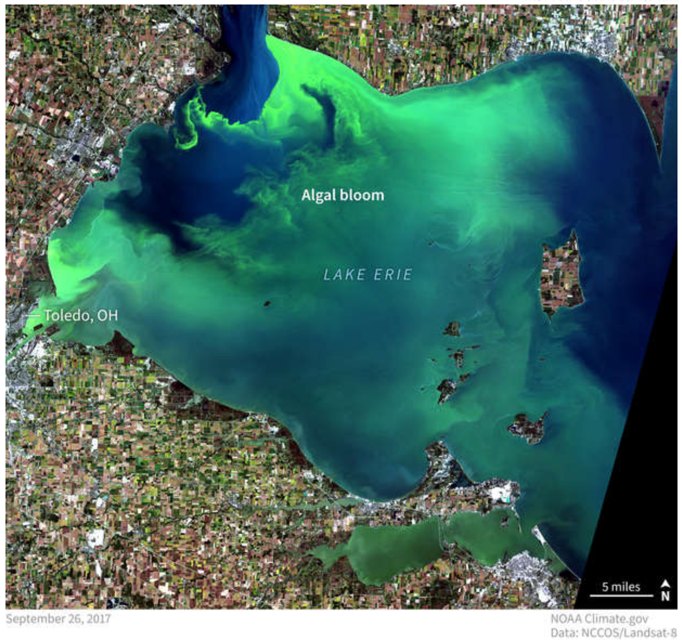
https://www.epa.gov/climate-indicators/climate-change-indicators-high-and-low-temperatures

# Zmiany klimatyczne: Wielkie Jeziora




Satellite image of the Great Lakes on March 1, 2024 showing very little ice cover during normal peak ice season, which ranges from mid-February to early March.




A harmful algal bloom across western Lake Erie on September 26, 2017. Graphic by NOAA Climate.gov, satellite imagery from Landsat-8/NOAA National Centers for Coastal Ocean Science.

https://www.climate.gov/media/15942
https://www.climate.gov/news-features/event-tracker/how-warm-winters-and-low-ice-may-impact-great-lakes

# Opady w USA

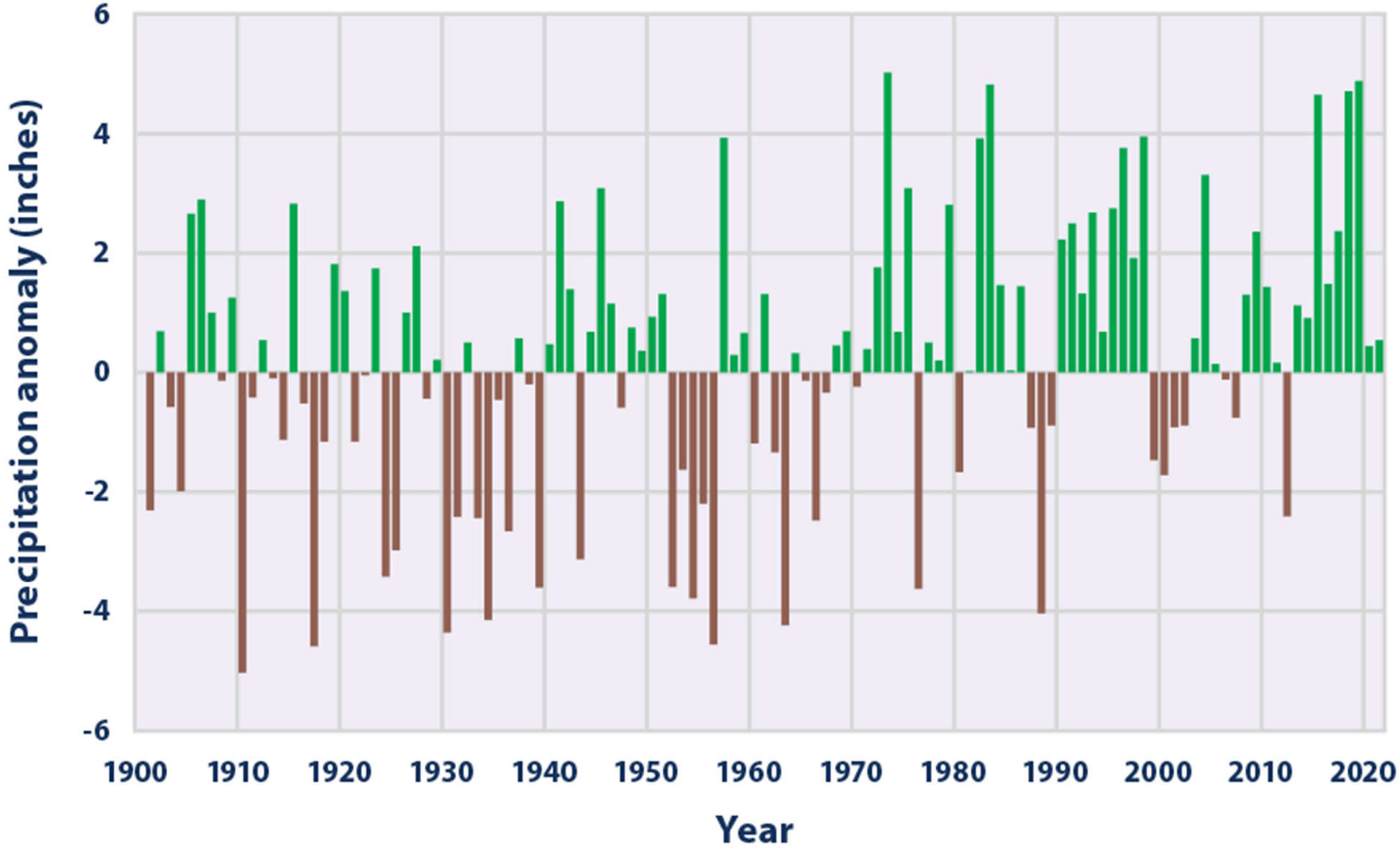



**Figure 1.** Precipitation in the Contiguous 48 States, 1901–2021

**Opady wykazują spore wahania, ale systematycznie rosną**

https://www.epa.gov/climate-indicators/climate-change-indicators-us-and-global-precipitation

# Susze w południowo-zachodnich stanach USA

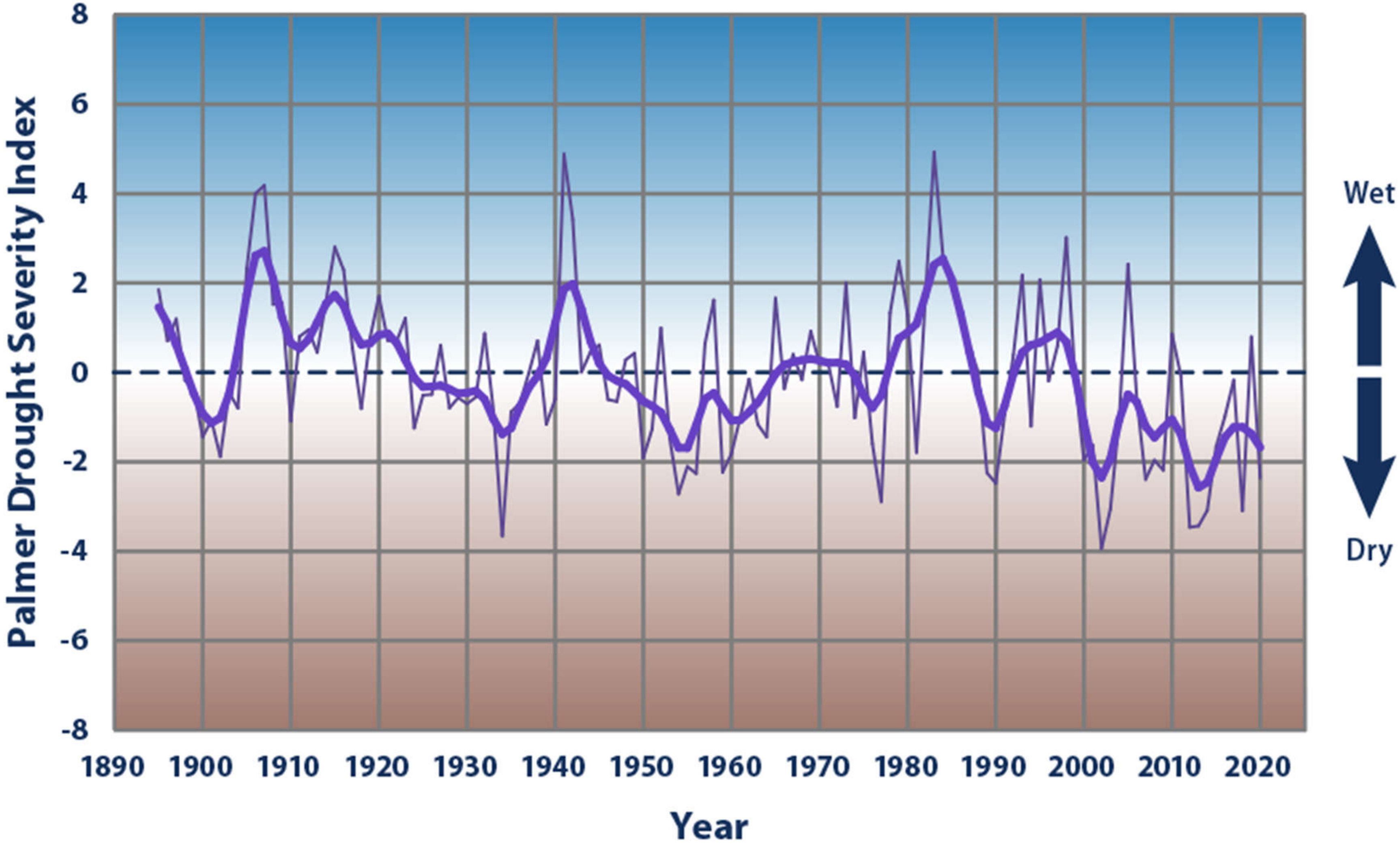



**Figure 3.** Drought Severity in the Southwestern United States, 1895–2020

# Lodowce w USA

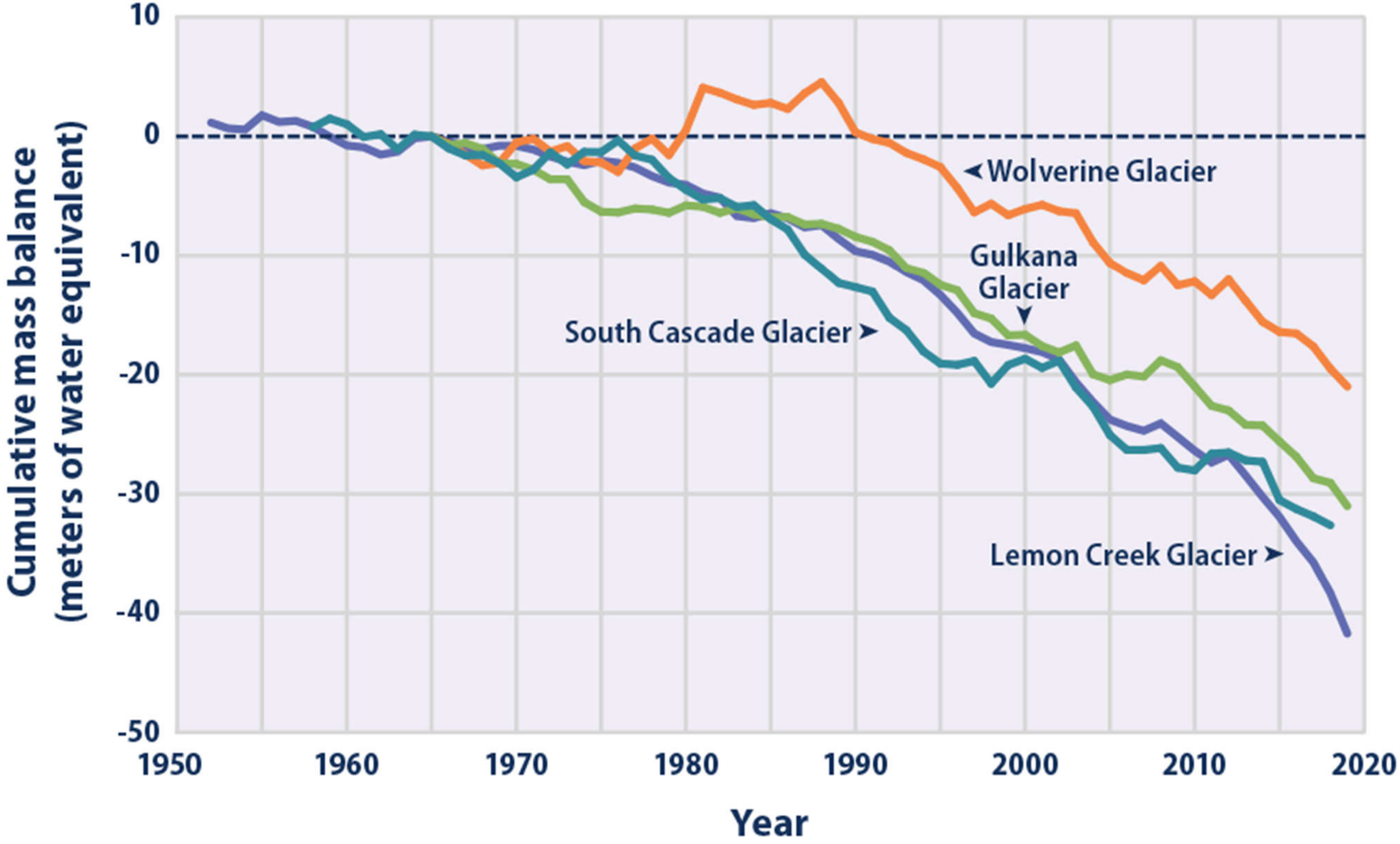



**Figure 2.** Cumulative Mass Balance of Four U.S. Glaciers, 1952–2019

https://www.epa.gov/climate-indicators/climate-change-indicators-glaciers

# Lodowce arktyczne

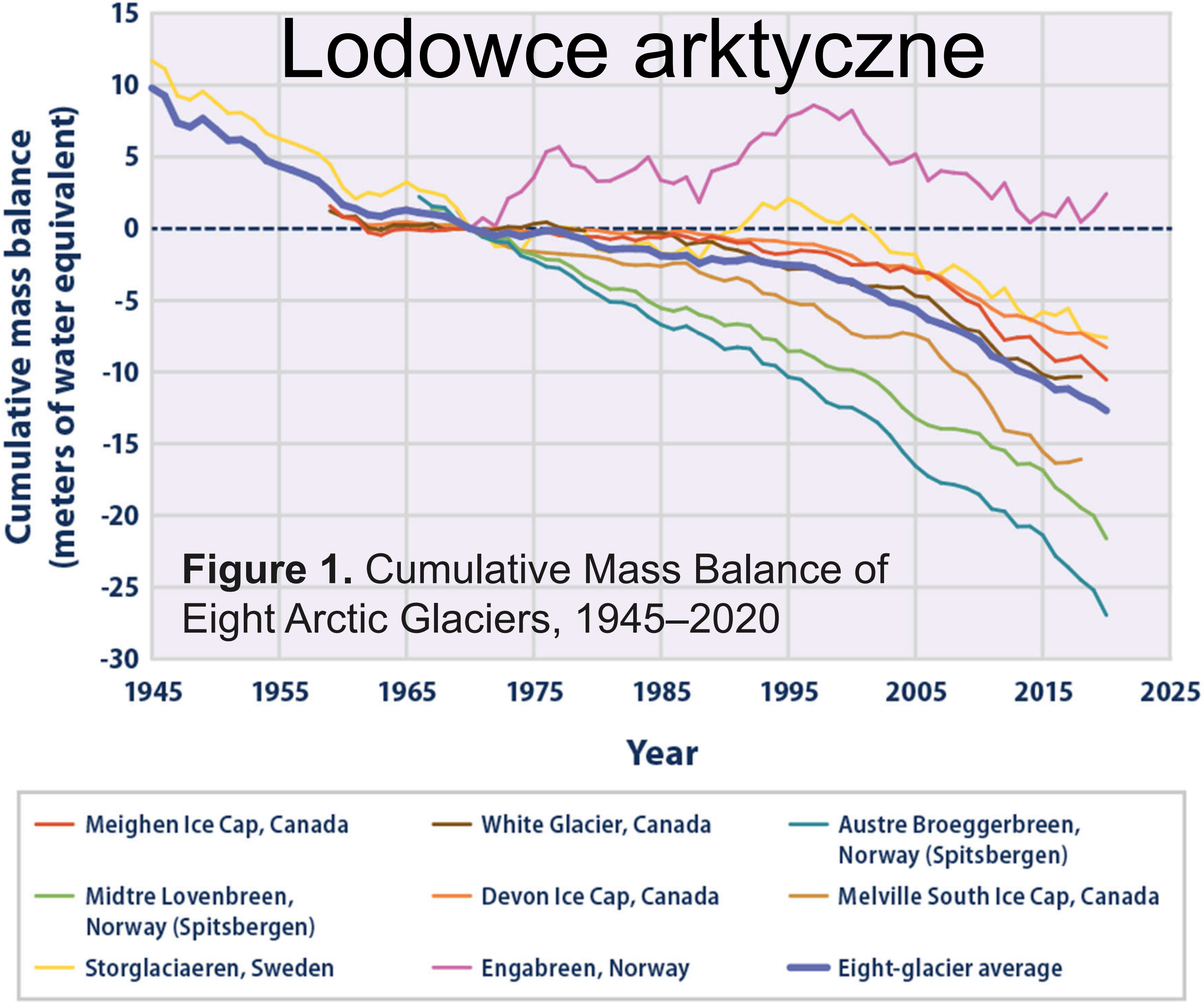
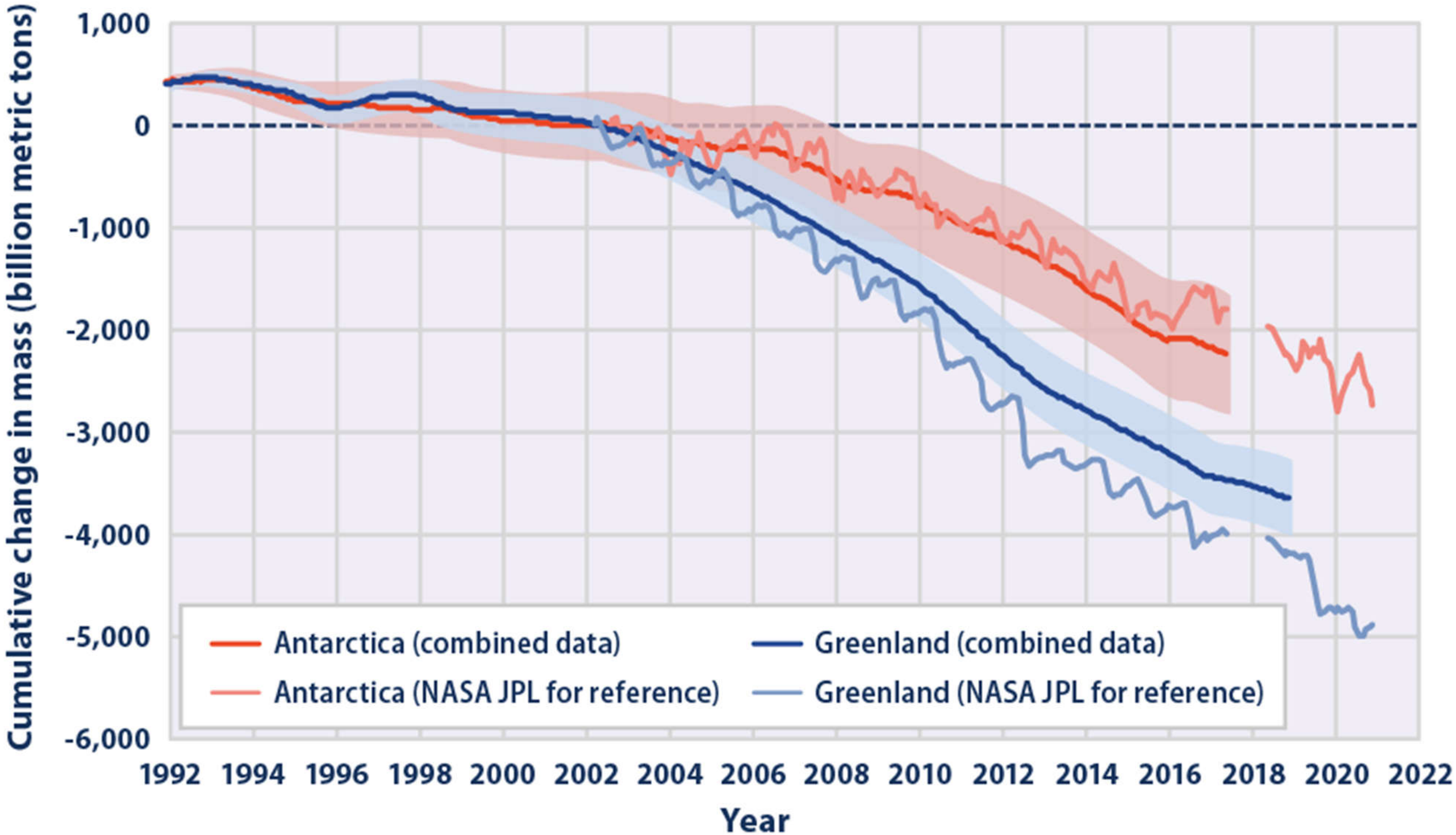



**Figure 1.** Cumulative Mass Balance of Eight Arctic Glaciers, 1945–2020

Najbardziej topnieją lodowce na Spitzbergenie (w strumieniu Prądu Zatokowego)

https://www.epa.gov/climate-indicators/climate-change-indicators-arctic-glaciers

# Pokrywa lodowa na biegunach

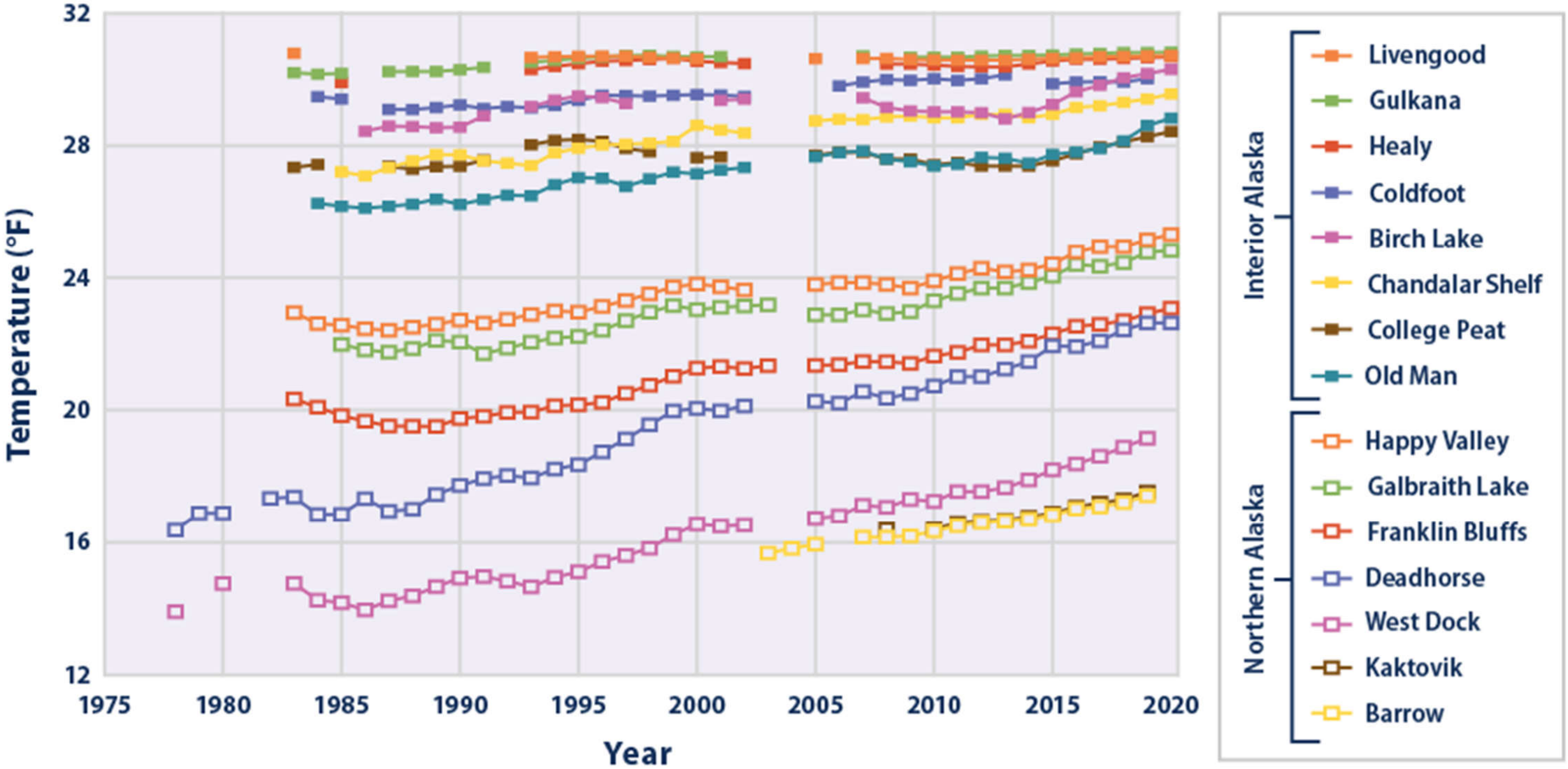



Bardziej topnieje pokrywa lodowa w Arktyce, o zasadniczym znaczeniu dla dynamiki Prądu Zatokowego (Golfstromu) a przez to globalnego prądu głębinowego (conveyor belt)

**Figure 1.** Cumulative Mass Balance of Greenland and Antarctica, 1992–2020

https://www.epa.gov/climate-indicators/climate-change-indicators-ice-sheets

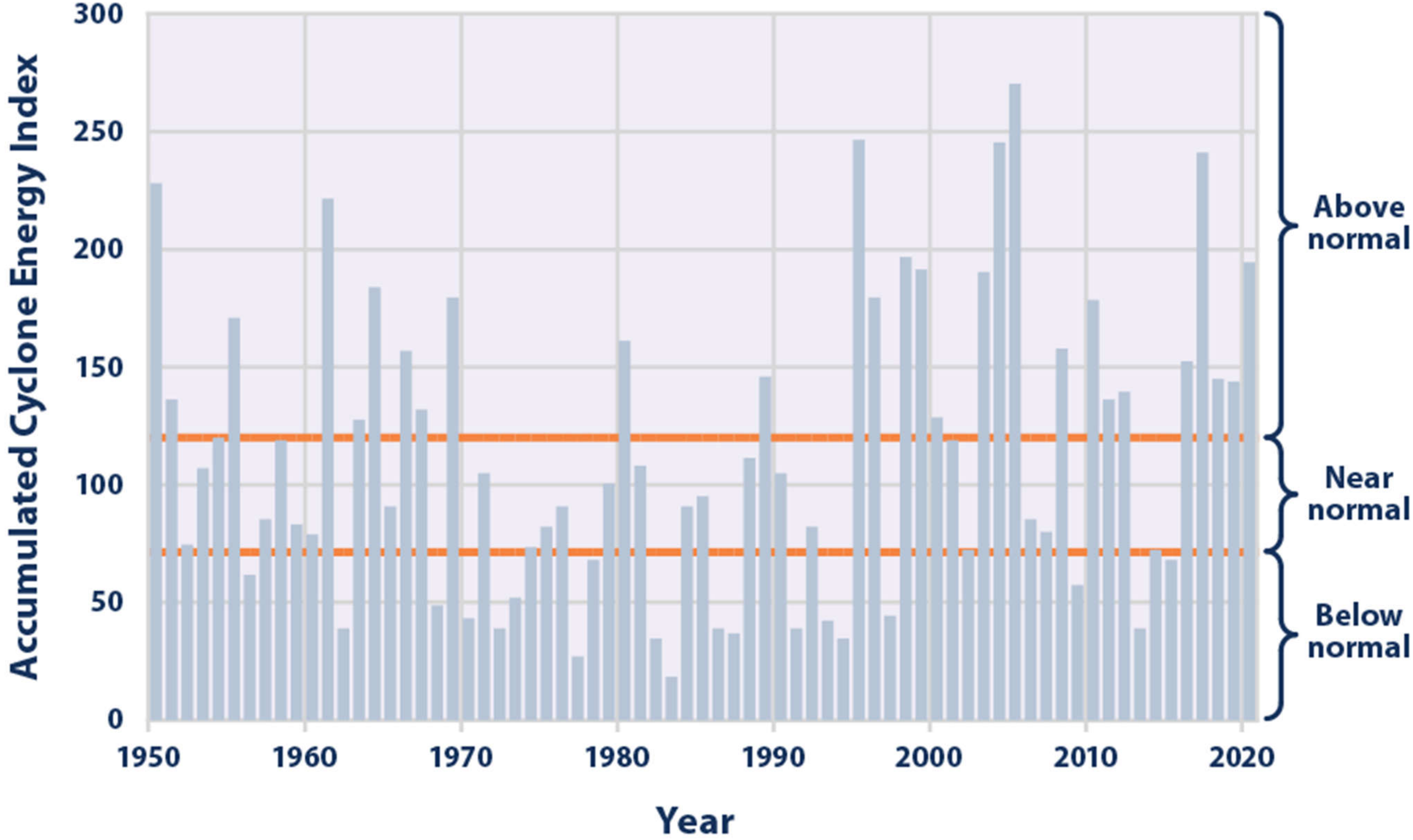
# Permafrost




**Najbardziej rośnie temperatura na północy Alaski: tundra rozmarza, z konsekwencjami w postaci emisji $CH4_4$ – „potężnego” gazu cieplarnianego**

**Figure 1.** Permafrost Temperatures in Alaska, 1978–2020

# Energia cyklonów tropikalnych




This figure shows total annual Accumulated Cyclone Energy (ACE) Index values, which account for cyclone **strength, duration, and frequency**, from 1950 through 2020. The National Oceanic and Atmospheric Administration has defined “near normal,” “above normal,” and “below normal” ranges based on the distribution of ACE Index values over the 30 years from 1981 to 2010.

# Chapter 7: Believe it or not

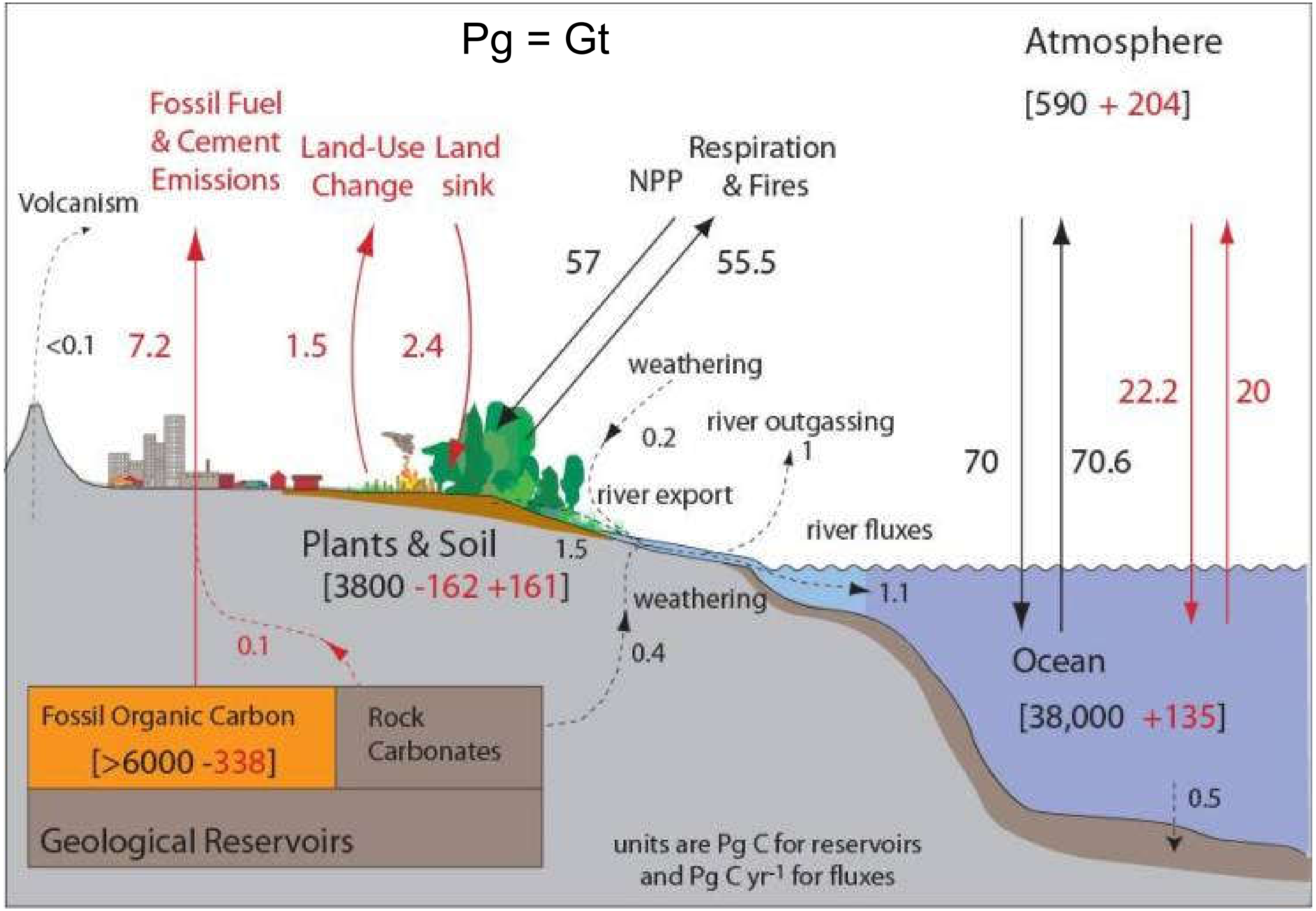
The sign of a good theory is when models based on it get more detailed and more precise theoretical predictions based on the improved models then agree better with the data. […] The physical principles behind the calculation of the radiative forcing – the Chief driver of climate changes – are the same as those that underline the two-hundred-years-old explanation of why the Earth's surface is 33oC warmer than it would be without its current atmosphere.

When discussion turns to the issue of global Warming, it is easy to lose the forest for the trees. […] Each successive complexity that is included, from the detailed structure of the atmosphere, both vertically and across Earth's Surface, to the role of Convection, the importance of clouds, ocean mixing and currents, pollution, Earth's albedo, and so on, is sometimes portrayed as a possible new Achilles heel. […] A following relation between $CO_2$ and radiative forcing

$$\text{Radiative Forcing } (\Delta P) = 5.35\ (\pm 0.5)\ \ln (C/C_0)\ \text{W/m}^2$$

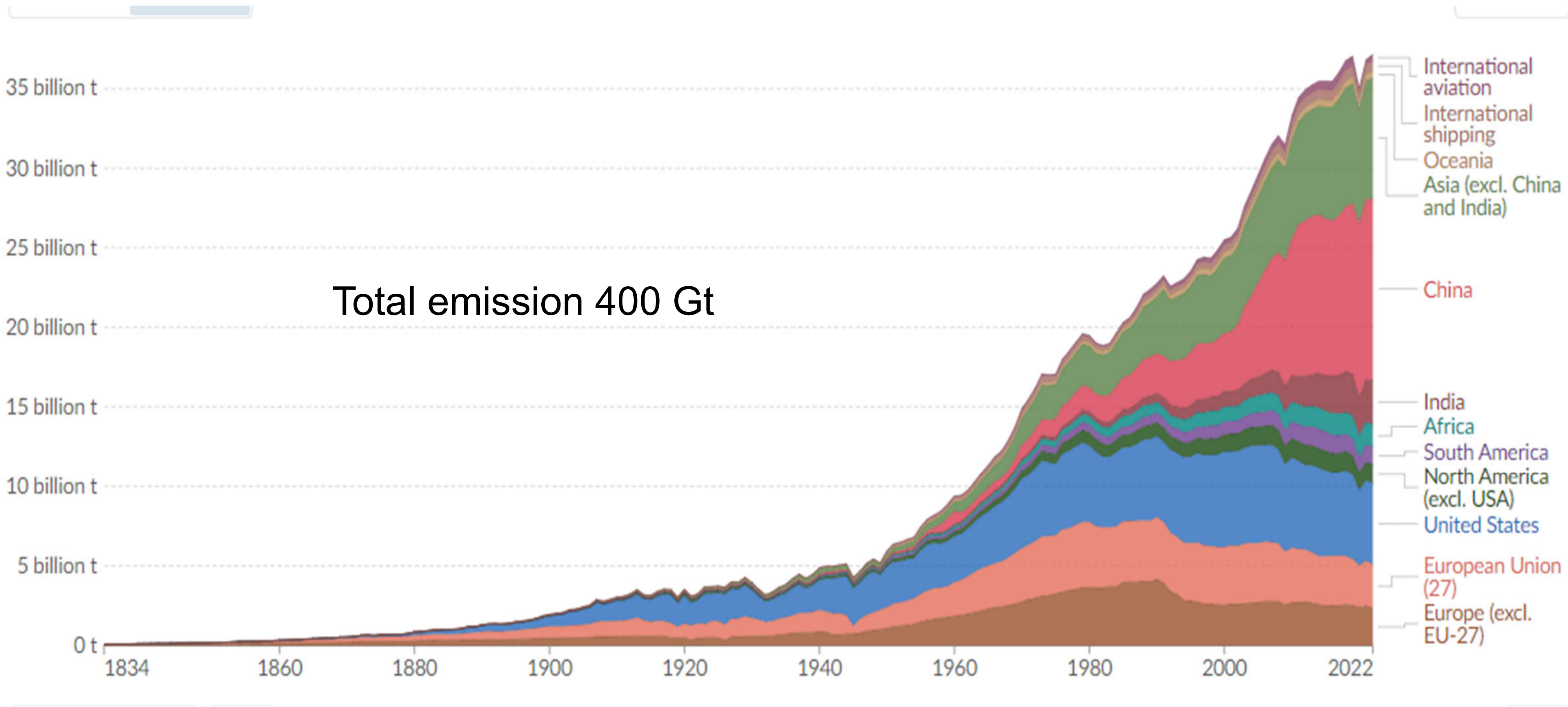
This is not straightforward, and it is not clear that the same conversion factor would prevail for different $CO_2$ and temperature values due to a host of other effects that can enter as temperatures increase, from increased water pressure in the atmosphere to effects of conversion, clouds, Surface albedo, heat storage in the oceans, the temperaturę variation across the globe. (p. 85-87)

# Carbon balance



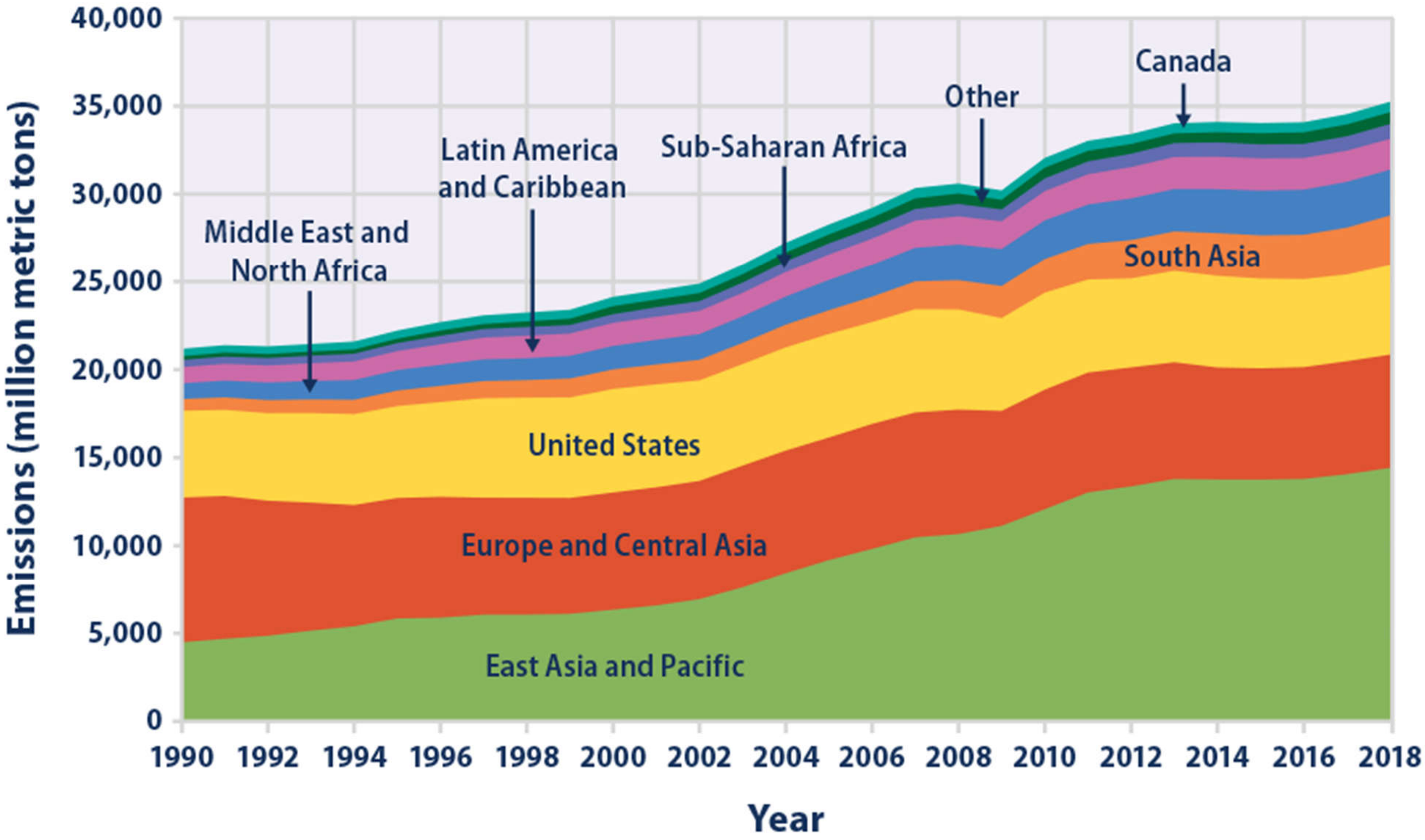

https://www.pmel.noaa.gov/co2/files/carbon_cycle.jpg

# Carbon emission



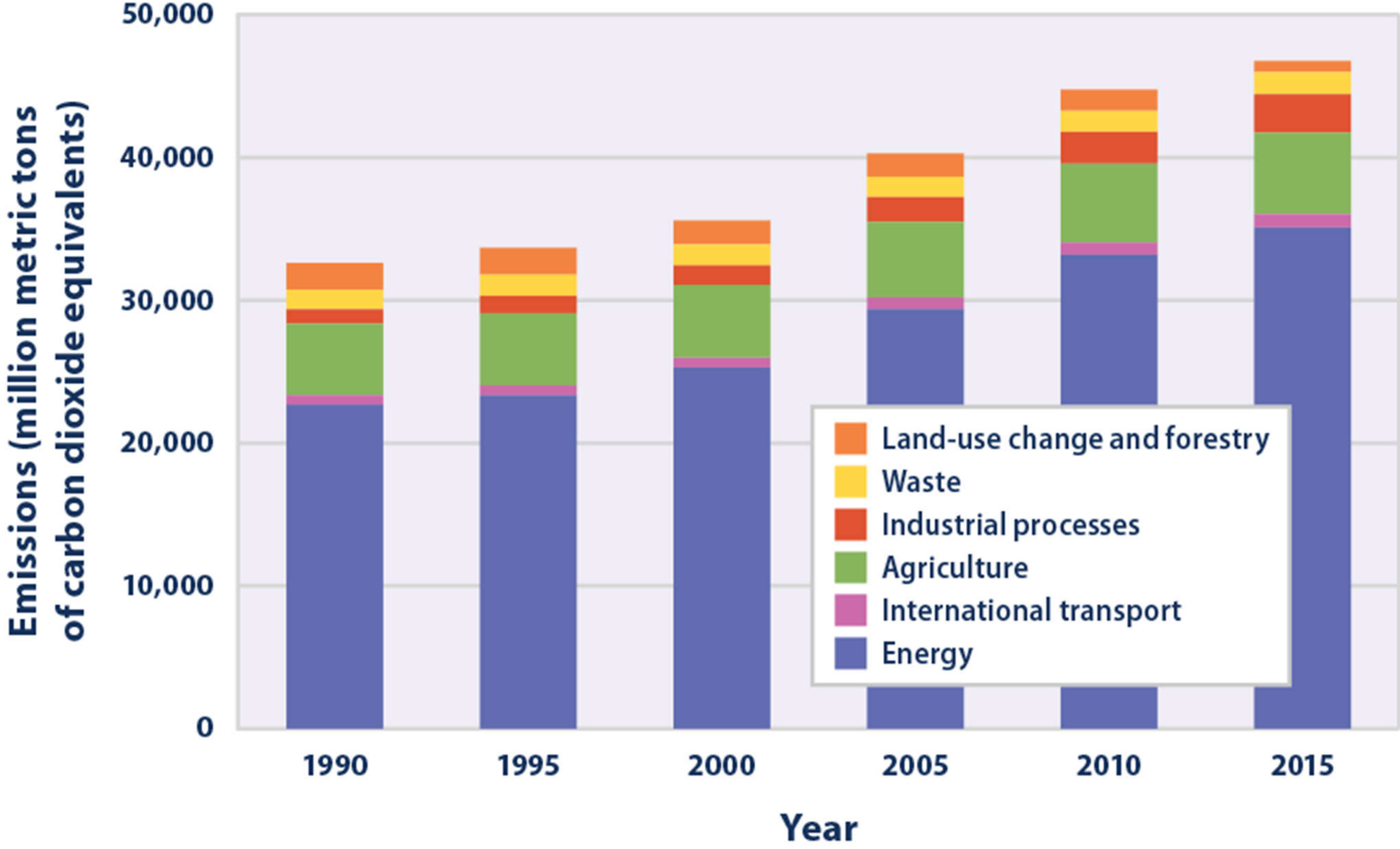

https://ourworldindata.org/grapher/annual-co-emissions-by-region?time=1834..latest

# Carbon emission



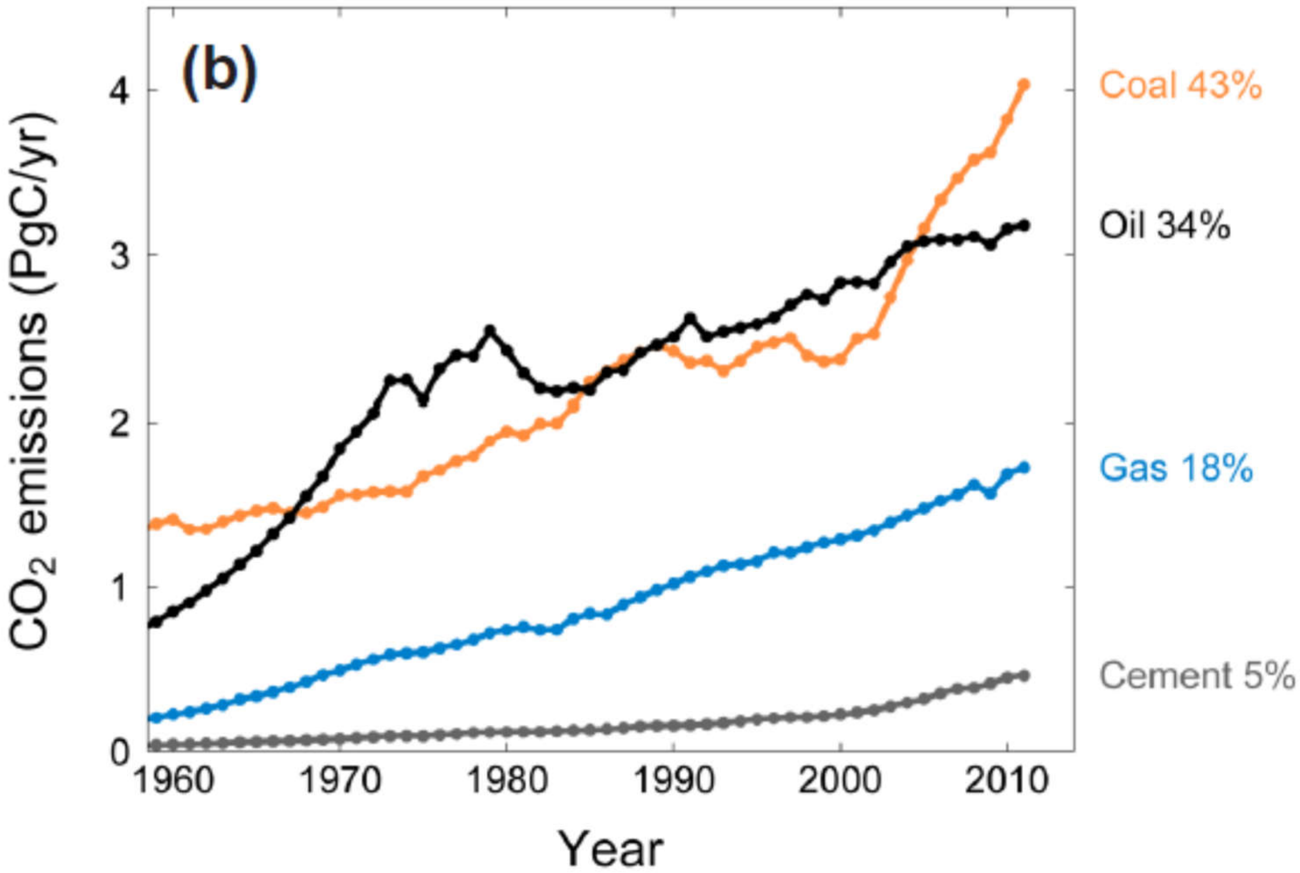

https://www.epa.gov/climate-indicators/climate-change-indicators-global-greenhouse-gas-emissions

# Carbon emission by sectors




https://www.epa.gov/climate-indicators/climate-change-indicators-global-greenhouse-gas-emissions

# Carbon emission




https://www.geokniga.org/bookfiles/geokniga-co2sequestration.pdf

# Carbon sequestring

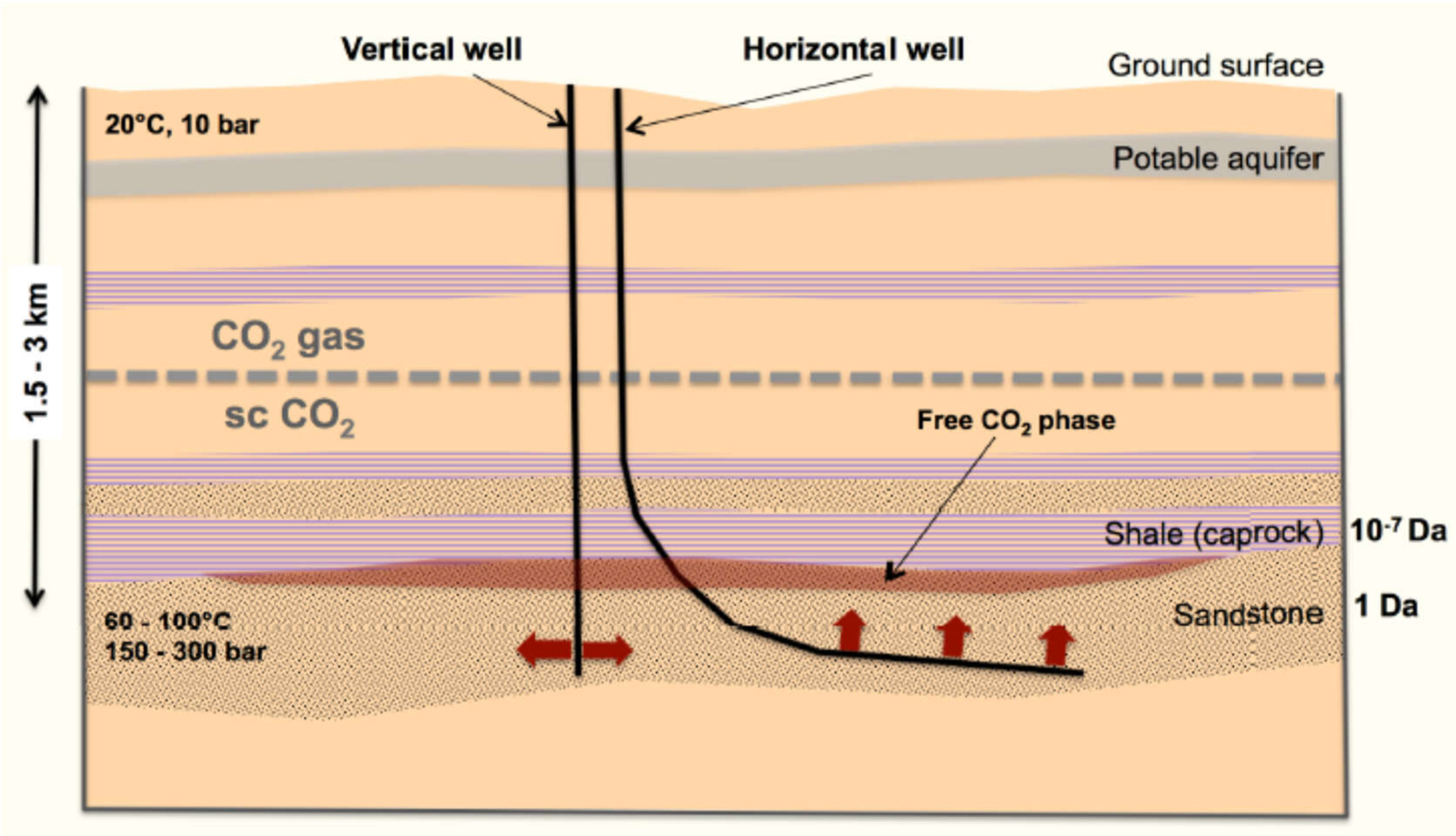



**Figure 2.** Schematic diagram of a carbon sequestration system shown as geologic cross section and illustrating the typical conditions and rock properties encountered. The transition of gaseous $CO_2$ to supercritical $CO_2$ typically occurs at depths of 1-1.5 km.

$$CO_2 + CaAl_2Si_2O_8 + 2H_2O = Al_2Si_2O_5(OH)_4 + CaCO_3$$

Donald DePaolo, LBL
https://www.geokniga.org/bookfiles/geokniga-co2sequestration.pdf

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

# Mineral sequestration of carbon dioxide in basalt: A pre-injection overview of the CarbFix project

Sigurdur Reynir Gislason [a,*], Domenik Wolff-Boenisch [a], Andri Stefansson [a], Eric H. Oelkers [b], Einar Gunnlaugsson [c], Hólmfridur Sigurdardottir [c], Bergur Sigfusson [c], Wallace S. Broecker [d], Juerg M. Matter [d], Martin Stute [d], Gudni Axelsson [e], Thrainn Fridriksson [e]

[a] Institute of Earth Sciences, University of Iceland, Iceland
[b] CNRS/UMR 5563, Université Paul Sabatier, France
[c] Reykjavik Energy, Iceland
[d] Lamont-Doherty Earth Observatory, Columbia University, USA
[e] Iceland GeoSurvey, Reykjavík, Iceland

$$CO_{2(g)} + H_2O = H_2CO_3$$

$$H_2CO_3 = HCO_3^- + H^+$$

$$(Fe, Ca, Mg)^{2+} + CO_2 + H_2O = \underbrace{(Fe, Ca, Mg)CO_3}_{\text{carbonate minerals}} + 2H^+$$

ARTICLE INFO

*Article history:*
Received 30 April 2009
Received in revised form 5 November 2009
Accepted 16 November 2009
Available online 22 January 2010

*Keywords:*
$CO_2$ fixation
$CO_2$ sequestration
Mineral carbonation
Mineral storage
Basalt carbonation
Dissolution rate

In this paper we describe the thermodynamic and kinetic basis for mineral storage of carbon dioxide in basaltic rock, and how this storage can be optimized. Mineral storage is facilitated by the dissolution of $CO_2$ into the aqueous phase. The amount of water required for this dissolution decreases with decreased temperature, decreased salinity, and increased pressure. Experimental and field evidence suggest that the factor limiting the rate of mineral fixation of carbon in silicate rocks is the release rate of divalent cations from silicate minerals and glasses. Ultramafic rocks and basalts, in glassy state, are the most promising rock types for the mineral sequestration of $CO_2$ because of their relatively fast dissolution rate, high concentration of divalent cations, and abundance at the Earth's surface. Admixture of flue gases, such as $SO_2$ and HF, will enhance the dissolution rates of silicate minerals and glasses. Elevated temperature increases dissolution rates but porosity of reactive rock formations decreases rapidly with increasing temperature. Reduced conditions enhance mineral carbonation as reduced iron can precipitate in carbonate minerals. Elevated $CO_2$ partial pressure increases the relative amount of carbonate minerals over other secondary minerals formed. The feasibility to fix $CO_2$ by carbonation in basaltic rocks will be tested in the CarbFix project by: (1) injection of $CO_2$ charged waters into basaltic rocks in SW Iceland, (2) laboratory experiments, (3) studies of natural analogues, and (4) geochemical modelling.

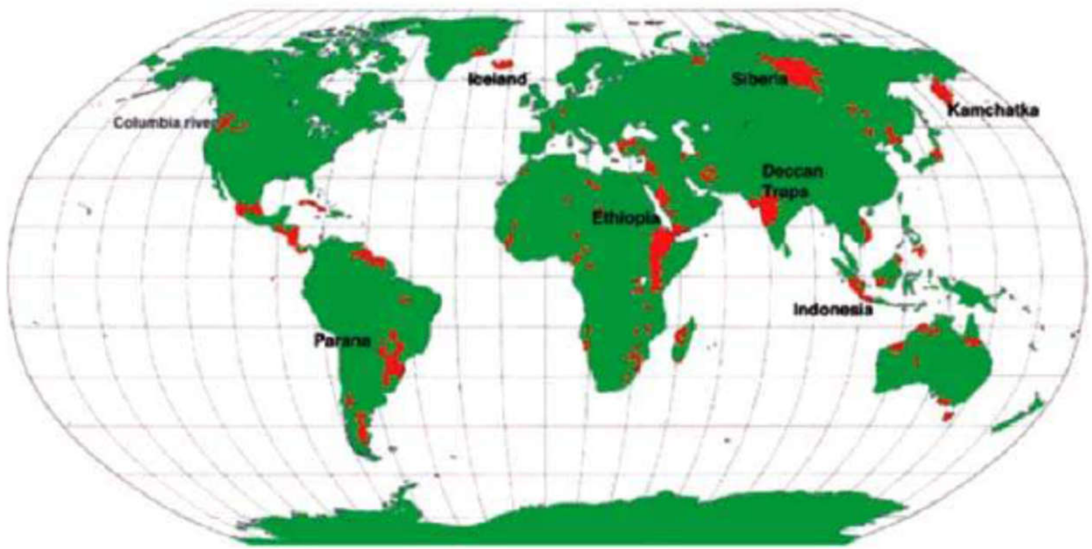
# „rozpuszczanie kationów”

$$\underset{\text{Forsterite}}{Mg_2SiO_4} + 4H^+ \rightarrow 2Mg^{2+} + 2H_2O + SiO_{2(aq)} \qquad (3)$$

$$\underset{\text{Ca-plagioclase}}{CaAl_2Si_2O_8} + 8H^+ \rightarrow Ca^{2+} + 2Al^{3+} + 2SiO_{2(aq)} + 4H_2O \qquad (4)$$

and

$$\underset{\text{Basaltic glass}}{SiAl_{0.36}Ti_{0.02}Fe(III)_{0.02}Ca_{0.26}Mg_{0.28}Fe(II)_{0.17}Na_{0.08}K_{0.008}O_{3.36}} + 6.72H^+$$
$$= Si^{4+} + 0.36Al^{3+} + 0.02Ti^{4+} + 0.02Fe^{3+} + 0.17Fe^{2+}$$
$$+ 0.26Ca^{2+} + 0.28Mg^{2+} + 0.08Na^+ + 0.008K^+$$
$$+ 3.36H_2O$$



# Islandia, Kamczatka, Etiopia

3 g $CO_2/m^2/day$

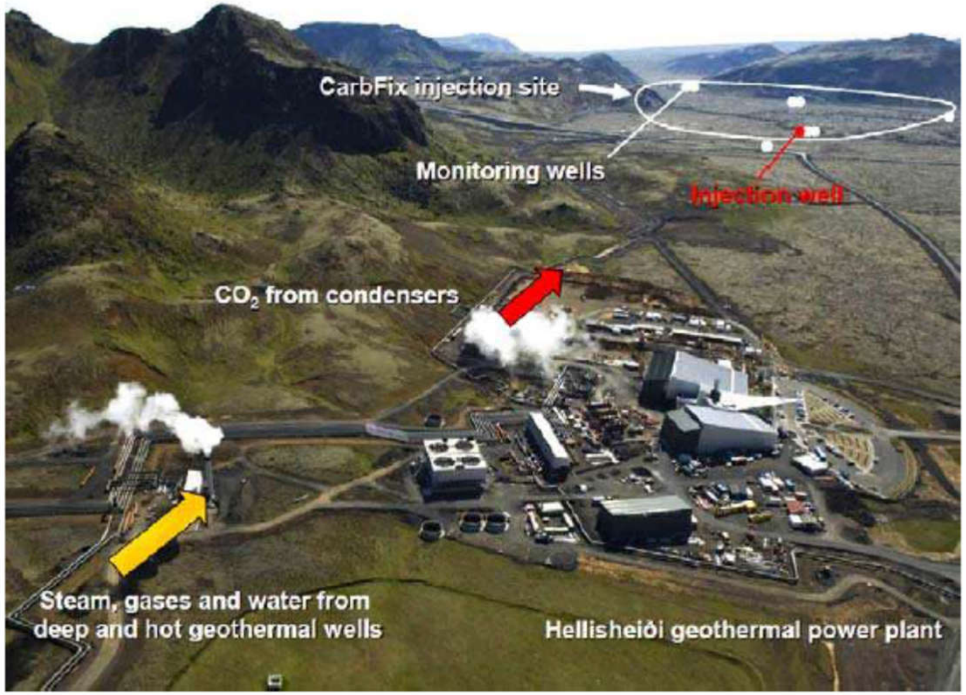



**Fig. 6.** Aerial photograph of the Hellisheidi geothermal power plant and the CarbFix injection site which includes an injection and several monitoring wells. The geothermal power plant as a source of the $CO_2$ is approximately 3 km to the north of the injection site. The moss covered post-glacial basaltic lava flows cover the ground in the upper right part of the figure. The hill to the left of the power plant is a hyaloclastite (broken glass) ridge. This formation is mostly basaltic glass, formed under glacier during the last glaciations.

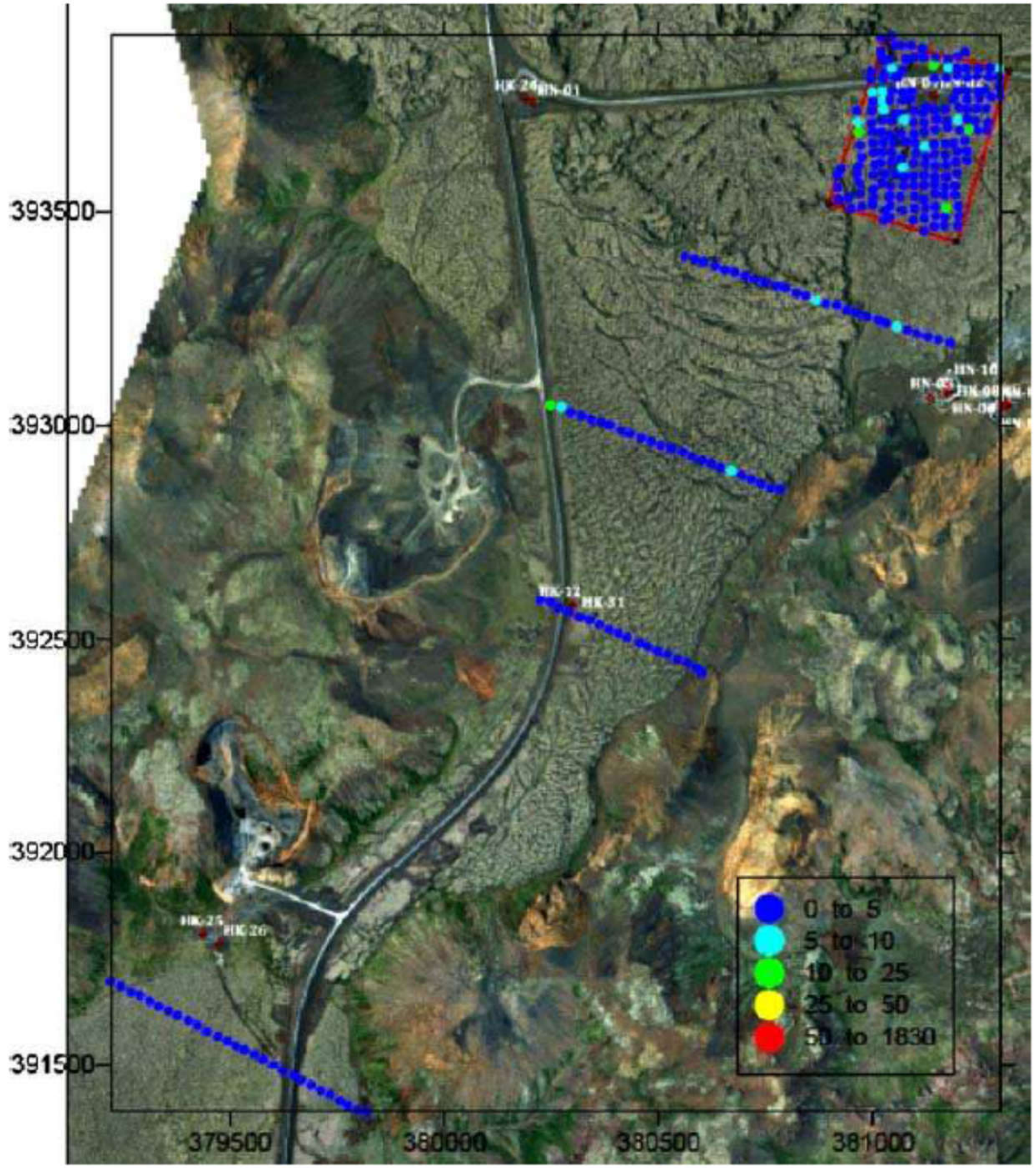



**Fig. 9.** Arial photo of the CarbFix injection site at Hellisheidi. The soil degassing sample spots are superimposed on the figure. The colour of the spots indicates the flux from 0 to 1830 $gCO2/m^2/day$. The sample spots are concentrated around the injection well (HN-2) and the first two monitoring wells (HN-4 and HK-34). The flux is uniform with few excursions. The average flux is 3 $gCO_2/m^2/day$.

# Podsumowanie

- Dane, zebrane (GK) z różnych, najnowszych źródeł wskazują na nasilenie się procesów sygnalizowanych w moim „klasycznym” wykładzie z Politechniki w Mediolanie (1999), Politechnik w Gdańsku (2000) a ostatni TV UMK

- Dane te zostały zebrane jako ilustracja tez i pytań z książki L. Kraussa

- Autor ten pyta jednak „przytomnie”, czy nasilanie się efektu cieplarnianego będzie miało jakąś granicę „nasycenia”

- Na egzamin obowiązuje opowiedzenie, jakie wskaźniki zostały w tym wykładzie przywołane

Toruń, 08.01.2025