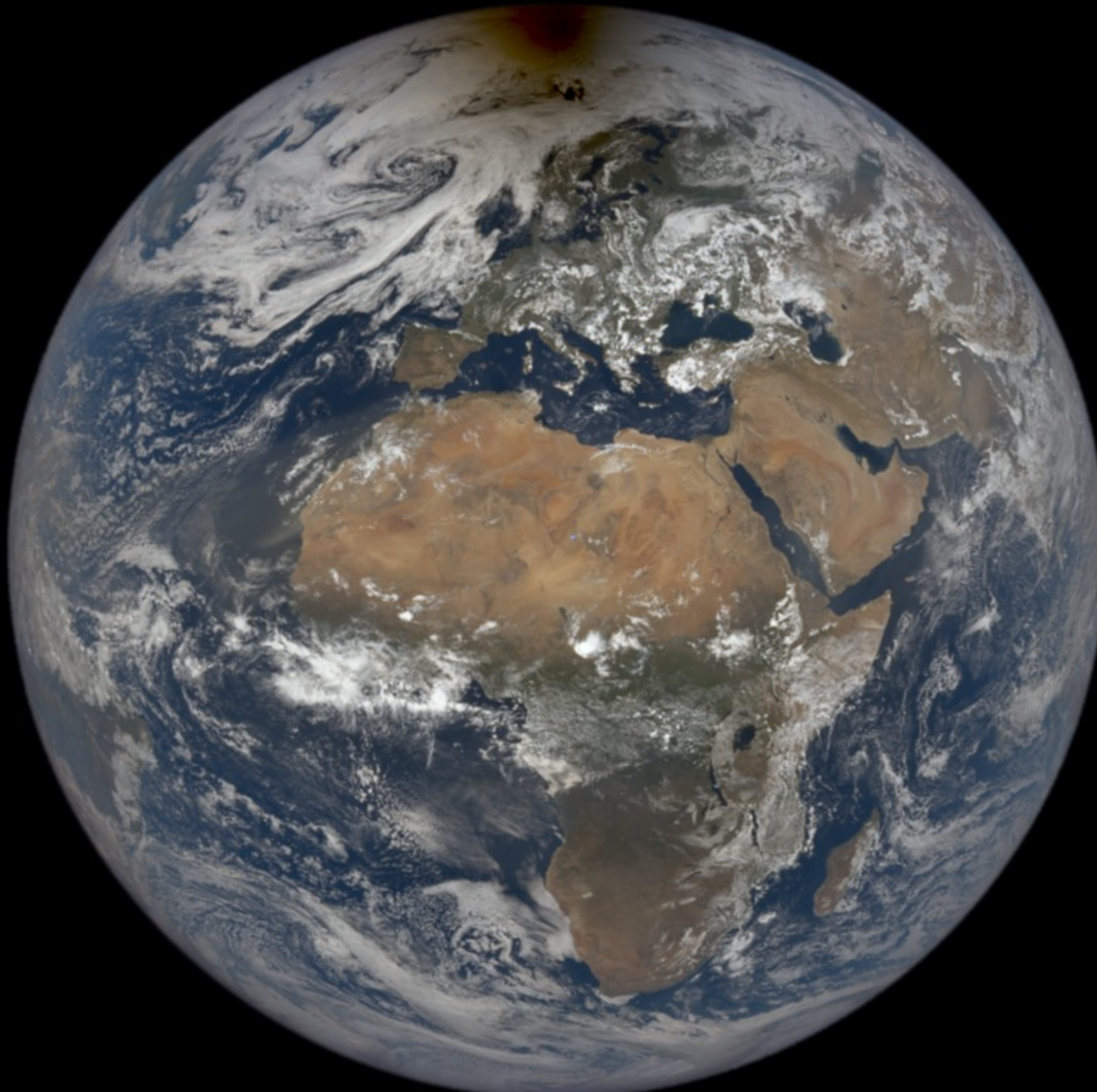
Fundamental Physics of Climate and the Earth System



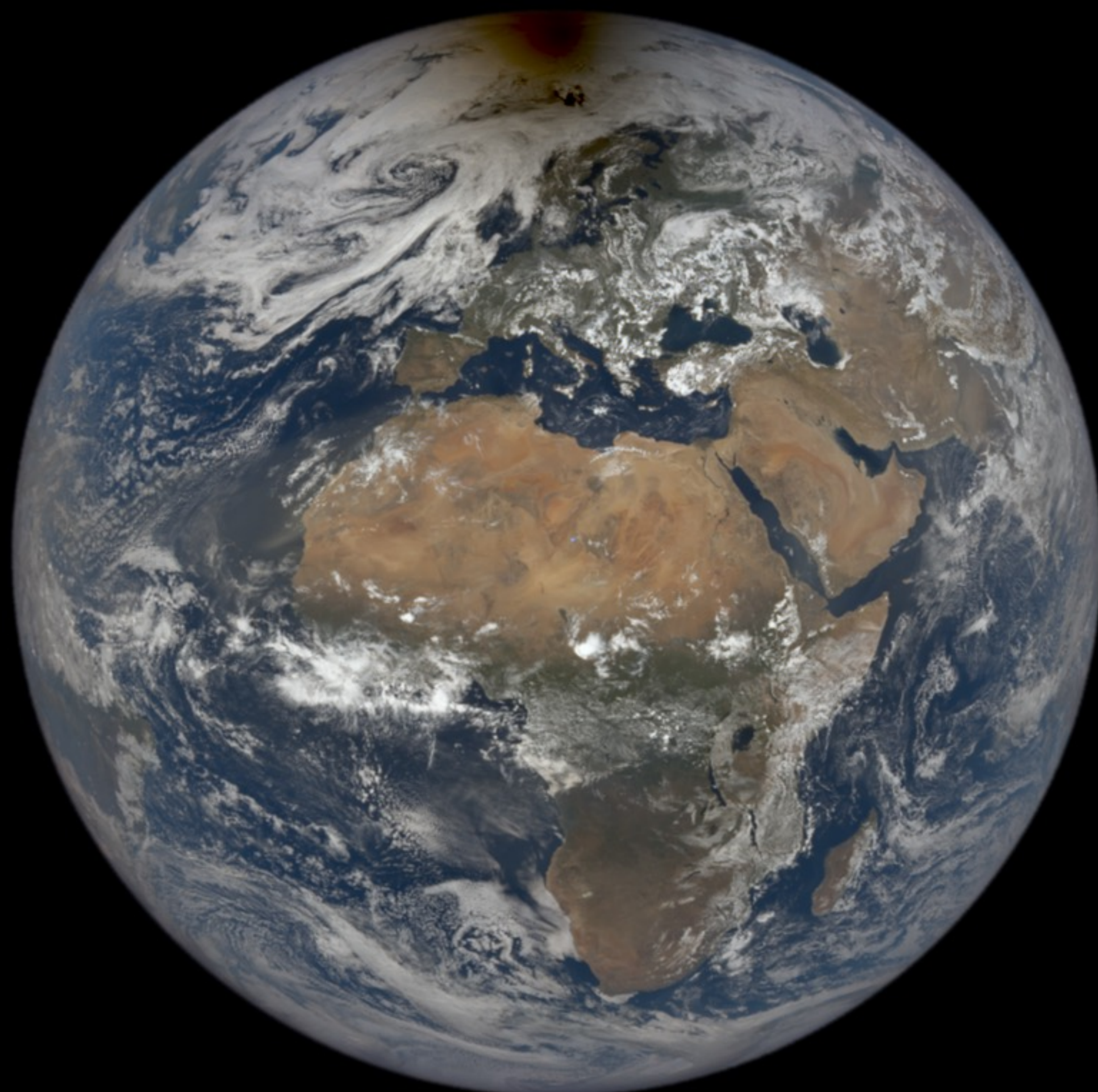
Ankur Desai
Dept of Atmospheric and Oceanic Sciences
University of Wisconsin-Madison

Peking University Summer School
August 2023

Part 1. Climate

Living in a thin fluid on a rotating sphere

From more than a million miles away…



NASA EPIC

ATS-1 1966

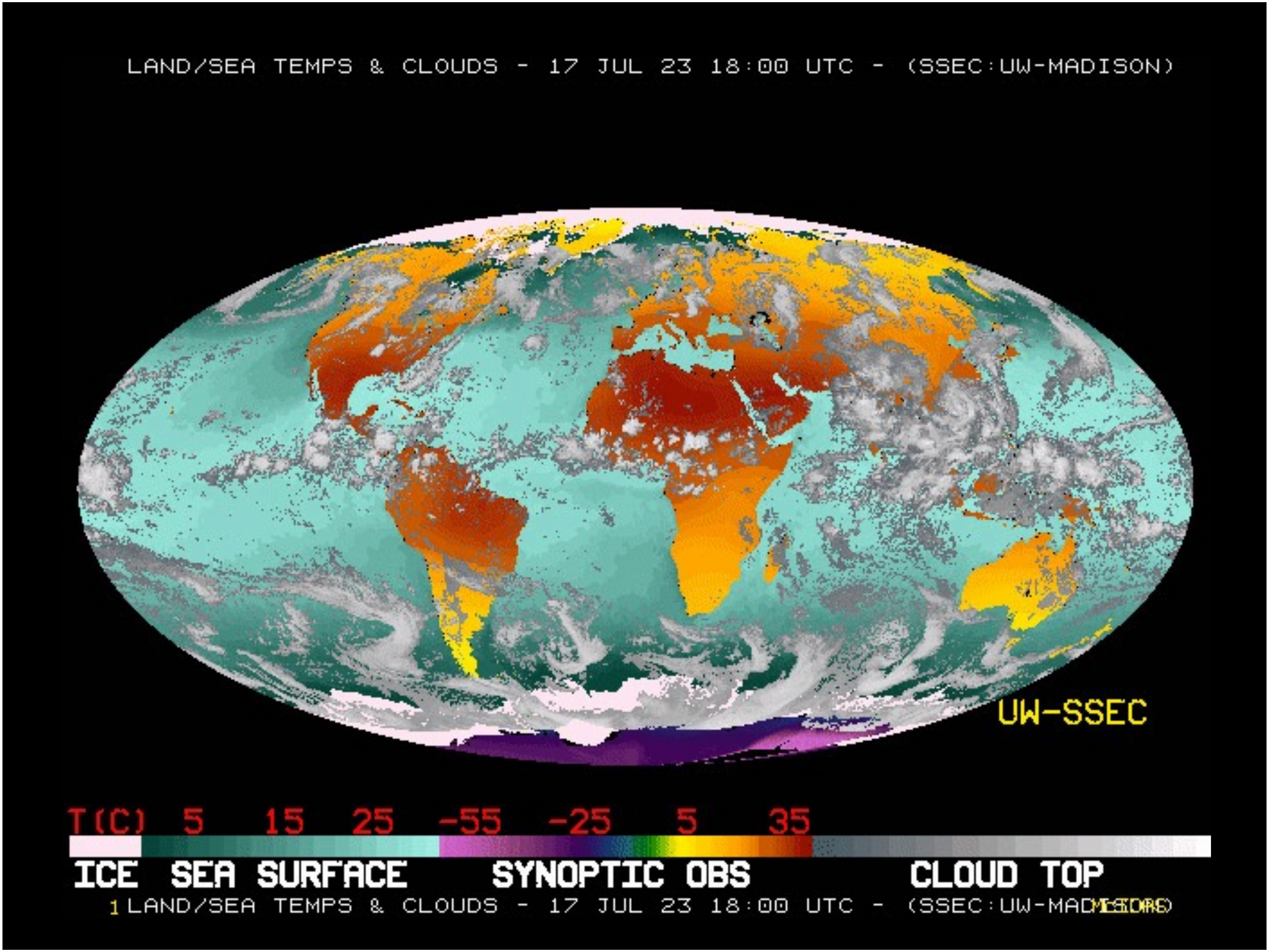

NASA ISS

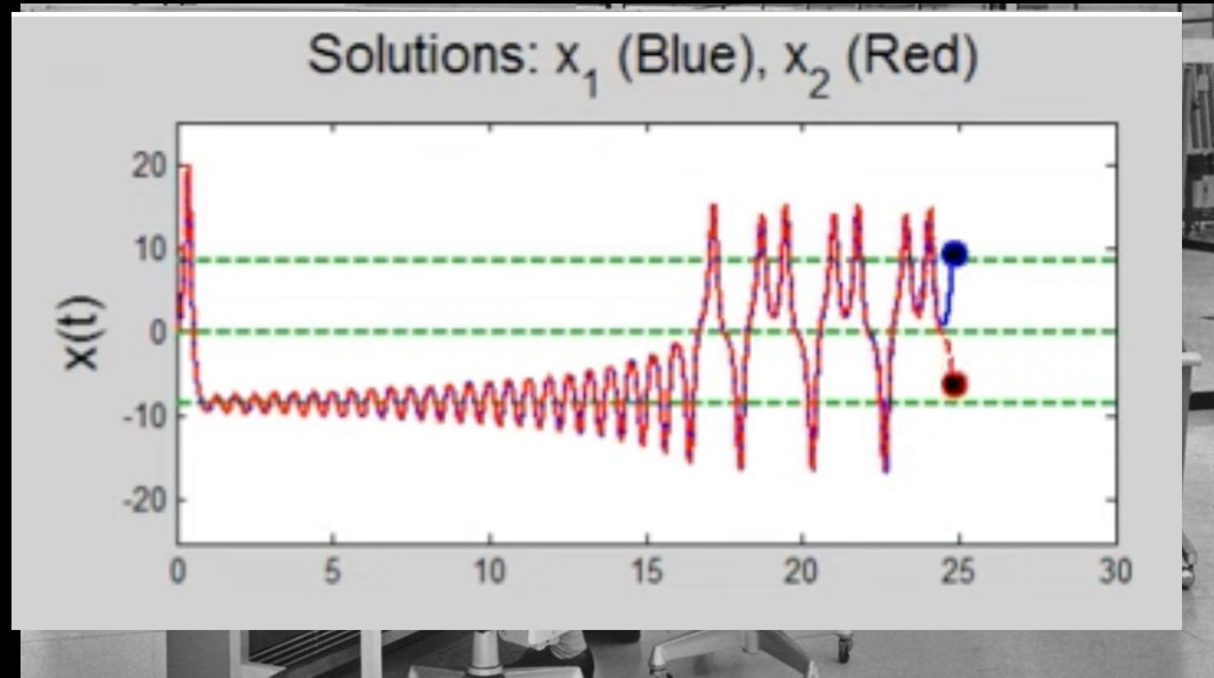
Jeff Miller UW-Communications

Some July Heat: 'Virtually Impossible' Without Climate Change, Analysis Finds

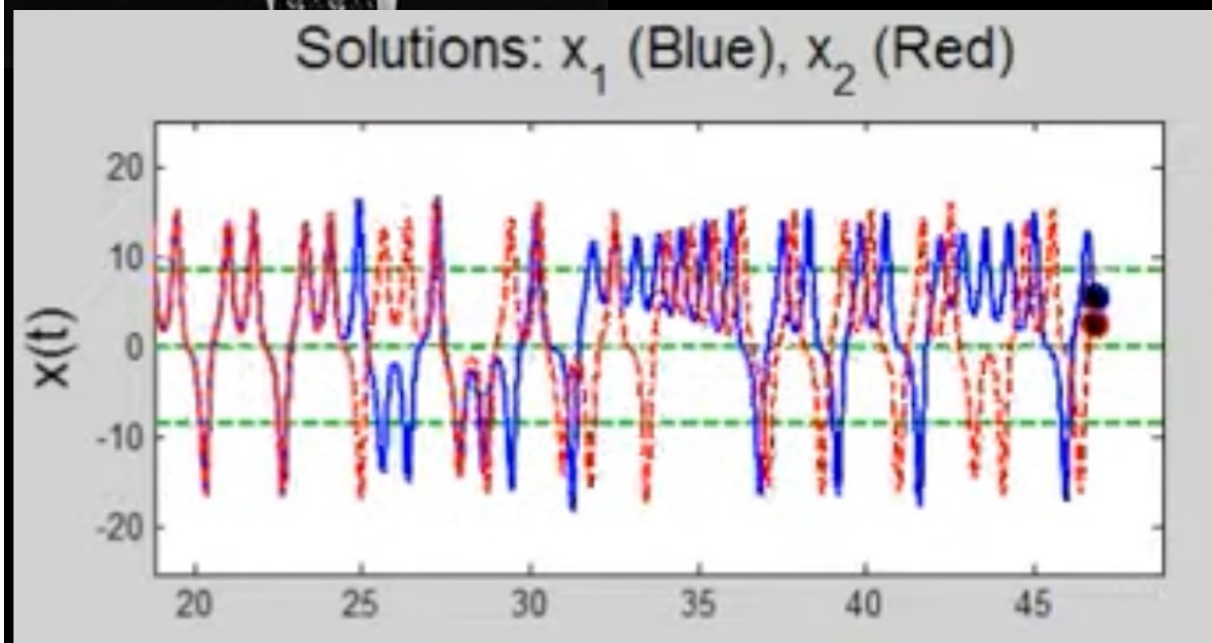
The latest study from World Weather Attribution scientists predicts that extreme heat waves will return more frequently.

NYTimes

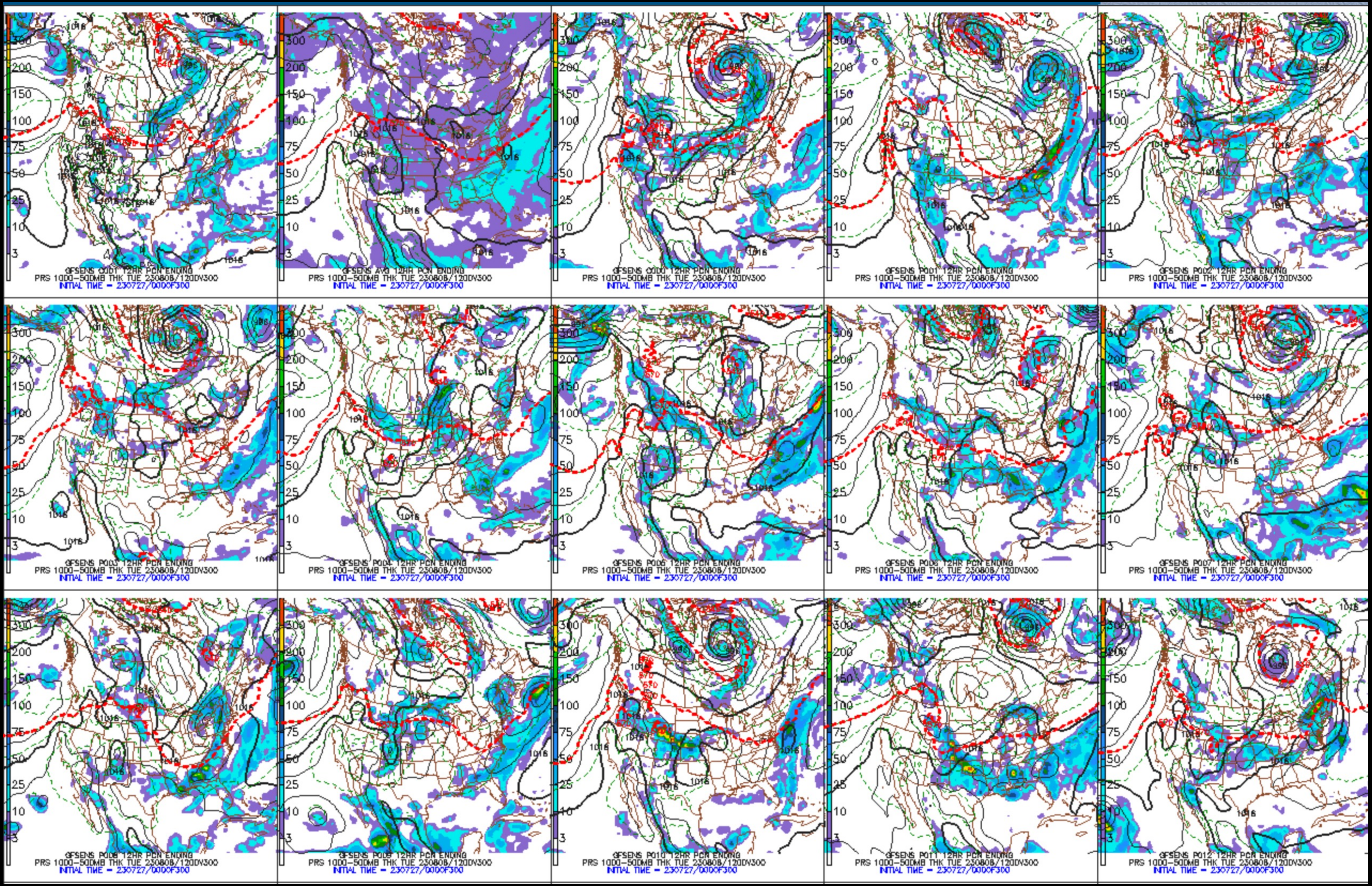

LAND/SEA TEMPS & CLOUDS - 17 JUL 23 18:00 UTC - (SSEC:UW-MADISON)
UW-SSEC
T(C) 5 15 25 -55 -25 5 35
ICE SEA SURFACE SYNOPTIC OBS CLOUD TOP
1 LAND/SEA TEMPS & CLOUDS - 17 JUL 23 18:00 UTC - (SSEC:UW-MADISON)
McIDAS



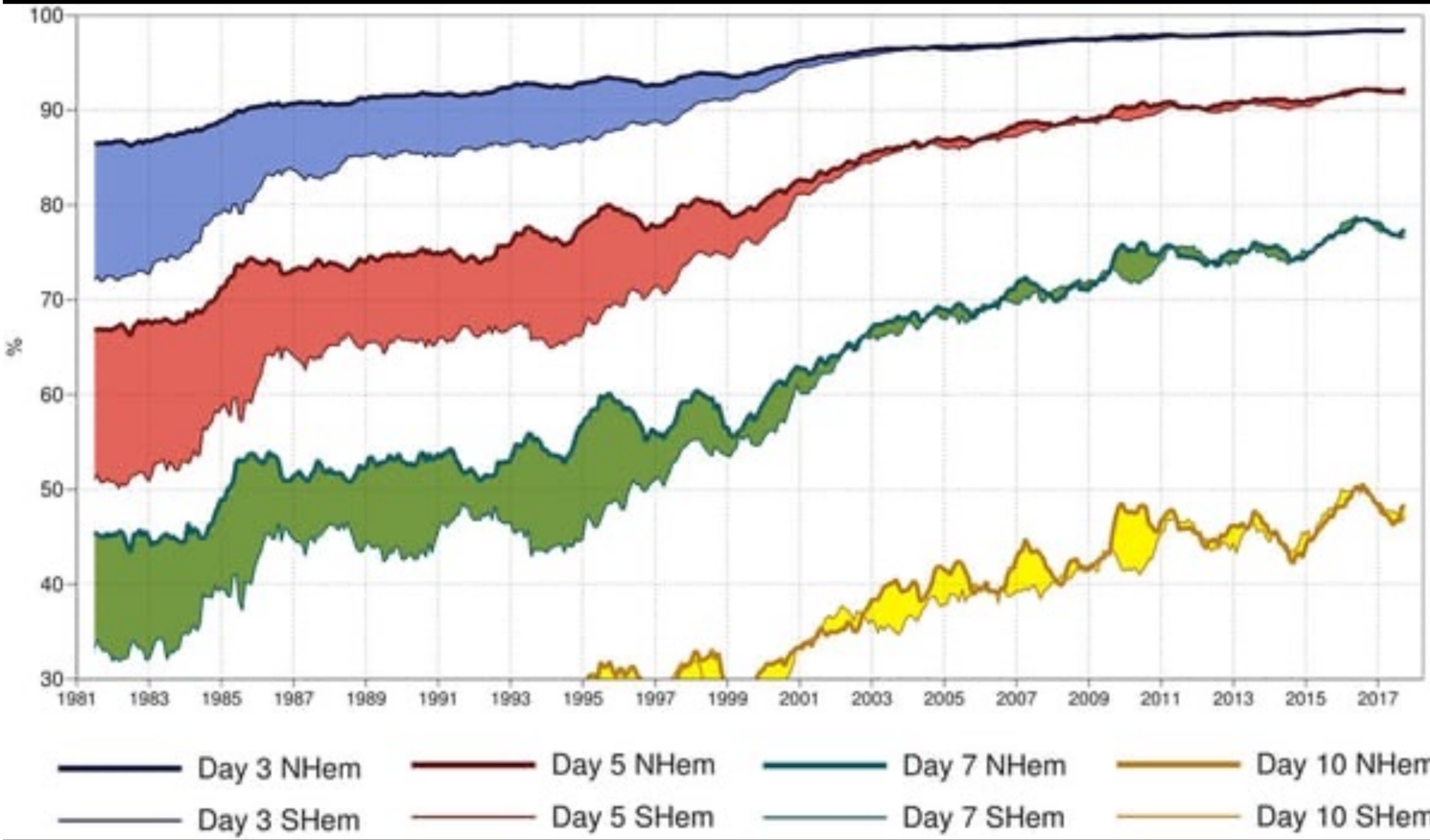
Deterministic Chaos



https://brunomarion.com/butterfly-effect/



http://www.meteo.psu.edu/ewall/ewall.html


100
90
80
70
60
50
40
30
%
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
Day 3 NHem
Day 5 NHem
Day 7 NHem
Day 10 NHem
Day 3 SHem
Day 5 SHem
Day 7 SHem
Day 10 SHem

ECMWF

Climate = Average of Weather over space and time, typically regions and decades

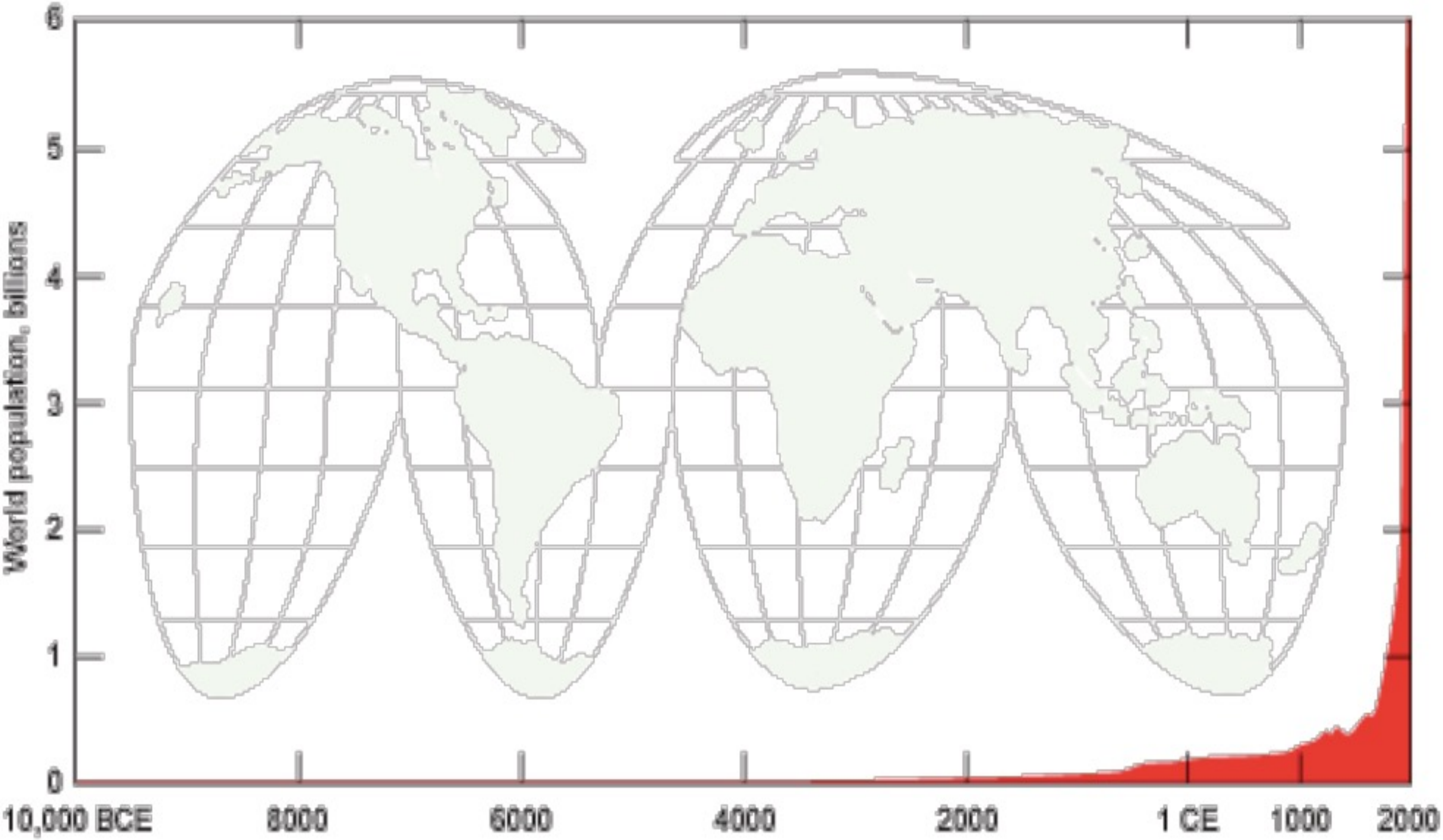
Climate is what you expect

- Weather is what you get

Climate is your personality

- Weather is your mood

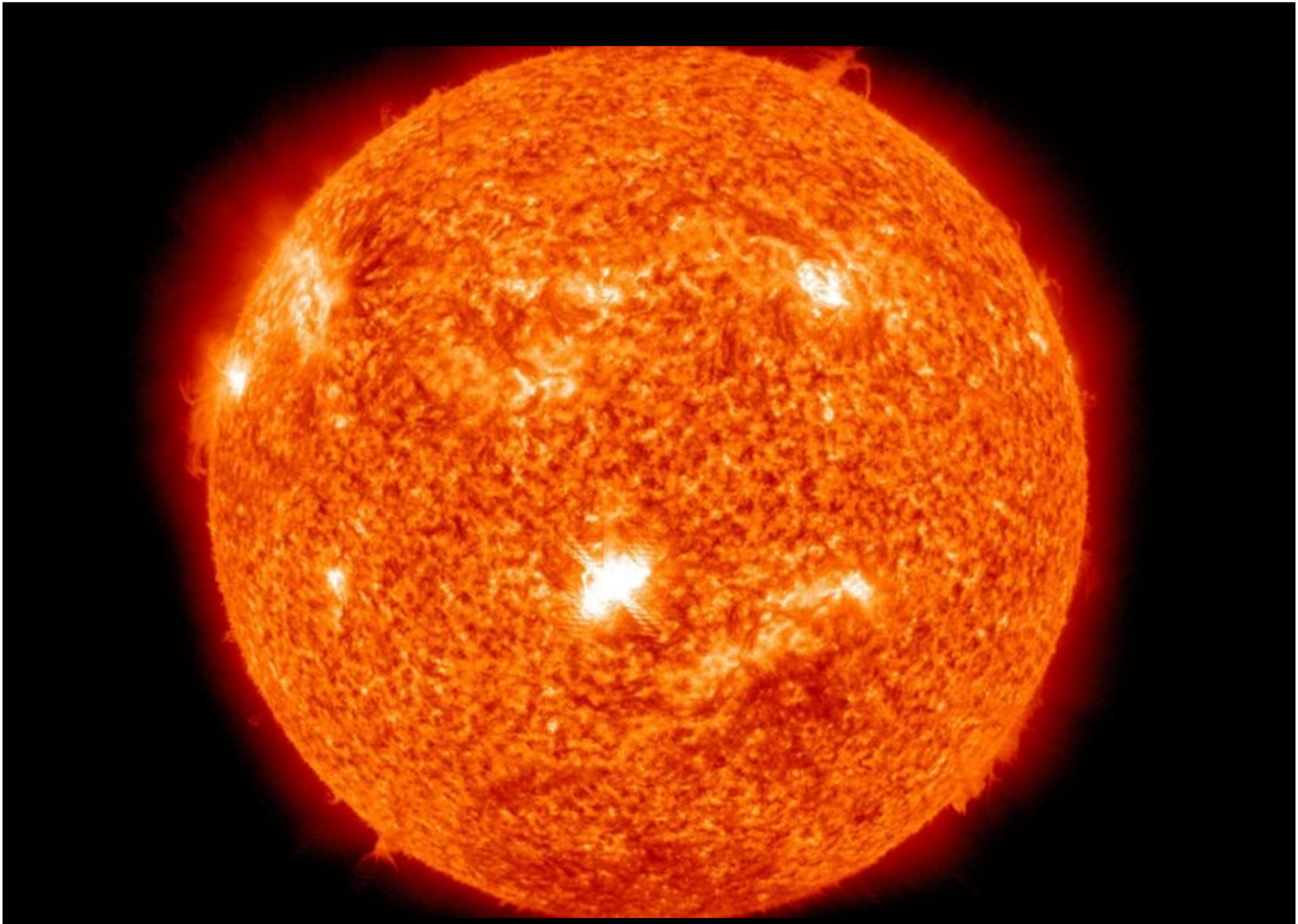
The Anthropocene



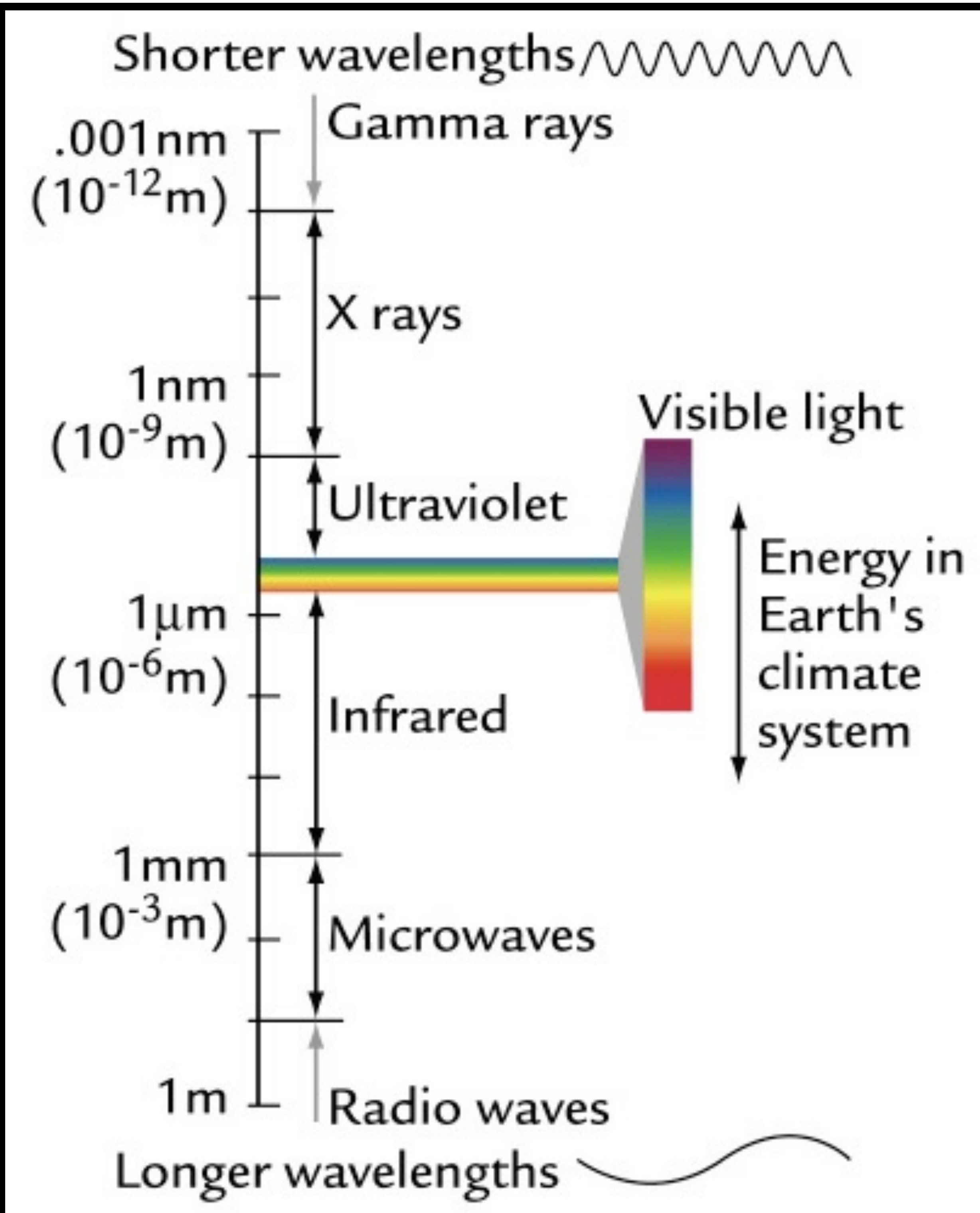
Human population increase (in red) from 10,000 BCE to 2000 CE

The Earth System

- Atmosphere
- Land
  - Biosphere
  - Pedosphere
  - Lithosphere
- Water
  - Hydrosphere: ocean + freshwater
  - Cryosphere: ice
- People



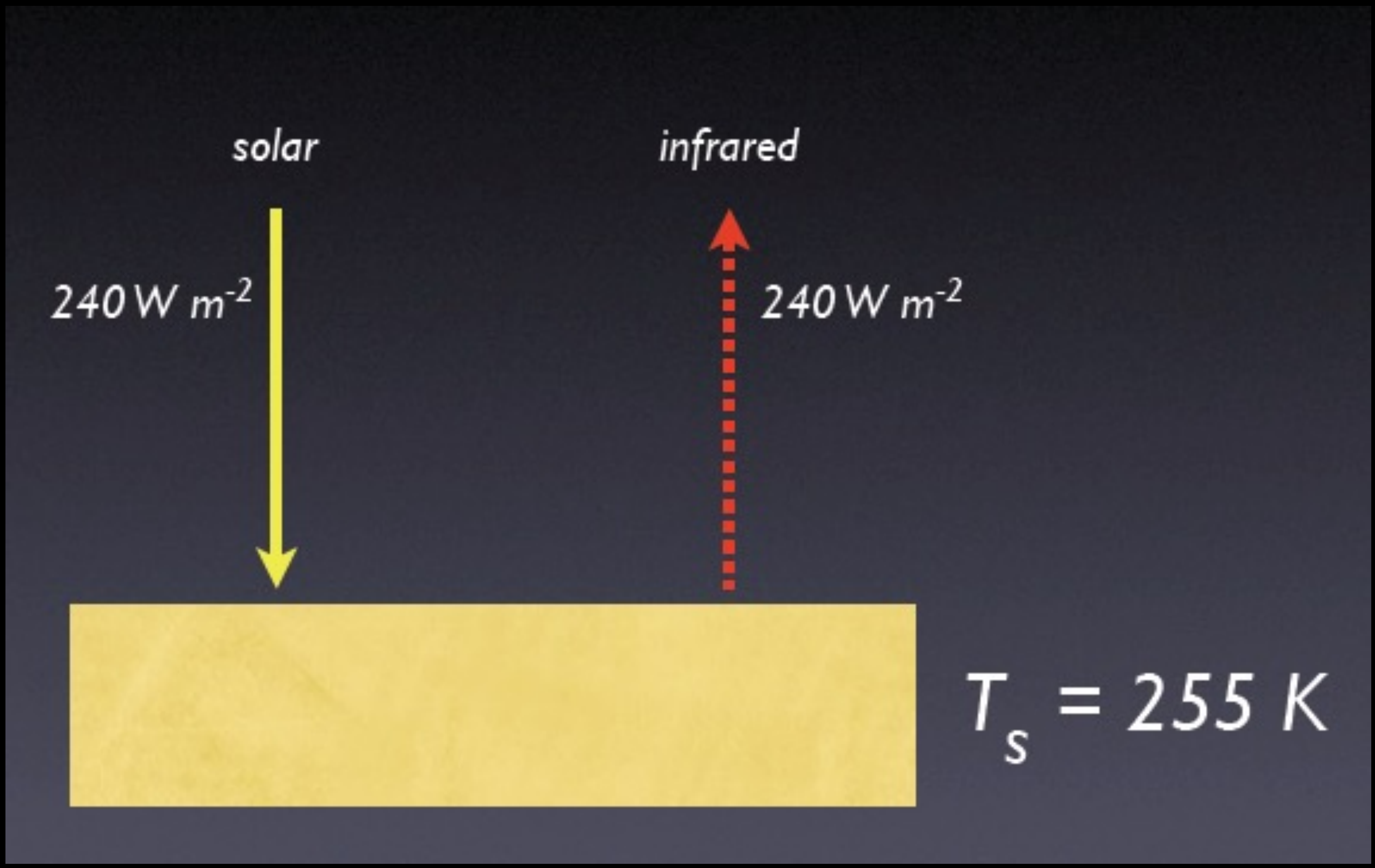
NASA / https://education.nationalgeographic.org/resource/sun/


Shorter wavelengths
.001nm
(10-12m)
Gamma rays
X rays
1nm
(10-9m)
Ultraviolet
Visible light
Energy in
Earth's
climate
system
1µm
(10-6m)
Infrared
1mm
(10-3m)
Microwaves
1m
Radio waves
Longer wavelengths

ENERGY IN = ENERGY OUT

- ENERGY IN
  - S – Solar incoming at 1 AU = ~1340 W m^{-2}
  - Impinging on circular cross section of earth
  - $= S \pi r_e^2$
  - Some is reflected back, albedo = α
  - $= S \pi r_e^2 (1-\alpha)$
- ENERGY OUT
  - σT_s^4 - Stefan-Boltzmann Law for Integrated Blackbody Radiation, emitted all directions
  - $= \sigma T_s^4 \, 4\pi r_e^2$
- Set these equal, solve for T_s

Solution



255 K is

A. A reasonable rough estimate of the global temperature of the earth-atmosphere system
B. Too cold - we didn’t consider the effect of radiative absorption by atmospheric trace gases
C. Too cold - we didn’t consider the residual heat content of oceans
D. Too hot - we didn’t consider the effect of clouds on solar incoming radiation
E. Too hot - we didn’t consider the effect of Earth’s tilt

255 K is

A. A reasonable rough estimate of the global temperature of the earth-atmosphere system
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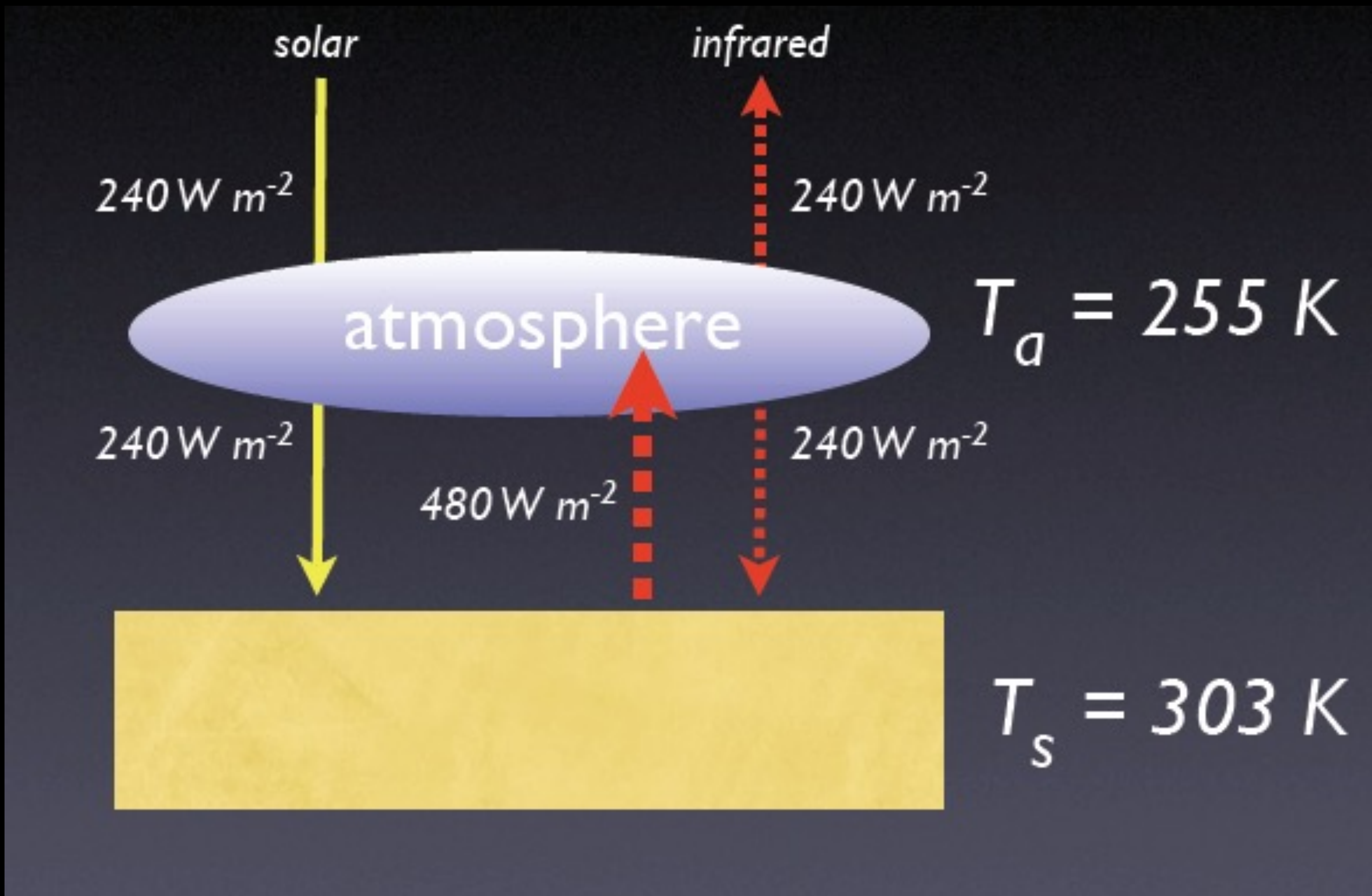
ENERGY IN = ENERGY OUT

Take 2

- ENERGY IN
  - S – Solar incoming at 1 AU = ~1340 W m^{-2}
  - Impinging on circular cross section of earth
  - $= S \pi r_e^2$
  - Some if reflected back, albedo = α
  - $= S \pi r_e^2 (1-\alpha)$
  - $\varepsilon\sigma T_a^4$ - Stefan-Boltzmann Law for Integrated Greybody Radiation, emitted all directions:
    - Top of atmosphere: $S \pi r_e^2 (1-\alpha)$
    - At surface: $S \pi r_e^2 (1-\alpha) + \varepsilon\sigma T_a^4 4\pi r_e^2$
- ENERGY OUT
  - Top of atmosphere: $= \varepsilon\sigma T_a^4 4\pi r_e^2$
  - Bottom of atmosphere $= \sigma T_s^4 4\pi r_e^2$
- Let's try $\varepsilon = 1$
- Set these equal, solve for T_s and T_a

Perfect Greenhouse



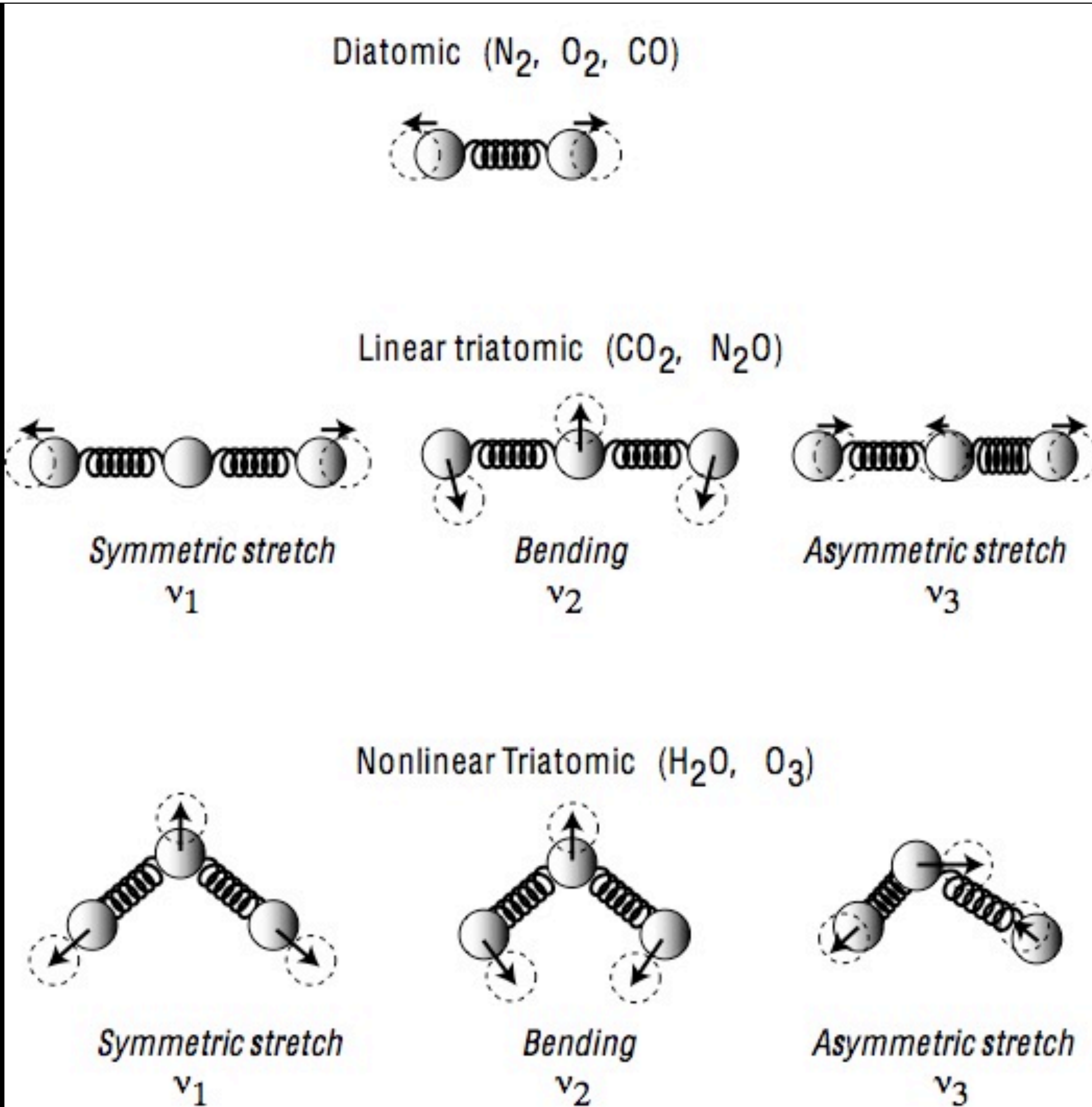
What's in the air?

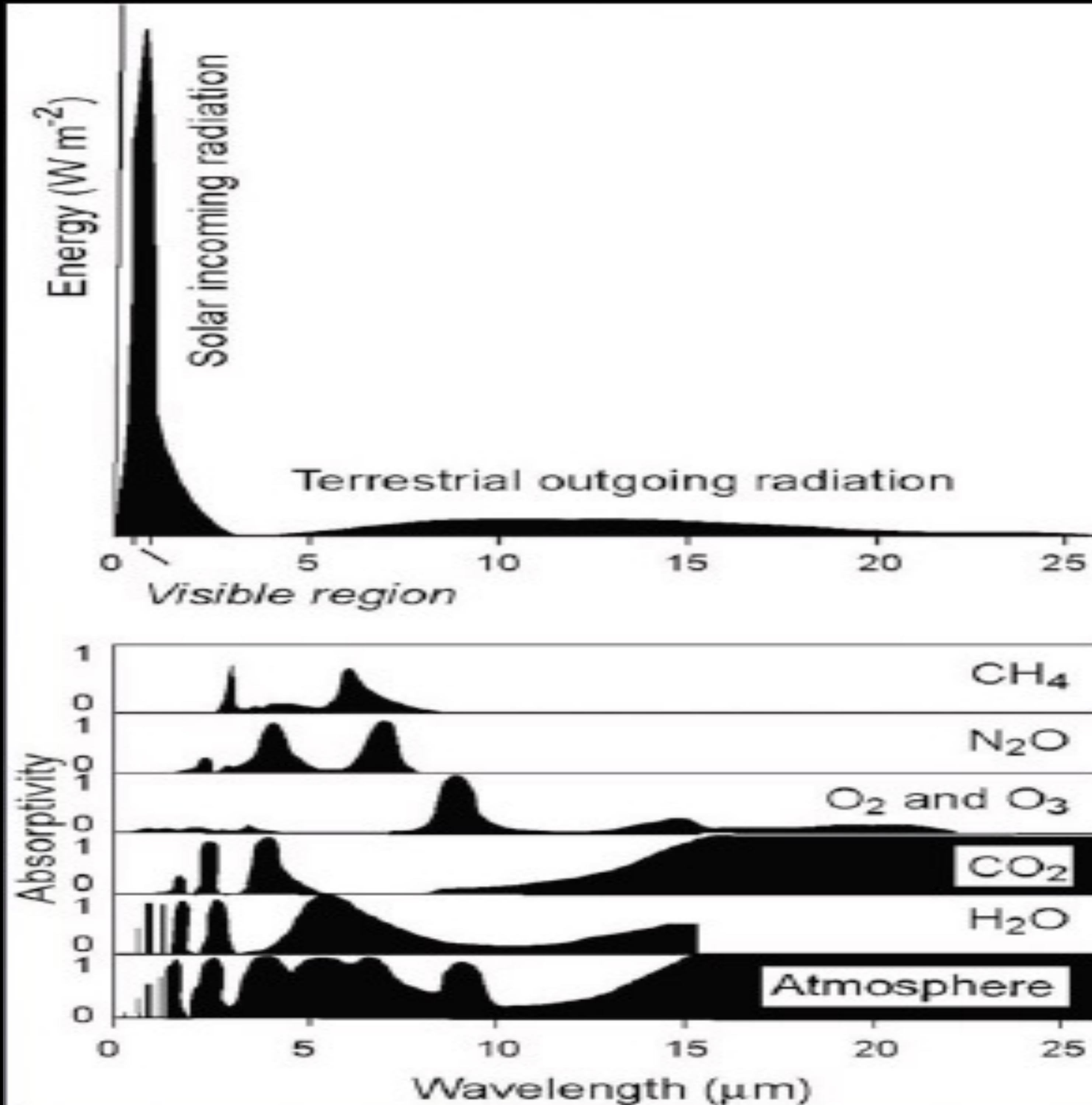
Table 1.1 Composition of the Atmosphere Near the Earth's Surface

PERMANENT GASES			VARIABLE GASES			
Gas	Symbol	Percent (by Volume) Dry Air	Gas (and Particles)	Symbol	Percent (by Volume)	Parts per Million (ppm)*
Nitrogen	N_2	78.08	Water vapor	H_2O	0 to 4	
Oxygen	O_2	20.95	Carbon dioxide	CO_2	0.037	374*
Argon	Ar	0.93	Methane	CH_4	0.00017	1.7
Neon	Ne	0.0018	Nitrous oxide	N_2O	0.00003	0.3
Helium	He	0.0005	Ozone	O_3	0.000004	0.04†
Hydrogen	H_2	0.00006	Particles (dust, soot, etc.)		0.000001	0.01–0.15
Xenon	Xe	0.000009	Chlorofluorocarbons (CFCs)		0.00000002	0.0002

*For CO_2, 374 parts per million means that out of every million air molecules, 374 are CO_2 molecules.

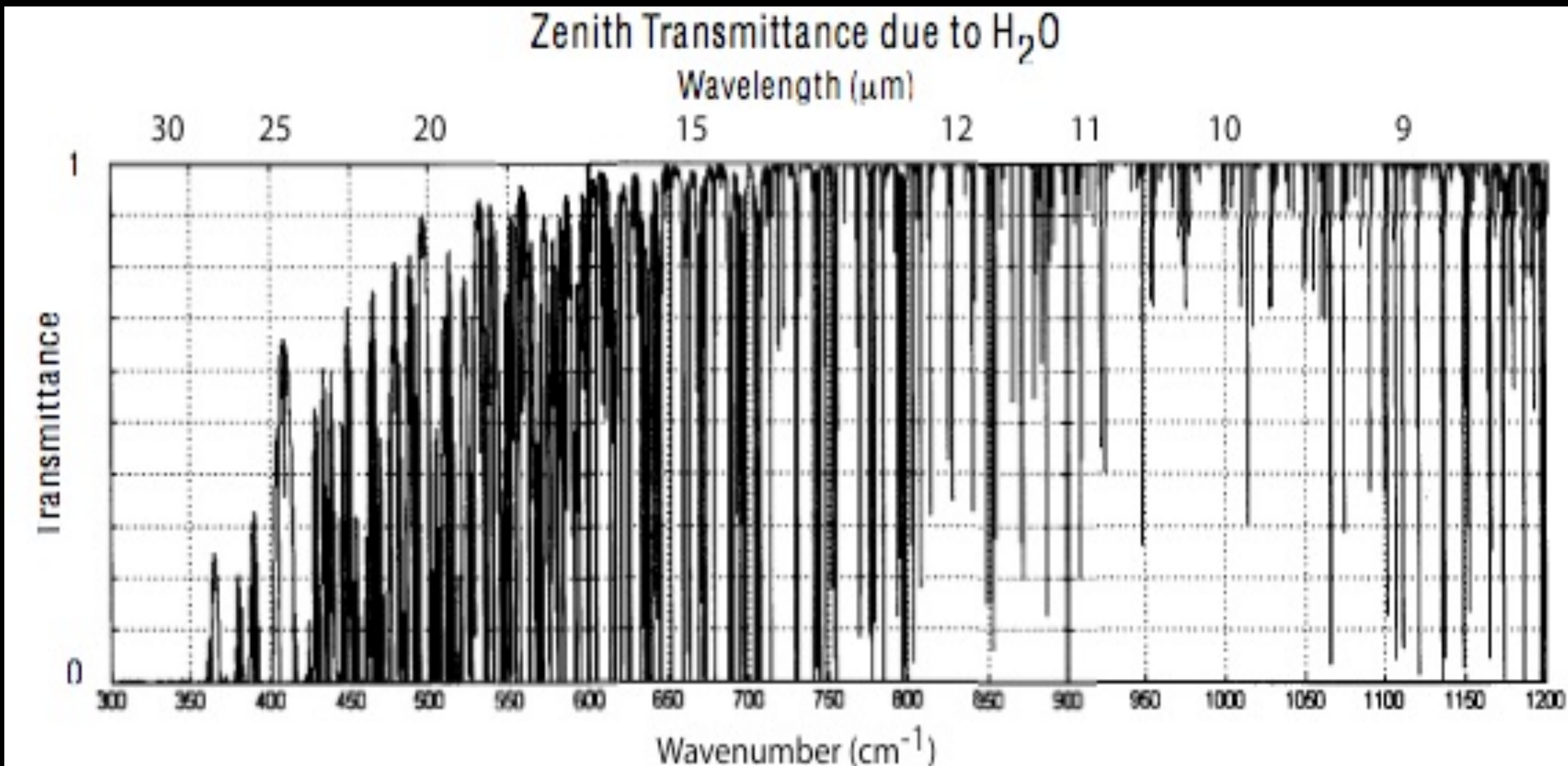
†Stratospheric values at altitudes between 11 km and 50 km are about 5 to 12 ppm.


Diatomic (N_2, O_2, CO)
Linear triatomic (CO_2, N_2O)
Symmetric stretch
ν_1
Bending
ν_2
Asymmetric stretch
ν_3
Nonlinear Triatomic (H_2O, O_3)
Symmetric stretch
ν_1
Bending
ν_2
Asymmetric stretch
ν_3

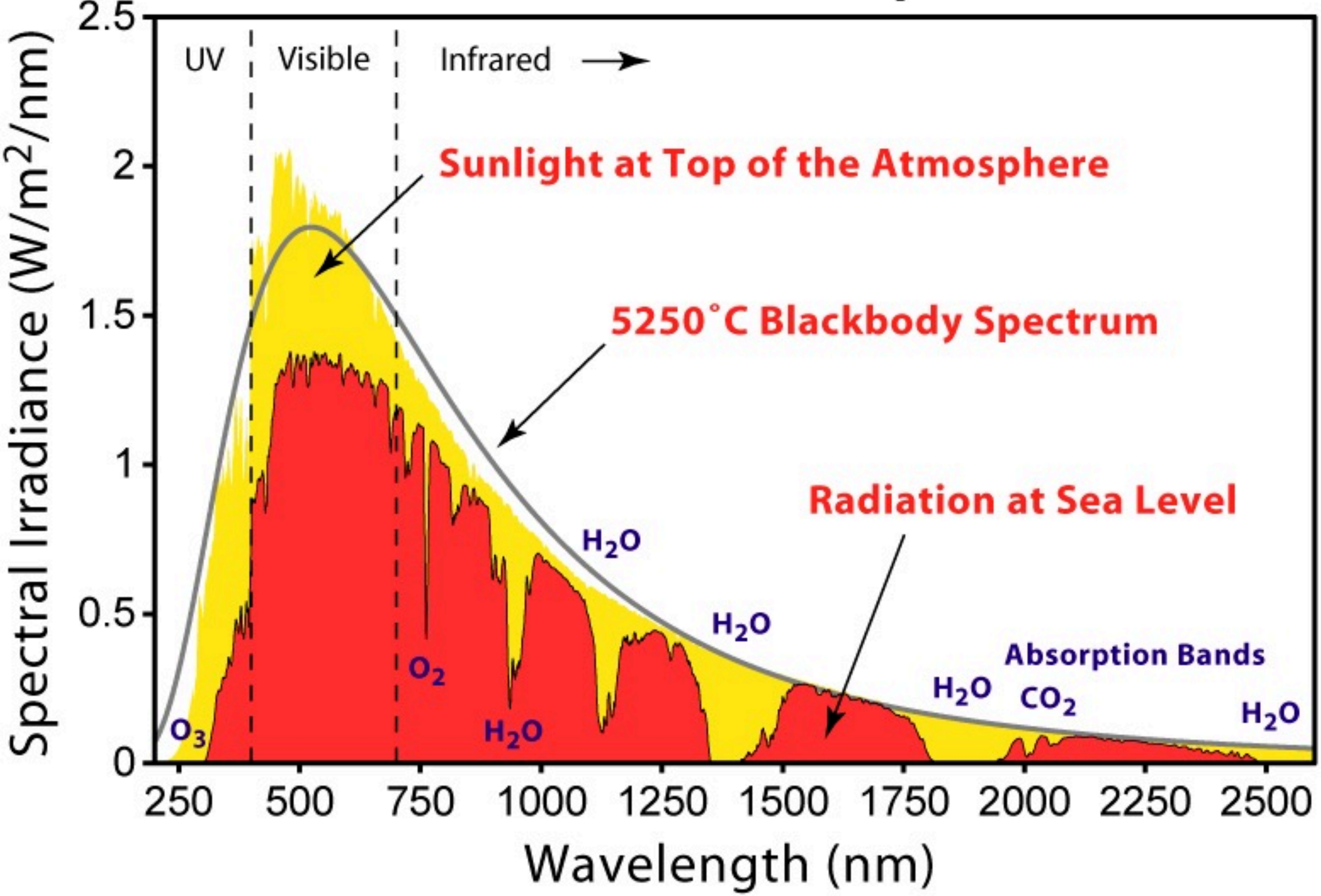


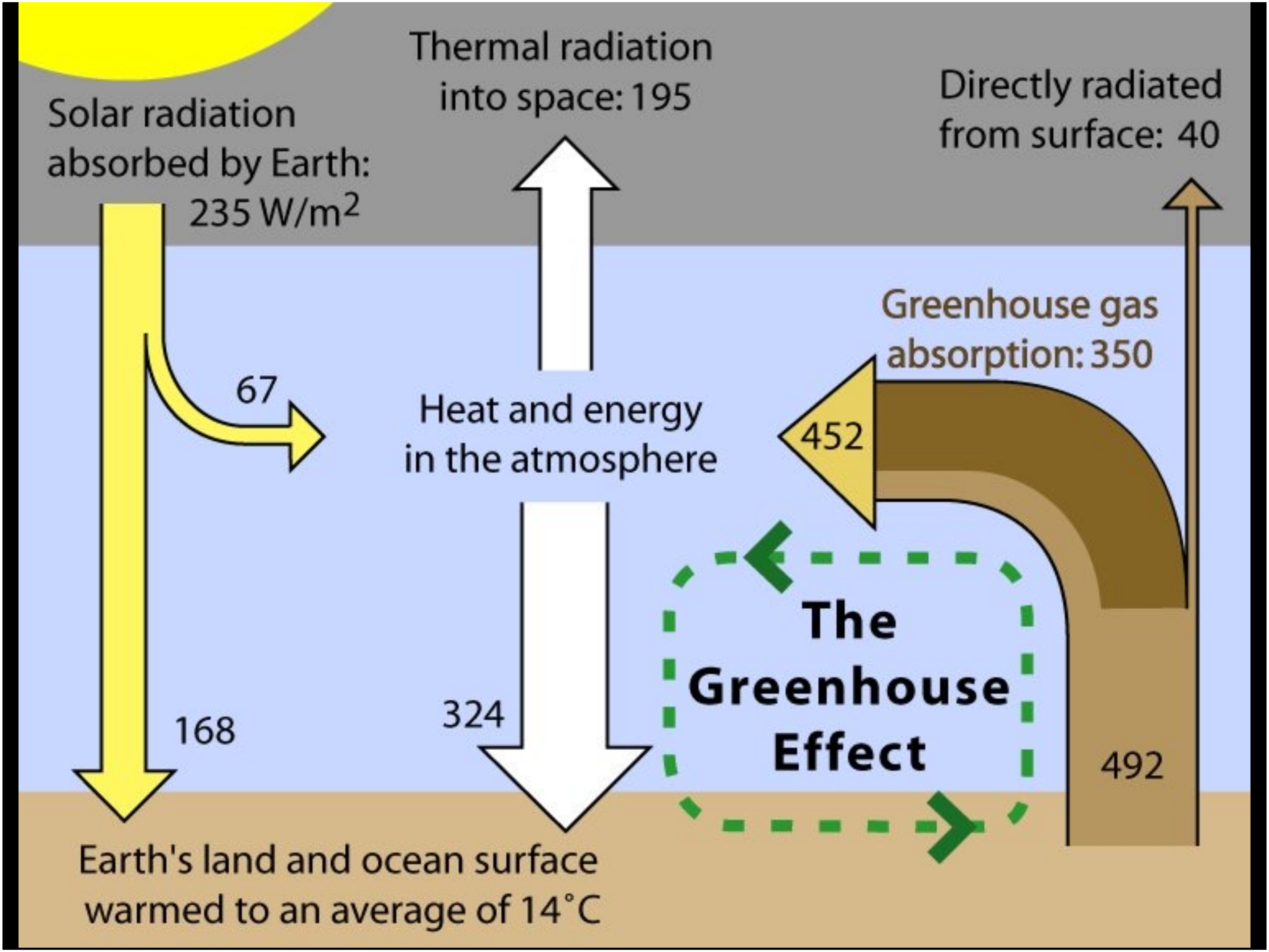
Energy (W m^{-2})
Solar incoming radiation
Terrestrial outgoing radiation
0
5
10
15
20
25
Visible region
Absorptivity
1
0
CH_4
N_2O
O_2 and O_3
CO_2
H_2O
Atmosphere
Wavelength (µm)

Water Vapor is the biggest greenhouse gas (but can not be directly controlled)



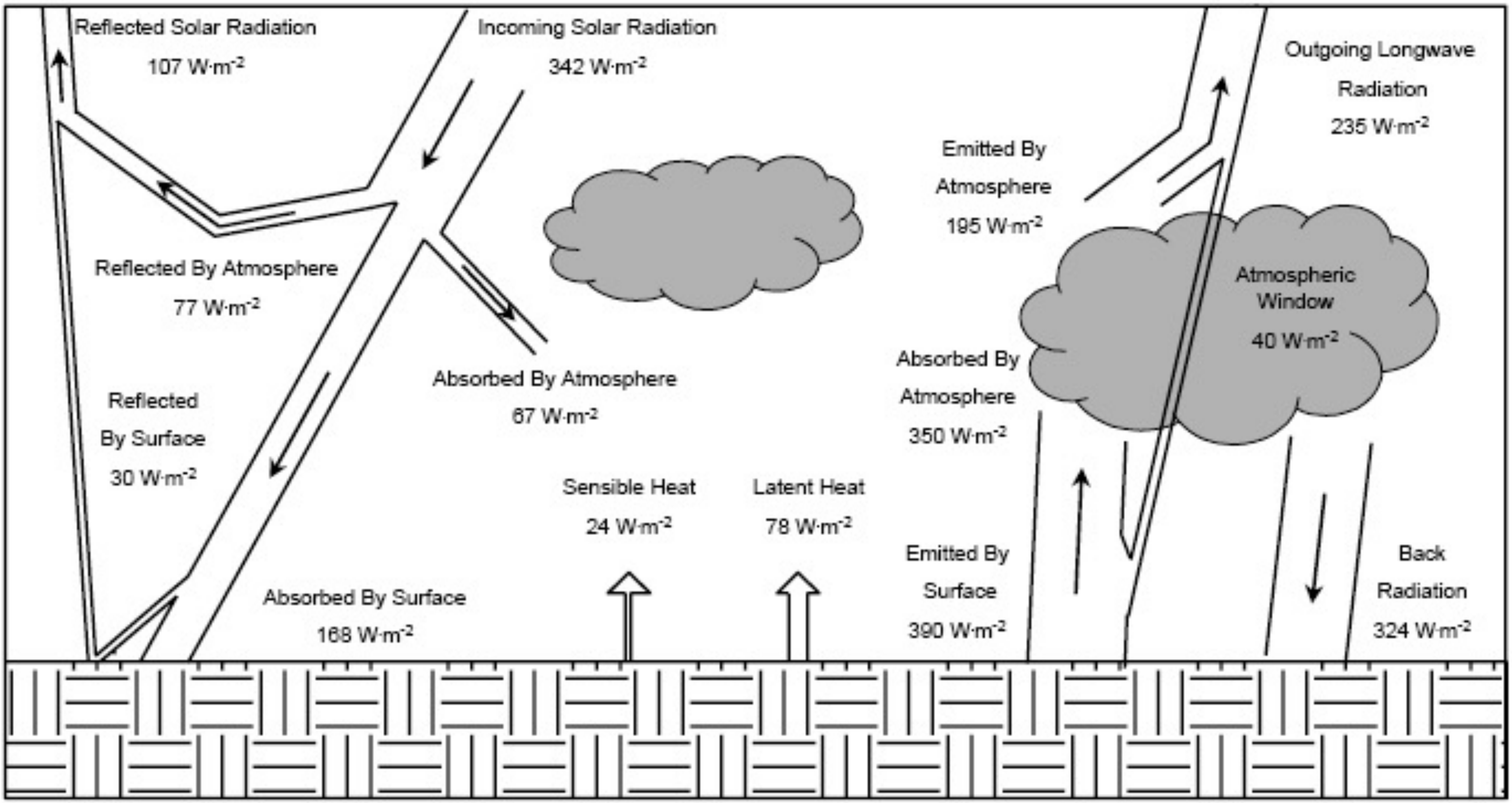
Solar Radiation Spectrum



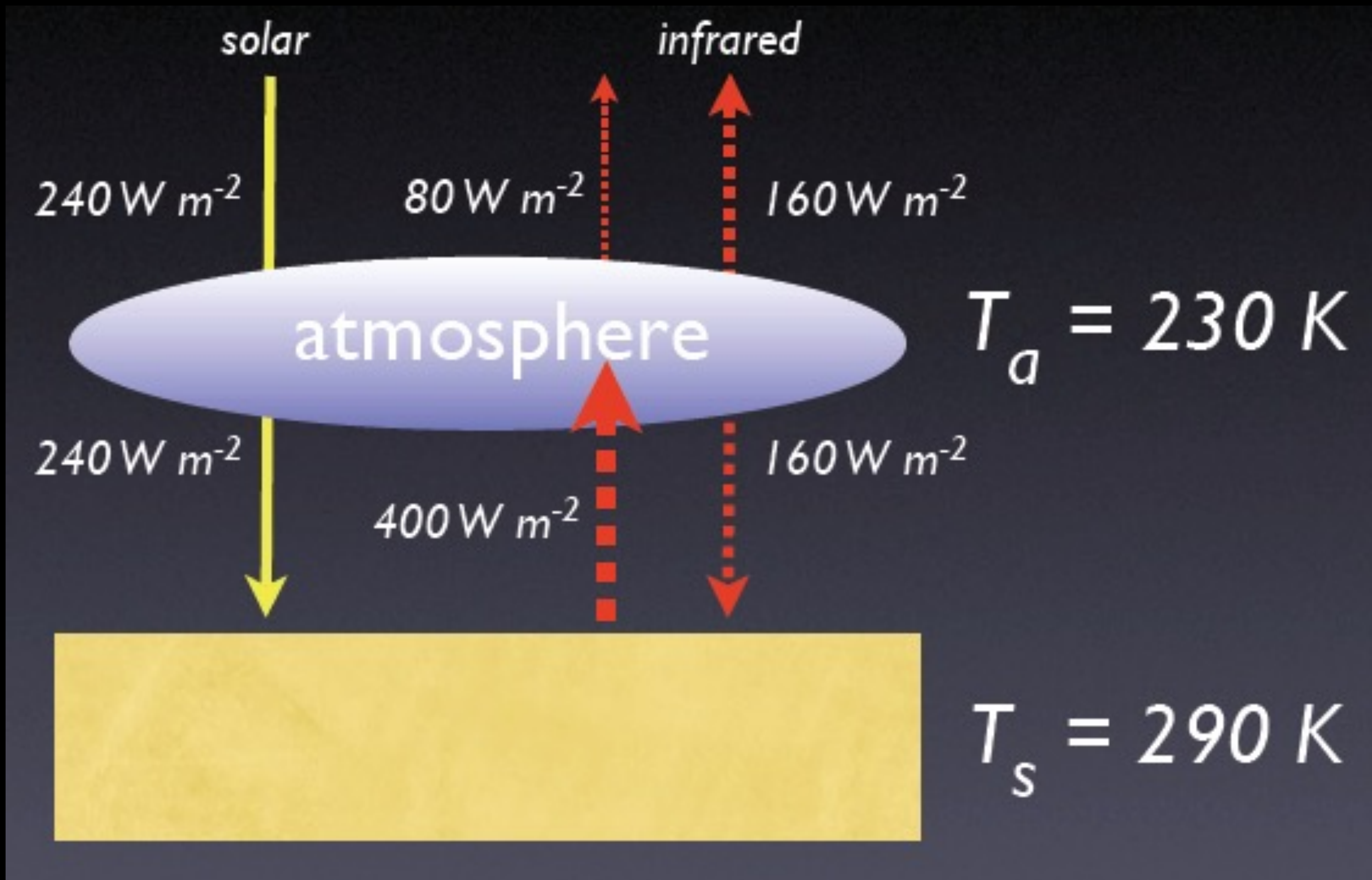


Solar radiation absorbed by Earth: 235 W/m2
Thermal radiation into space: 195
Directly radiated from surface: 40
67
Heat and energy in the atmosphere
Greenhouse gas absorption: 350
452
The Greenhouse Effect
168
324
492
Earth's land and ocean surface warmed to an average of 14˚C

Earth's Annual Global Energy Budget

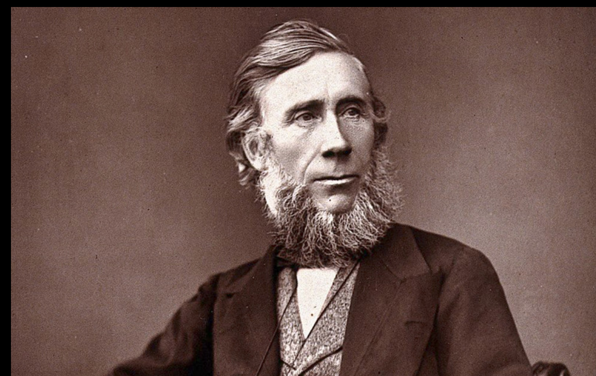


Realistic Greenhouse



This is not “new” science

Eunice Foote 1856



Tyndall 1859

Arrehenius 1896

Callendar 1938

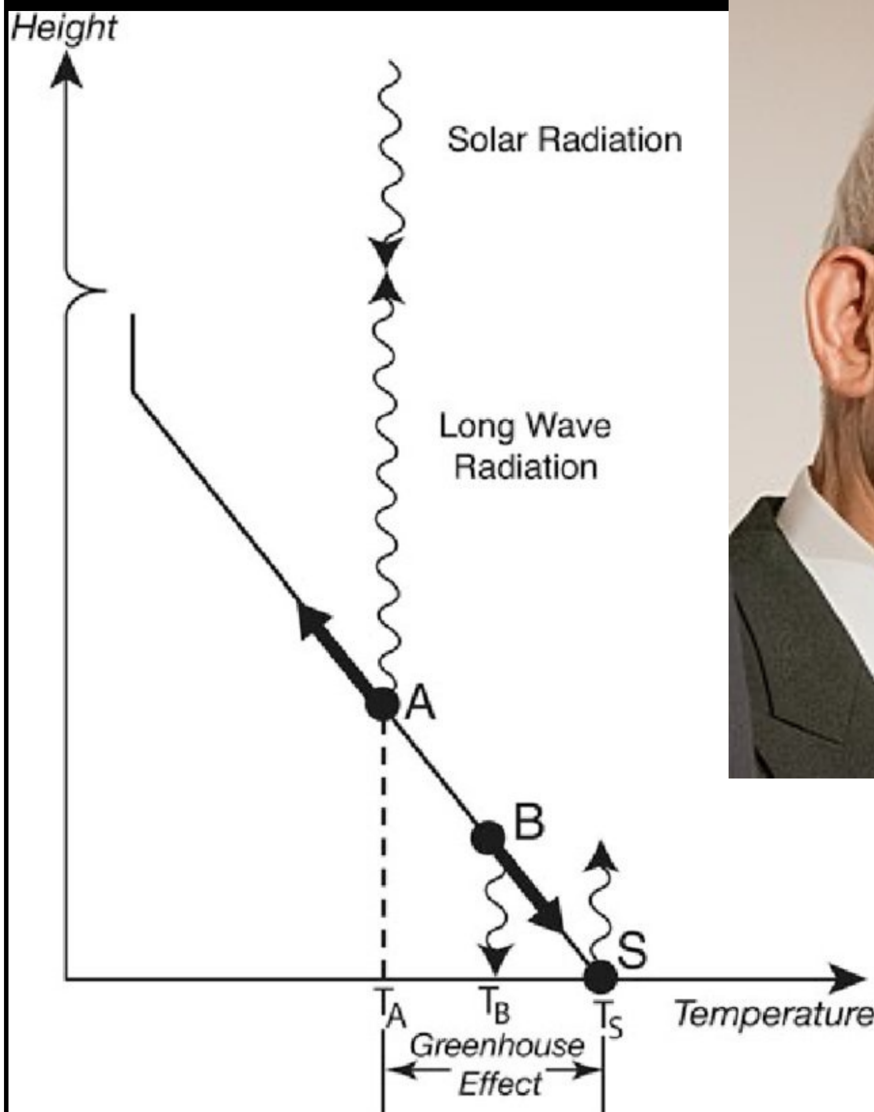
Plass 1953

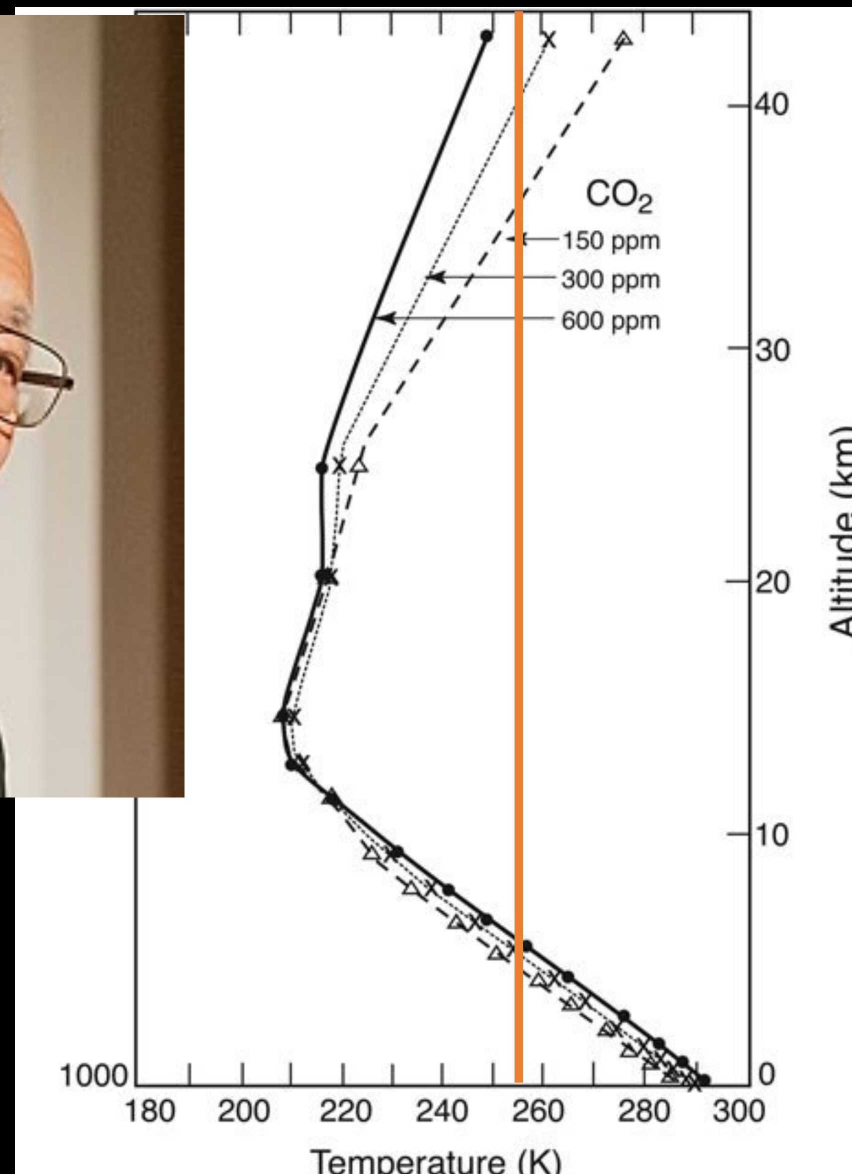
Simpson 1958

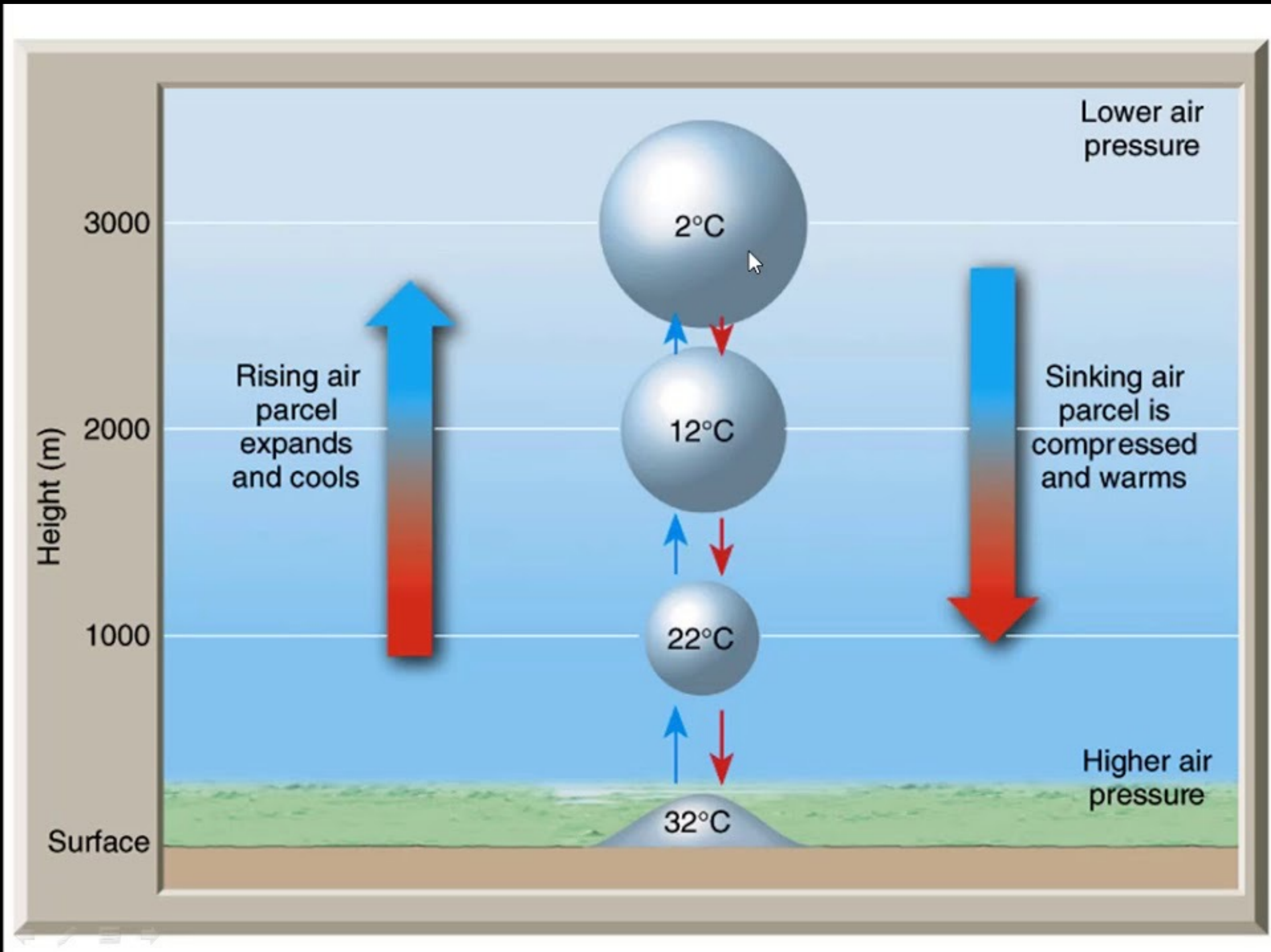
Role of greenhouse gas in climate change**

Nobel Prize for Physics 2021

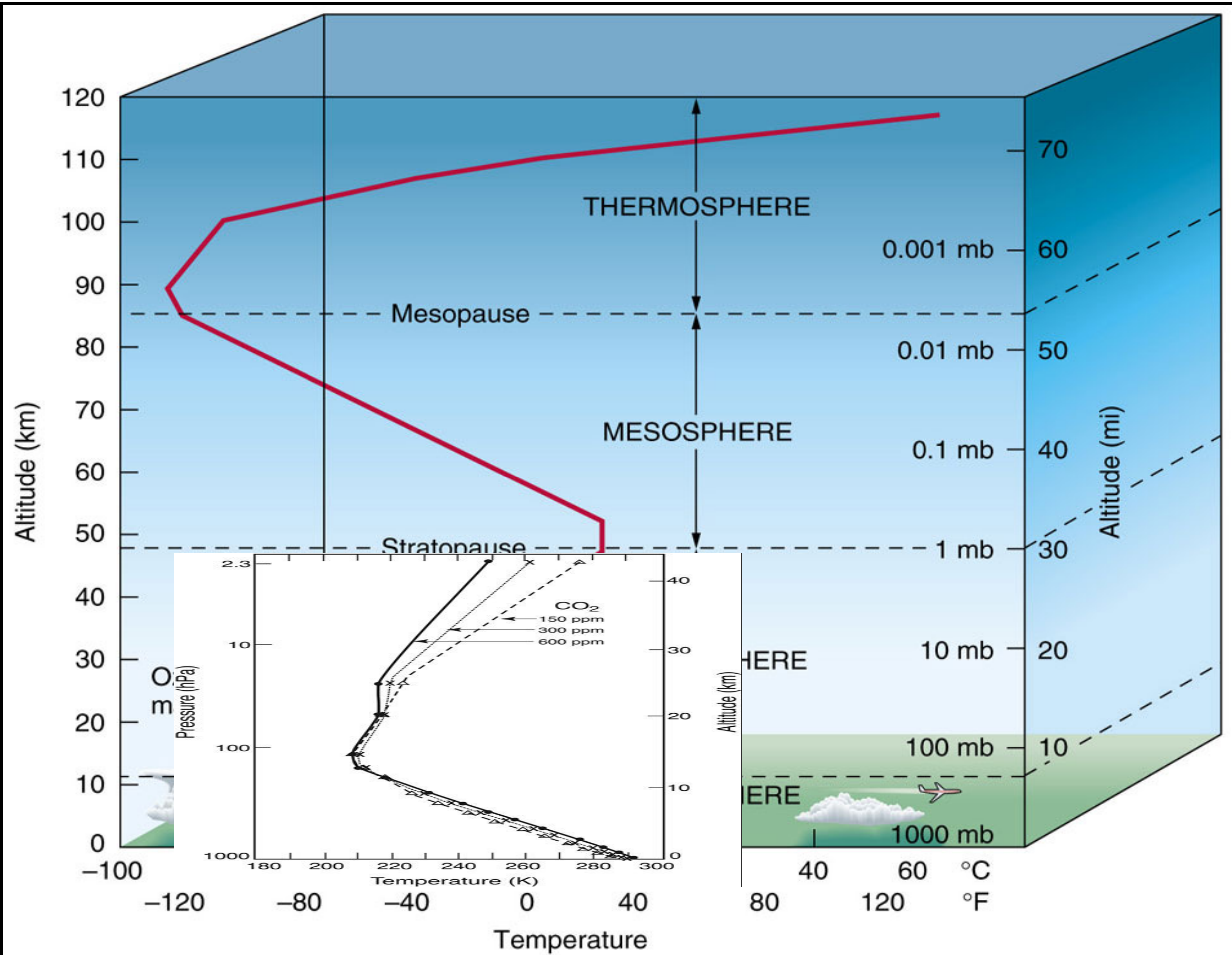
By SYUKURO MANABE*, *Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA*



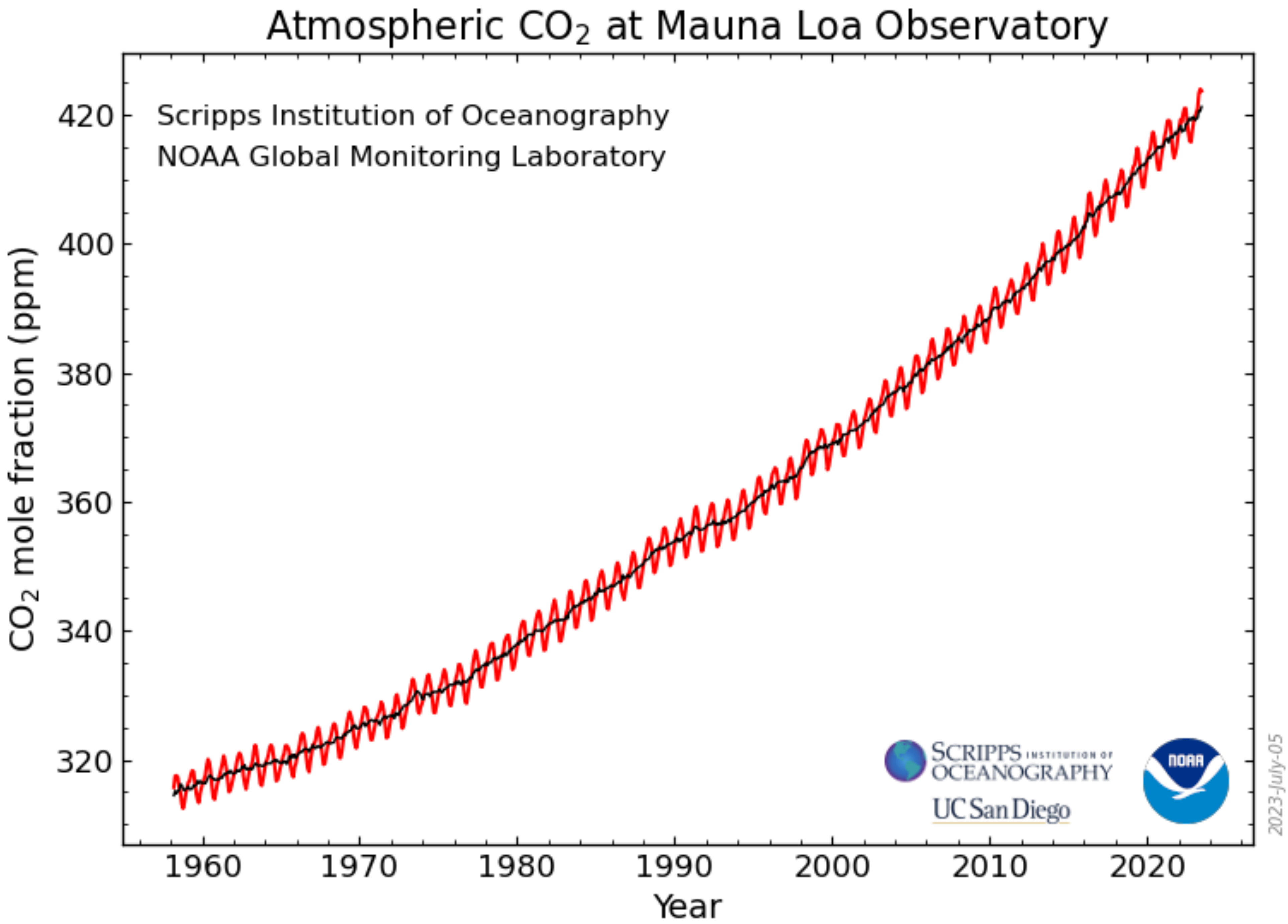




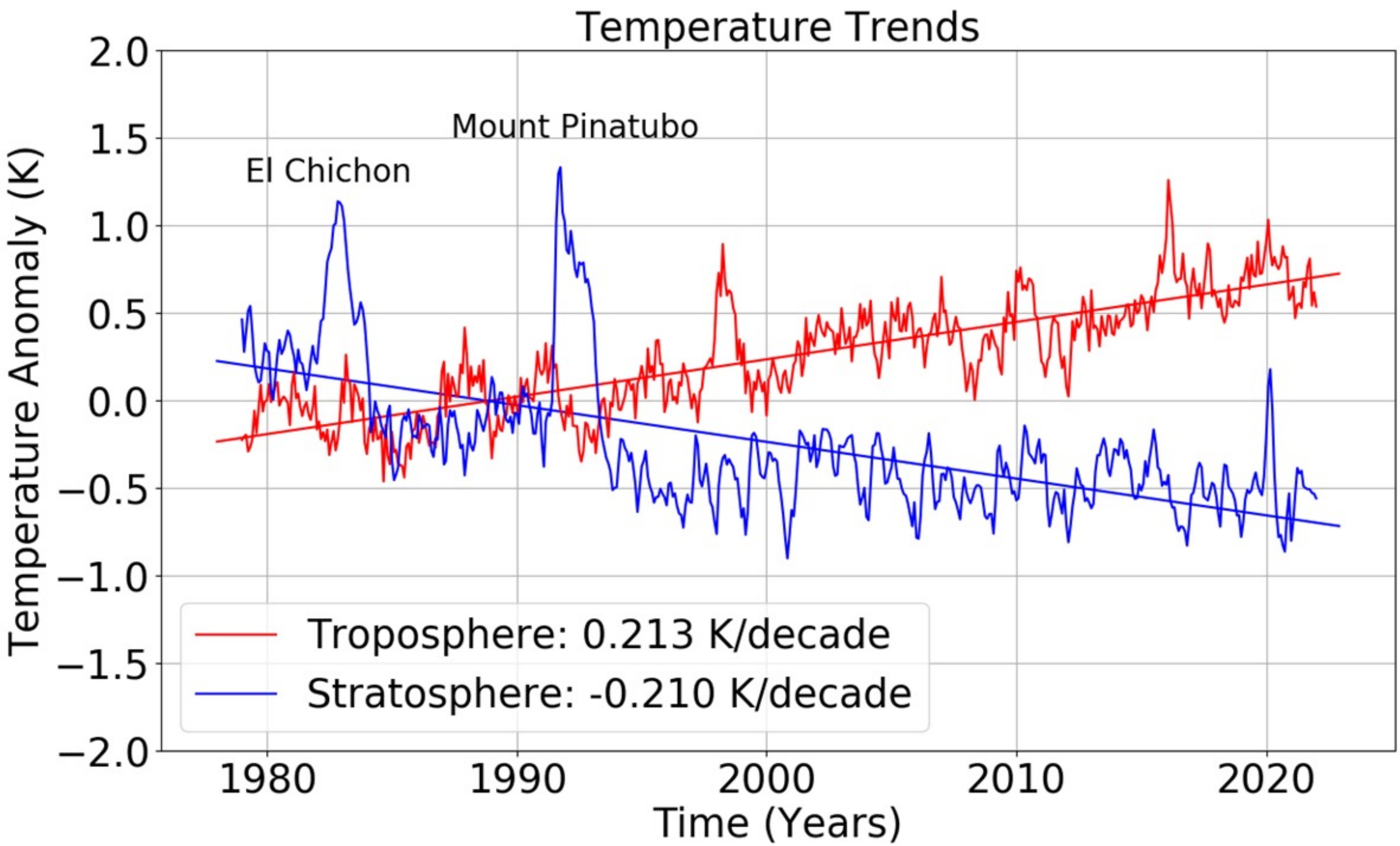
https://www.youtube.com/watch?v=nS5ReAWncHc



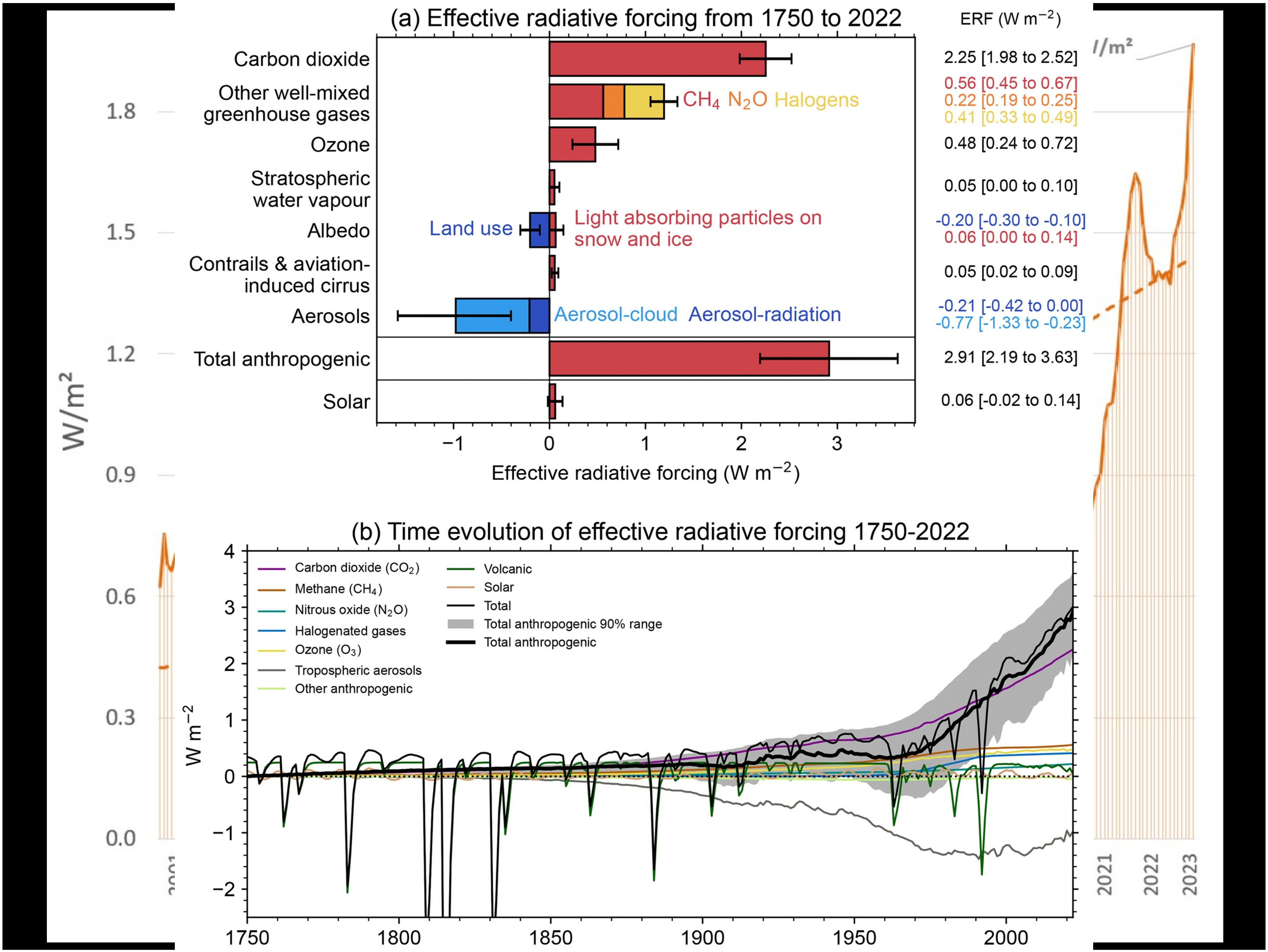
https://robertcarrollweather.files.wordpress.com/2014/11/agburt01_09.jpg

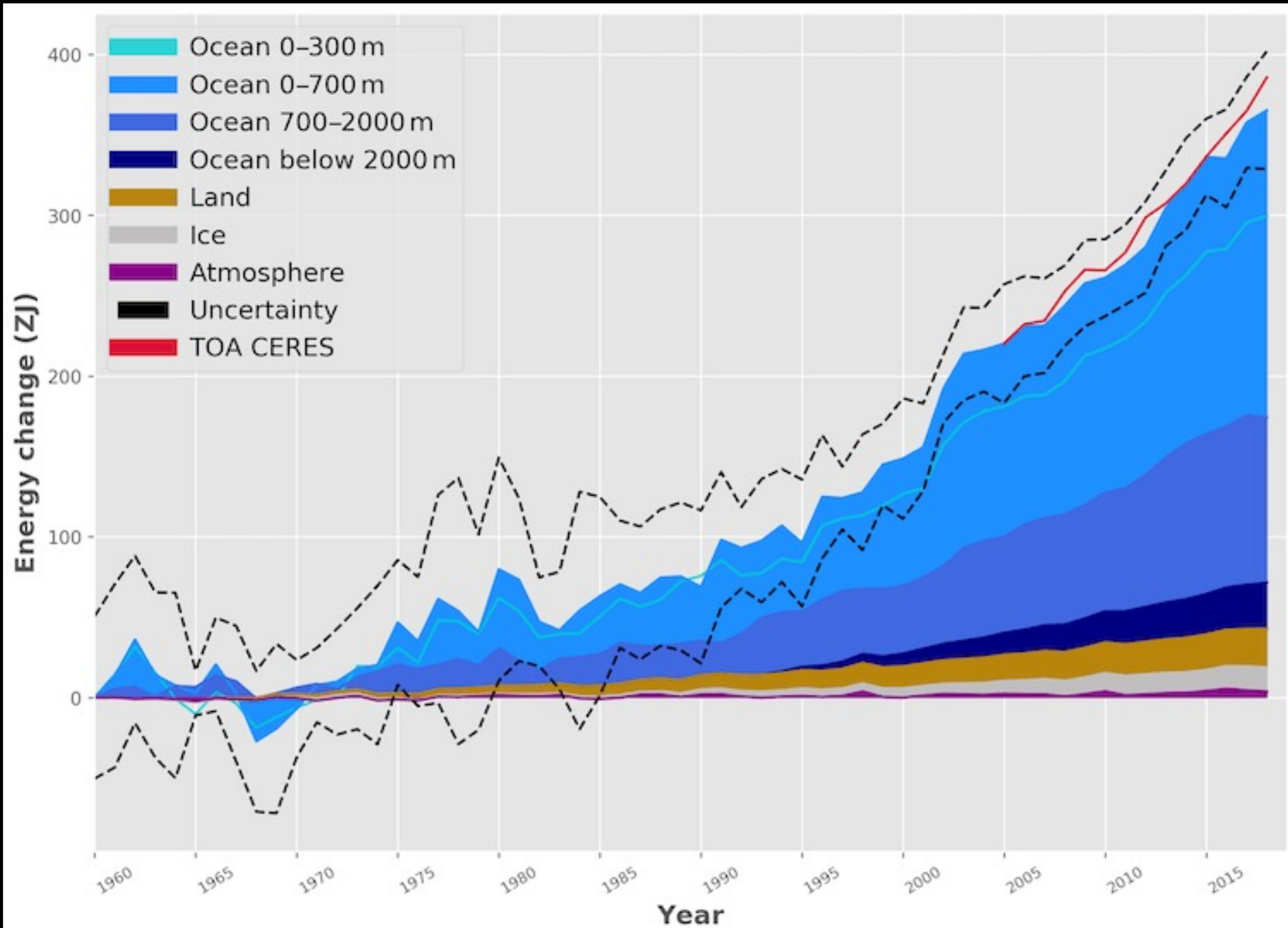

Atmospheric CO_2 at Mauna Loa Observatory
Scripps Institution of Oceanography
NOAA Global Monitoring Laboratory
CO_2 mole fraction (ppm)
420
400
380
360
340
320
1960
1970
1980
1990
2000
2010
2020
Year
SCRIPPS INSTITUTION OF OCEANOGRAPHY
UC San Diego
NOAA
2023-July-05

[redacted]



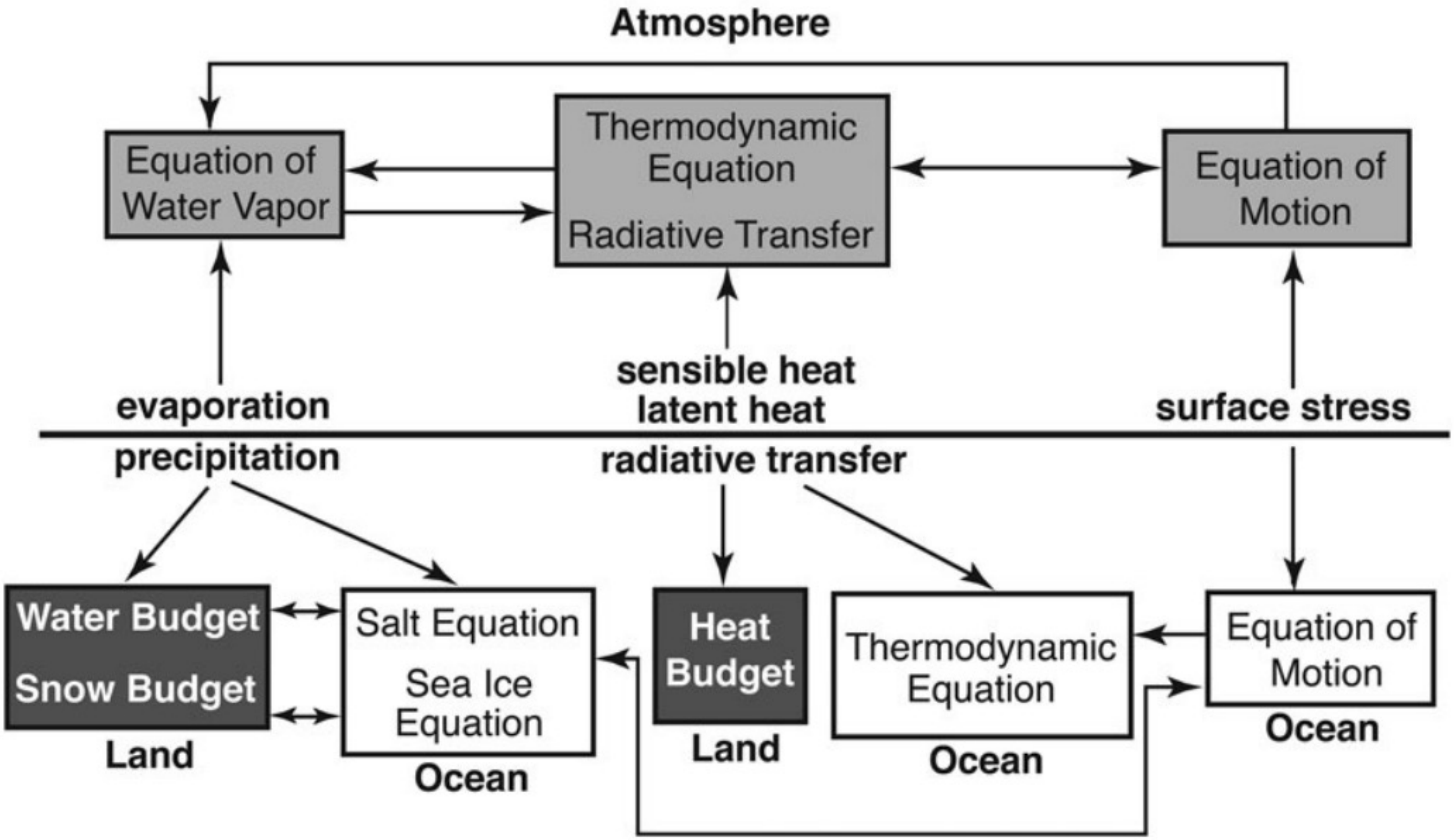
[redacted]

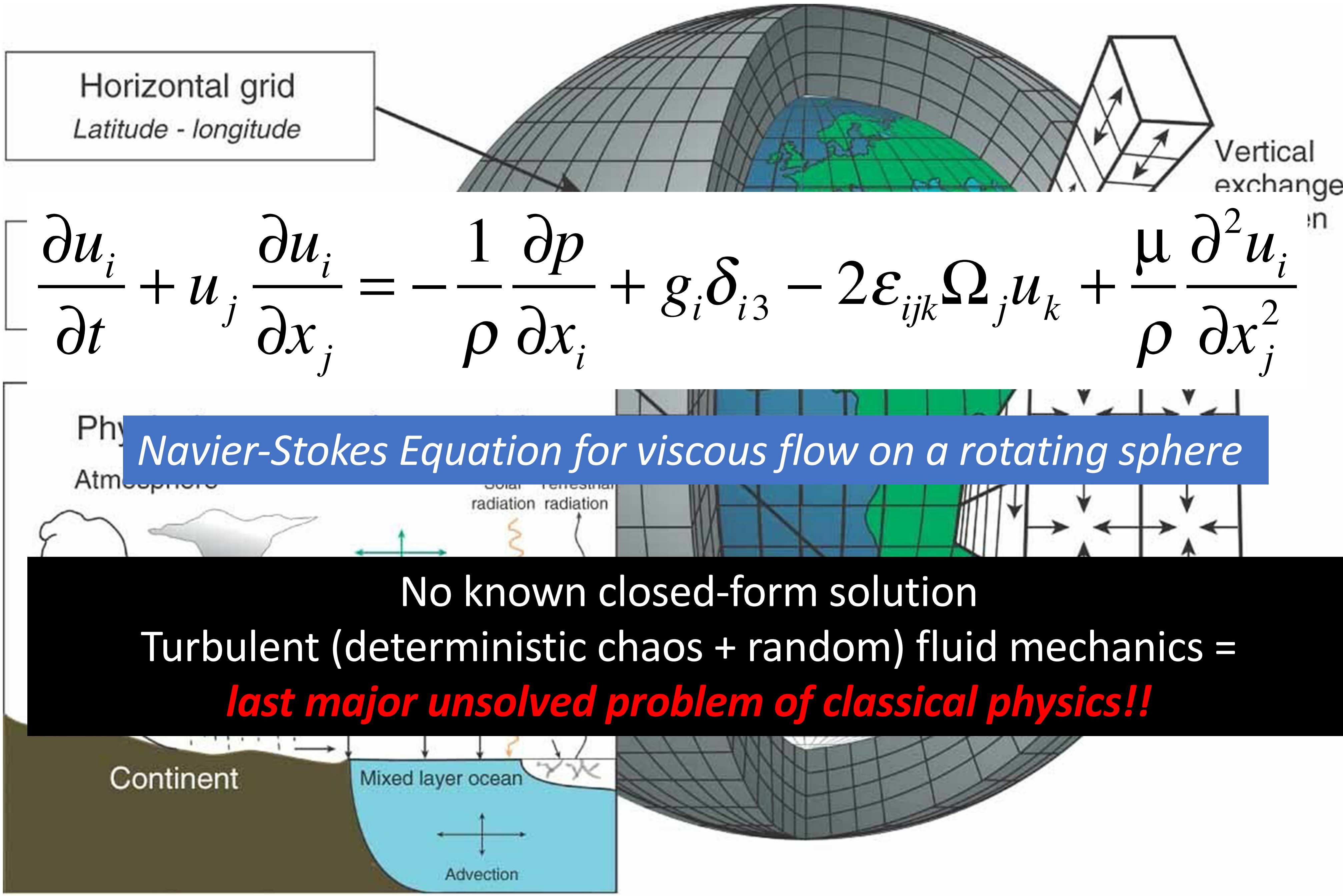

(a) Effective radiative forcing from 1750 to 2022
ERF (W m−2)
Carbon dioxide
2.25 [1.98 to 2.52]
Other well-mixed greenhouse gases
CH4 N2O Halogens
0.56 [0.45 to 0.67]
0.22 [0.19 to 0.25]
0.41 [0.33 to 0.49]
Ozone
0.48 [0.24 to 0.72]
Stratospheric water vapour
0.05 [0.00 to 0.10]
Albedo
Land use
Light absorbing particles on snow and ice
-0.20 [-0.30 to -0.10]
0.06 [0.00 to 0.14]
Contrails & aviation-induced cirrus
0.05 [0.02 to 0.09]
Aerosols
Aerosol-cloud
Aerosol-radiation
-0.21 [-0.42 to 0.00]
-0.77 [-1.33 to -0.23]
Total anthropogenic
2.91 [2.19 to 3.63]
Solar
0.06 [-0.02 to 0.14]
−1
0
1
2
3
Effective radiative forcing (W m−2)
(b) Time evolution of effective radiative forcing 1750-2022
Carbon dioxide (CO2)
Methane (CH4)
Nitrous oxide (N2O)
Halogenated gases
Ozone (O3)
Tropospheric aerosols
Other anthropogenic
Volcanic
Solar
Total
Total anthropogenic 90% range
Total anthropogenic
W m−2
4
3
2
1
0
−1
−2
1750
1800
1850
1900
1950
2000
W/m2
1.8
1.5
1.2
0.9
0.6
0.3
0.0
2021
2022
2023



von Schuckmann et al. (2020).

Coupled Ocean-Atmosphere-Land Model





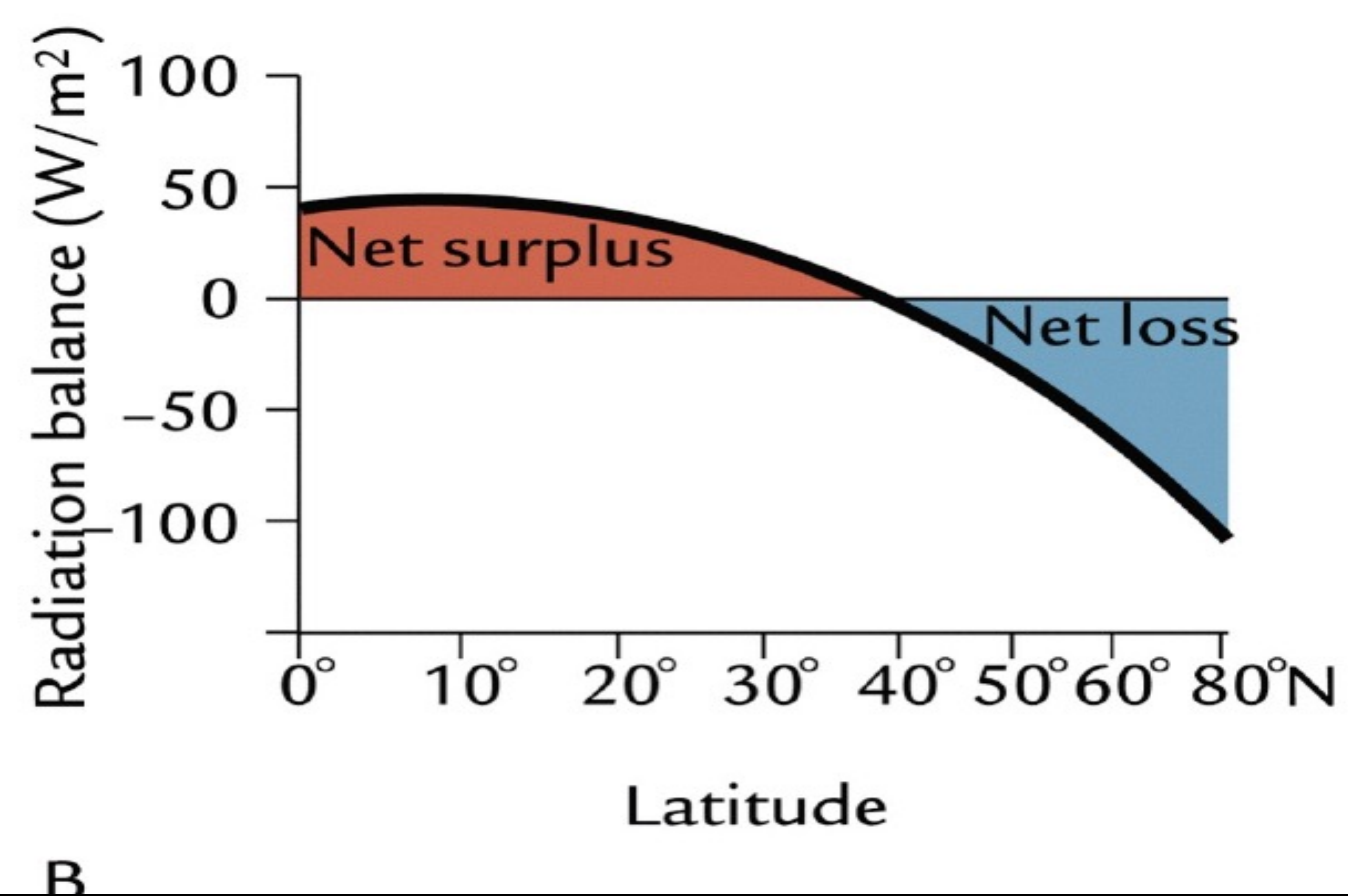
$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + g_i \delta_{i3} - 2\varepsilon_{ijk}\Omega_j u_k + \frac{\mu}{\rho}\frac{\partial^2 u_i}{\partial x_j^2}$$

Navier-Stokes Equation for viscous flow on a rotating sphere

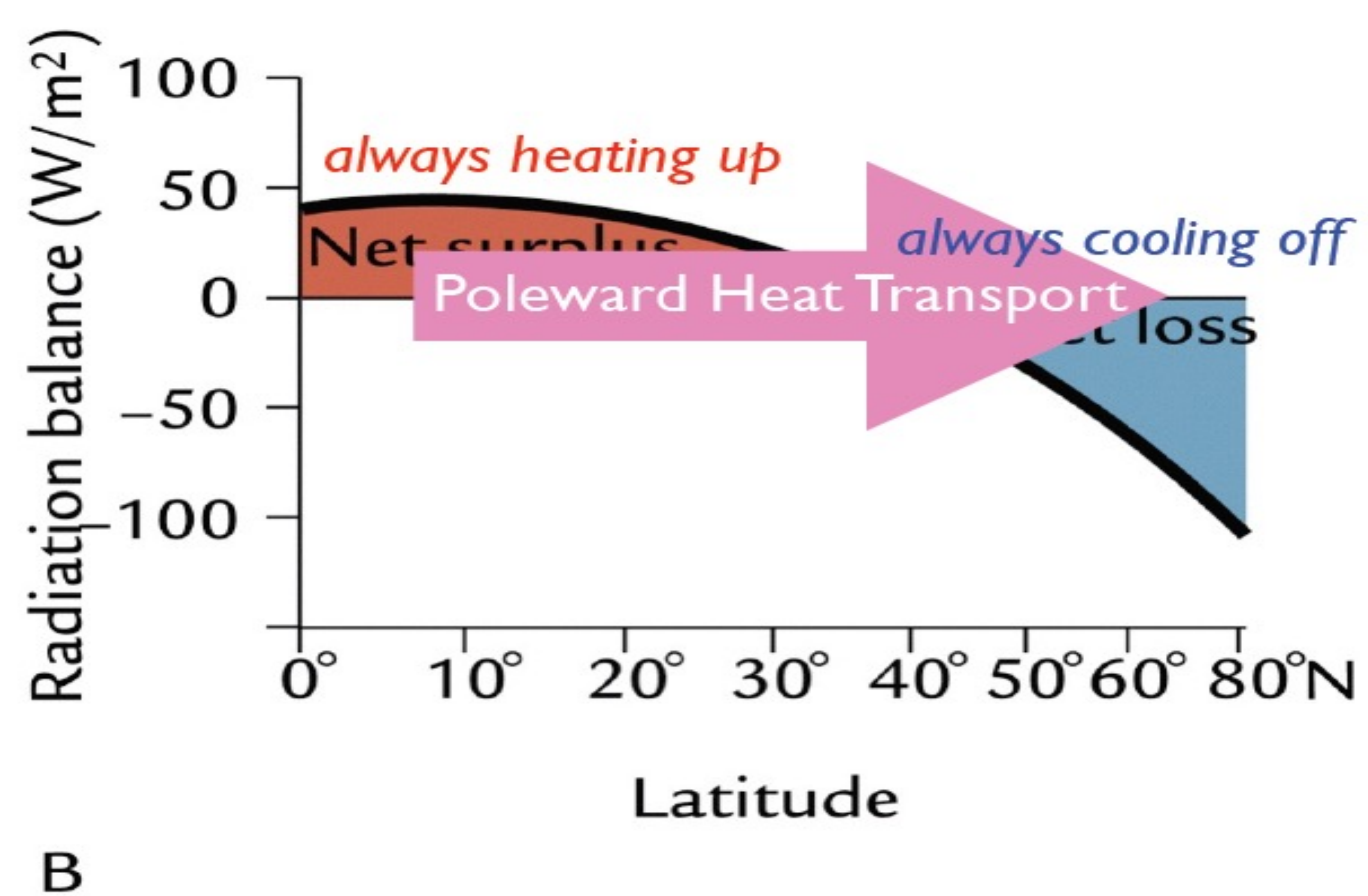
No known closed-form solution

Turbulent (deterministic chaos + random) fluid mechanics =

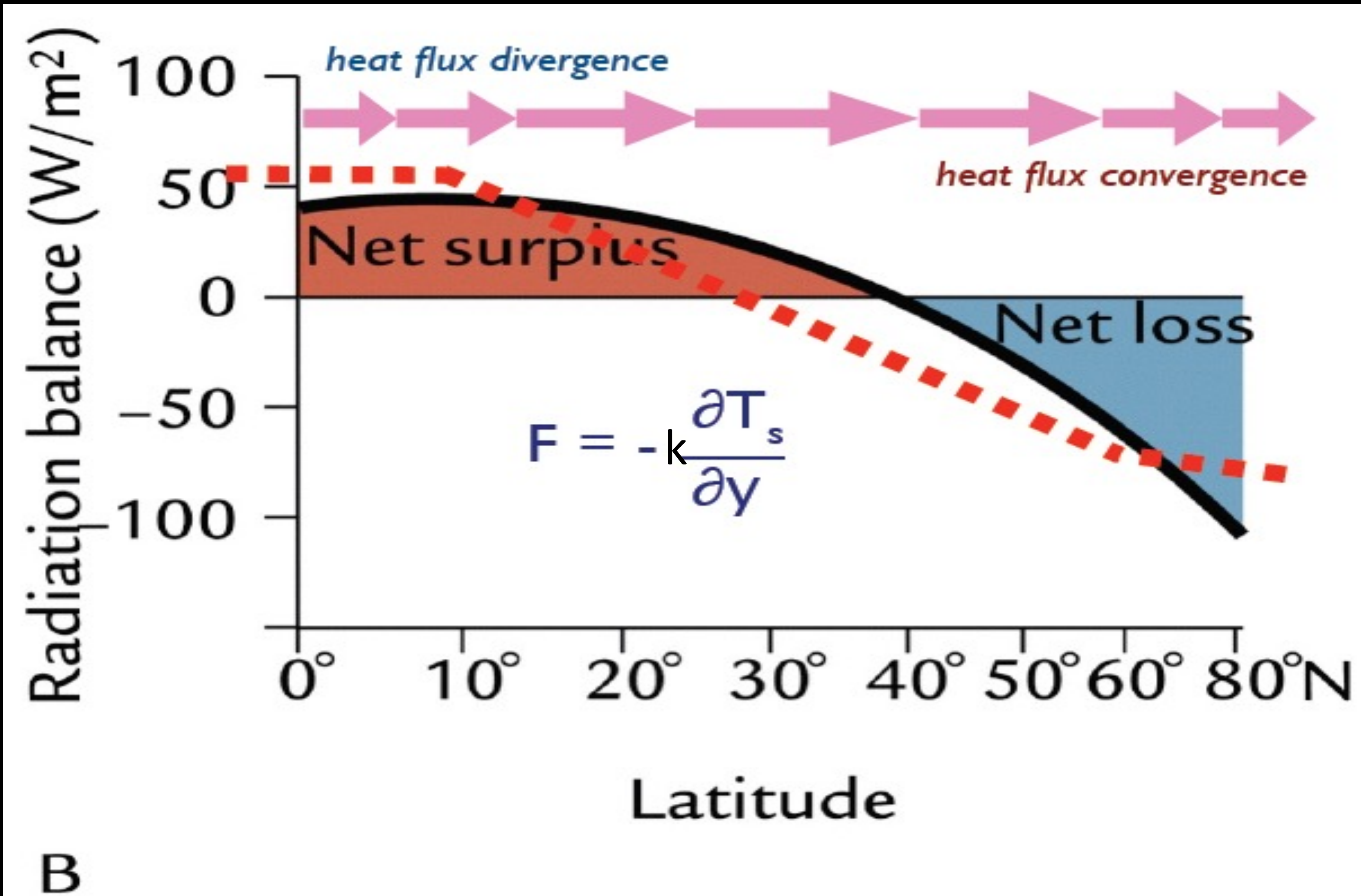
last major unsolved problem of classical physics!!



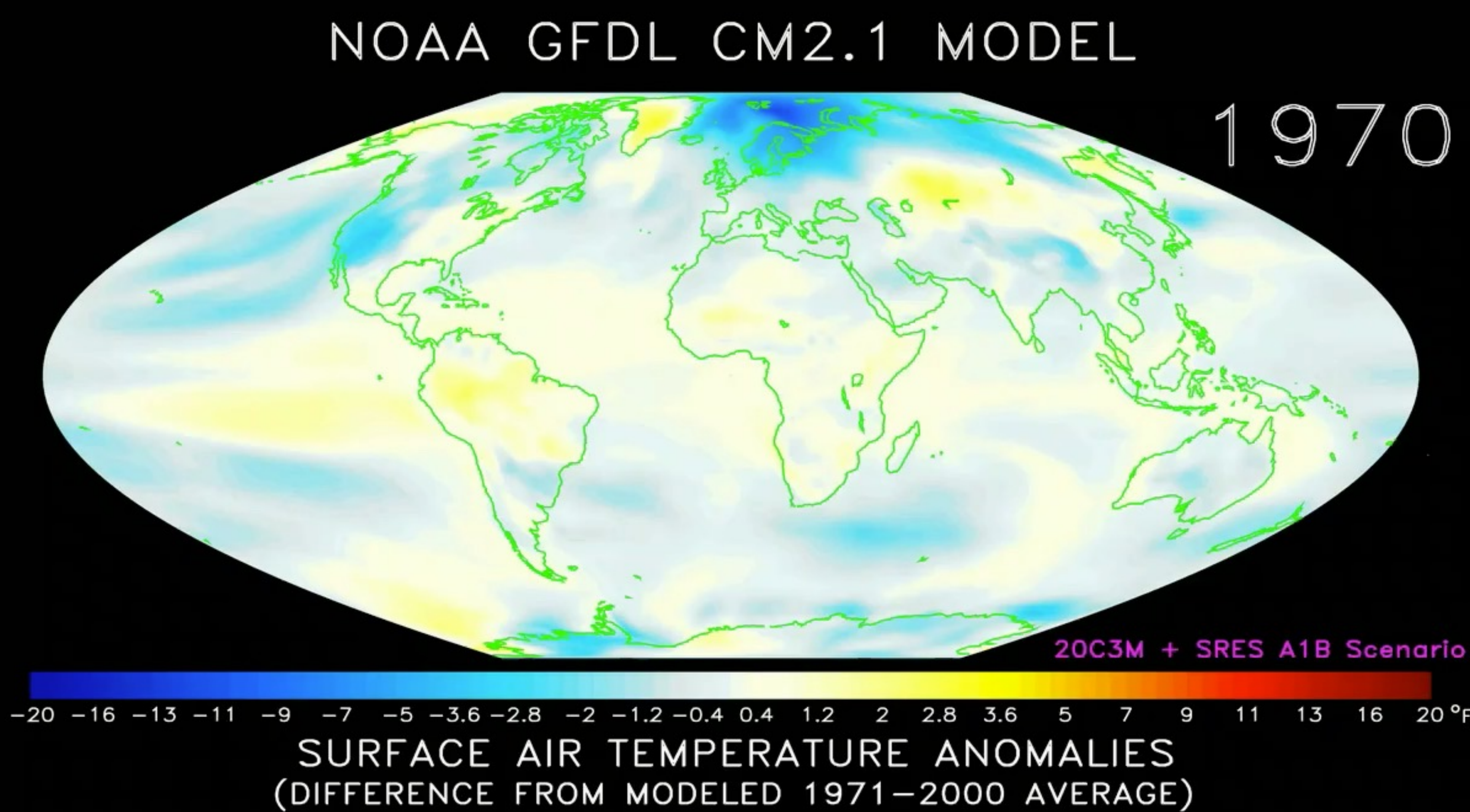
Radiation balance (W/m²)
100
50
0
-50
-100
Net surplus
Net loss
0°
10°
20°
30°
40°
50°
60°
80°N
Latitude
B



Radiation balance (W/m²)
100
50
0
−50
−100
always heating up
Net surplus
Poleward Heat Transport
always cooling off
et loss
0°
10°
20°
30°
40°
50°
60°
80°N
Latitude
B



heat flux divergence
heat flux convergence
Radiation balance (W/m²)
100
50
0
−50
−100
Net surplus
Net loss
F = -k ∂T_s/∂y
0°
10°
20°
30°
40°
50°
60°
80°N
Latitude
B

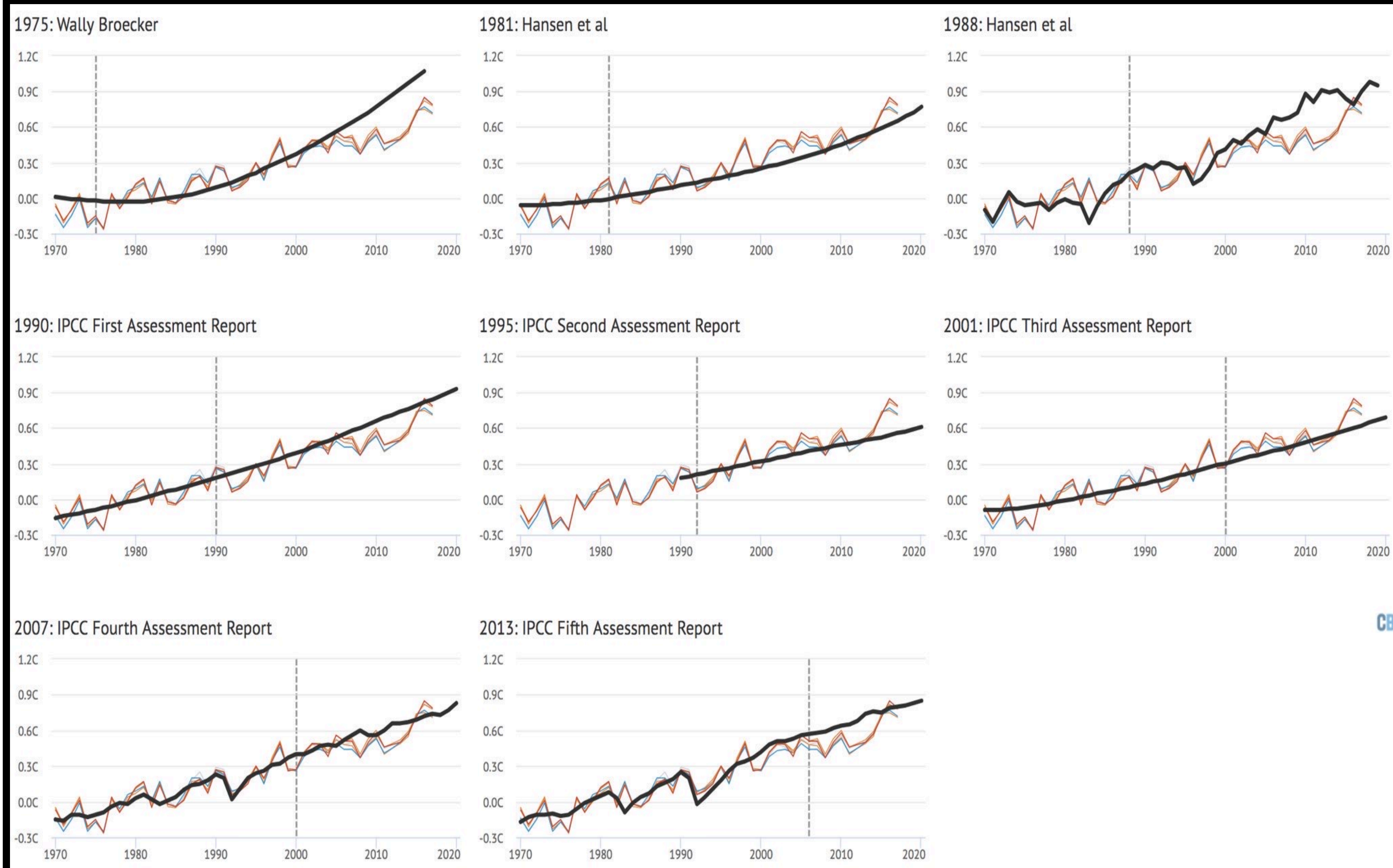


- Do all areas warm or cool equally? Where do you see major differences?
- What appears to be unique about 1992 and what might explain it?
- What pattern is seen in the tropical Pacific and what might explain it?
- Which parts of the world are first affected by warming? Why?
- Where is China today in comparison to the long term average? 2040? 2060? 2080?
- Which major areas experience long-term cooling? Does it negate the prediction of global warming?

https://www.gfdl.noaa.gov/visualizations-climate-prediction/

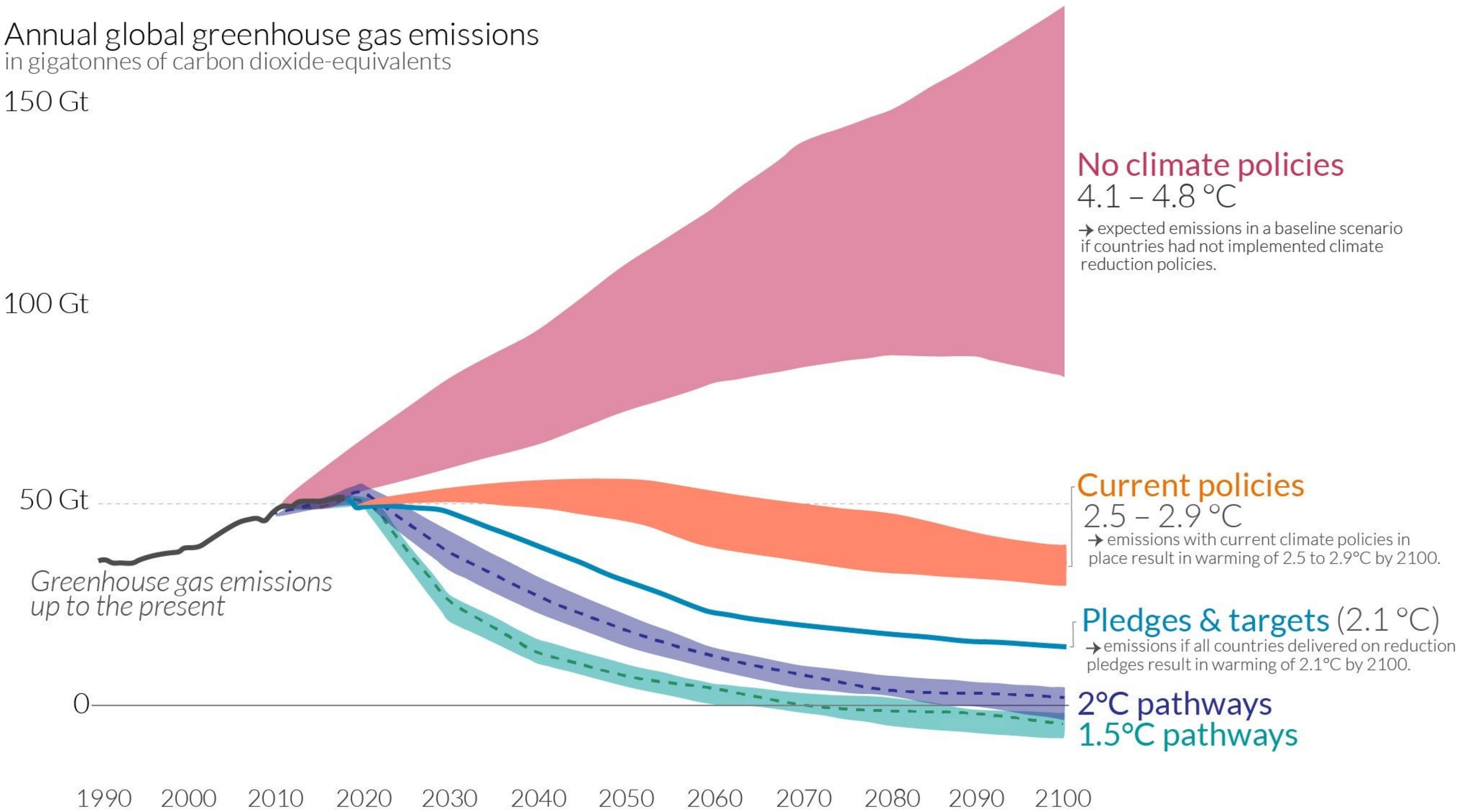
But it's also not "old" science

https://www.bloomberg.com/graphics/2015-whats-warming-the-world/


1975: Wally Broecker
1981: Hansen et al
1988: Hansen et al
1990: IPCC First Assessment Report
1995: IPCC Second Assessment Report
2001: IPCC Third Assessment Report
2007: IPCC Fourth Assessment Report
2013: IPCC Fifth Assessment Report
1.2C
0.9C
0.6C
0.3C
0.0C
-0.3C
1970
1980
1990
2000
2010
2020
CB

Global greenhouse gas emissions and warming scenarios

– Each pathway comes with uncertainty, marked by the shading from low to high emissions under each scenario.
– Warming refers to the expected global temperature rise by 2100, relative to pre-industrial temperatures.



Data source: Climate Action Tracker (based on national policies and pledges as of November 2021).
OurWorldinData.org – Research and data to make progress against the world's largest problems.

Last updated: April 2022.

Transient Climate Response to Emissions

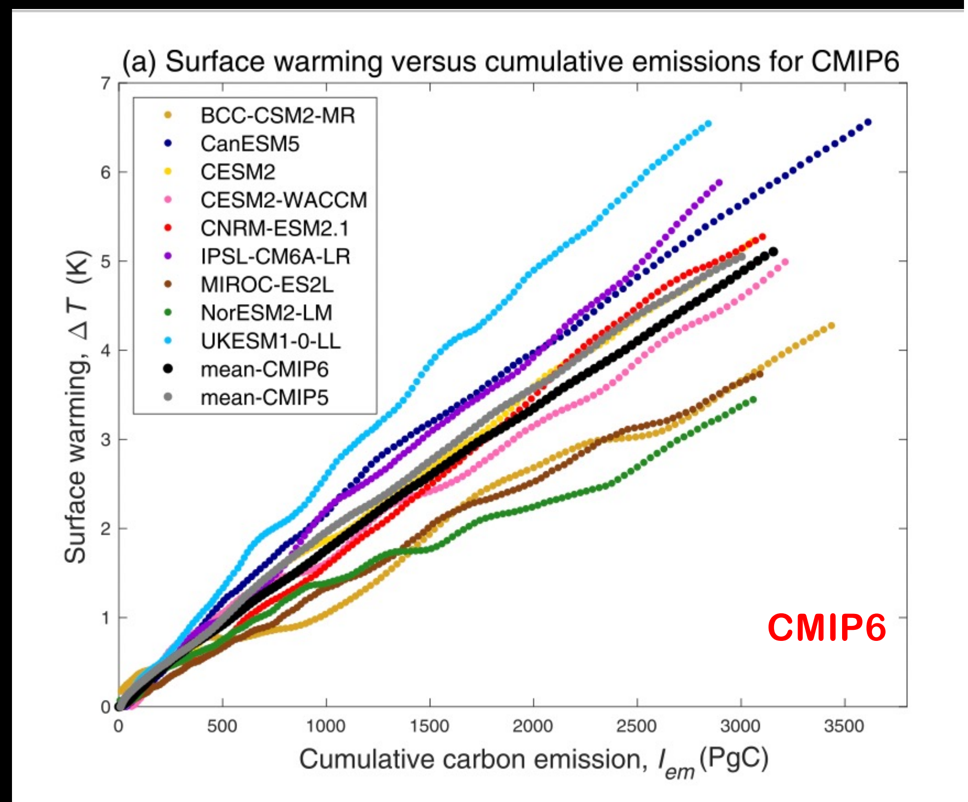
warming

CO_2 increment

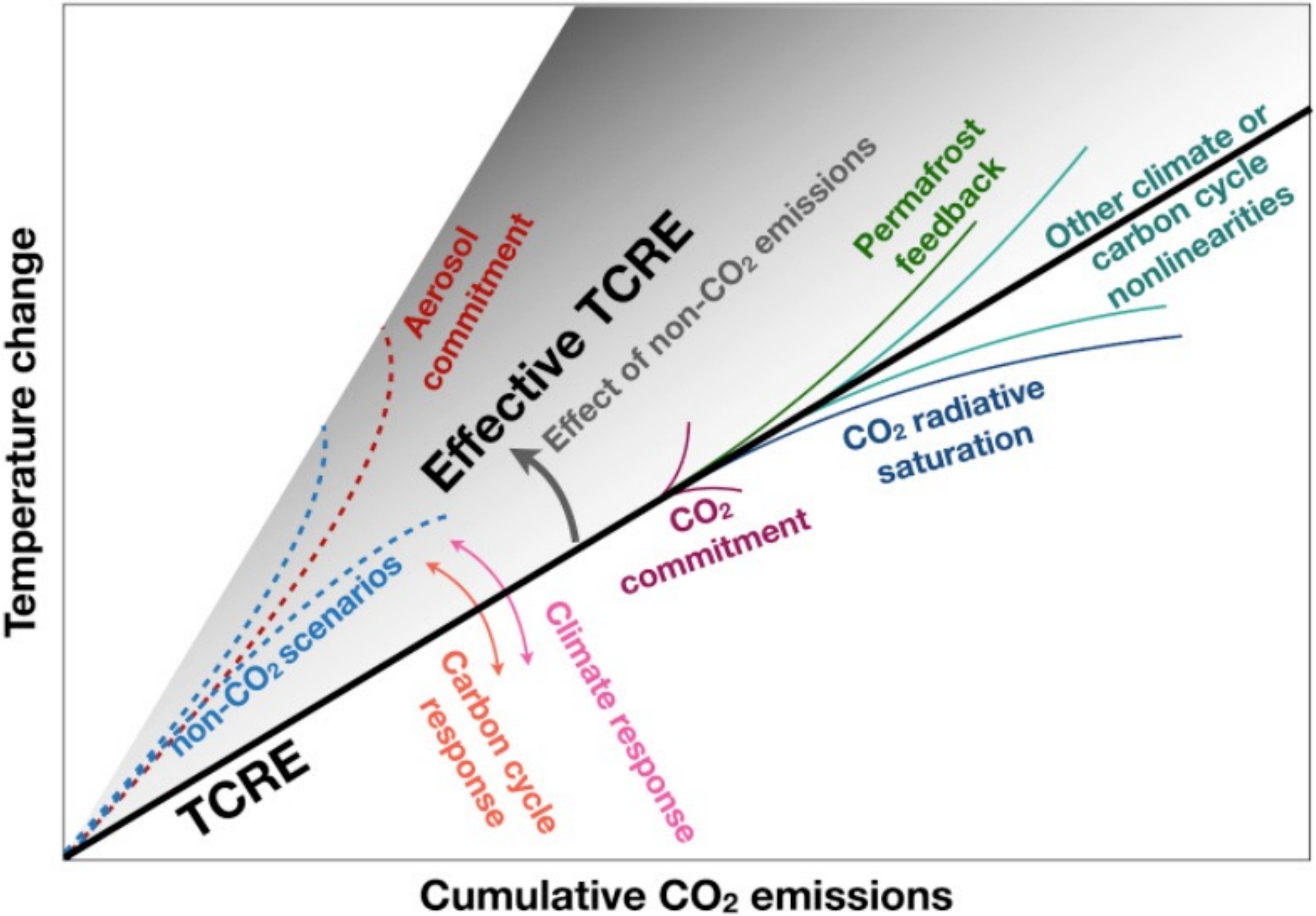
$$\Lambda = \frac{\Delta T}{E} = \frac{\Delta T}{\Delta C_a} \times \frac{\Delta C_a}{E}$$

TCRE

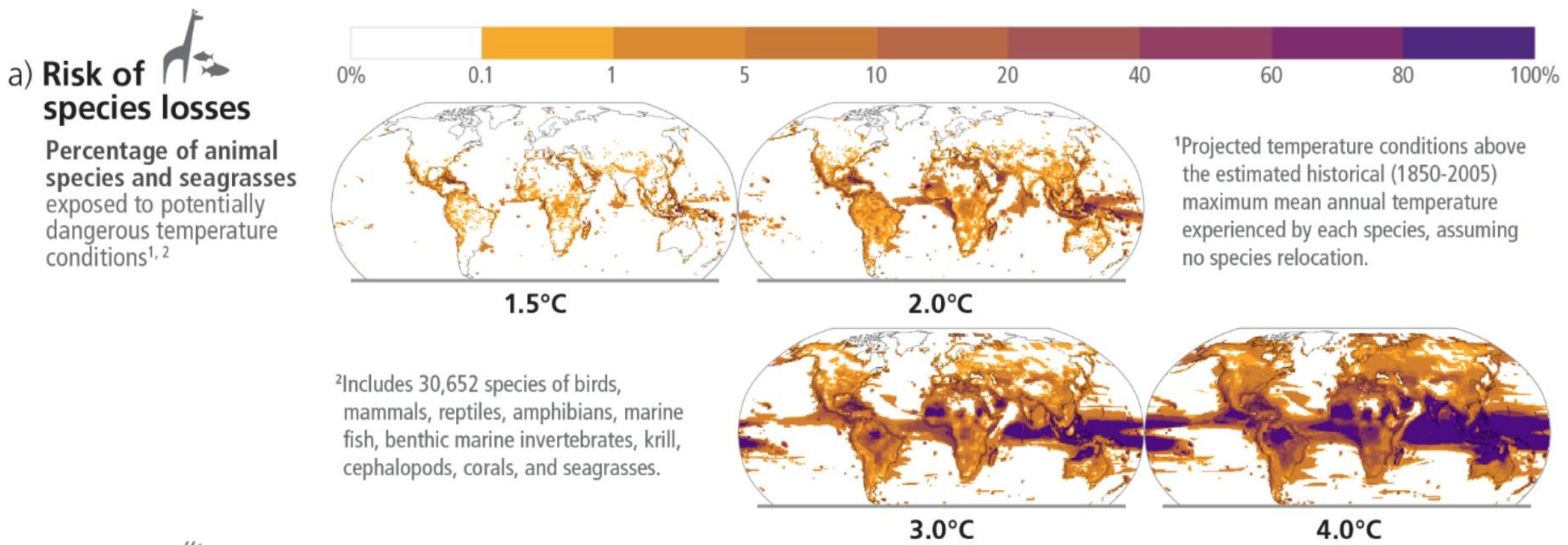
cumulative emissions

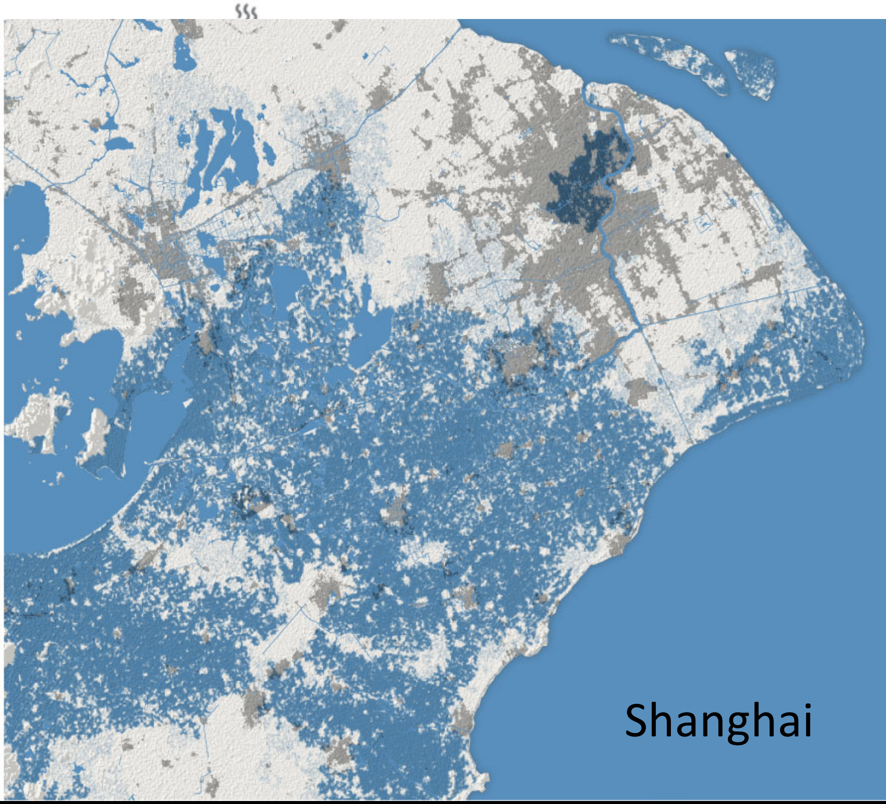


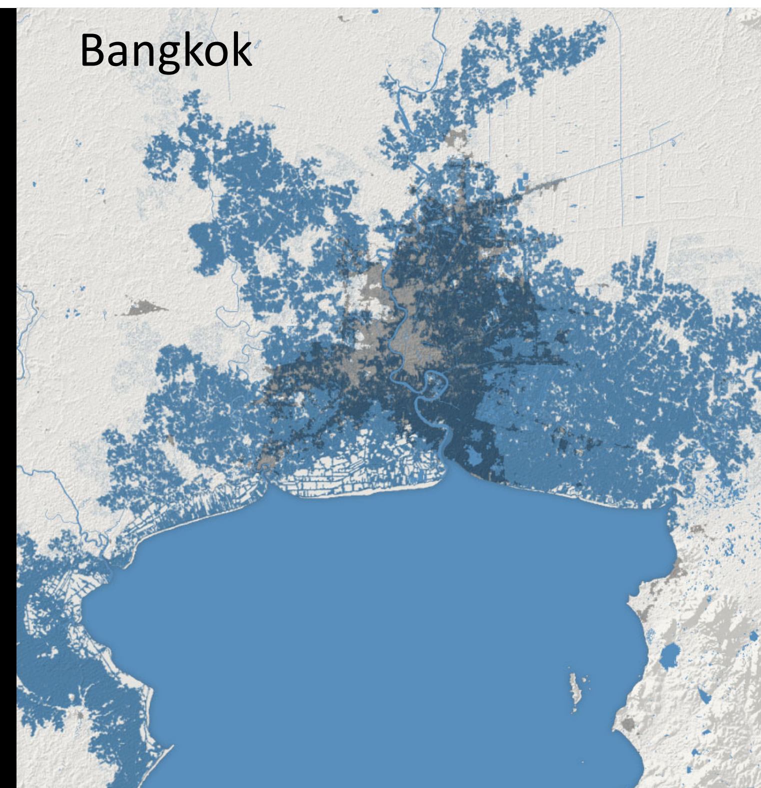
Scott Denning



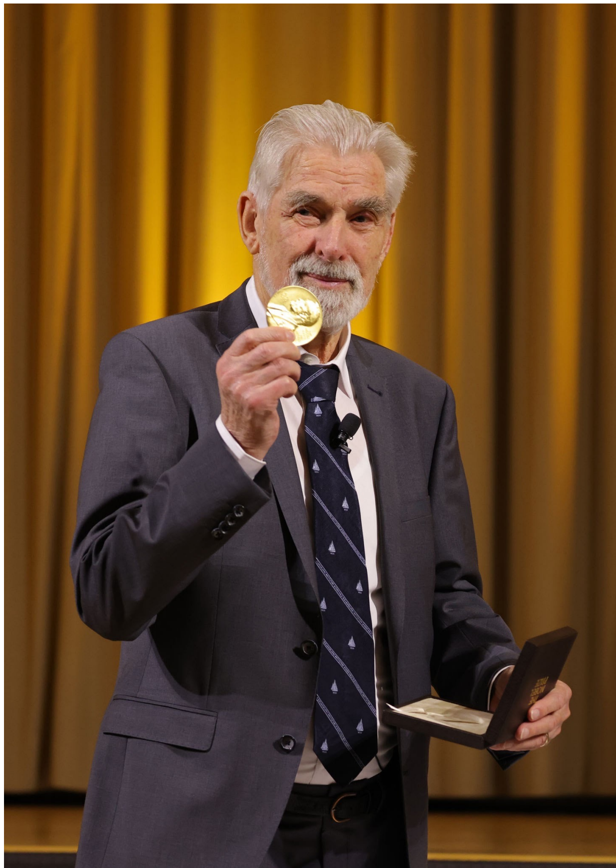
Temperature change
Cumulative CO2 emissions
TCRE
Effective TCRE
Effect of non-CO2 emissions
Aerosol commitment
non-CO2 scenarios
Carbon cycle response
Climate response
CO2 commitment
CO2 radiative saturation
Permafrost feedback
Other climate or carbon cycle nonlinearities

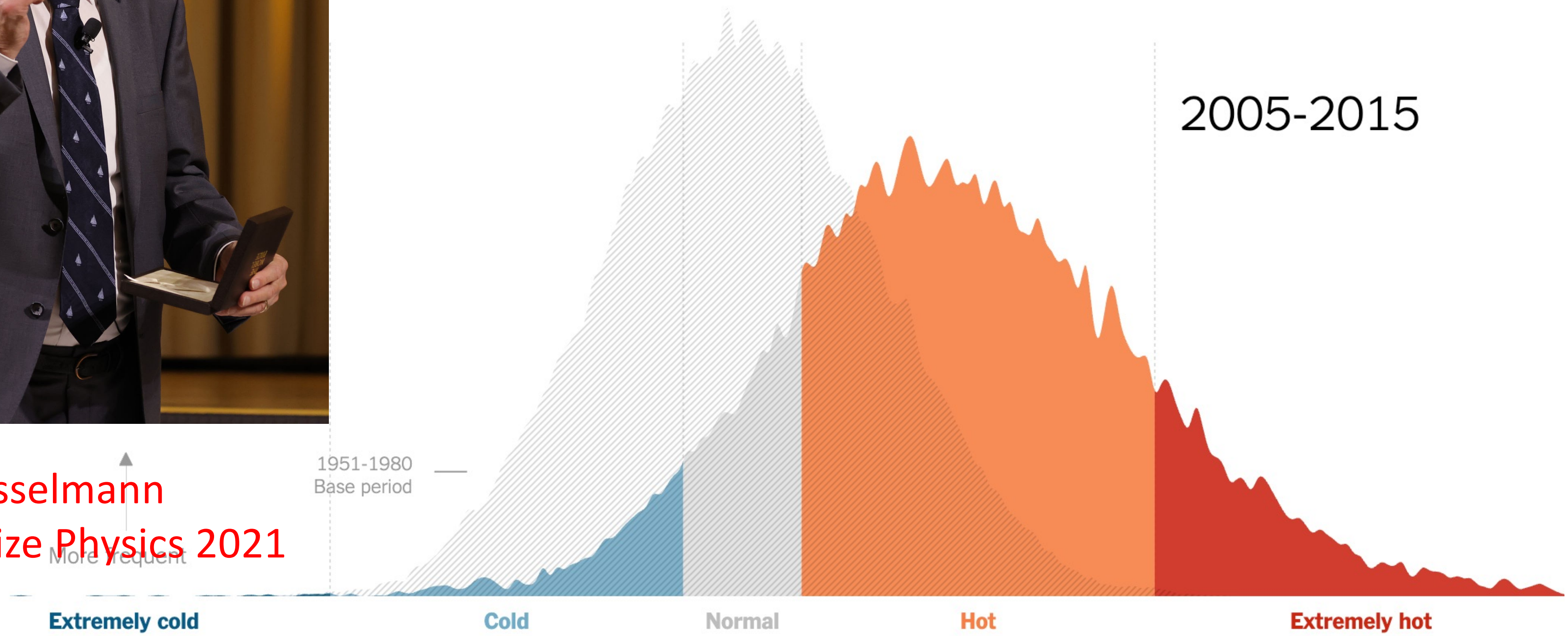






https://www.nytimes.com/interactive/2019/10/29/climate/coastal-cities-underwater.html





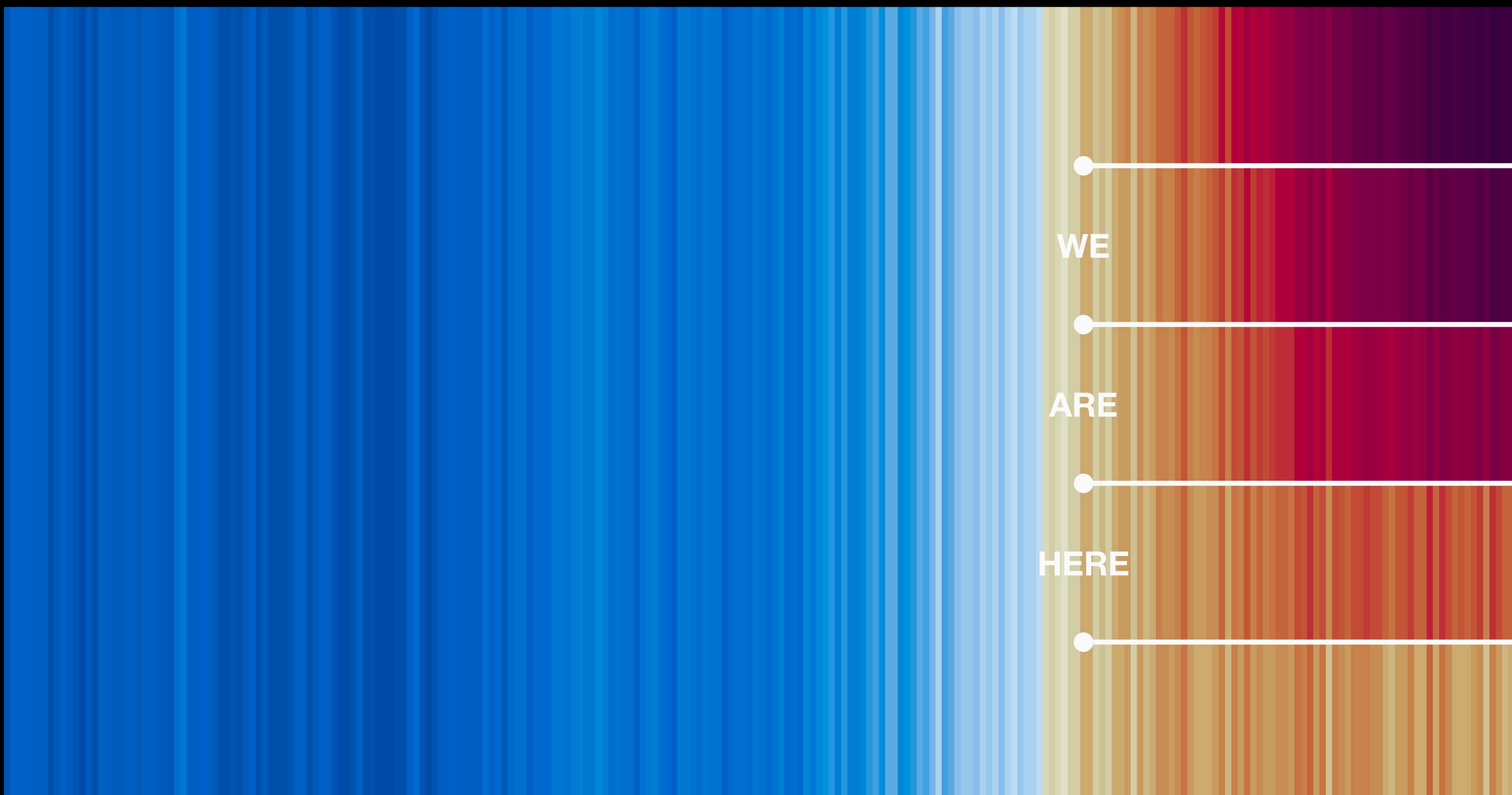
Klaus Hasselmann
Nobel Prize Physics 2021

https://www.nytimes.com/interactive/2017/07/28/climate/more-frequent-extreme-summer-heat.html

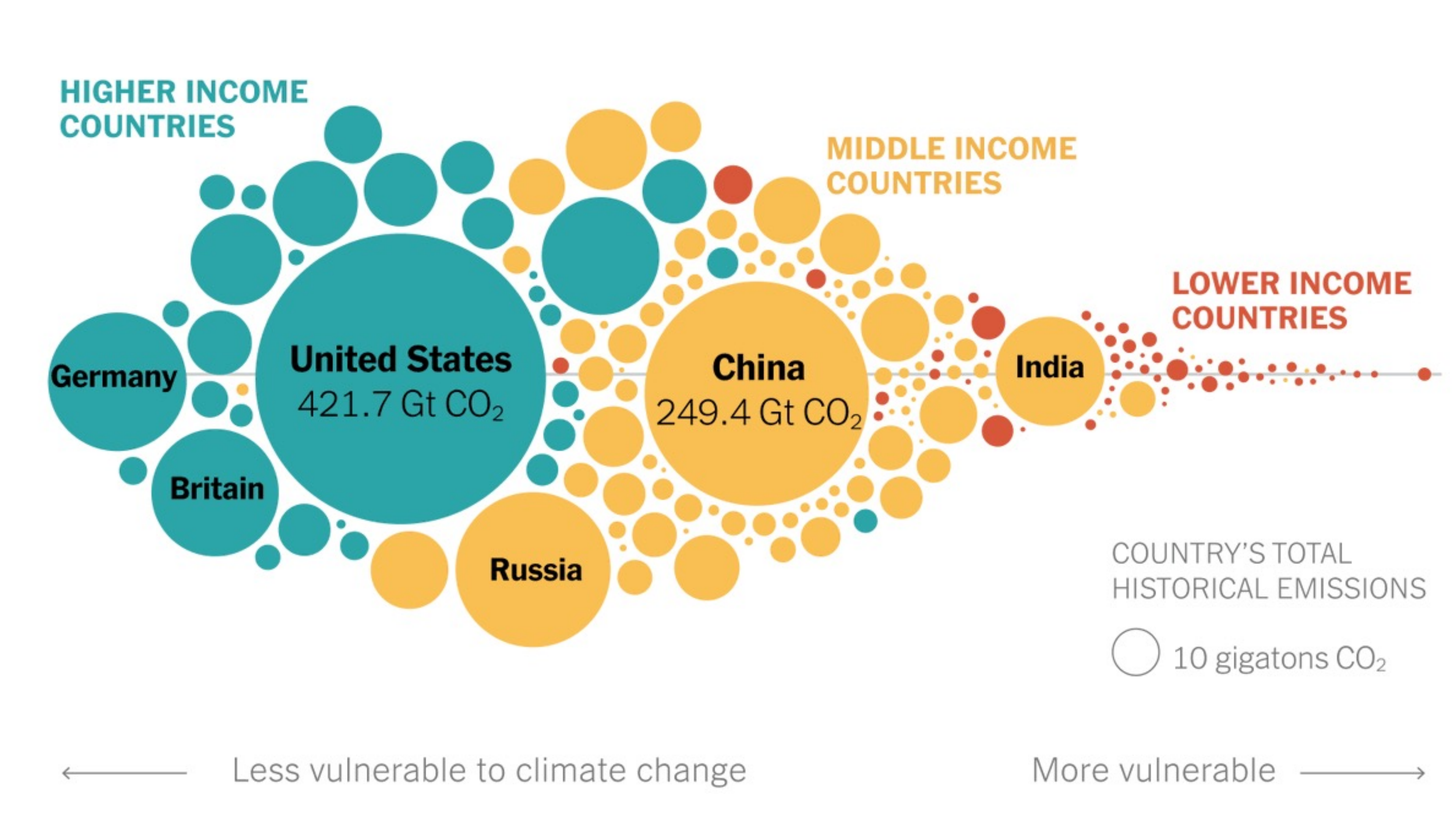
What can *WE* do about climate change? *A lot!*

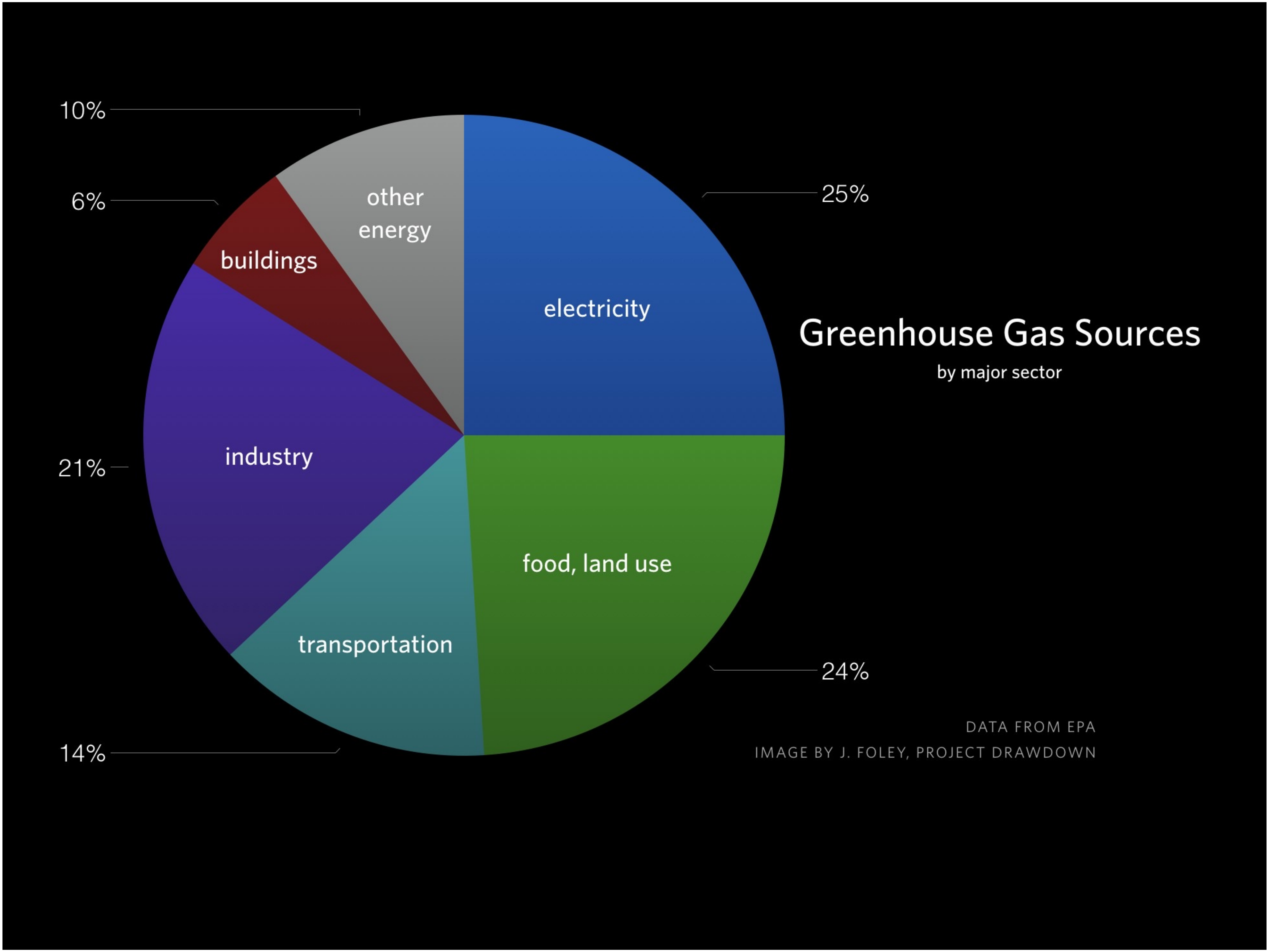
Global temperature change since 1850

Future choices up to 2100



Ed Hawkins


HIGHER INCOME COUNTRIES
MIDDLE INCOME COUNTRIES
LOWER INCOME COUNTRIES
Germany
Britain
United States
421.7 Gt CO_2
Russia
China
249.4 Gt CO_2
India
COUNTRY'S TOTAL HISTORICAL EMISSIONS
10 gigatons CO_2
Less vulnerable to climate change
More vulnerable


Greenhouse Gas Sources
by major sector
other energy
buildings
electricity
industry
transportation
food, land use
10%
6%
21%
14%
25%
24%
DATA FROM EPA
IMAGE BY J. FOLEY, PROJECT DRAWDOWN

Solutions are abundant

- https://www.drawdown.org/solutions

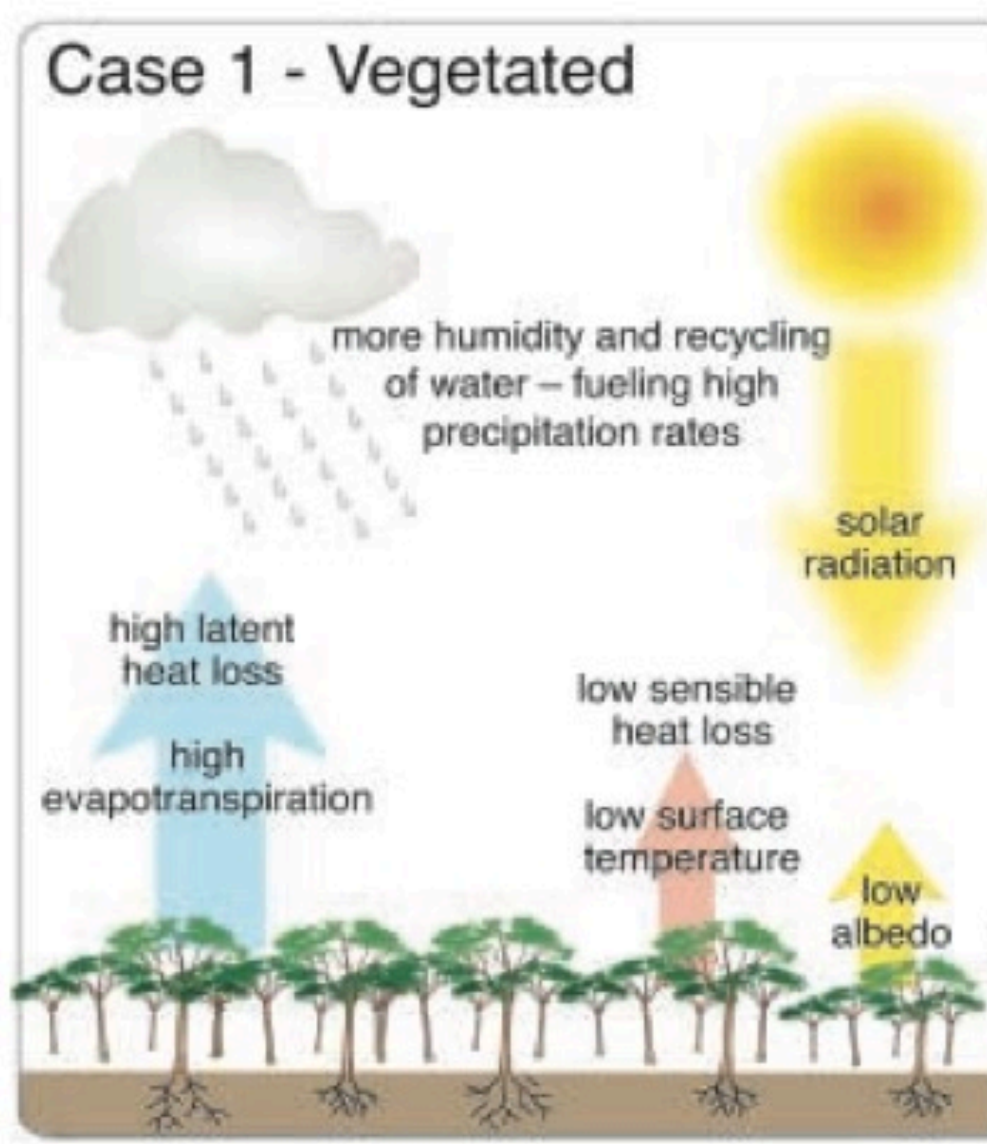
Solutions by Rank

Rank	Solution	Sector	TOTAL ATMOSPHERIC CO2-EQ REDUCTION (GT)	NET COST (BILLIONS US $)	SAVINGS (BILLIONS US $)
1	**Refrigerant Management**	Materials	89.74	N/A	$-902.77
2	**Wind Turbines (Onshore)**	Electricity Generation	84.60	$1,225.37	$7,425.00
3	**Reduced Food Waste**	Food	70.53	N/A	N/A
4	**Plant-Rich Diet**	Food	66.11	N/A	N/A
5	**Tropical Forests**	Land Use	61.23	N/A	N/A
6	**Educating Girls**	Women and Girls	51.48	N/A	N/A
7	**Family Planning**	Women and Girls	51.48	N/A	N/A
8	**Solar Farms**	Electricity Generation	36.90	$-80.60	$5,023.84
9	**Silvopasture**	Food	31.19	$41.59	$699.37
10	**Rooftop Solar**	Electricity Generation	24.60	$453.14	$3,457.63

SEE ALL SOLUTIONS BY RANK

Green surprise? How terrestrial ecosystems could affect earth's climate

Jonathan A Foley[1], Marcos Heil Costa[2], Christine Delire[1], Navin Ramankutty[1], and Peter Snyder[1]

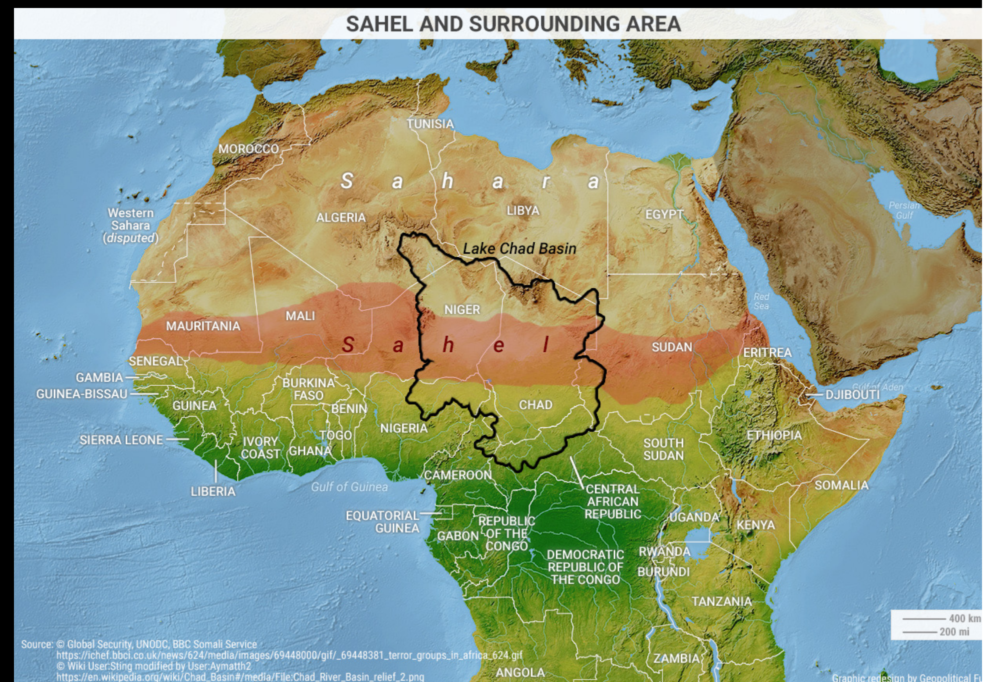


Dynamics of deserts and drought in the Sahel†

J. G. Charney

First published: April 1975 | https://doi.org/10.1002/qj.49710142802 | Citations: 1,046

Positive vegetation-rainfall feedback: Low greenness -> Higher albedo -> Low-level cooling -> Increased stability of atmosphere ->Subsidence -> Drying



Greener vegetation -> Higher moisture recycling

Less vegetation -> More dust emissions

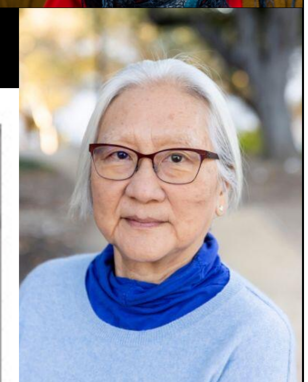
Observed positive vegetation-rainfall feedbacks in the Sahel dominated by a moisture recycling mechanism

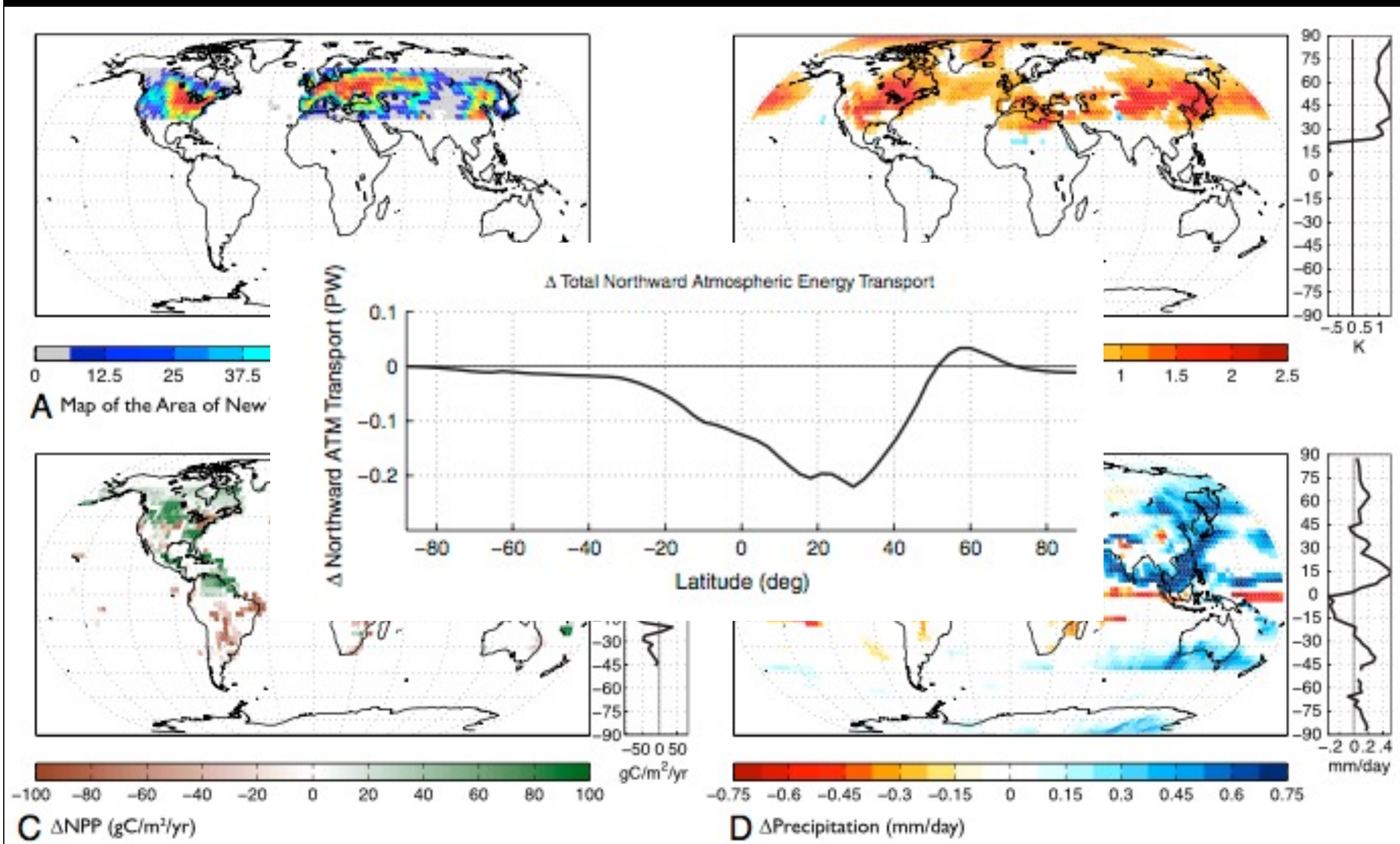
Yan Yu, Michael Notaro, Fuyao Wang, Jiafu Mao, Xiaoying Shi & Yaxing Wei

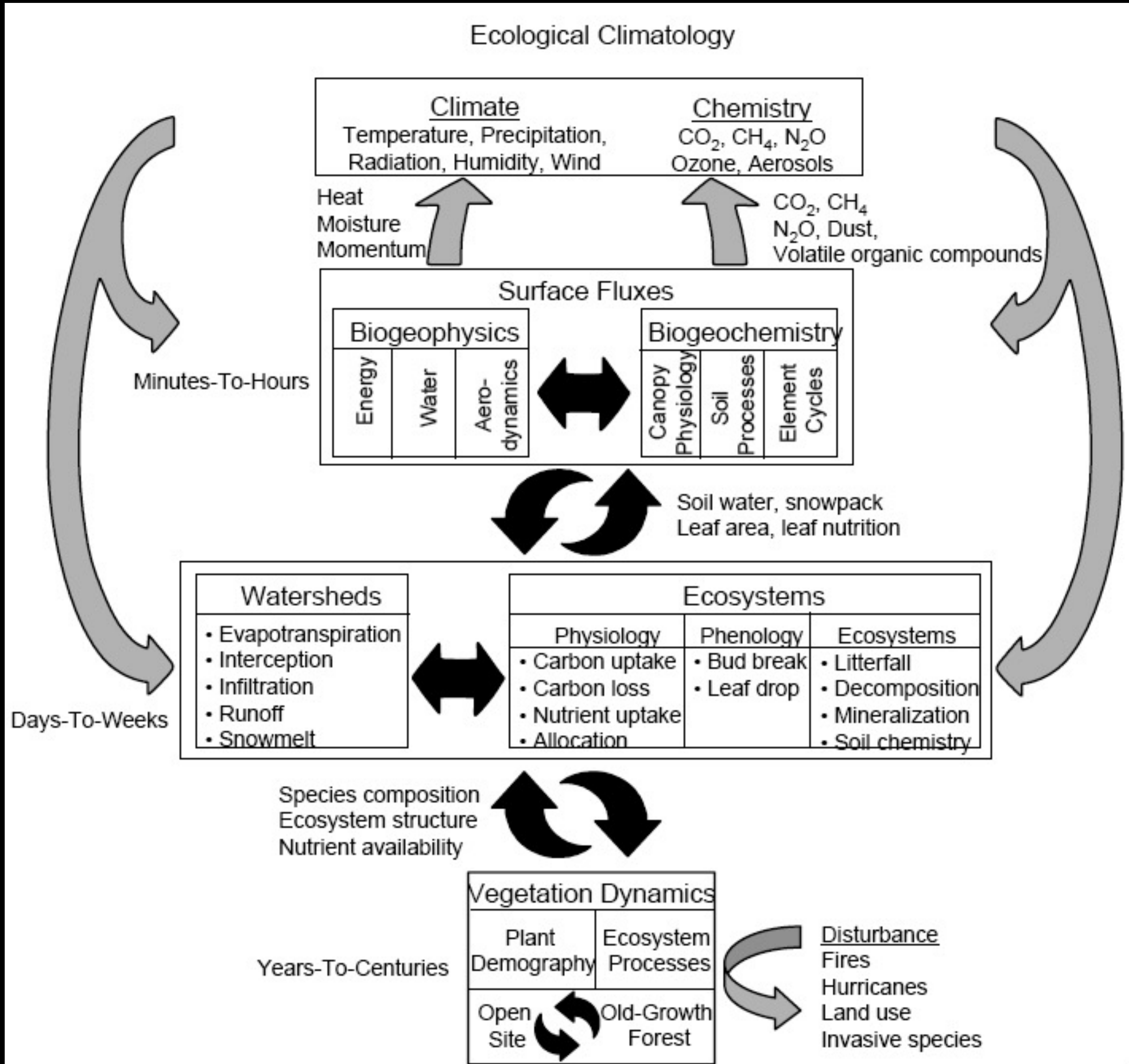
Nature Communications **8**, Article number: 1873 (2017) | Cite this article

Mid-latitude afforestation shifts general circulation and tropical precipitation

Abigail L. S. Swann[a,b,c,1], Inez Y. Fung[c], and John C. H. Chiang[d]







Ecological Climatology
Climate
Temperature, Precipitation, Radiation, Humidity, Wind
Chemistry
CO_2, CH_4, N_2O Ozone, Aerosols
Heat
Moisture
Momentum
CO_2, CH_4
N_2O, Dust,
Volatile organic compounds
Surface Fluxes
Biogeophysics
Energy
Water
Aero-dynamics
Biogeochemistry
Canopy Physiology
Soil Processes
Element Cycles
Minutes-To-Hours
Soil water, snowpack
Leaf area, leaf nutrition
Watersheds
• Evapotranspiration
• Interception
• Infiltration
• Runoff
• Snowmelt
Ecosystems
Physiology
• Carbon uptake
• Carbon loss
• Nutrient uptake
• Allocation
Phenology
• Bud break
• Leaf drop
Ecosystems
• Litterfall
• Decomposition
• Mineralization
• Soil chemistry
Days-To-Weeks
Species composition
Ecosystem structure
Nutrient availability
Vegetation Dynamics
Plant Demography
Ecosystem Processes
Open Site
Old-Growth Forest
Years-To-Centuries
Disturbance
Fires
Hurricanes
Land use
Invasive species


STEAK & EGGS
SCRAMBLER
PLAIN OMELET
ORIENTAL CHICKEN OMELET W/ YANKS
CHILI CHEESE OMELET W/ YANKS
FRENCH TOAST
BUTTERMILK PANCAKES
BANANA NUT PANCAKES
GRIDDLE CAKES (OATMEAL, APPLE, RAISIN)
CHOCOLATE CHIP PANCAKES
STRAWBERRY PANCAKES
CAJUN CHICKEN SANDWICH
CHICKEN CLUB SANDWICH
STEAK SANDWICH
CAJUN STEAK SANDWICH
PHILLY CHEESESTEAK SANDWICH
LIVER & ONIONS
TUNA
TUNA MELT
HOT DOG
CHEESE CURDS
HOMEMADE CORNED BEEF HASH
HAM, BACON, OR SAUSAGE
CINNAMON ROLL COFFEE CAKE
TOAST ENGLISH MUFFIN OR BAGEL
HOMEMADE SOUP OR CHILI
GRILLED VEGGIES OR SIDE SALAD
CHEF SALAD OR CHICKEN SALAD
MILK
ROOTBEER FLOAT
SHAKES MALTS
In case you're out of the loop... restaurants are short staffed. Be kind to those who showed up.
Cinnamon Roll
Coffee Cake
Cajun Fries
EXIT
MADISON
RESTROOM

University of Wisconsin-Madison

Department of Atmospheric and Oceanic Sciences

Who We Are

Since 1948 we have grown into one of the leading departments in our field of Atmospheric and Oceanic Sciences. We have strong graduate and undergraduate programs which are nationally recognized. We graduate about 15 Ph.D. and M.S. students each year; our graduates are active in research labs and universities around the world. We graduate approximately 20 B.S. students each year; they choose options allowing a focus on weather systems or general atmospheric science.

Our faculty of 15 has long maintained breadth and special strength in three areas:

- Climate systems, including the ocean
- Satellite and remote sensing
- Weather systems, including synoptic-dynamic

SSEC

Space Science and Engineering Center
University of Wisconsin-Madison

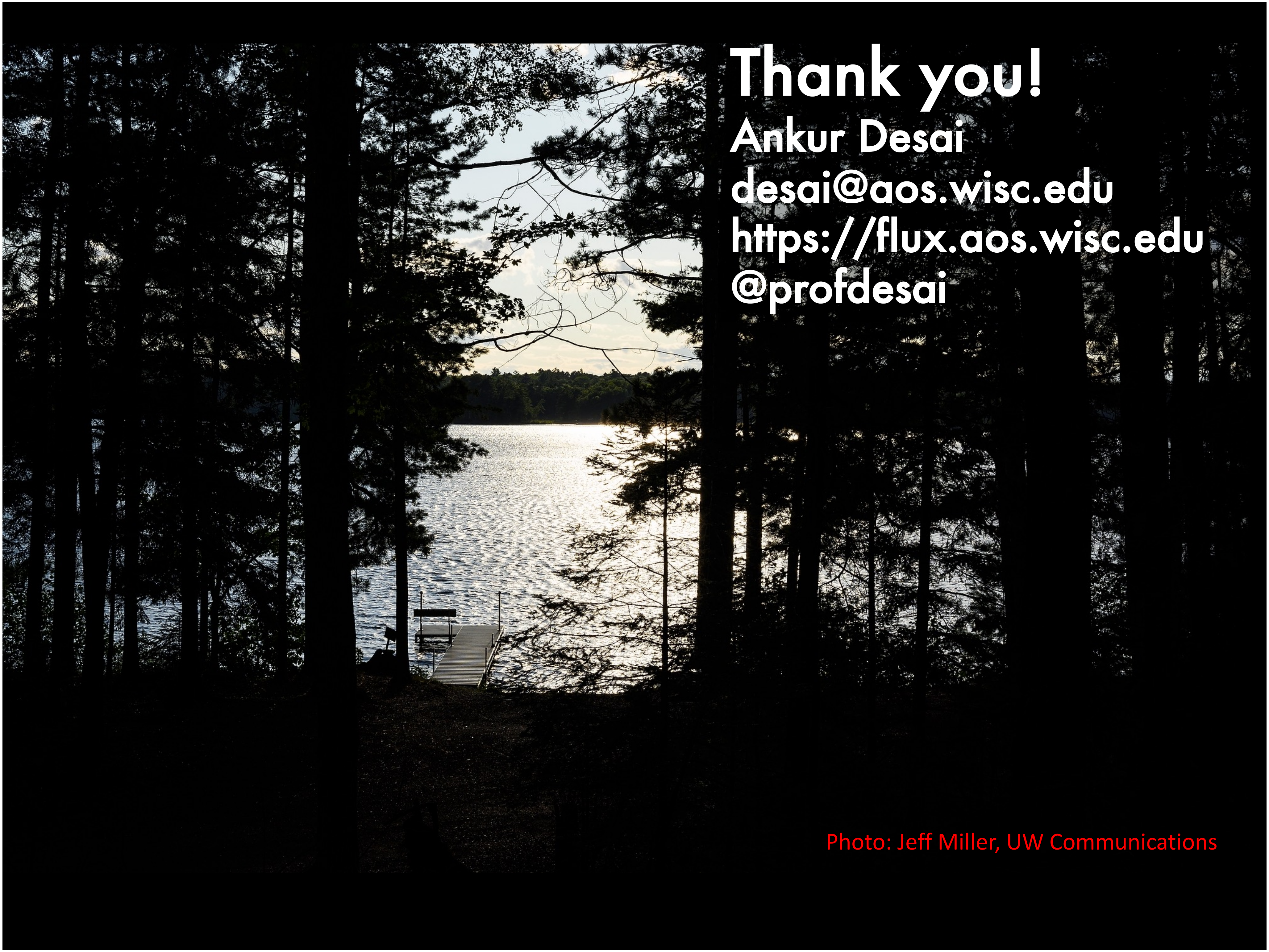
Center for Climatic Research
NELSON INSTITUTE
UNIVERSITY OF WISCONSIN–MADISON

Big challenges in climate physics

- Representation and effect of clouds and aerosols on climate
- Non-linear interactions and feedbacks of land, ocean, sea ice on atmosphere
- Predictability of seasonal to decadal ocean circulation and climate variations
- Impacts and feedbacks of climate change on regional ecosystems, society, economy, and policy
- Communication of risks and hazards for effective governance, technology development, and mitigation or adaptation

What questions do you have? Questions you might ask:

- Why is climate change so politically divisive?
- Are we doomed?
- What have been the primary contributions to improving weather forecasts?
- Will it rain tomorrow?
- Will we have a heatwave next summer?
- What research projects are your students doing?
- Are there “hot spots” or places of high sensitivity of land use and change on atmosphere?
- Is planting a trillion trees good for climate?
- What is it like to study in US or be a professor?
- As a journal editor, do you have insights into publication process?

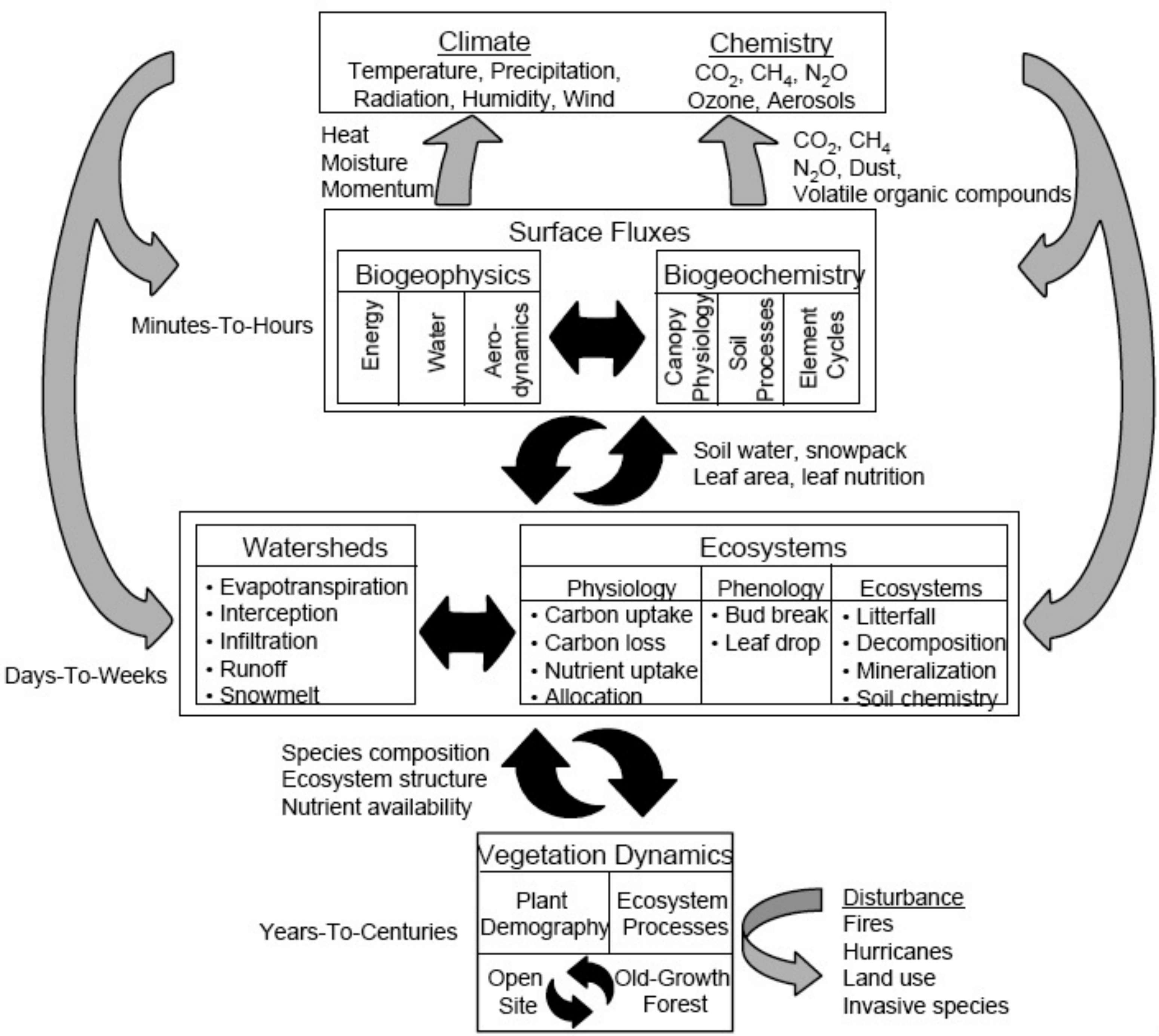

Thank you!
Ankur Desai
desai@aos.wisc.edu
https://flux.aos.wisc.edu
@profdesai
Photo: Jeff Miller, UW Communications

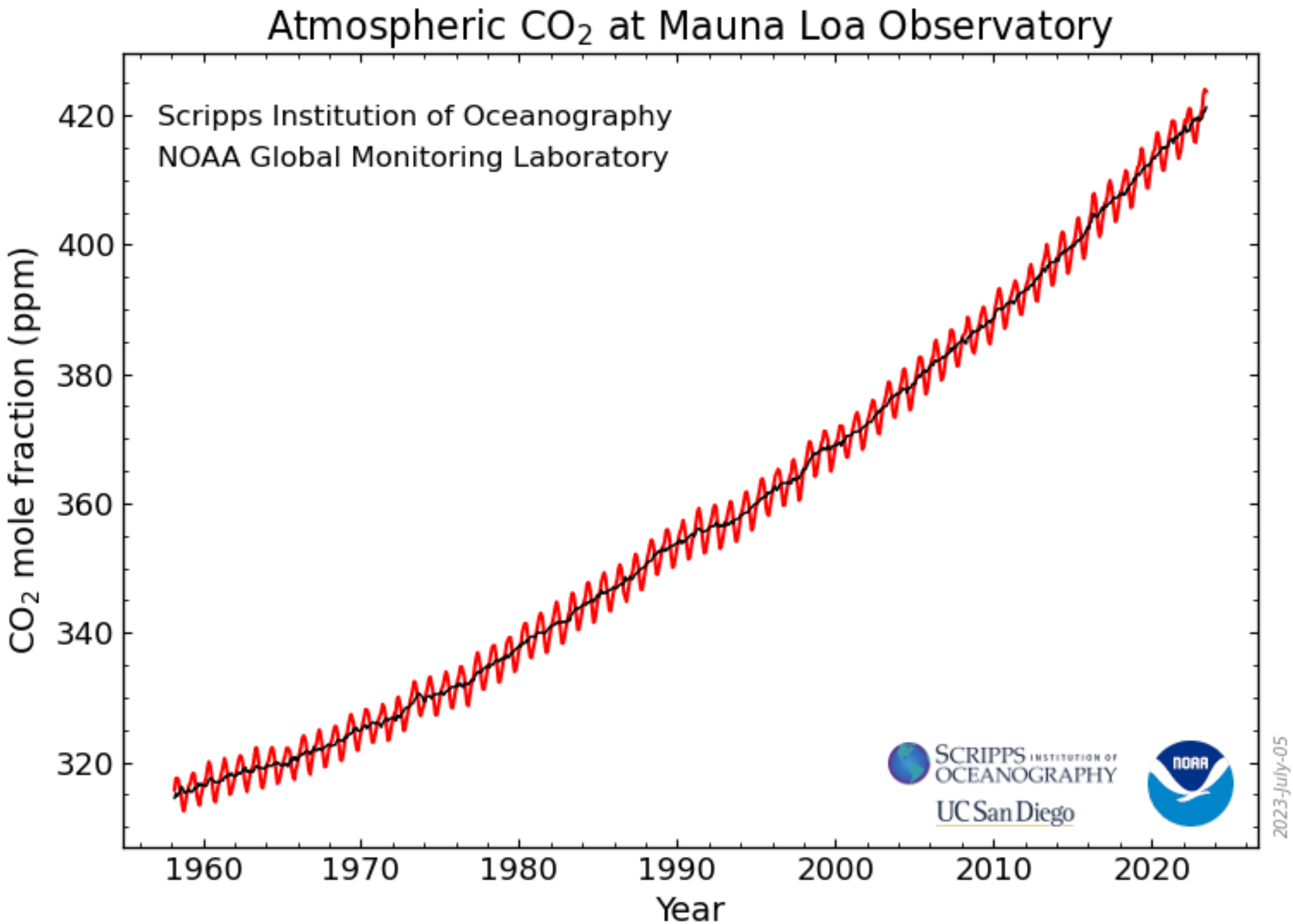
Part 2. Earth System

Ecosystem Biogeochemistry

It's mostly physics!

Ecological Climatology

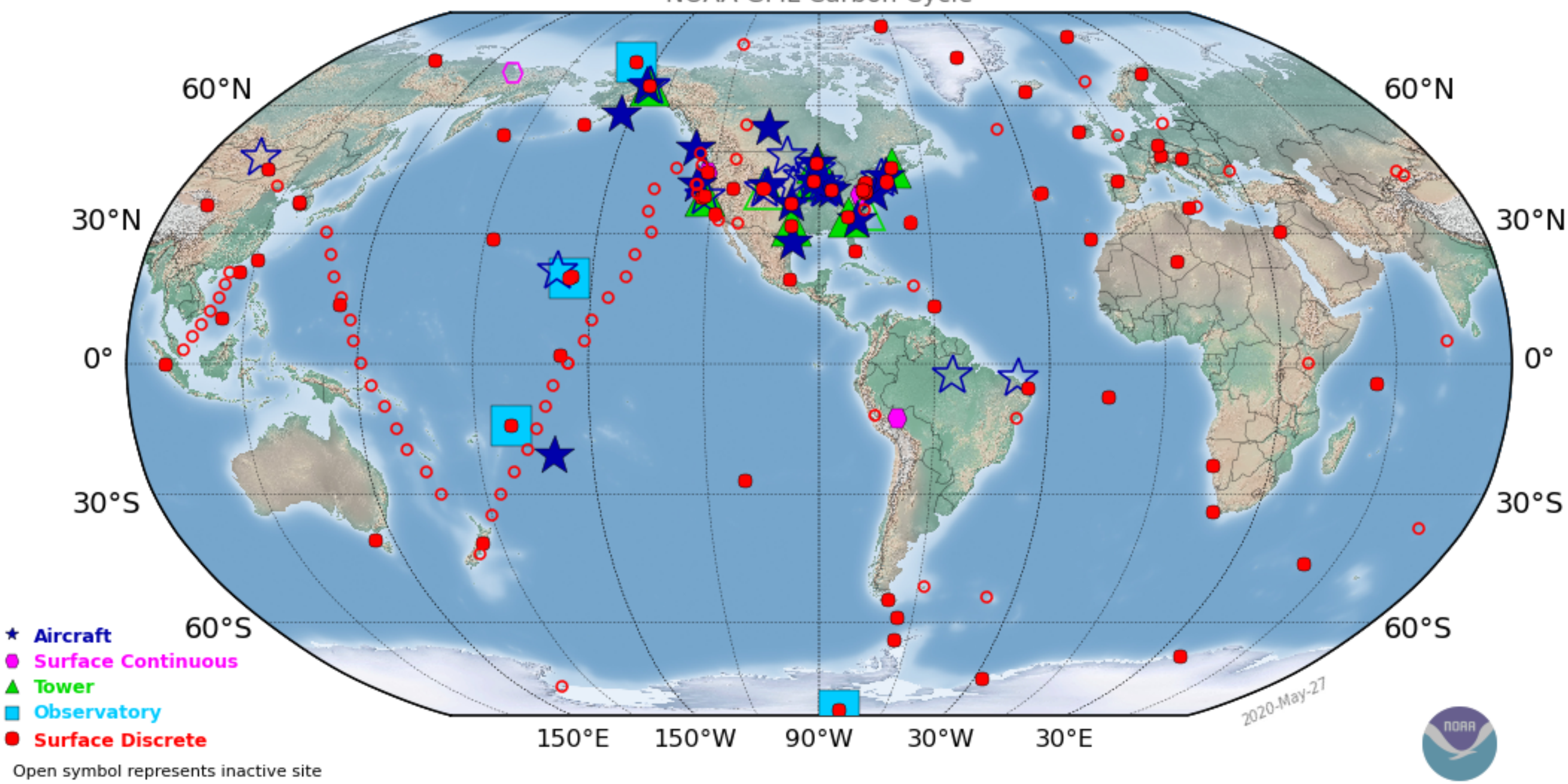




Atmospheric CO2 at Mauna Loa Observatory
Scripps Institution of Oceanography
NOAA Global Monitoring Laboratory
CO2 mole fraction (ppm)
420
400
380
360
340
320
1960
1970
1980
1990
2000
2010
2020
Year
SCRIPPS INSTITUTION OF OCEANOGRAPHY
UC San Diego
NOAA
2023-July-05

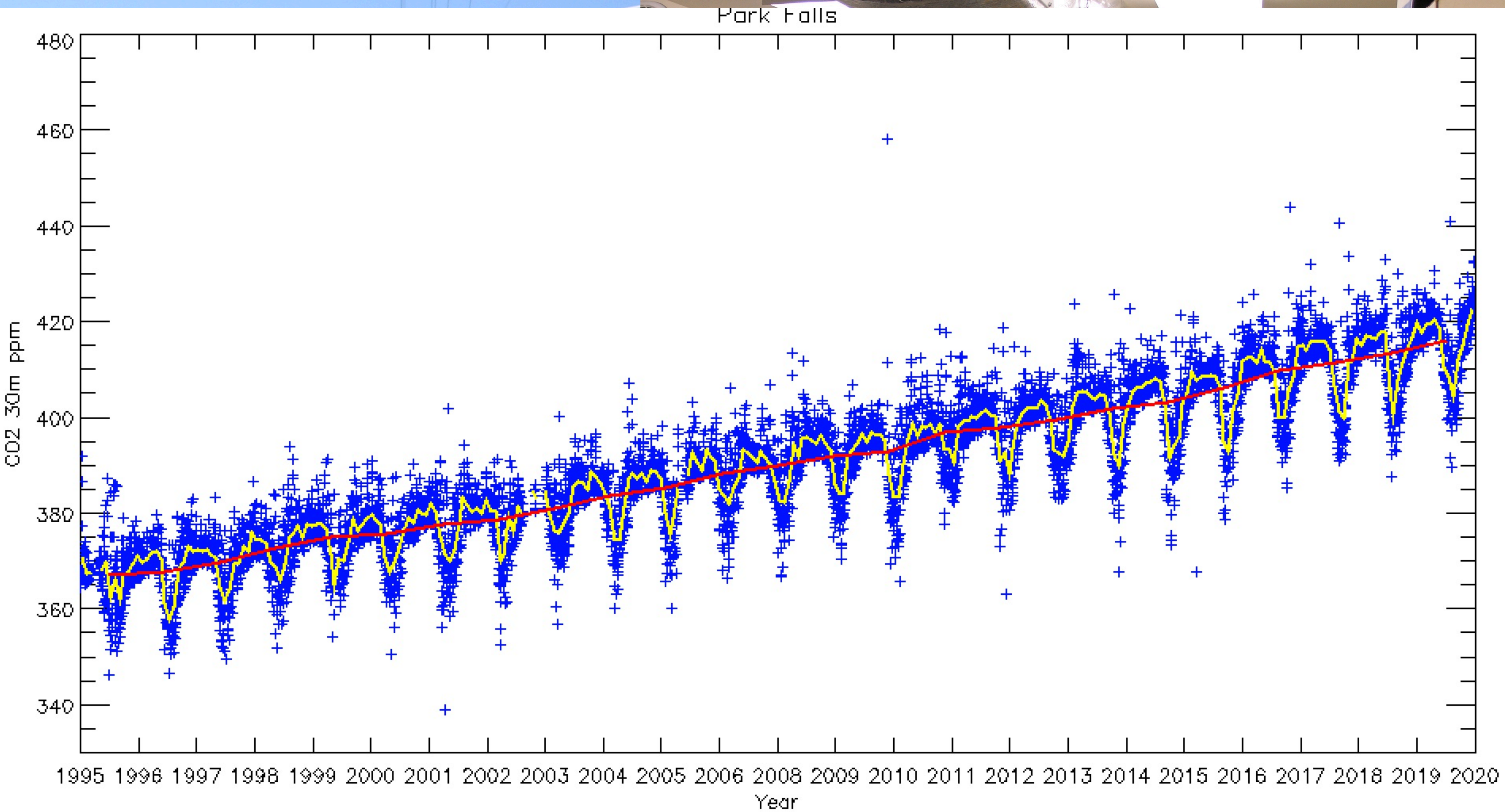
Cooperative Measurement Programs

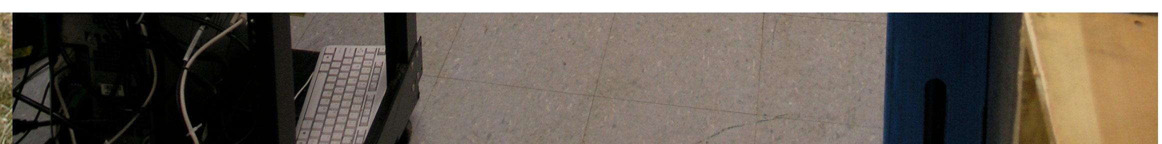
NOAA GML Carbon Cycle



NOAA GML Carbon Cycle operates several measurement programs. Semi-continuous measurements are made at 4 baseline observatories, a few surface sites and from tall towers. Discrete surface and aircraft samples are measured in Boulder, CO. Presently, atmospheric carbon dioxide, methane, carbon monoxide, hydrogen, nitrous oxide, sulfur hexafluoride, the stable isotopes of carbon dioxide and methane, and halocarbon and volatile organic compounds are measured.
Contact: Dr. Arlyn Andrews, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6773, arlyn.andrews@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.


PALL


Park Falls
CO2 30m ppm
480
460
440
420
400
380
360
340
1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year

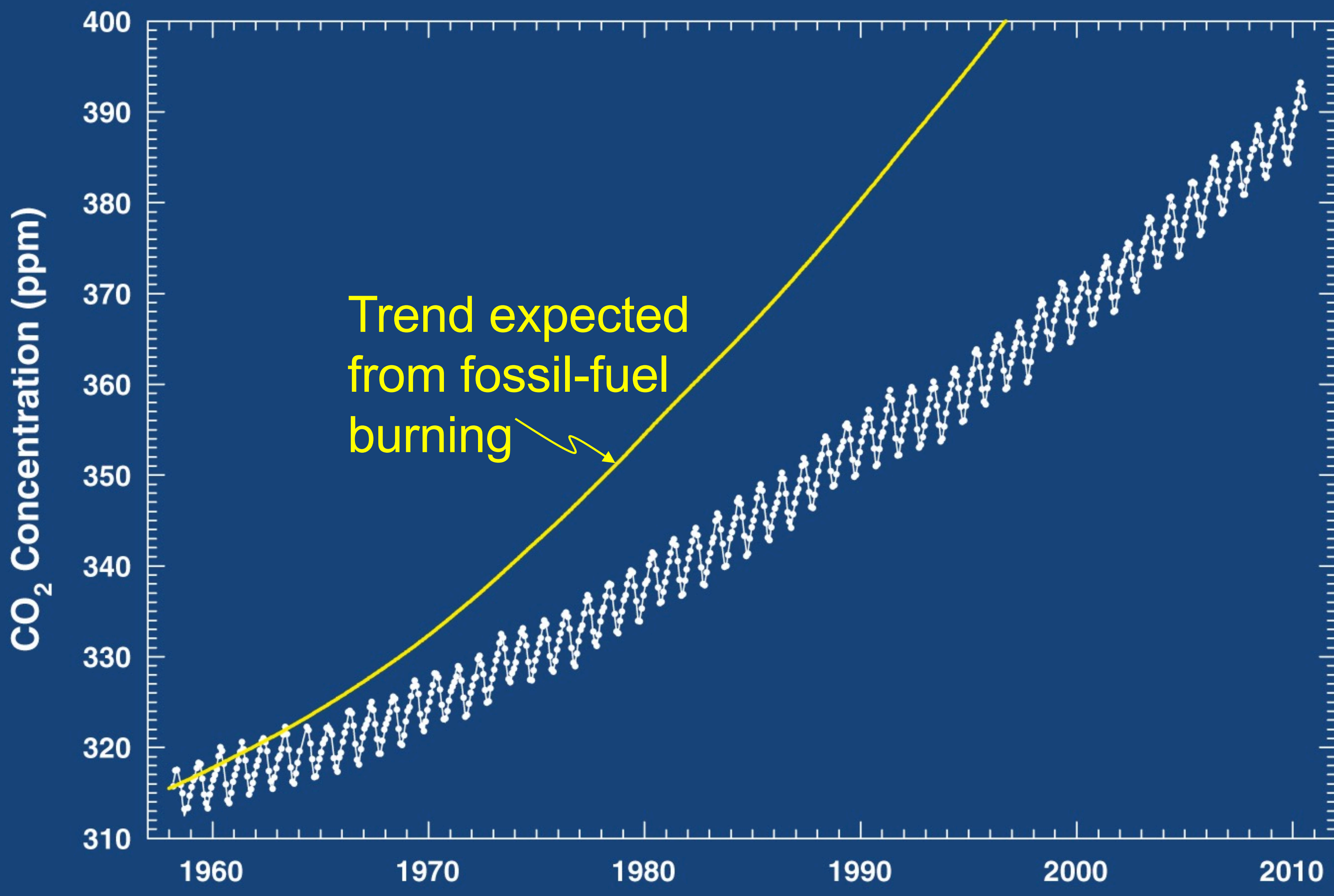


What did we learn?

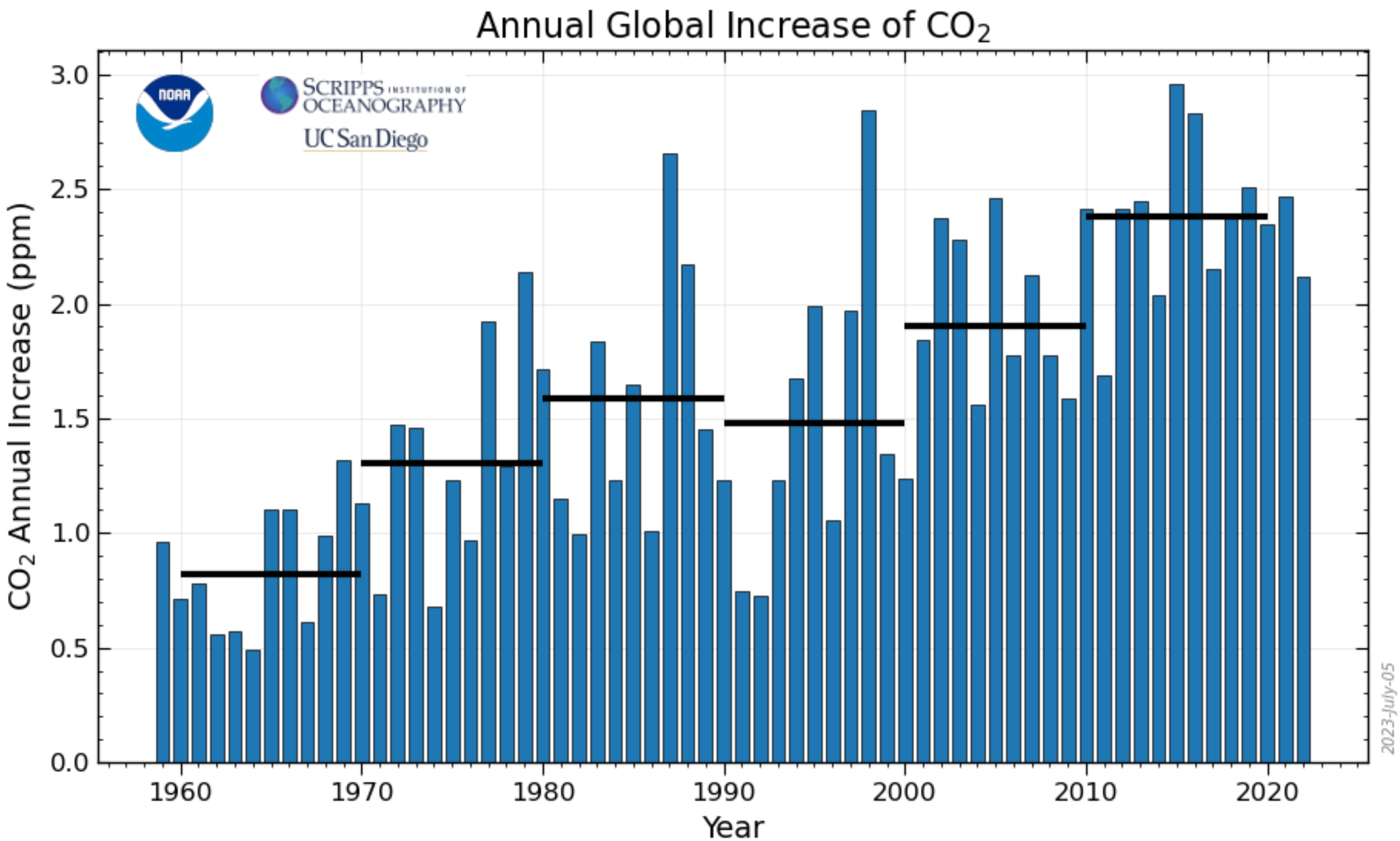
- CO_2 increasing 2.5 ppm per year today, increase from 1 ppm per year in 1960s
- It has a strong seasonal cycle that tracks northern hemisphere plant lifecycle
- Southern hemisphere concentrations are lagged from Northern hemisphere by ~1-2 years
- Methane and nitrous oxide also increasing
- Post aboveground nuclear testing ban, radiocarbon ^{14}C fraction is decreasing
- Stable isotope fraction $^{13}C/^{12}C$ also decreasing
- Why?

FOSSIL FUELS!

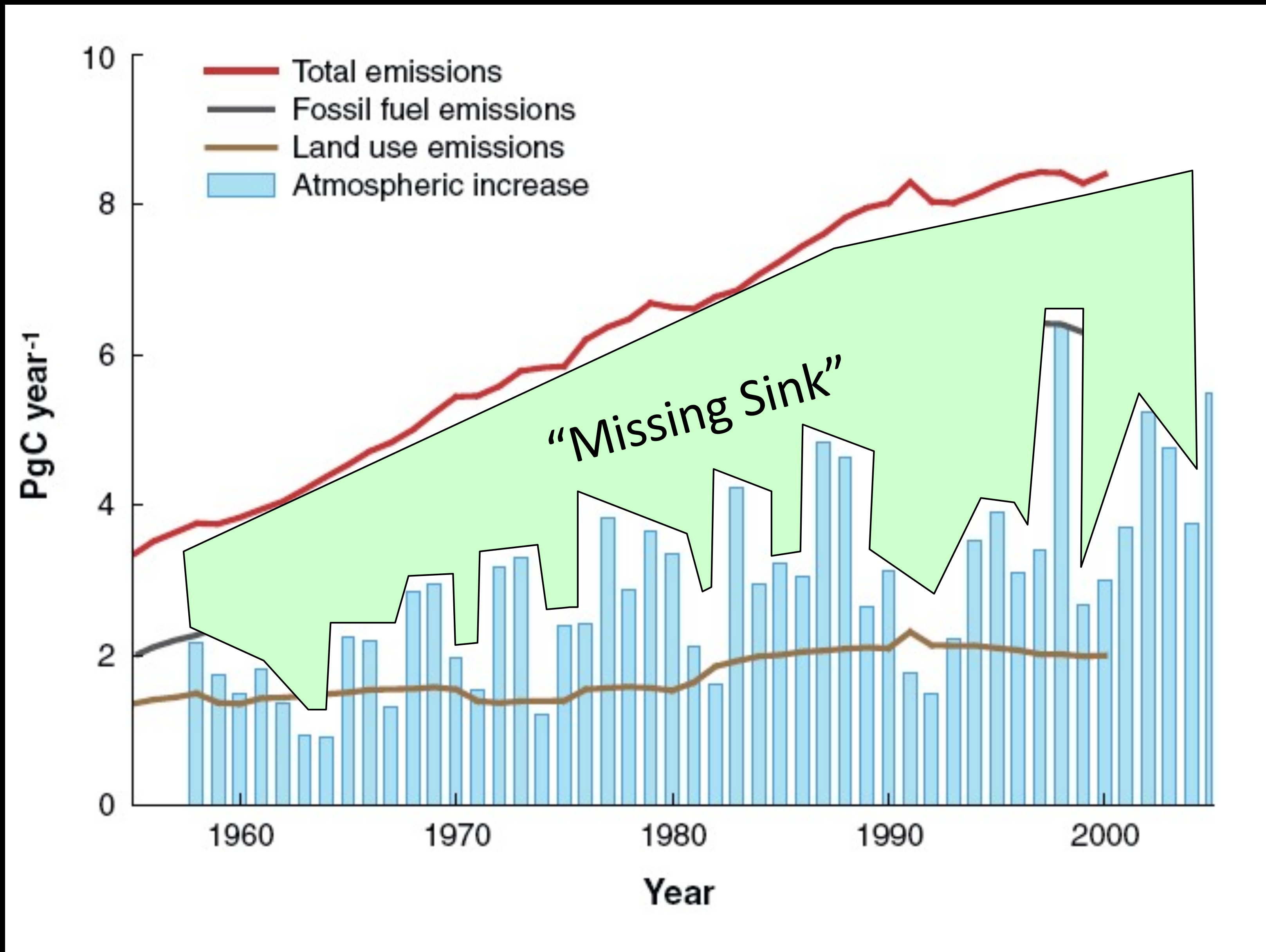
Problem: CO_2 should by increasing twice as fast!



Problem: CO_2 rate of increase in atmosphere is not smooth



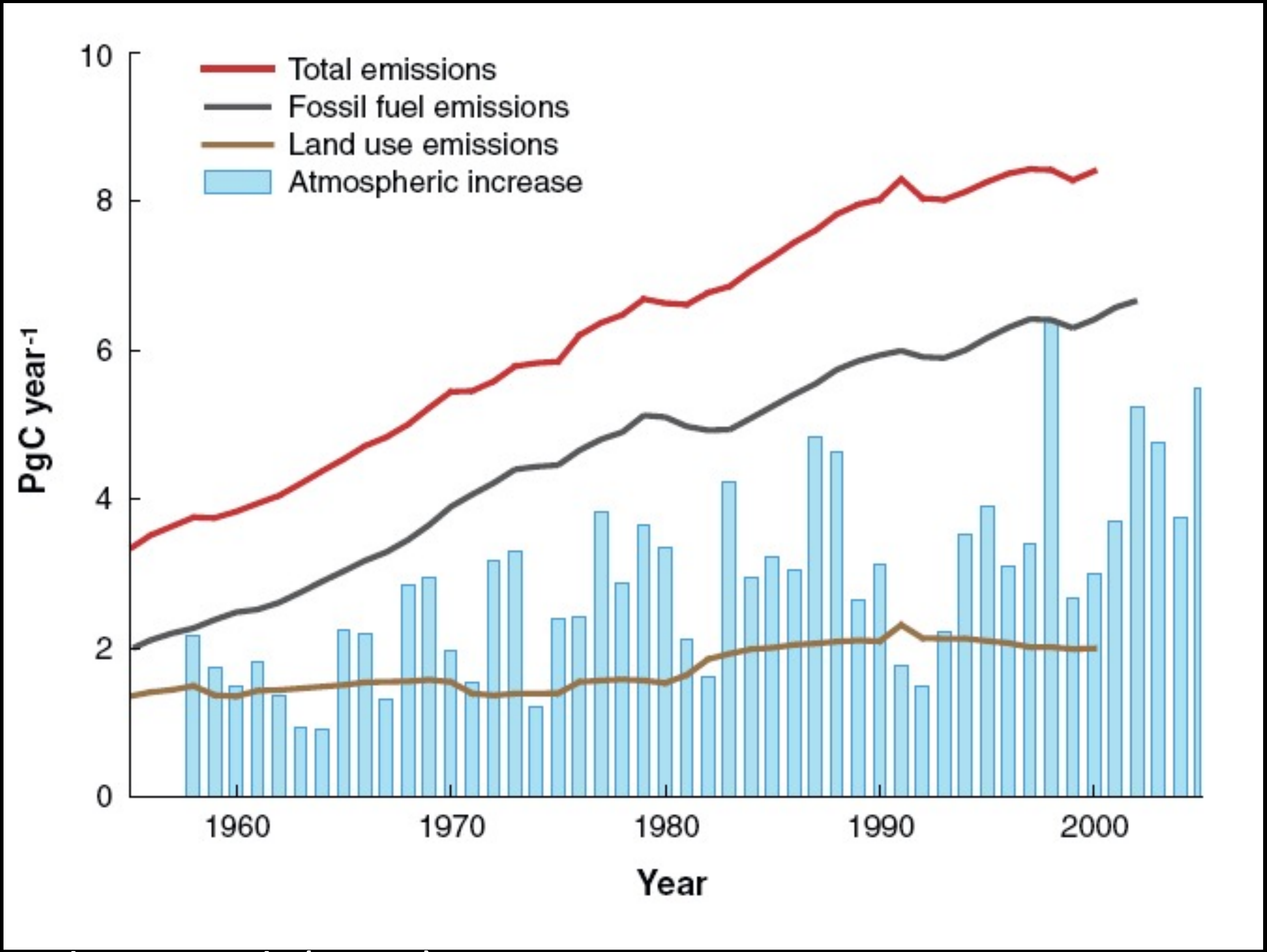
Implication: CO_2 is going somewhere, but not consistently



Houghton et al. (2007)


Ocean (Dissolved)
Land (Vegetation and Soil)
Rocks (Sediment)
Accounting error (We are bad at math)

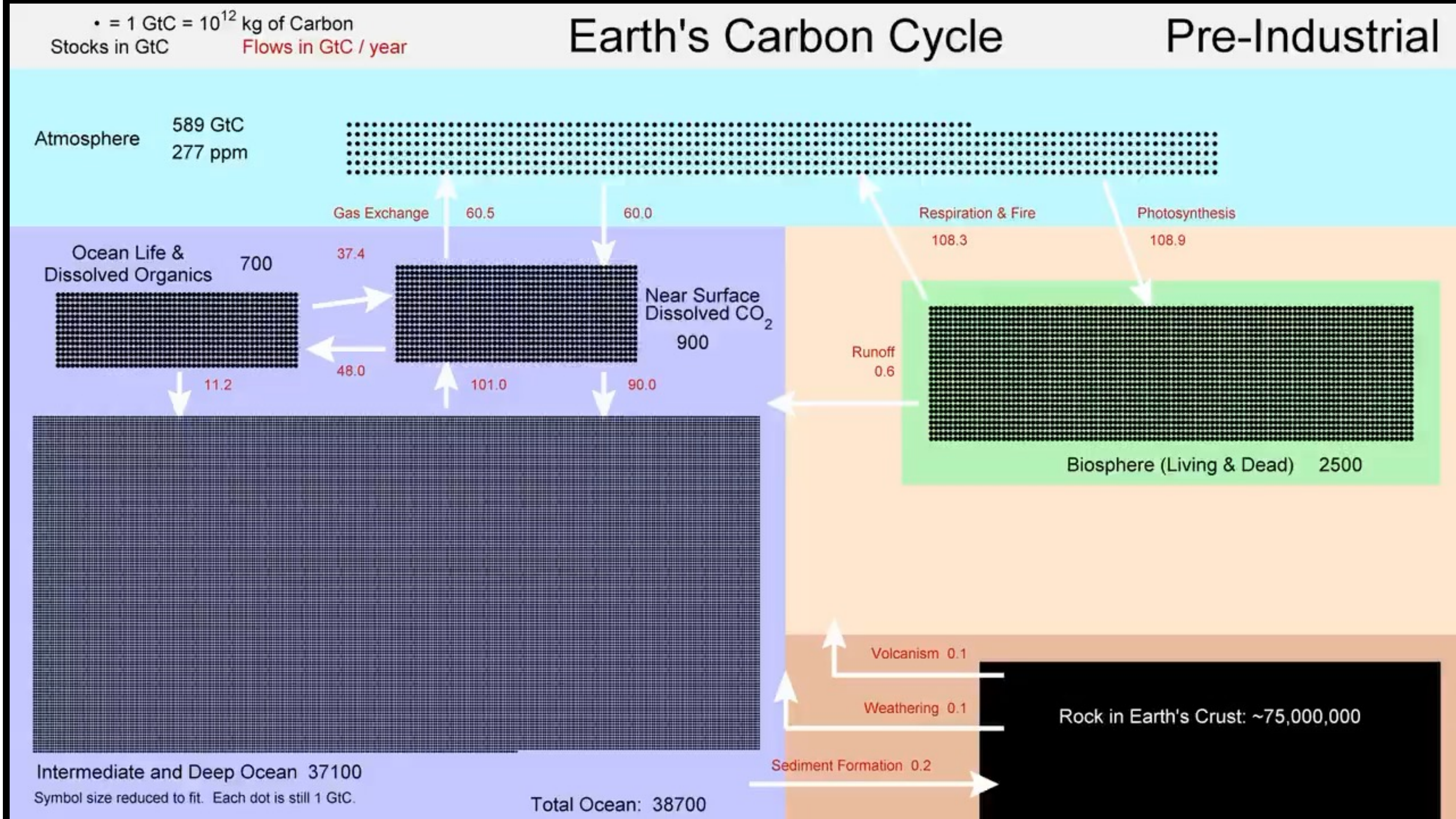
Implication: CO2 is going somewhere, but not consistently



Houghton et al. (2007)

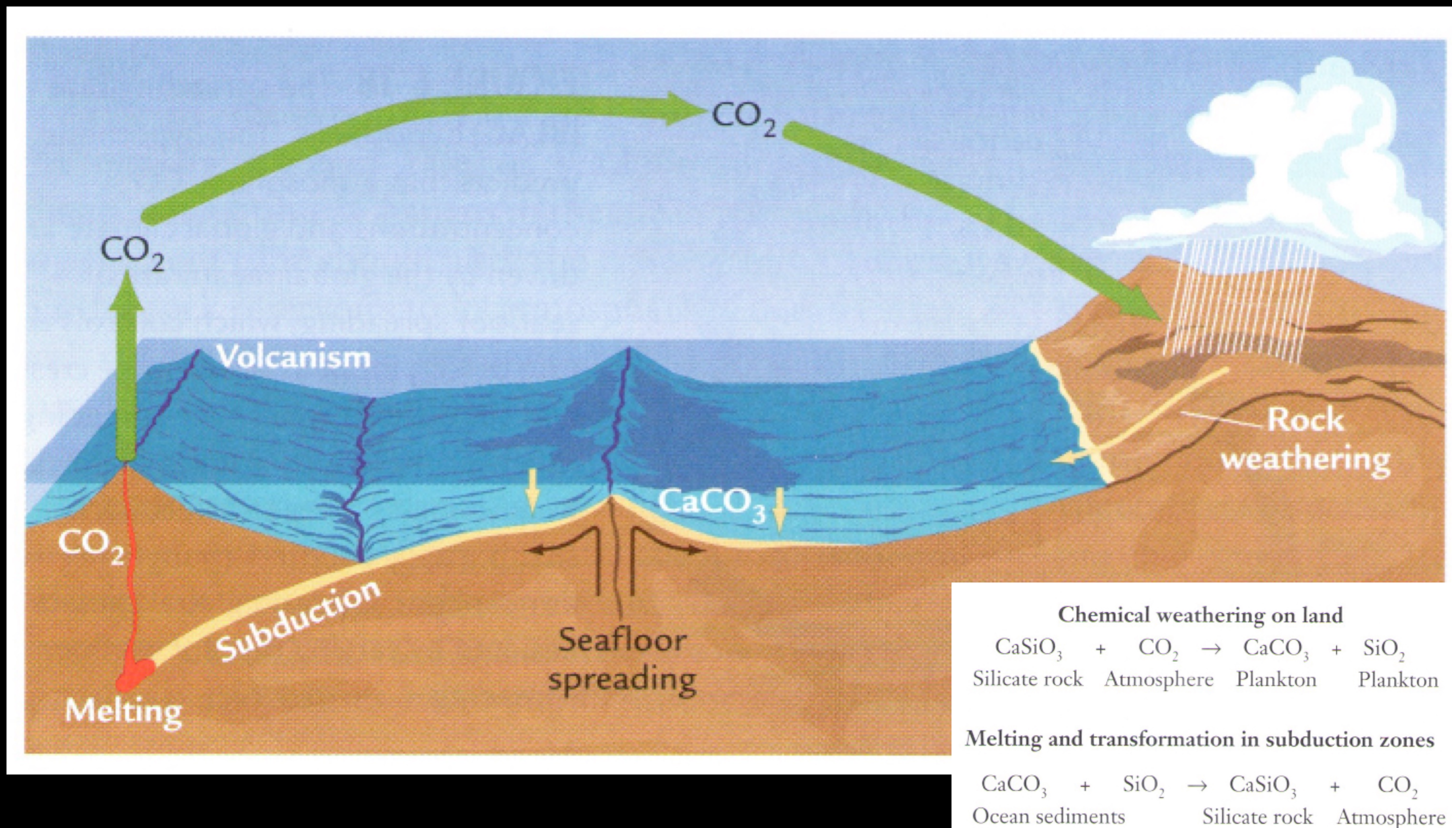
Where is the missing sink?

- A. In the high-latitude oceans, Henry's Law requires that oceans low in CO_2 like the polar oceans absorb carbon dioxide to be in equilibrium in atmosphere
- B. In equatorial oceans, where biological productivity is high, since there is high light and warm water
- C. In mid-latitude ecosystems, given the vast expanse of forests and peat wetlands in Canada, Russia, China, and low rates of decomposition given the cold winters
- D. In the tropical forests of the Amazon, Africa, Indonesia, with the high year-round productivity and biodiversity
- E. Somewhere else: semi-arid sub-tropics, urban areas, permafrost, coastal oceans, professor's bathroom, geological plate subduction



Robert Rohdes

Plate Tectonics and CO_2



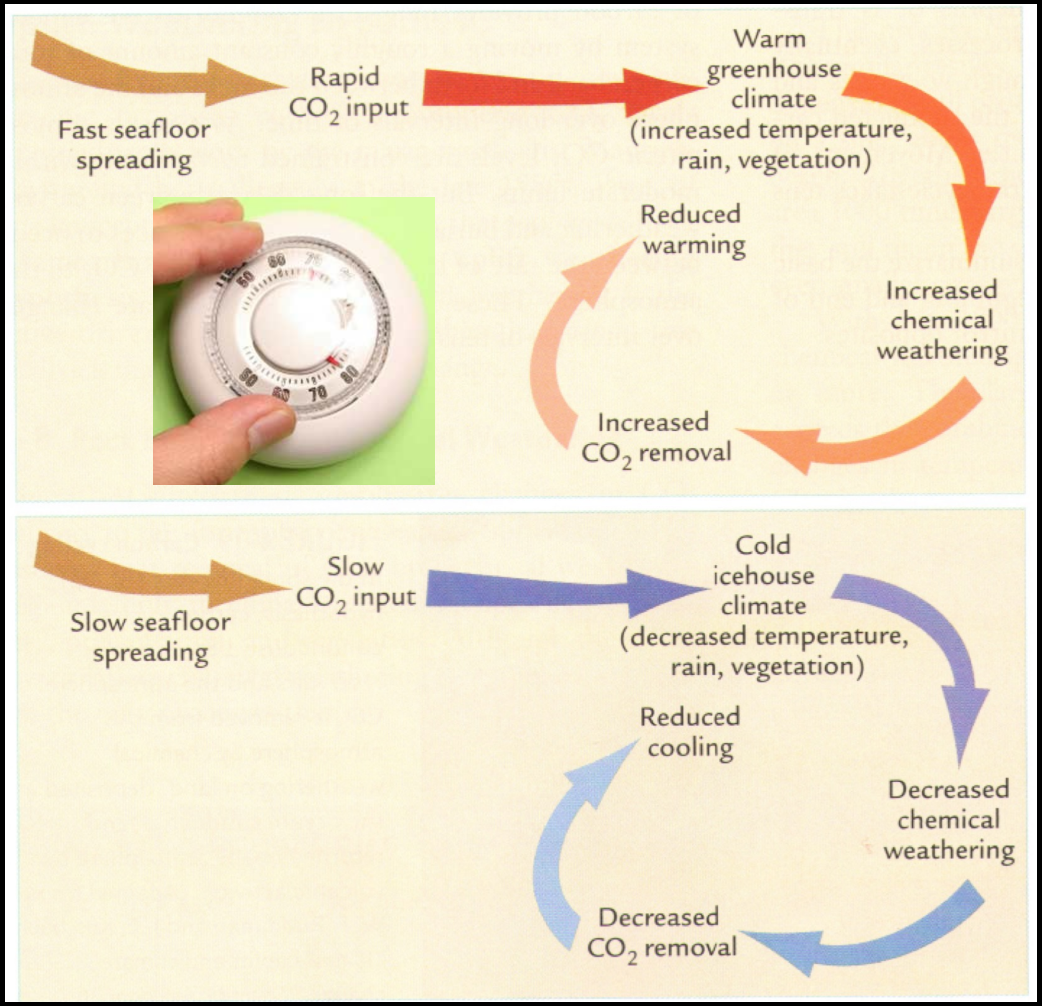
- **Seafloor spreading -- > volcanos release CO_2**
- **Mountain building enhances chemical weathering --> consumes CO_2**
- **Very slow process (10,000+ years)**

Scott Denning

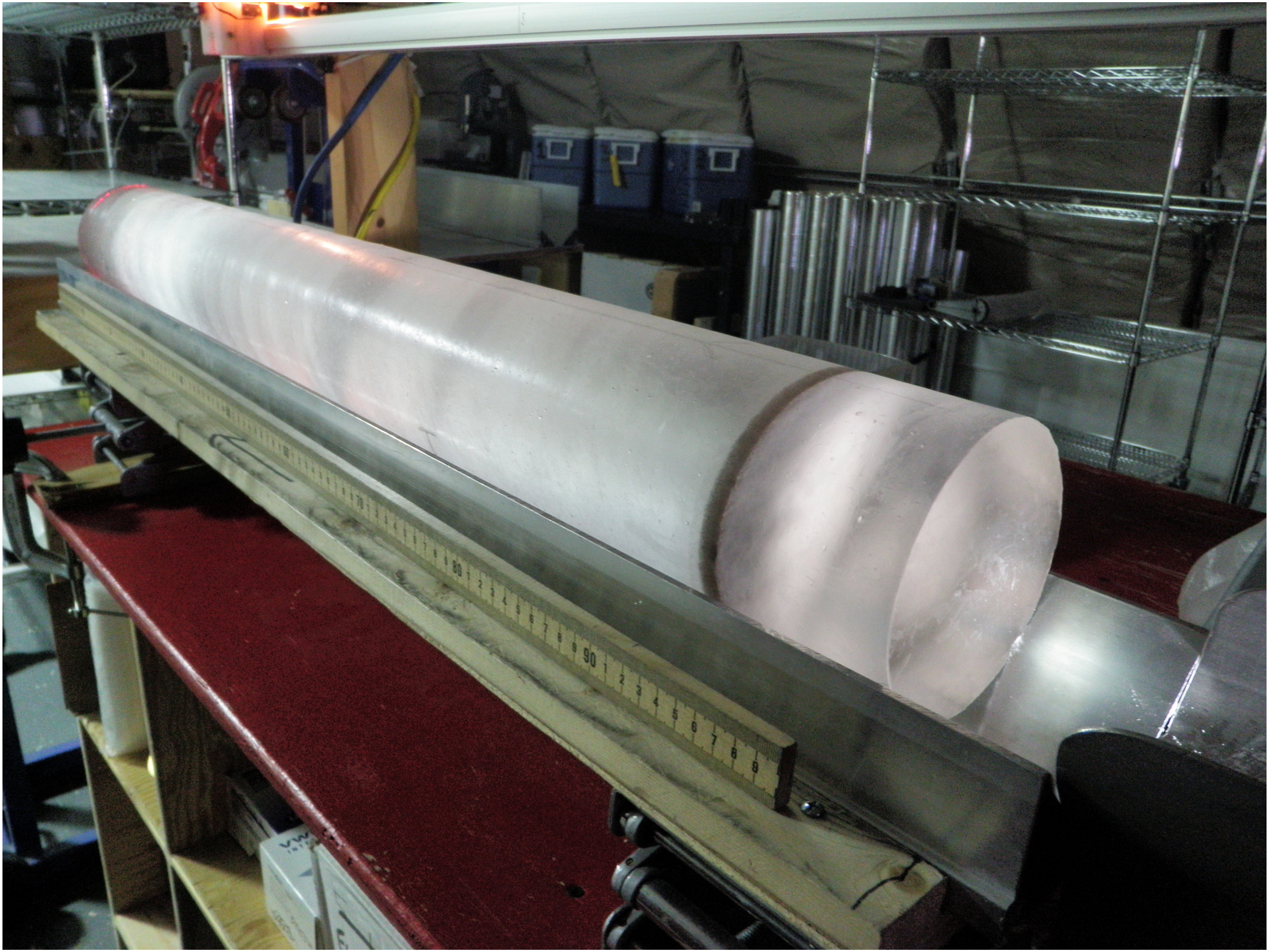
CO_2 is Earth's Geologic Thermostat

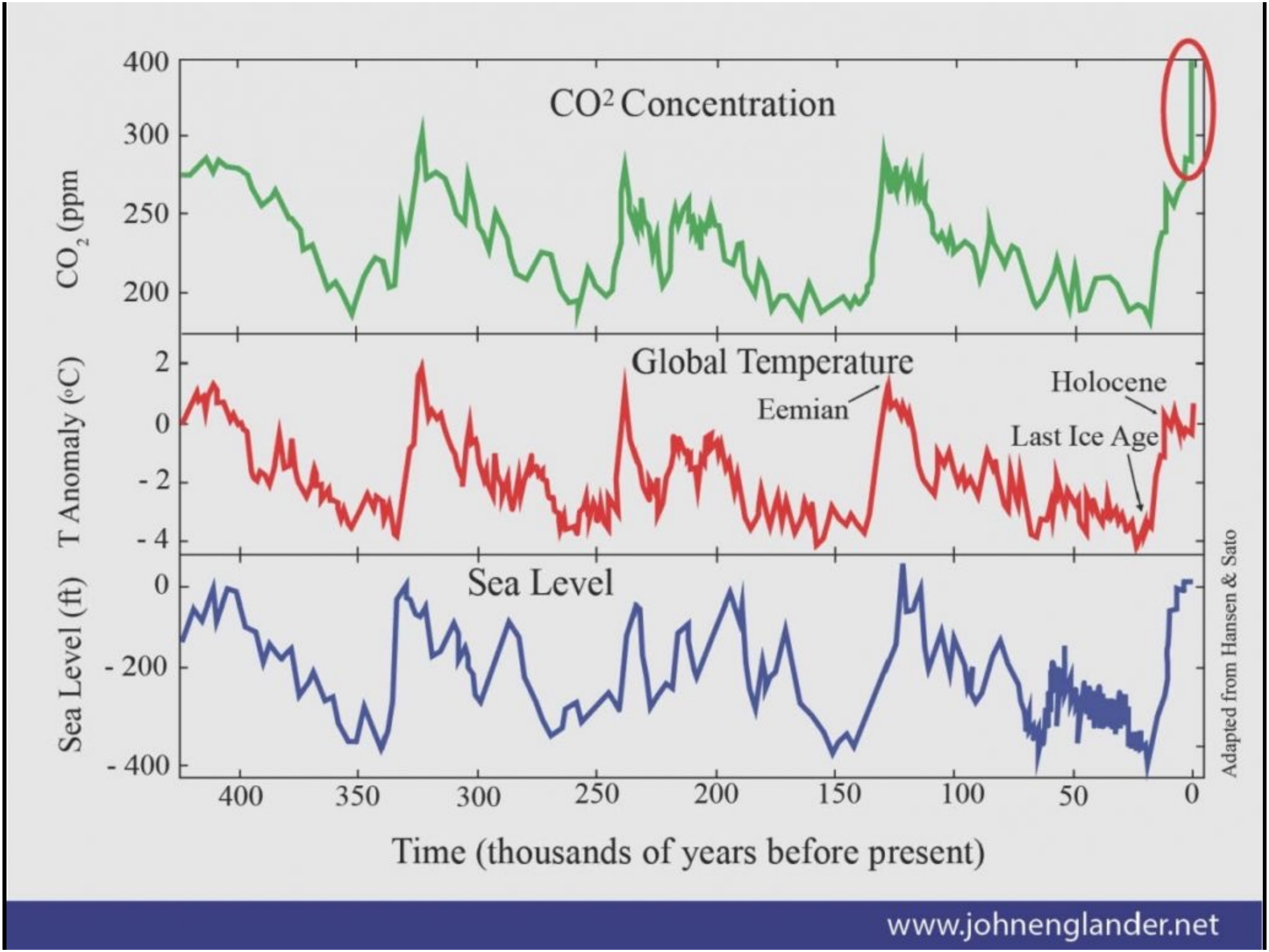
"Negative Feedback"

- Warming leads to cooling
- Cooling leads to warming

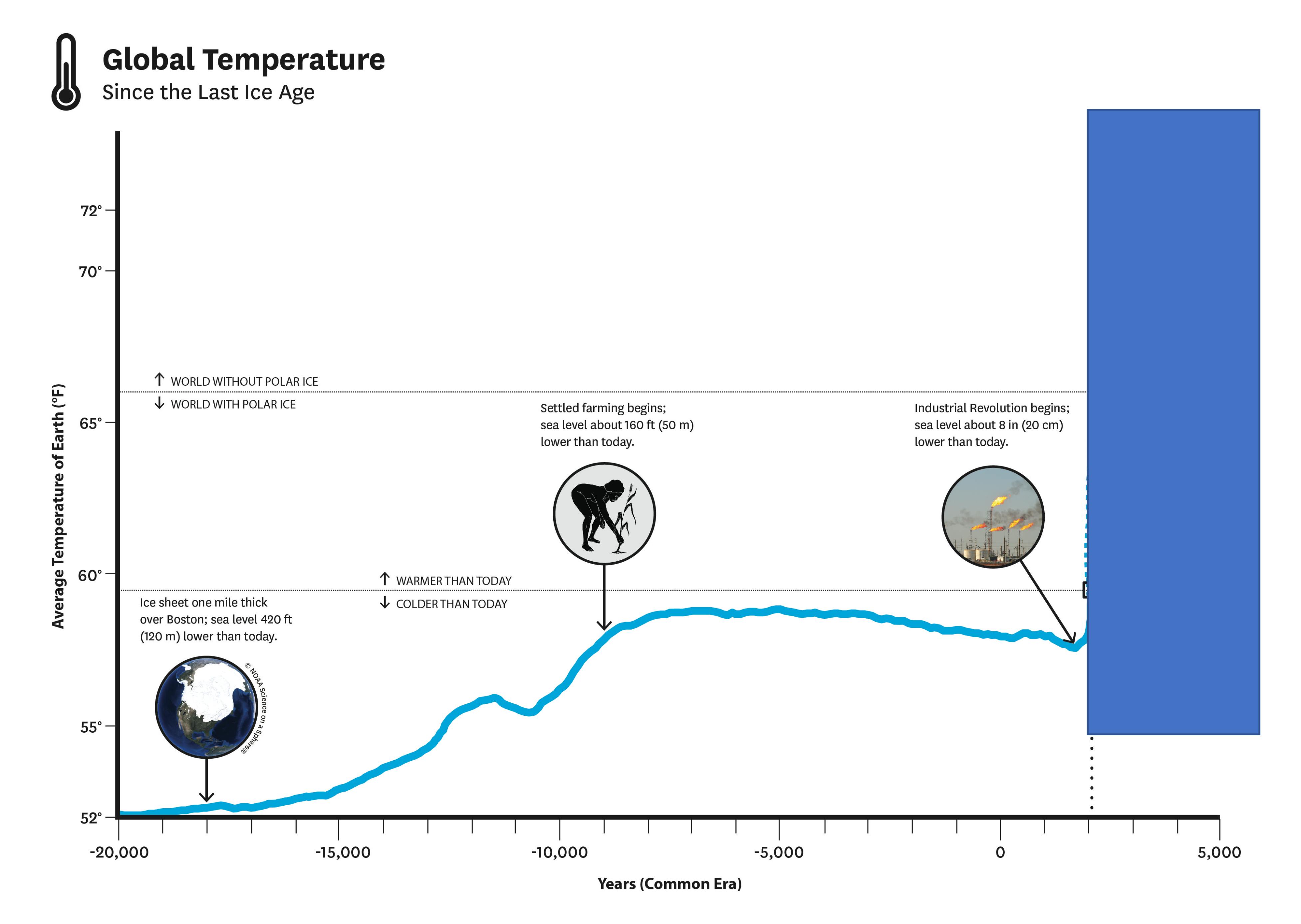


Scott Denning



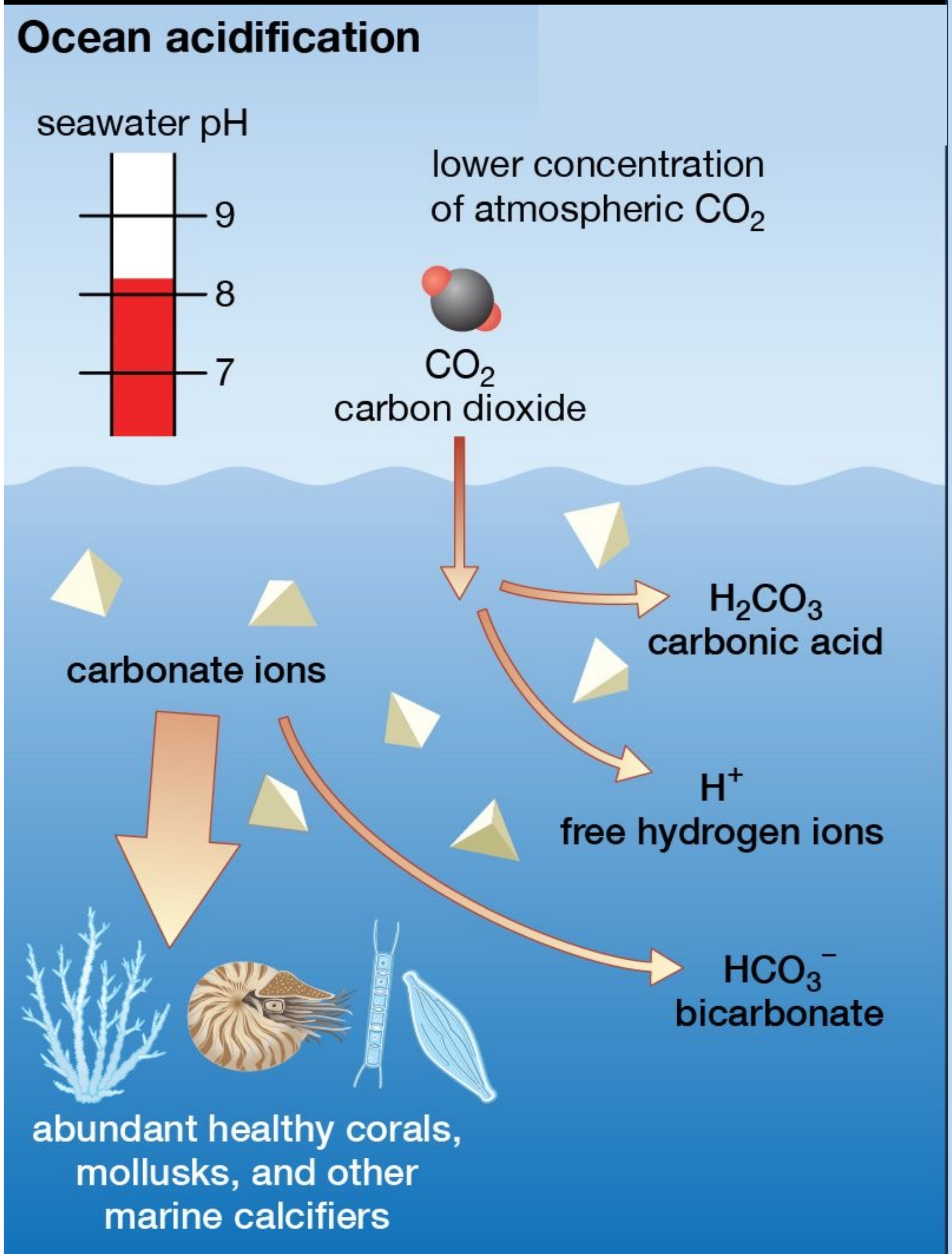


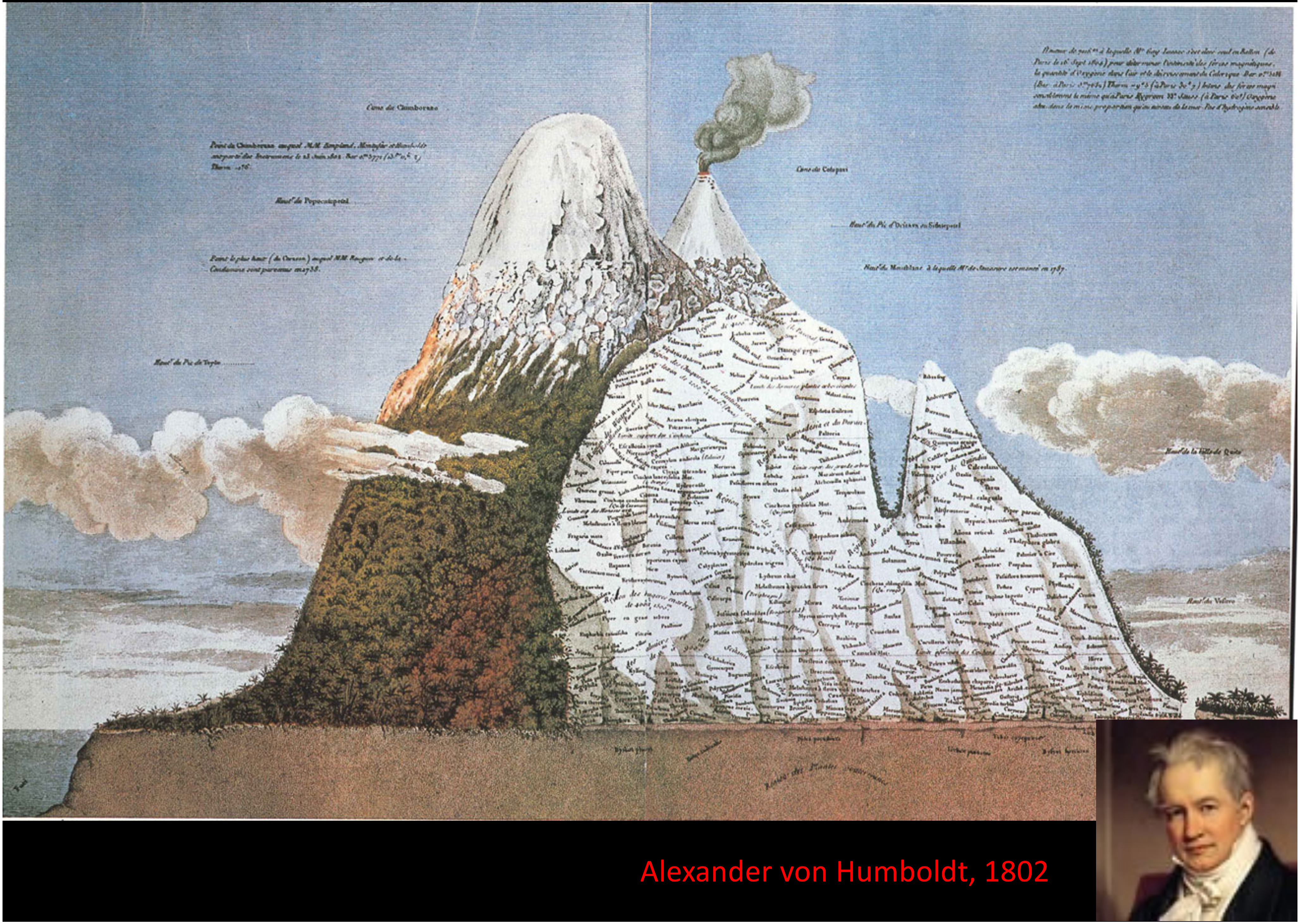
CO2 Concentration
CO2 (ppm
400
300
250
200
Global Temperature
T Anomaly (°C)
2
0
- 2
- 4
Eemian
Holocene
Last Ice Age
Sea Level
Sea Level (ft)
0
- 200
- 400
400
350
300
250
200
150
100
50
0
Time (thousands of years before present)
Adapted from Hansen & Sato
www.johnenglander.net



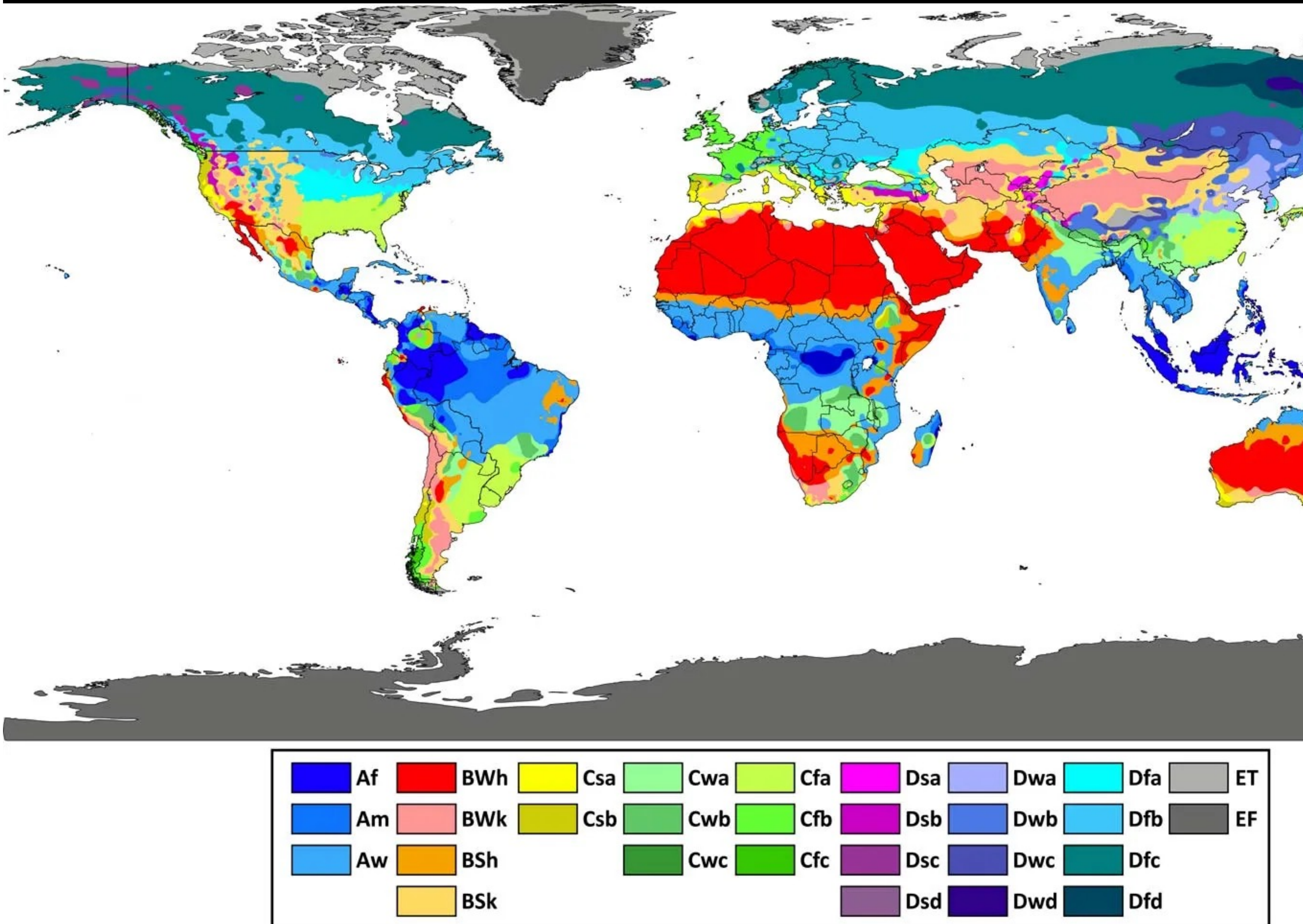
Credits: Smithsonian

https://www.cbsnews.com/pictures/magnificent-microscopic-creatures-of-the-seas/2/

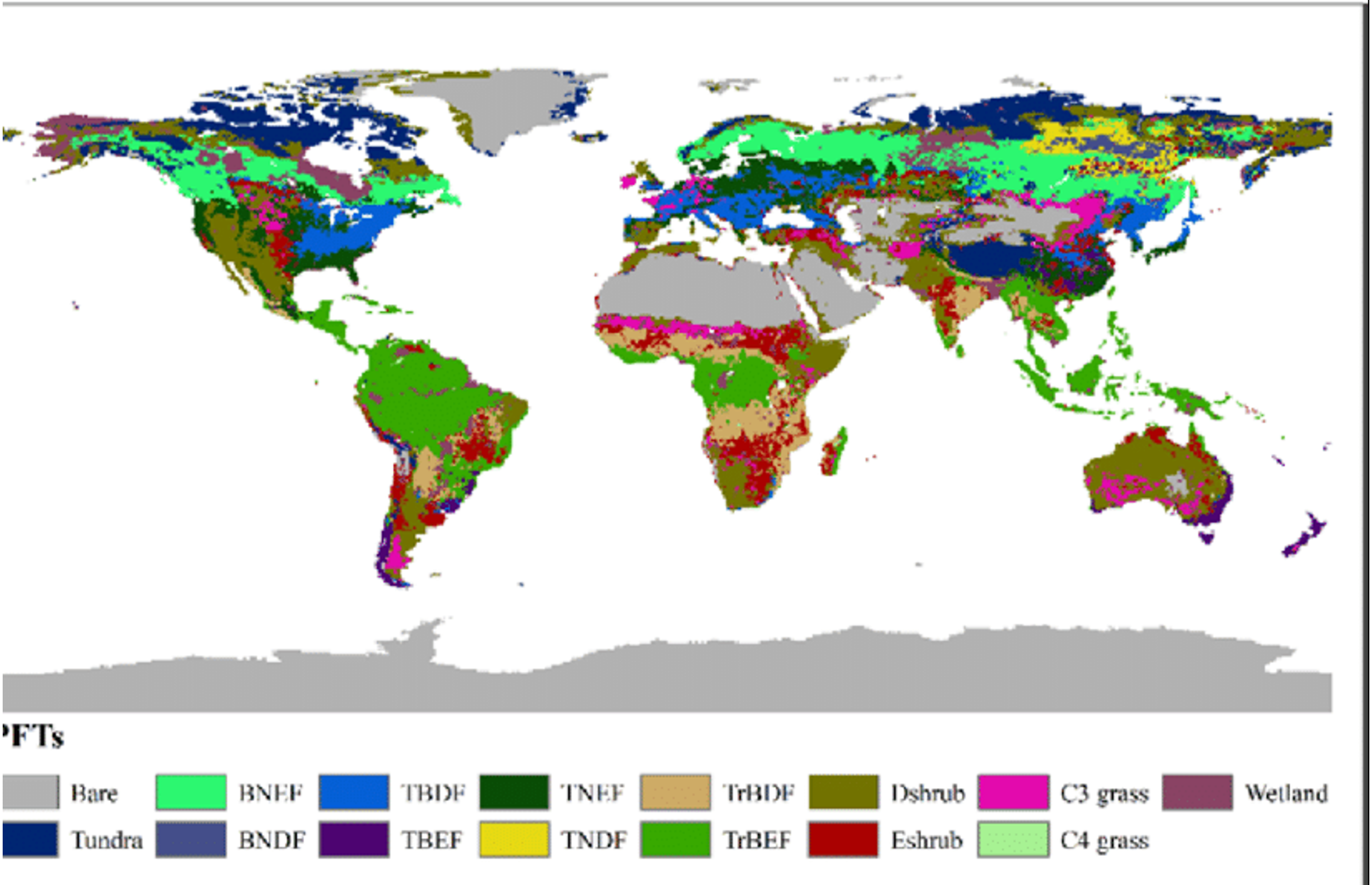

Ocean acidification
seawater pH
9
8
7
lower concentration of atmospheric CO_2
CO_2 carbon dioxide
H_2CO_3 carbonic acid
H^+ free hydrogen ions
HCO_3^- bicarbonate
carbonate ions
abundant healthy corals, mollusks, and other marine calcifiers



Alexander von Humboldt, 1802



Wladimir Köppen, 1846



FTs
Bare
BNEF
TBDF
TNEF
TrBDF
Dshrub
C3 grass
Wetland
Tundra
BNDF
TBEF
TNDF
TrBEF
Eshrub
C4 grass

Carbon Storage in Earth's Ecosystems

Achieving net-zero by 2050 depends on the Earth's natural carbon sinks.

Forests play a critical role in regulating the global climate. They absorb carbon from the atmosphere and then store it, acting as natural carbon sinks.

Where is Carbon Stored?

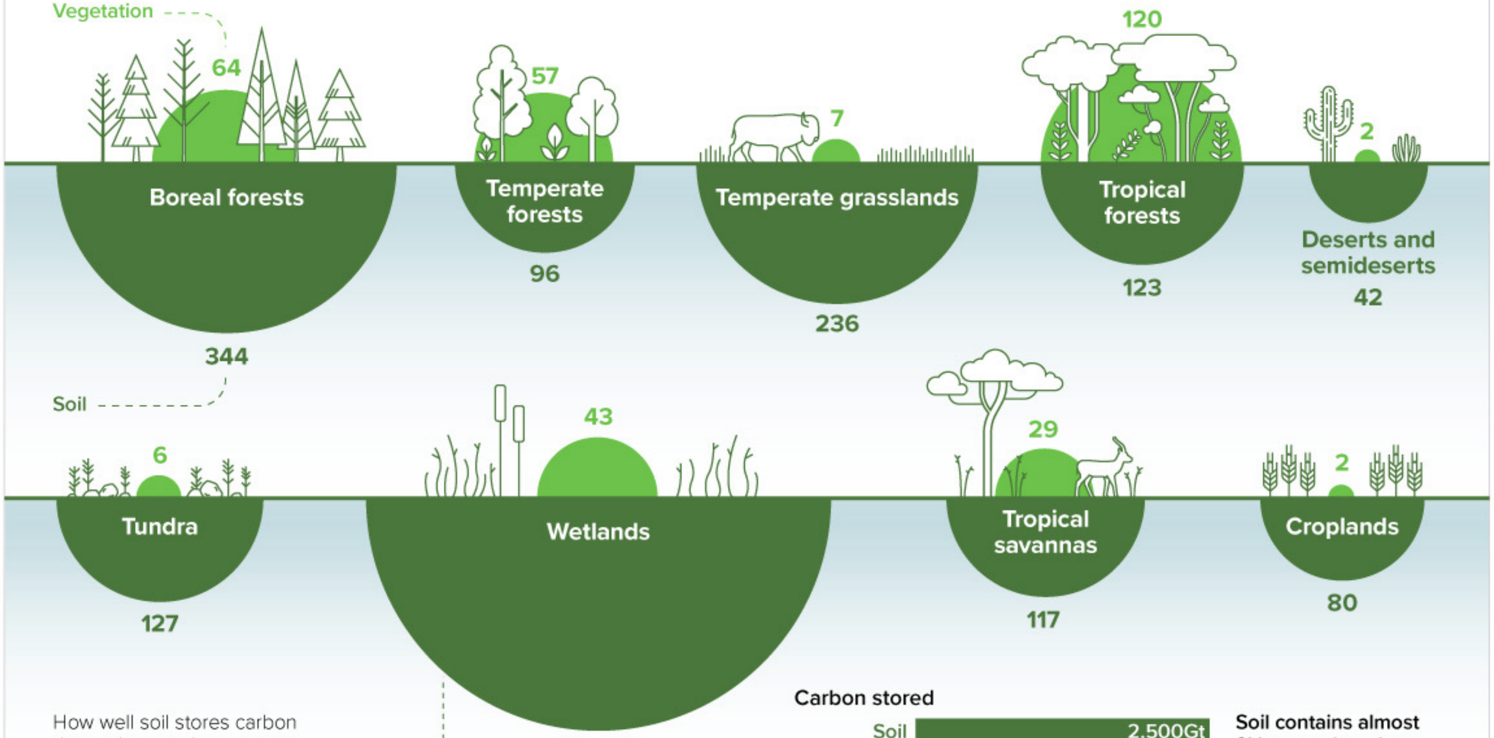
There are various carbon pools in a forest ecosystem.

Carbon Storage

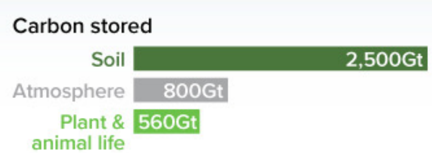
Tonnes of Carbon per Hectare*

The world's forests absorb around **15.6 gigatonnes** of CO_2 each year. That's around 3X the annual CO_2 emissions of the United States.

However, around **8.1 gigatonnes of CO_2 leaks back into the atmosphere** due to deforestation, fires and other disturbances.



How well soil stores carbon depends on soil type, vegetation and climate. In general, the **wetter and colder**, the better.



Soil contains almost 2X as much carbon as the atmosphere and living flora and animals combined.

*At a ground depth of one meter

Sources: IPCC; NASA

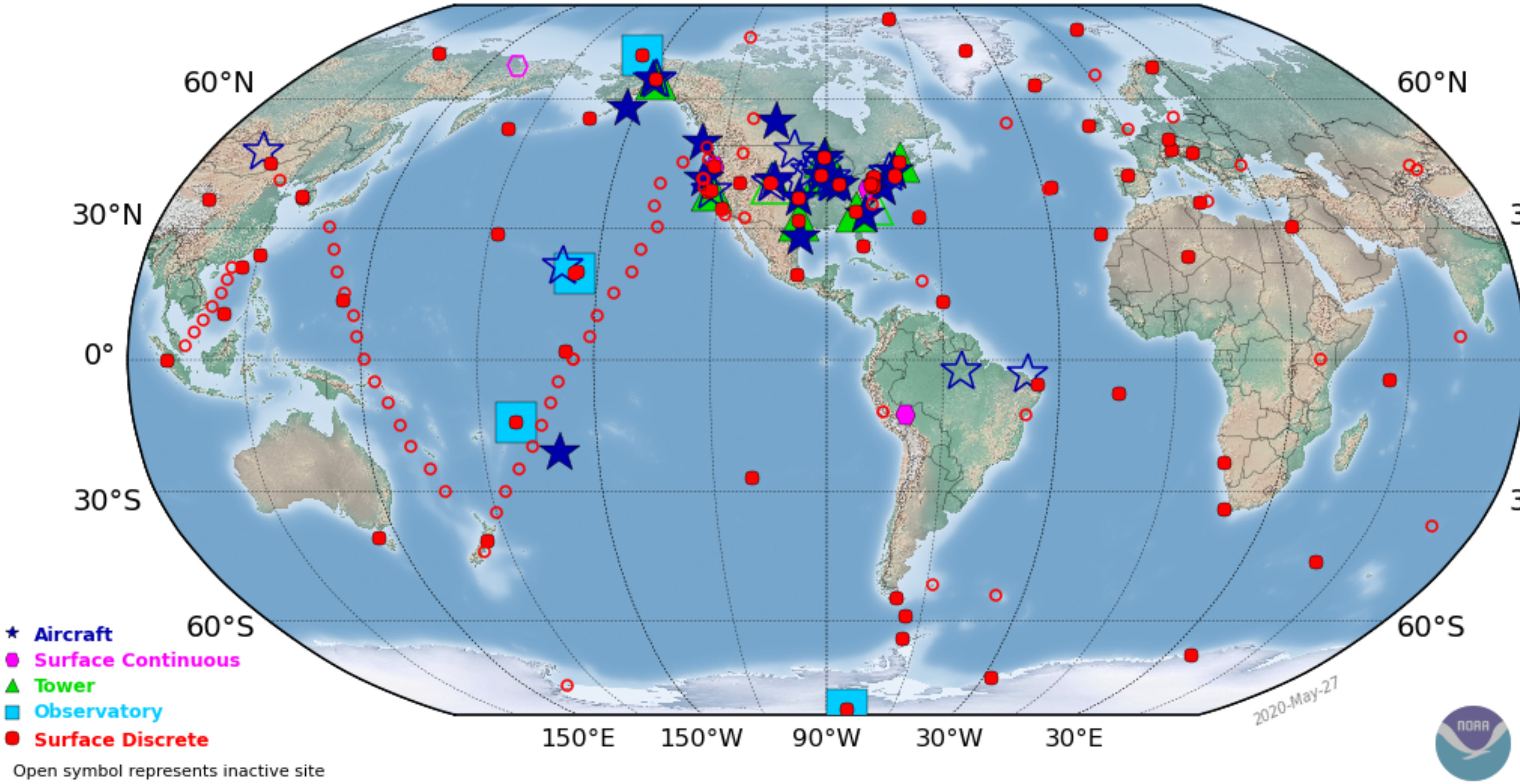
Global Net Primary Productivity - 1983

		-180			-150			-120			-90			-60			-30			0			30			60			90			120			150		
LAT	J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
90.0	24																																				
82.2	23								0	0	0	0	0	0	0	0	0	0	0		0	0	0						0	0							
74.3	22	0		0	0			3	3	1	2	3	0	0	0	0	0	2				0	0		1	0	1	2	4	7	6	5	3	3	1	0	
66.5	21	4	1	14	23	18	16	14	7	6	5	2	5	0	2	0	0	2	0		5	17	24	14	18	19	17	20	24	23	27	28	22	18	22	19	12
58.7	20	0	0	9	8	7	18	25	20	17	4	2	8	2	0	0			1	5	17	14	27	28	28	29	25	26	28	29	29	30	30	17	8	9	3
50.9	19						6	28	34	30	22	22	27	15	2				4	23	32	33	34	36	28	31	35	36	28	34	33	34	34	20		3	
43.0	18							30	32	40	36	36	22	3					8	21	19	31	20	27	13	10	11	22	11	21	33	36	27	10			
35.2	17							14	22	39	42	31							8	14	9	4	6	20	29	23	26	10	10	31	40	23	19	13			
27.4	16							0	10	18	8	8							10	2	2	3	3	4	11	19	15	37	48	36	71	39					
19.6	15			0					1	21	28	3	7					2	5	9	7	7	2	6	2	1	9	38	25	63	26	8					
11.7	14										14	20	24	10				3	31	37	39	37	33	20	9		2	19		23	9	12	2				
3.9	13											29	72	75	24				16	20	54	74	52	26	6			4		34	23	35	6				
-3.9	12											42	94	94	82	15					29	73	38	15						22	35	22	16	51	13	1	
-11.7	11											11	79	72	54	15					7	23	22	14	4						2	4	13	17	7		
-19.6	10	1											23	32	45	24					3	36	31	12	20						1	13	25	33	16		1
-27.4	9												16	24	36						0	15	30	0	2						1	13	12	21	24		
-35.2	8	3											13	32	4							3	5									4	1	14	17		1
-43.0	7	3											23	1																					6		14
-50.9	6												19	0													0										
-58.7	5												1																								
-66.5	4												0	0						0	0	0	0	0	0	0	0	0	0	0	0	0					
-74.3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
-82.2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
-90.0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
LAT	J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31					
		-180			-150			-120			-90			-60			-30			0			30			60			90			120					

Fig. 2. Global distribution of NPP (× 10 gm $C/m^2/yr$) at the tracer model resolution.

Cooperative Measurement Programs

NOAA GML Carbon Cycle

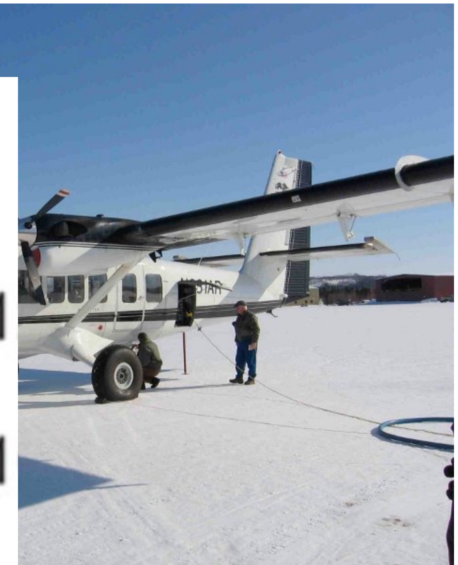


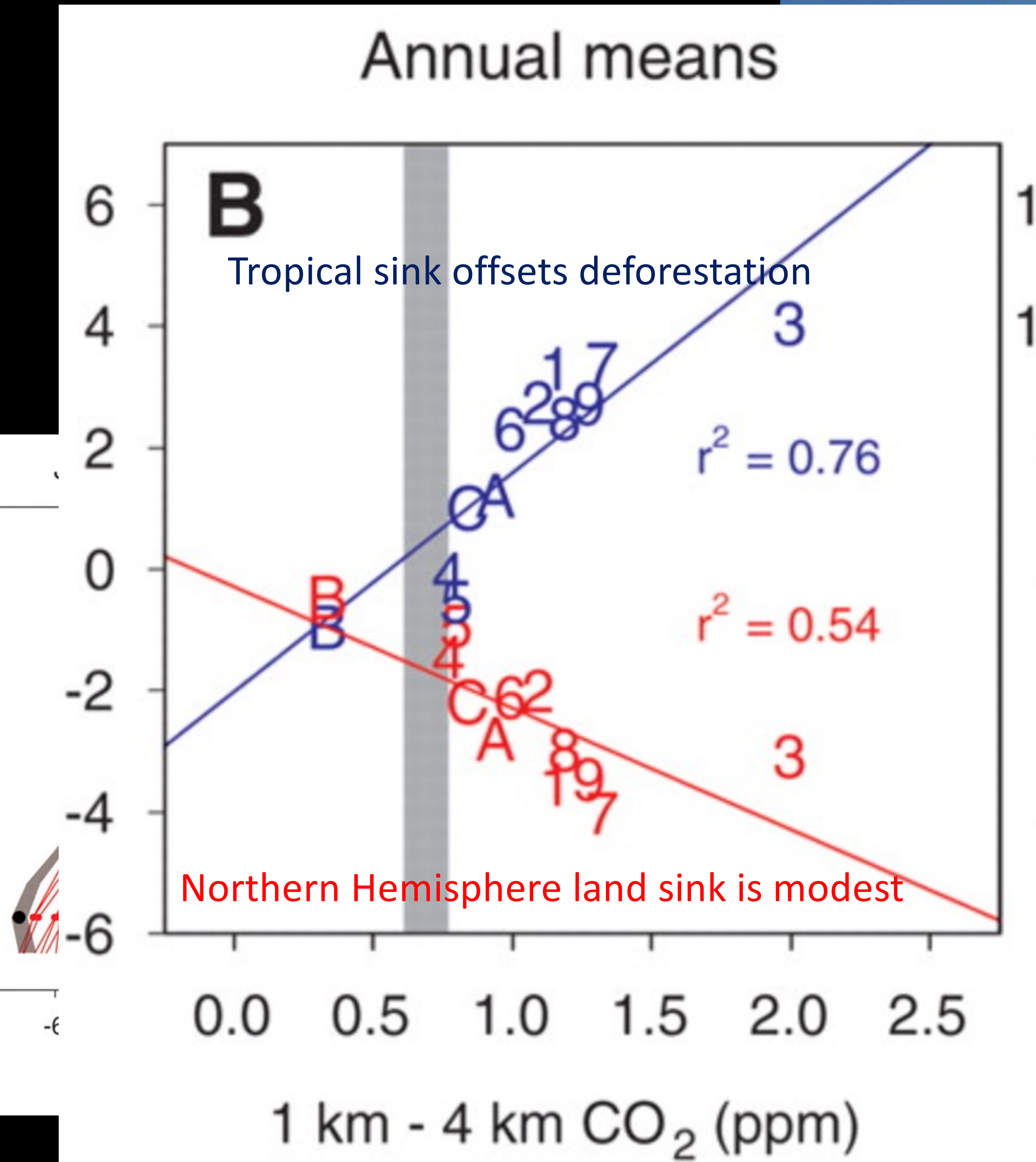
NOAA GML Carbon Cycle operates several measurement programs. Semi-continuous measurements are made at 4 baseline observatories, a few surface sites and from tall towers. Discrete surface and aircraft samples are measured in Boulder, CO. Presently, atmospheric carbon dioxide, methane, carbon monoxide, hydrogen, nitrous oxide, sulfur hexafluoride, the stable isotopes of carbon dioxide and methane, and halocarbon and volatile organic compounds are measured. Contact: Dr. Arlyn Andrews, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6773, arlyn.andrews@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.

Observational Constraints on the Global Atmospheric CO_2 Budget

PIETER P. TANS, INEZ Y. FUNG, TARO TAKAHASHI

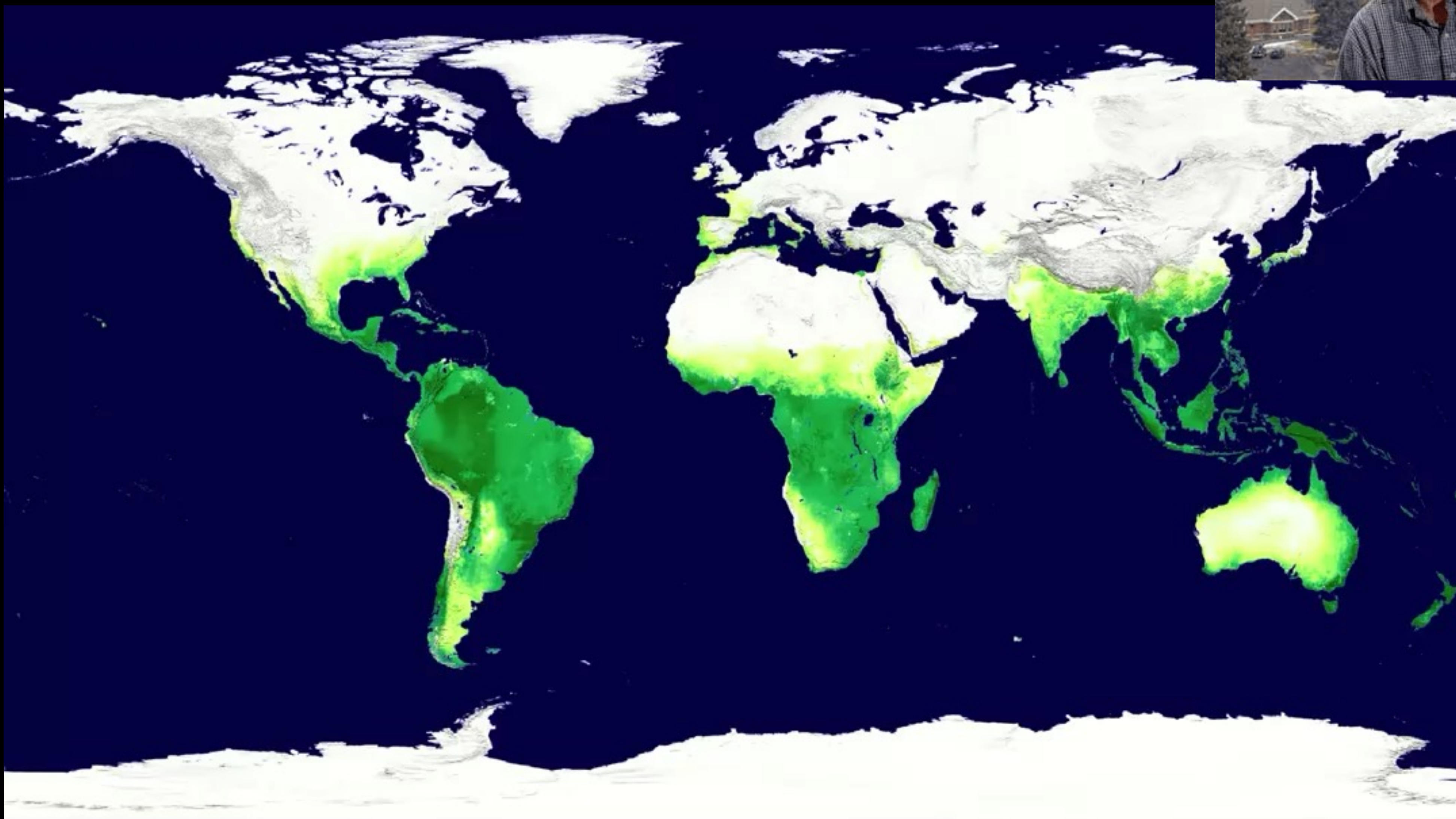
There must be a large terrestrial carbon sink in the Northern Hemisphere and/or Tropics!





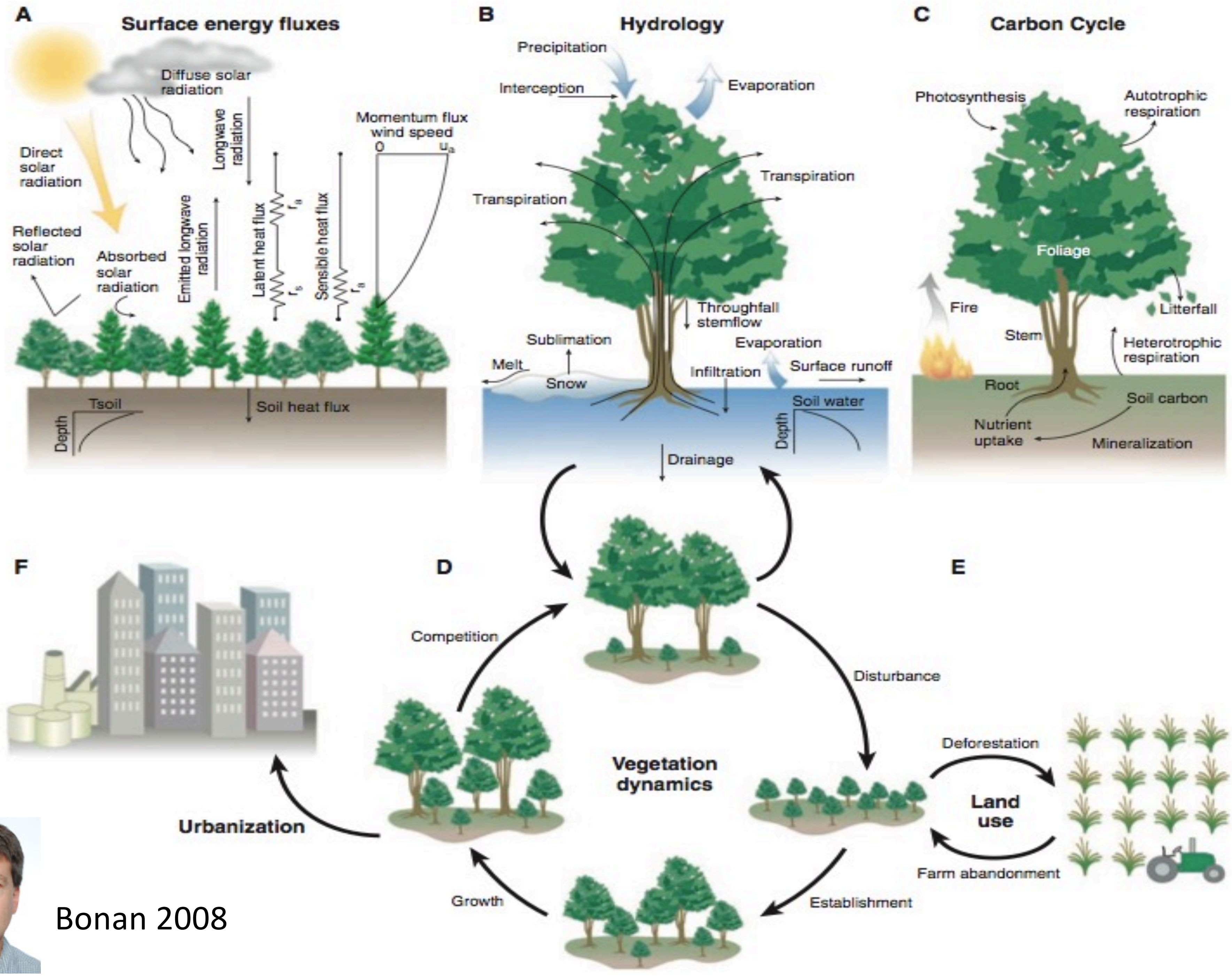
Stephens et al., 2007

GPP = Gross Primary Productivity = photosynthesis



MODIS GPP (NASA)

Forests in Flux



Bonan 2008

GLOBAL CARBON PROJECT

Fate of anthropogenic CO_2 emissions (2007–2016)

Sources = Sinks

34.4 $GtCO_2$/yr

88%

12%

4.8 $GtCO_2$/yr

17.2 $GtCO_2$/yr

46%

30%

11.0 $GtCO_2$/yr

24%

8.8 $GtCO_2$/yr

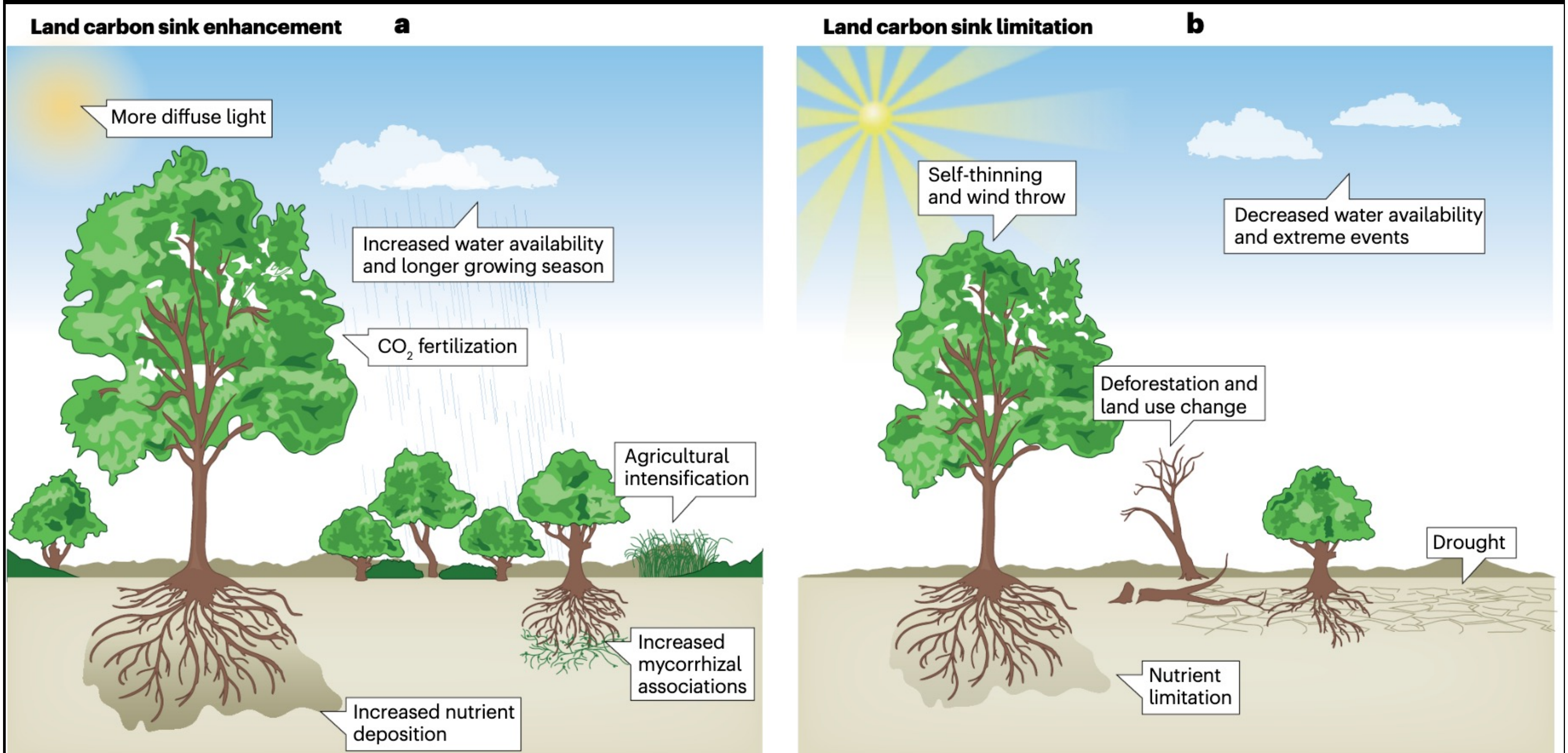
Source: CDIAC; NOAA-ESRL; Houghton and Nassikas 2017; Hansis et al 2015; Le Quéré et al 2017; Global Carbon Budget 2017

Where[illegible] the missing sink?

ALL OF THE ABOVE!!!

- A. In the high-[illegible]ceans, Henry's Law requires that oceans low in C[illegible]e polar oceans absorb carbon dioxide to be in eq[illegible] in atmosphere
- B. In equatorial ocea[illegible] biological productivity is high, since there is high[illegible] warm water
- C. In mid-latitude ecosyste[illegible] the vast expanse of forests and peat wetlands in[illegible] Russia, China, and low rates of decomposition gi[illegible]old winters
- D. In the tropical forests of the A[illegible]Africa, Indonesia, with the high year-round productiv[illegible]iodiversity
- E. Somewhere else: semi-arid sub-trop[illegible]ban areas, permafrost, coastal oceans, professor's [illegible]athroom, geological plate subduction

What is the future of this land sink?



"Physics and chemistry sets the law, biological organisms are the lawyers" – Dave Moore

nature reviews earth & environment

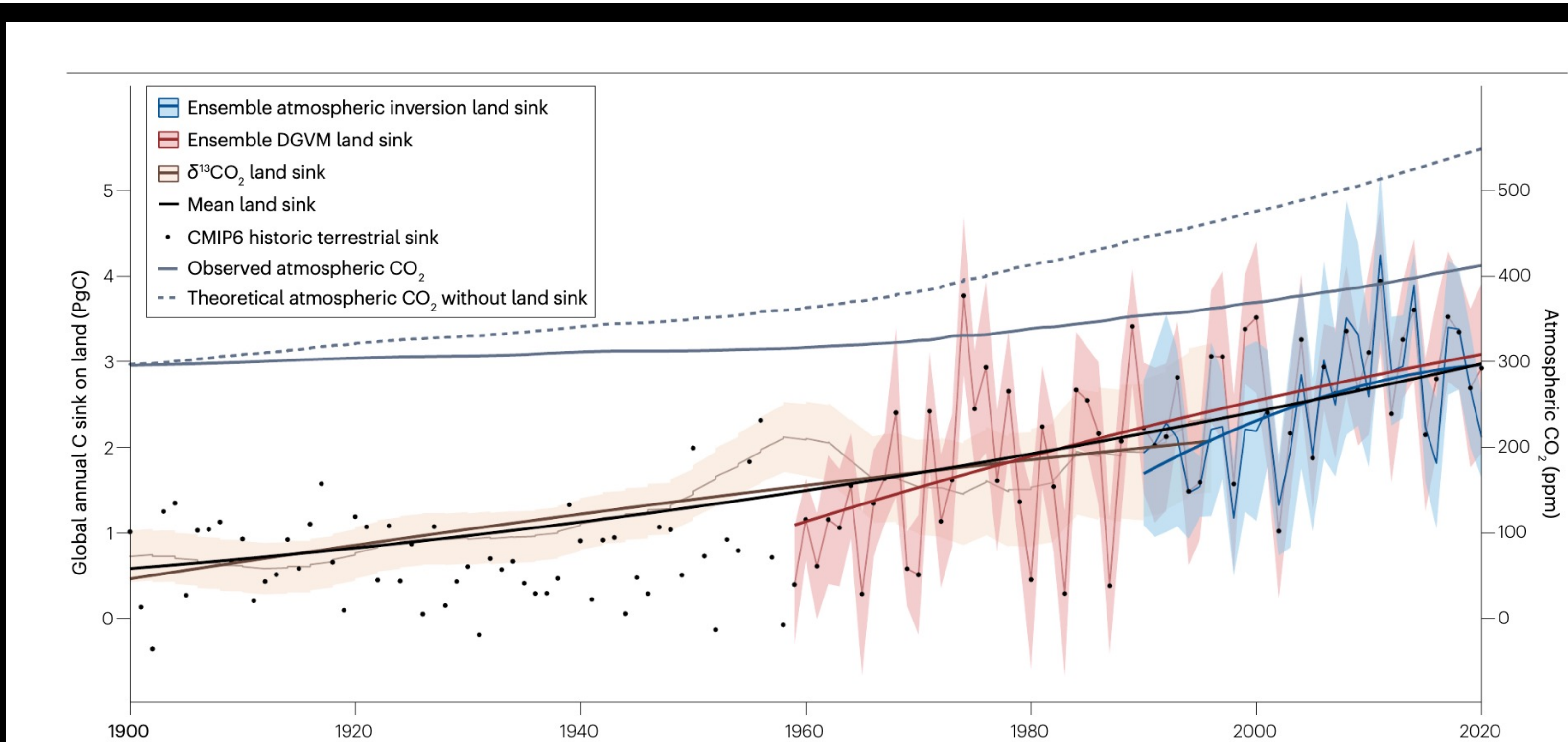
https://doi.org/10.1038/s43017-023-00456-3

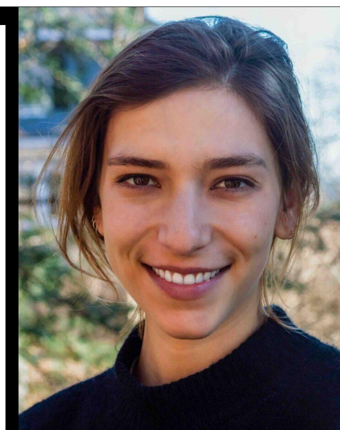
Review article

Check for updates

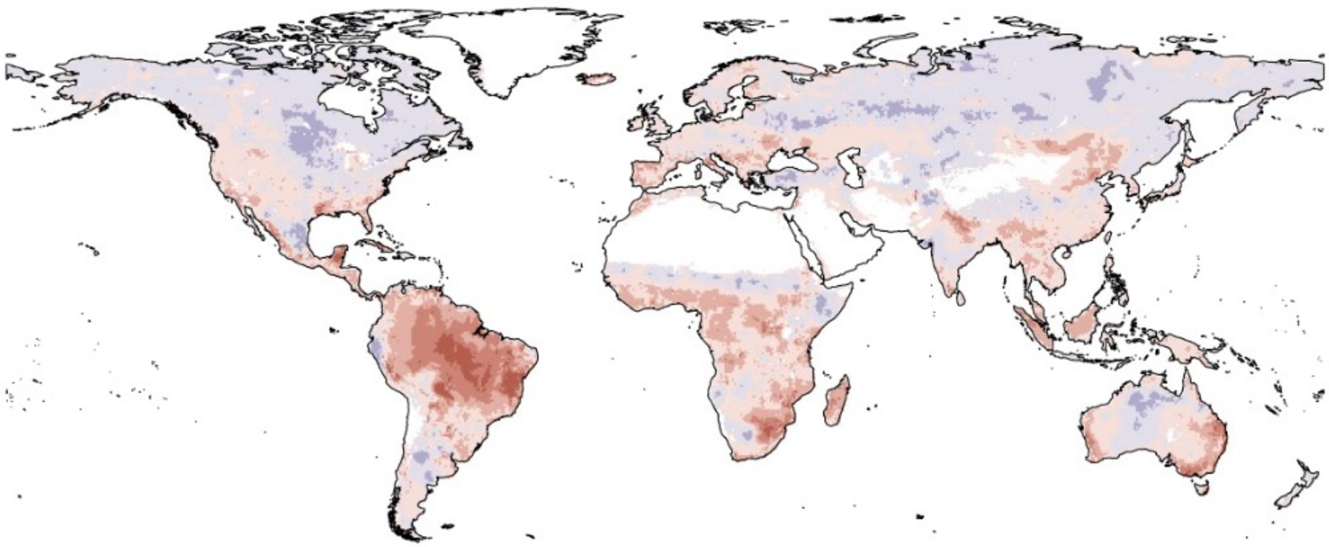
Evidence and attribution of the enhanced land carbon sink

Sophie Ruehr[1,2], Trevor F. Keenan[1,2], Christopher Williams[3], Yu Zhou[3,4], Xinchen Lu[1,2], Ana Bastos[5], Josep G. Canadell[6], Iain Colin Prentice[7,8], Stephen Sitch[9] & César Terrer[10]

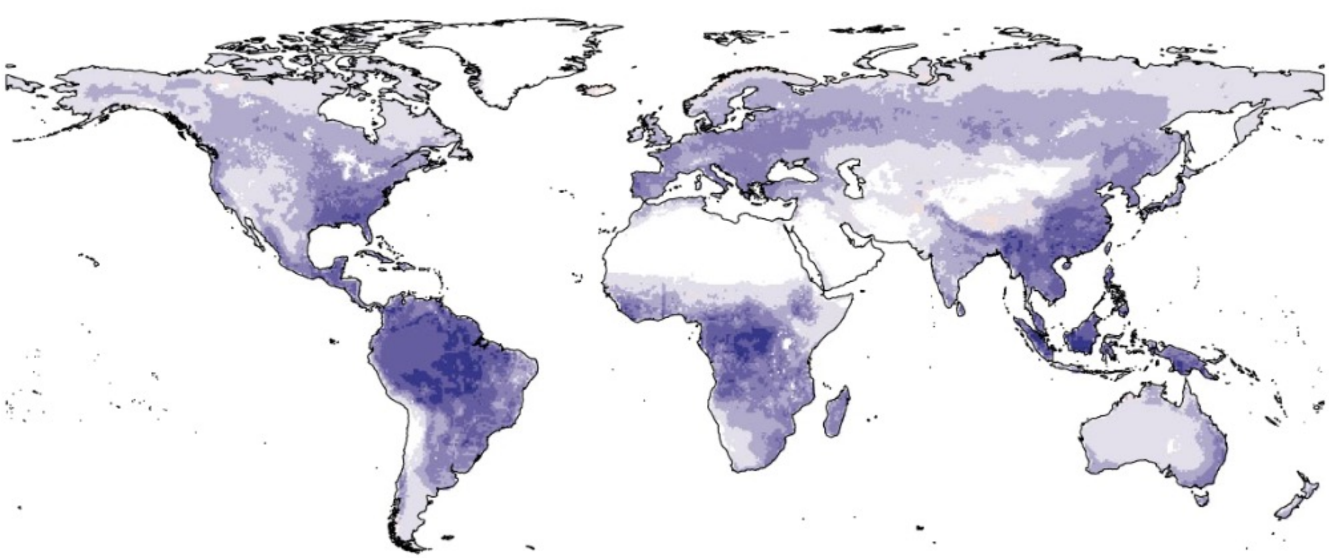




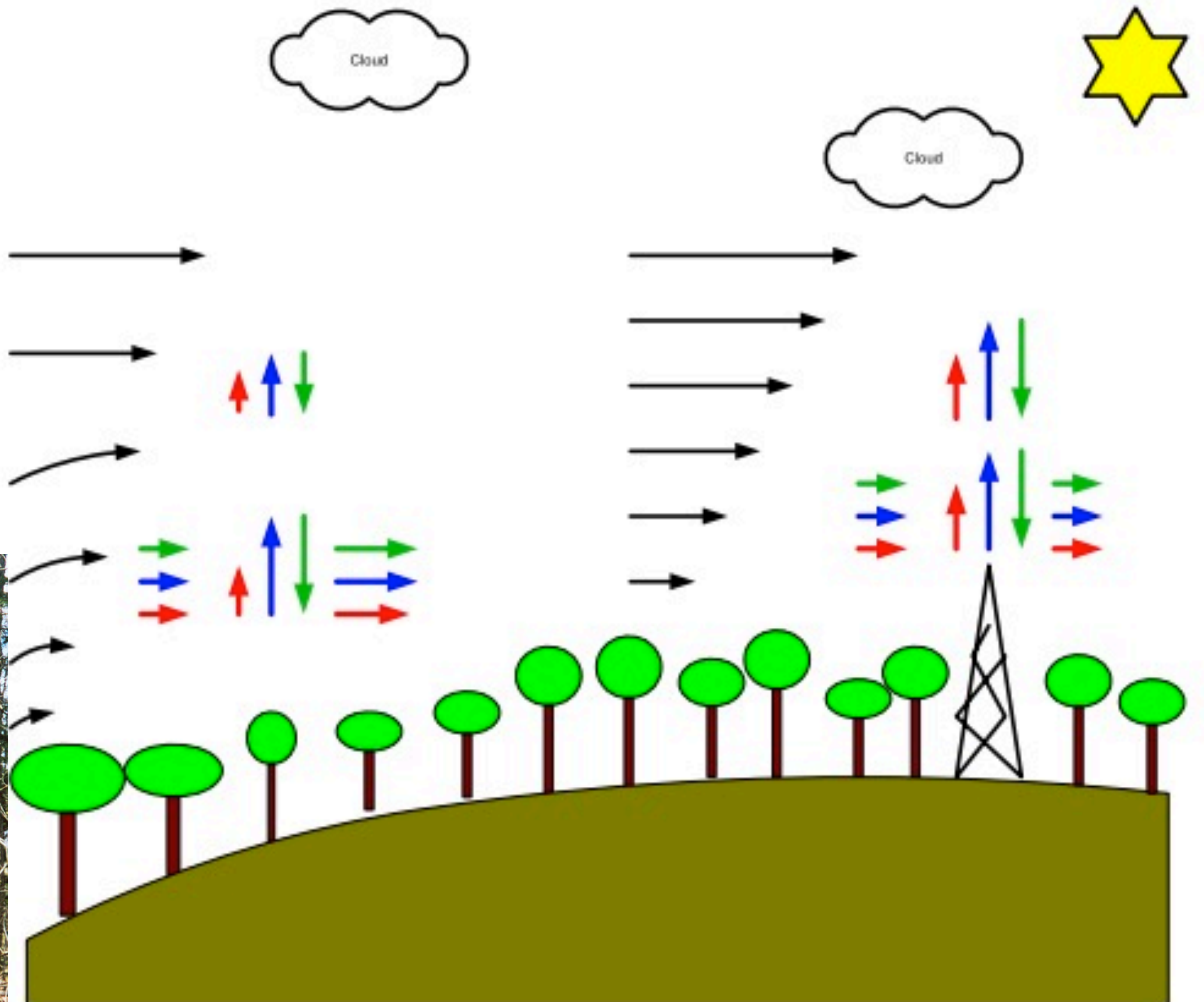
a Climate forcing



c CO_2 forcing

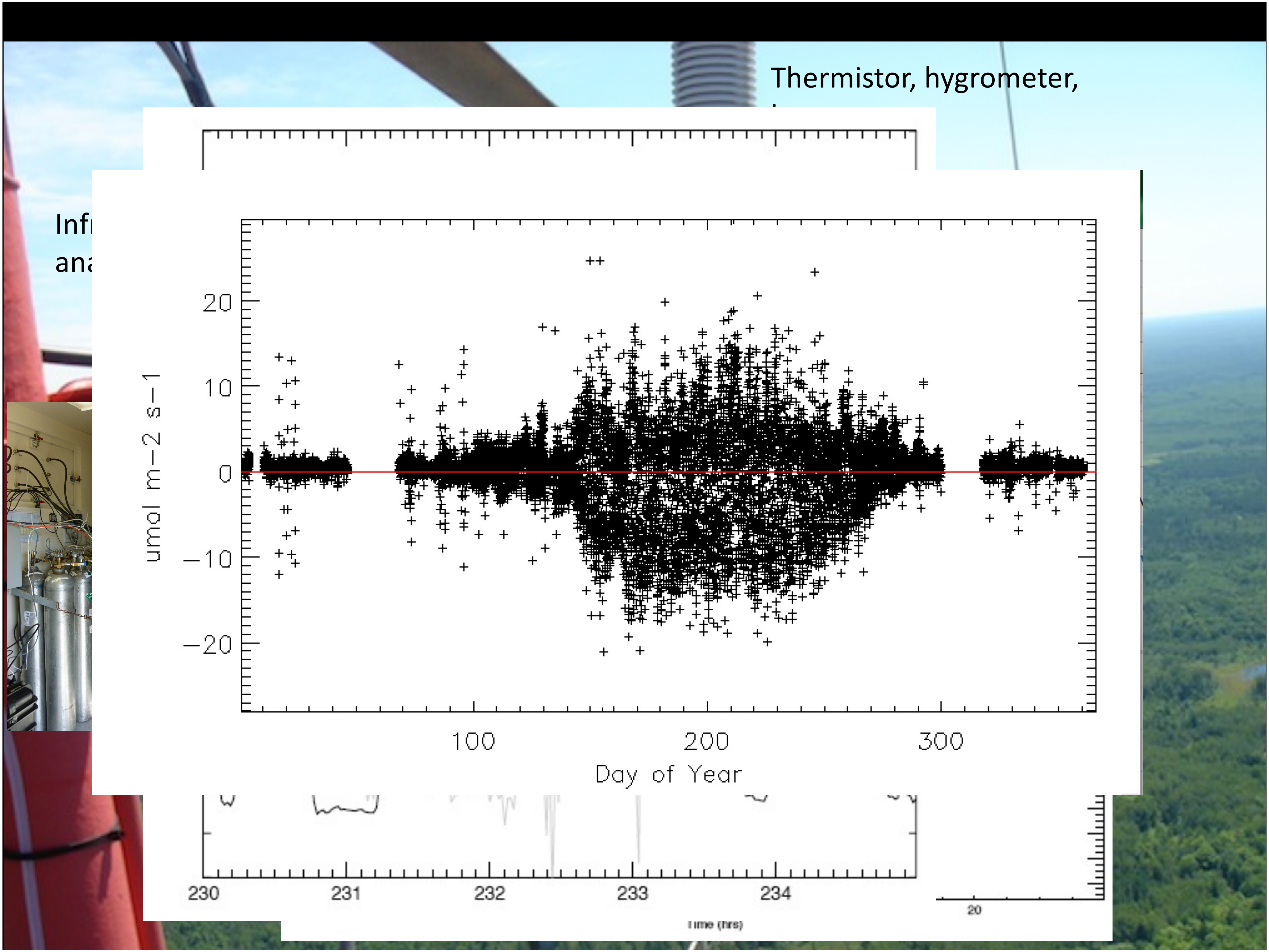


[redacted]



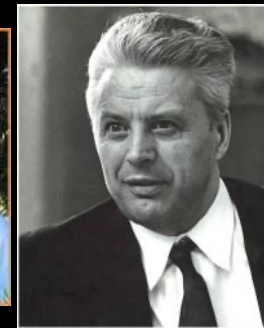
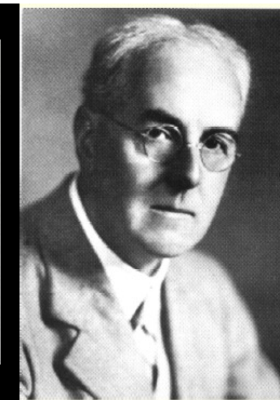
[redacted]

D. Baldocchi


Thermistor, hygrometer,
umol m−2 s−1
20
10
0
−10
−20
100
200
300
Day of Year
230
231
232
233
234
20





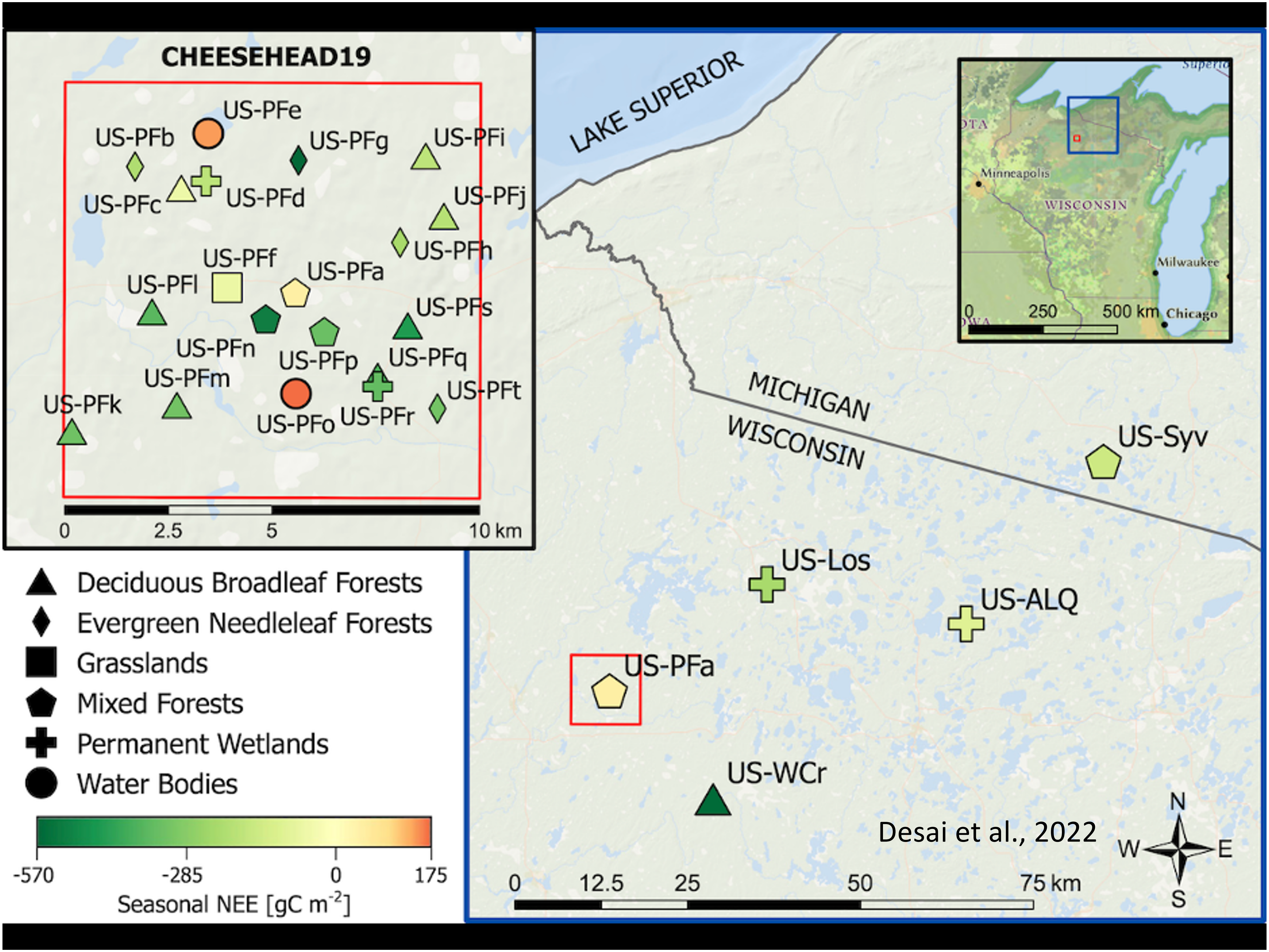


- 1880-1920s Turublence theory (Reynolds, Prandtl, Richardson, Taylor)
- 1940s-1950s Surface-layer theory (Monin-Obhukov, Kolmogorov), development of fast sensors for anemometry
- 1960s early measurements (Inoue, Wyngaard, Kaimal)
- 1970s forest fluxes (Raupach, Lenschow, Denmead)
- 1970s CO_2 fluxes (Desjardins, Leuning)
- 1980s Infrared gas analyzers (Verma, Anderson, Valentini)
- 1990s First long-term regional CO_2 flux networks (Wofsy, Baldocchi, Goulden, Law, Aubinet, Torn)
- 2000s Global syntheses (FLUXNET, Falge, Papale, Reichstein, Moffat, Novick)
- 2010s Model-data integration, development of operational measurements (NEON, ICOS, you?)

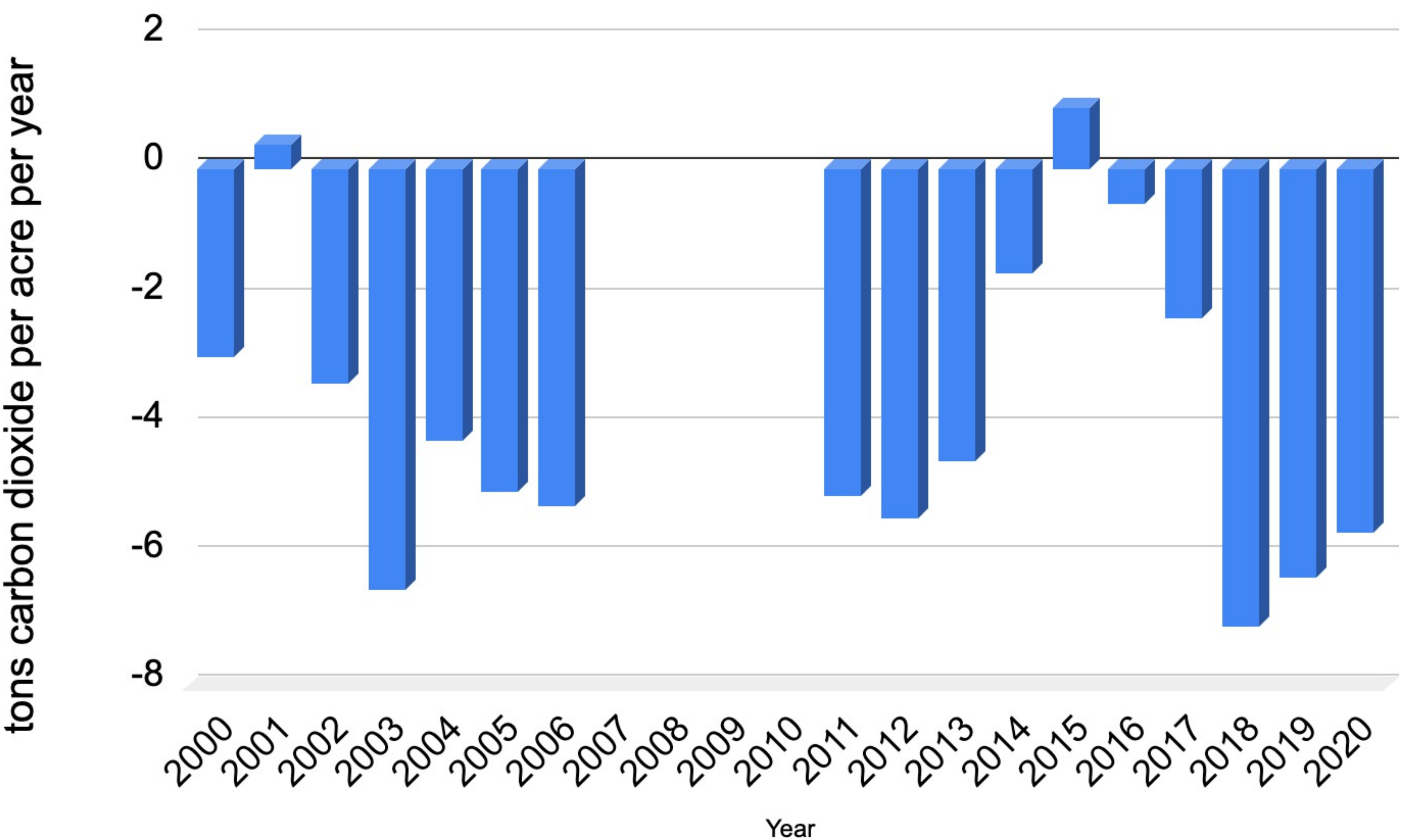


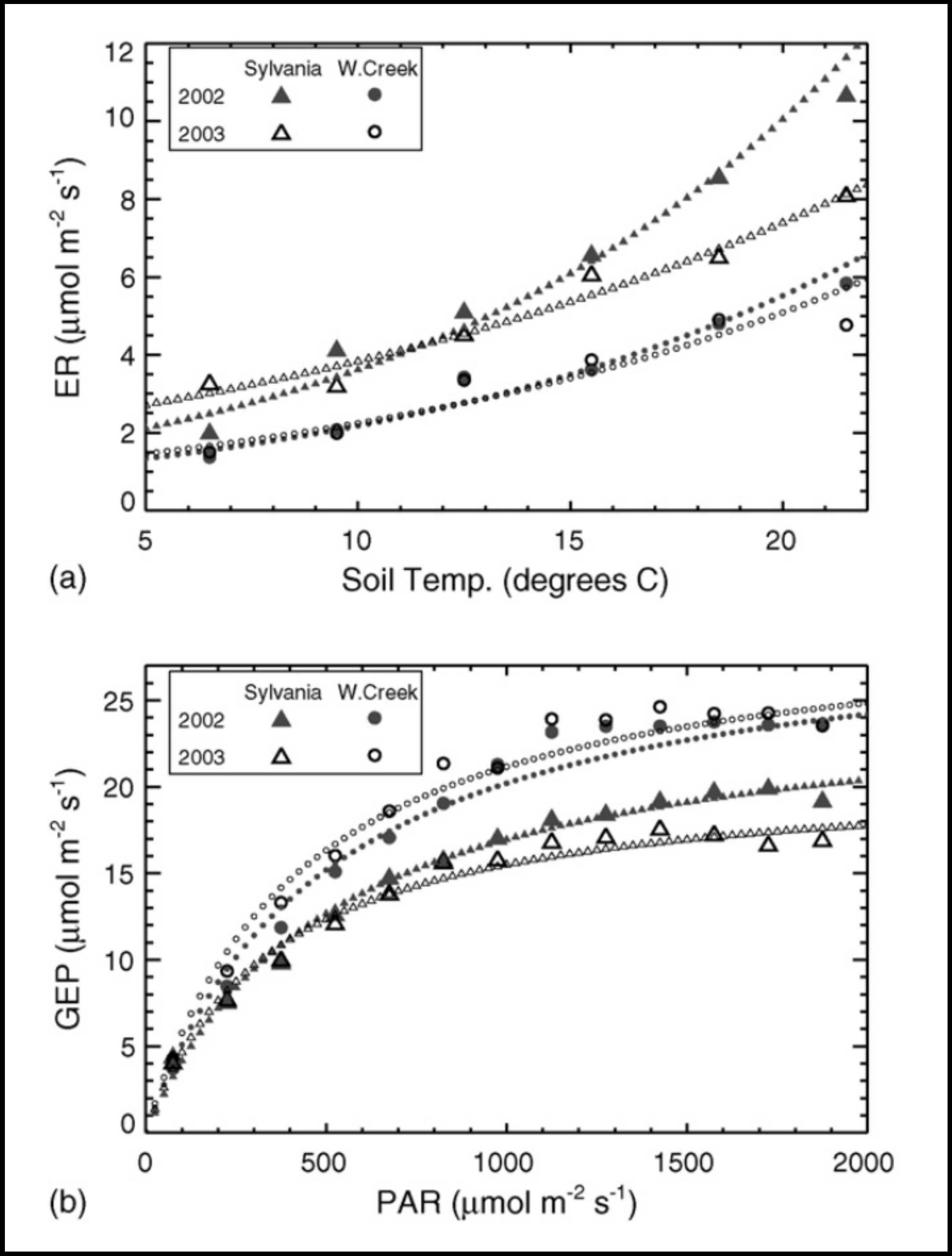



Photo: Jeff Miller, UW Communications


CHEESEHEAD19
US-PFe
US-PFb
US-PFg
US-PFi
US-PFc
US-PFd
US-PFj
US-PFh
US-PFf
US-PFa
US-PFl
US-PFs
US-PFn
US-PFp
US-PFq
US-PFm
US-PFt
US-PFk
US-PFo
US-PFr
0
2.5
5
10 km
LAKE SUPERIOR
Minneapolis
WISCONSIN
Milwaukee
Chicago
0
250
500 km
MICHIGAN
WISCONSIN
US-Syv
US-Los
US-ALQ
US-PFa
US-WCr
Deciduous Broadleaf Forests
Evergreen Needleleaf Forests
Grasslands
Mixed Forests
Permanent Wetlands
Water Bodies
-570
-285
0
175
Seasonal NEE [gC m-2]
Desai et al., 2022
N
W
E
S
0
12.5
25
50
75 km

Negative number = taking carbon dioxide out of the air





Desai et al., 2005

CHEESEHEAD 2019

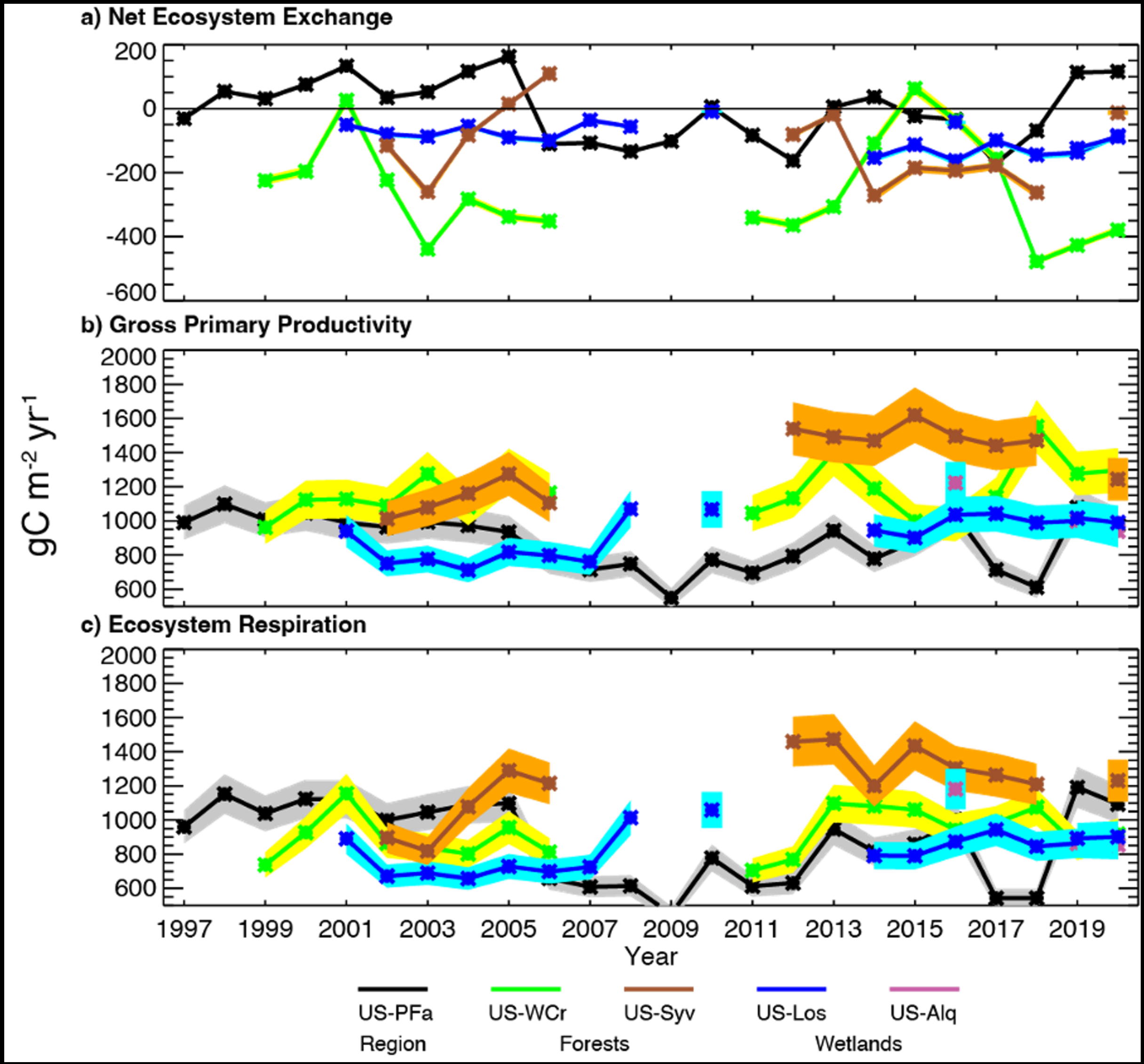
Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors

Interannual variations

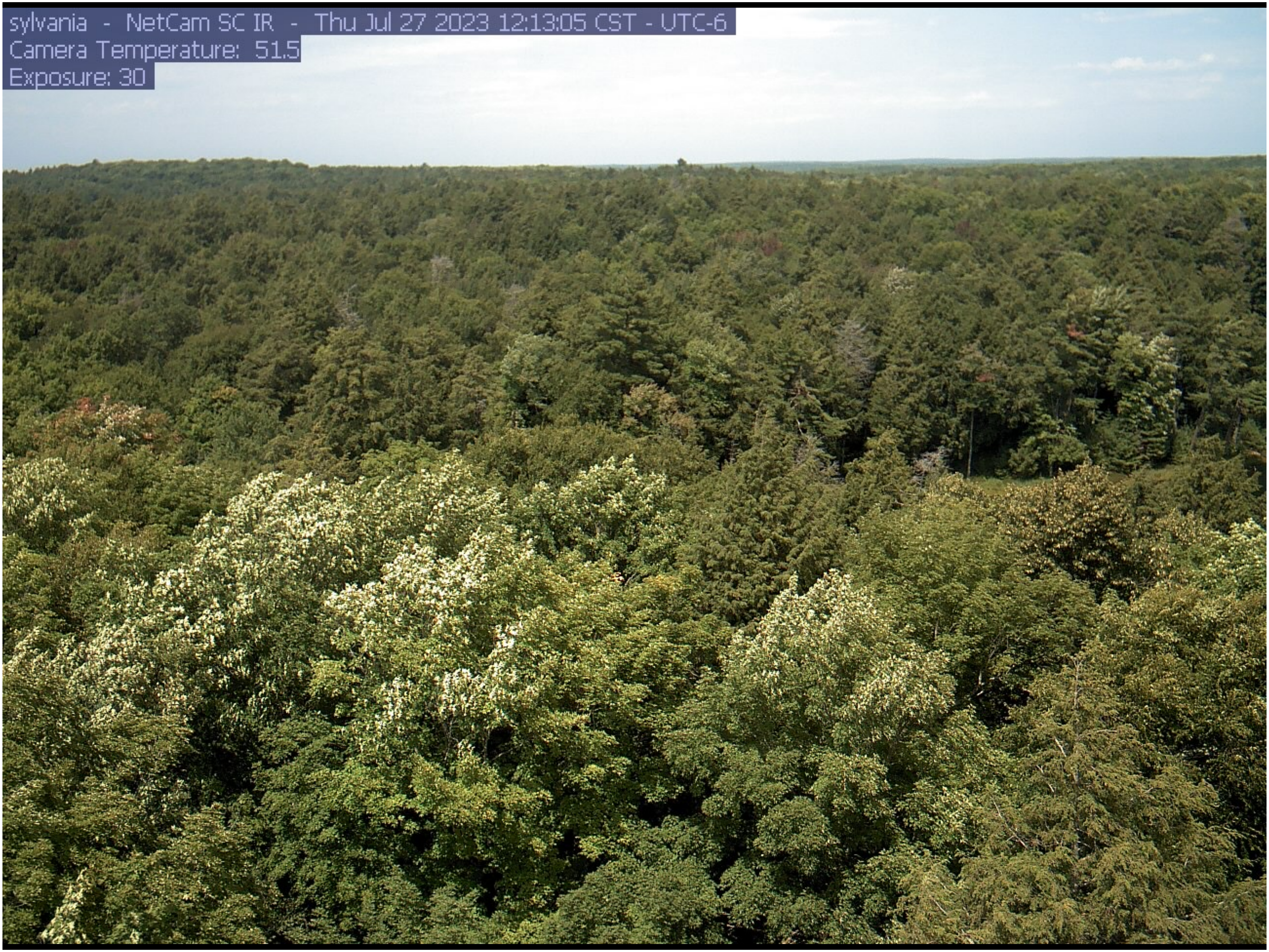
Region shifts from **source** to **sink** to **near neutral** over 25 year period

Limited coherence at the forest and wetland sites, which are more impacted by **local disturbances**

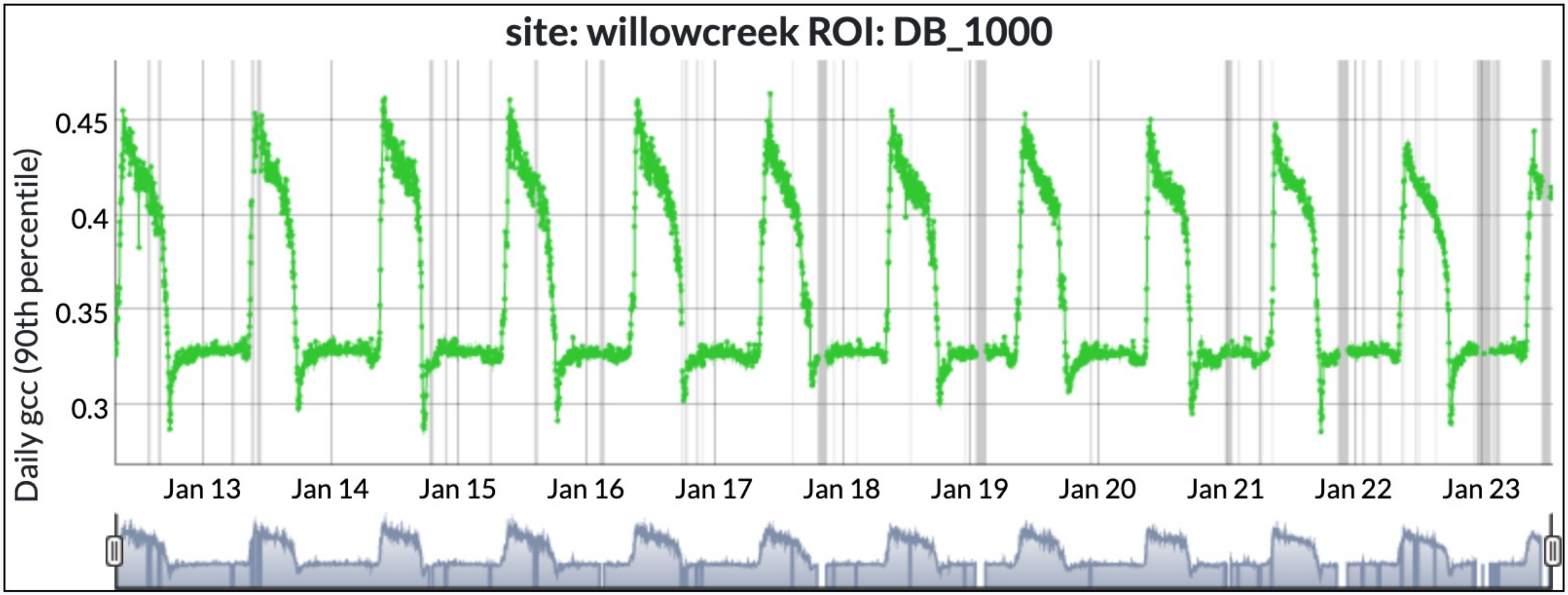
Older forests have highest GPP and respiration

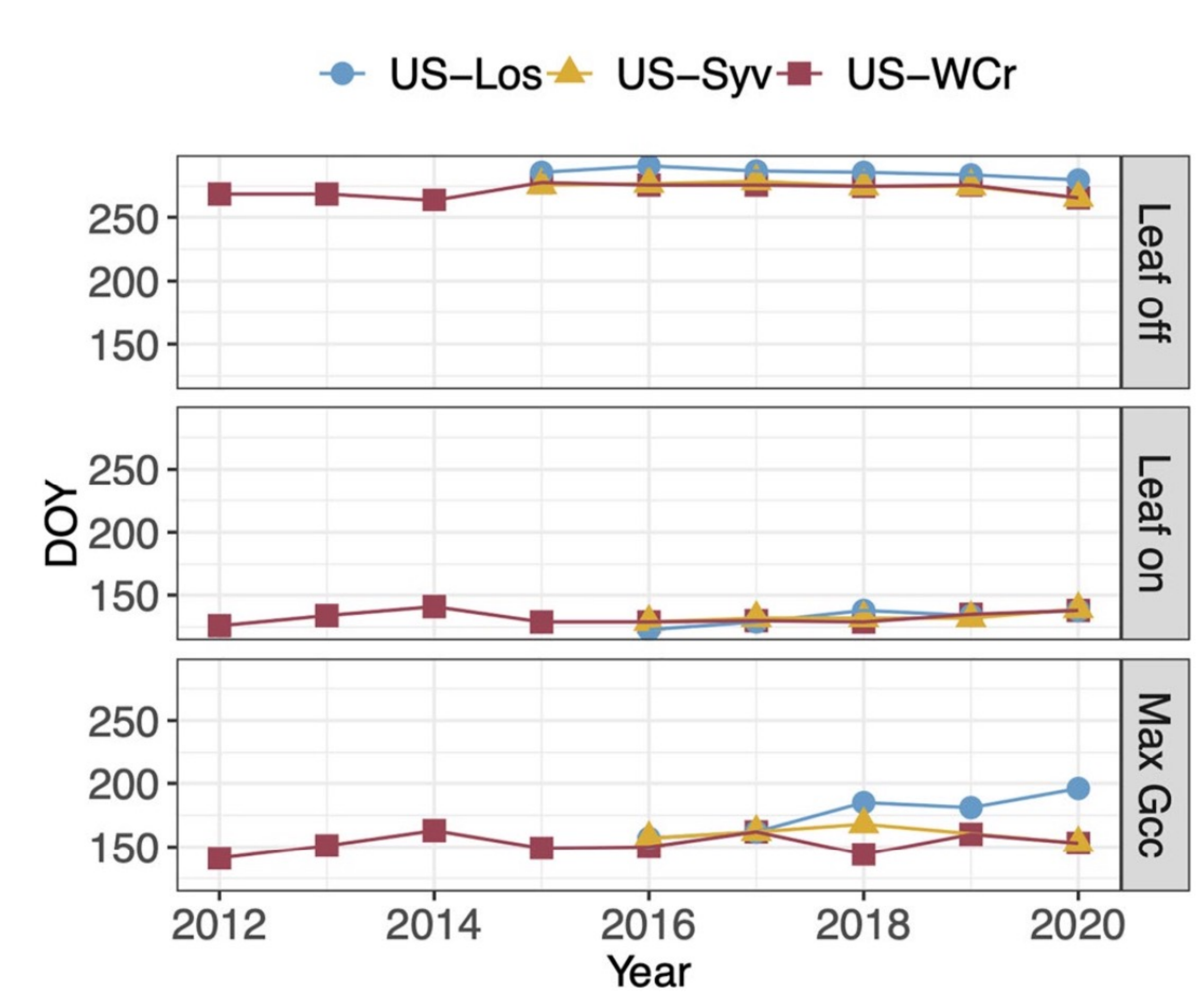


Desai et al., 2022

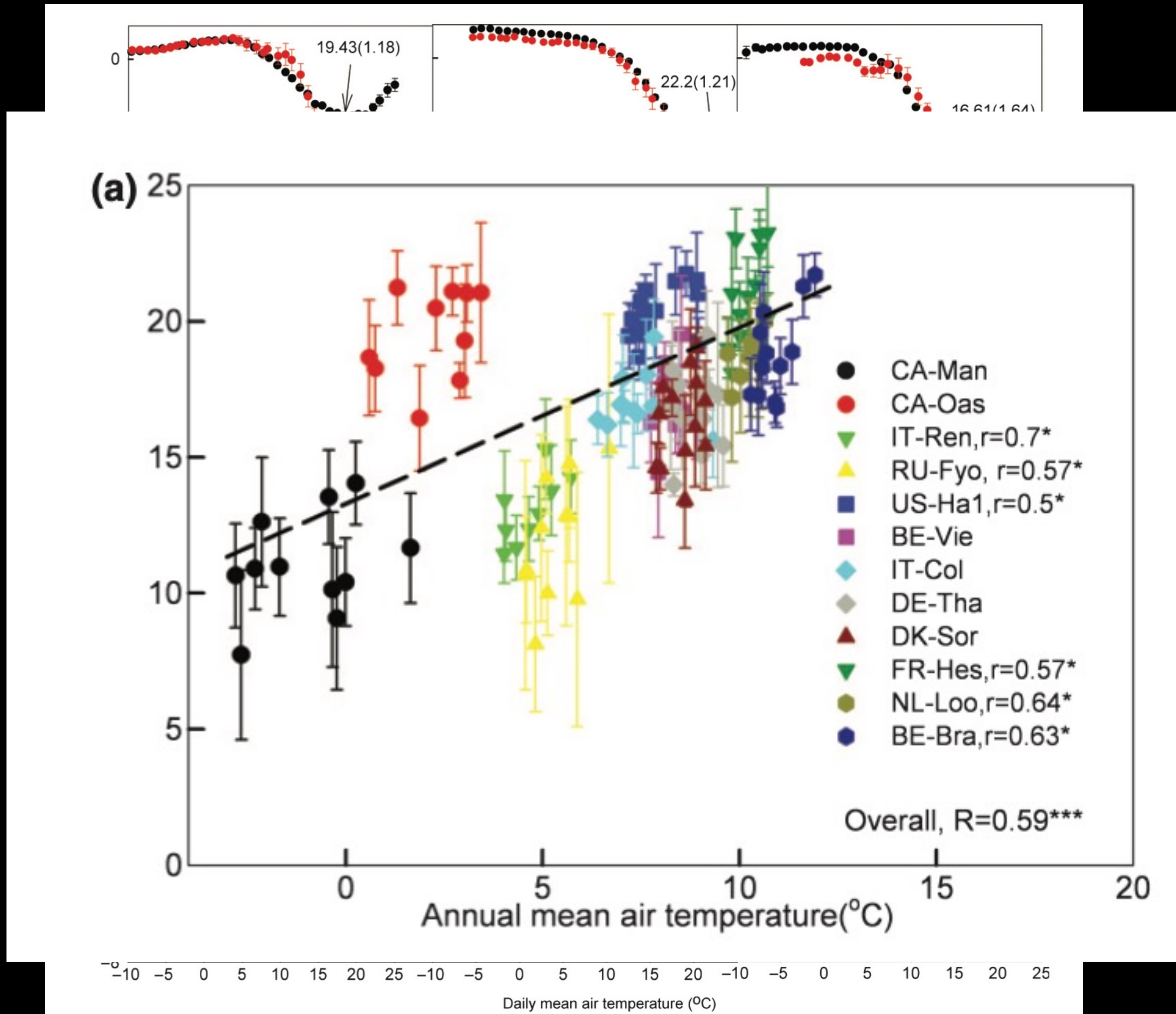

sylvania - NetCam SC IR - Thu Jul 27 2023 12:13:05 CST - UTC-6
Camera Temperature: 51.5
Exposure: 30

gcc (green chromatic coordinate) timeseries plot




US−Los
US−Syv
US−WCr
DOY
Leaf off
Leaf on
Max Gcc
250
200
150
2012
2014
2016
2018
2020
Year

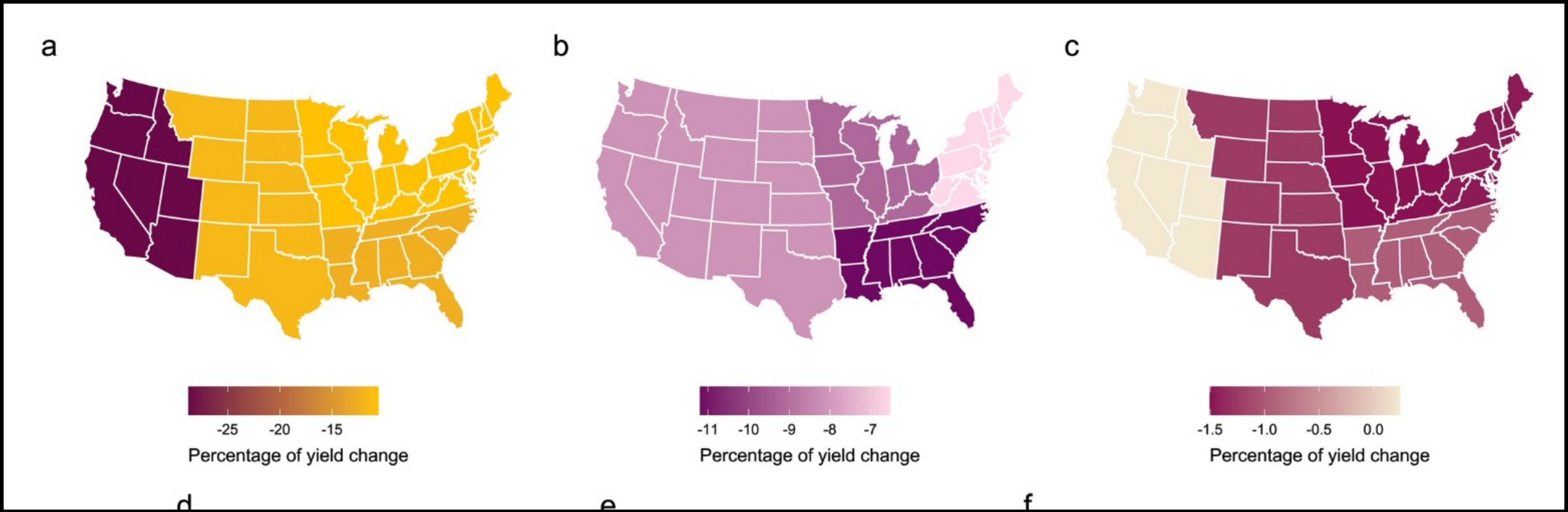
Lots of towers!



Niu et al., 2012

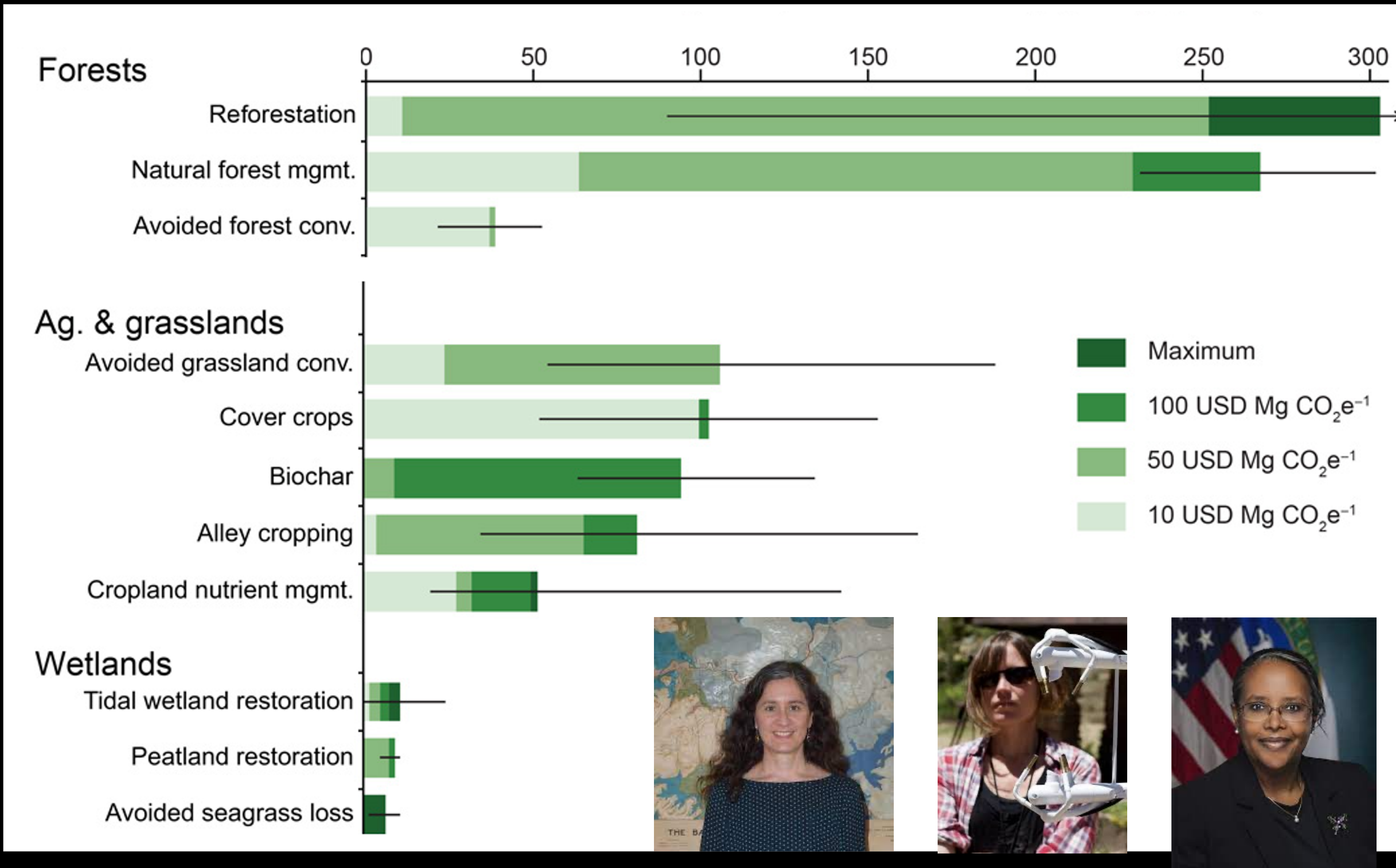
https://www.nytimes.com/2020/01/10/world/australia/australia-wildfires-photos.html

Intersection of air quality and climate change on productivity



Liu and Desai, Earth's Future, 2021

Nature-Based Climate Solutions



From Fargione et al. 2018


NASA
ooms

http://www.xinhuanet.com/english/2019-03/21/c_137913274.htm

Big challenges in ecosystem science

- Predicting fate of terrestrial carbon, water, and nutrients in ecosystems from leaf to continental scale
- Impacts of higher CO_2, longer growing seasons, nutrient deposition, shifting atmospheric water demand, and microbial population changes on ecosystem structure and function
- The future of plant mortality from disturbance, fire, pests in a changing climate
- Impact of management and land use on carbon storage and ecosystem services, including for climate change mitigation

Intersection of physics, biology, chemistry, geology, policy, economics, and computing!!!


Thank you!
Ankur Desai
desai@aos.wisc.edu
https://flux.aos.wisc.edu
@profdesai
Photo: Jonathan Thom, UW

What questions do you have? You could ask:

- Do ecosystems emit or sequester other greenhouse gases that are important for climate?
- Do eddy covariance flux towers sample all vegetation types and locations equally?
- How accurate is tower measurement?
- Do you have to climb the towers yourself?
- Are there other measurements you can make on the tower that are important for Earth system?
- Is there a limit to the carbon fertilization effect?
- What are your students' research projects in this area?
- What areas of biology should I study if I want to study this more?