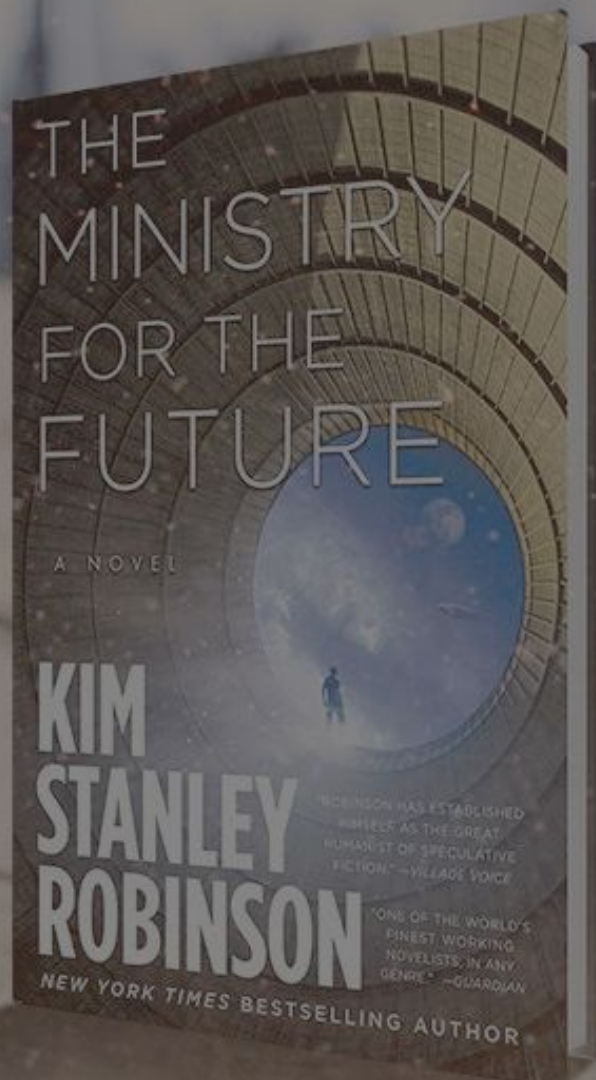


STIA 4102

CLEAN ENERGY INNOVATION

Lecture 10:
Carbon Removal & Geoengineering

WHAT TO EXPECT WHEN YOU'RE EXPECTING A WORST-CASE SCENARIO



We flew to sixty thousand feet, as high as the planes could get. Higher would have been better but we couldn't do it. [...]

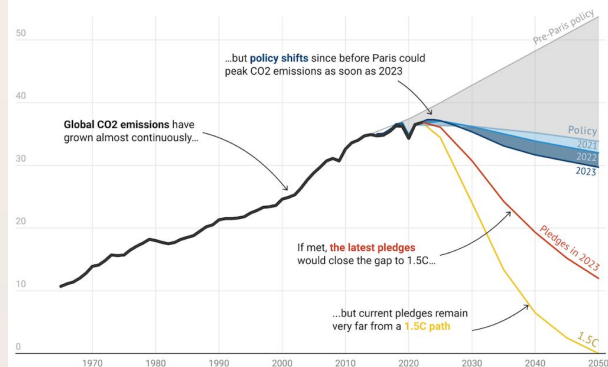
Once up there we deployed the fuel lines and pumped the aerosols into the air. The plumes looked like dumped fuel at first, but they were really **aerosol particulates, we were told mostly sulfur dioxide** and then some other chemicals, like from a volcano, but there wasn't ash like in a volcanic explosion, it was a mix made to stay up there and reflect sunlight.

[...] soon enough **what we released would get carried by the winds all over the stratosphere**, mostly in the northern hemisphere but eventually everywhere. There it would be deflecting some sunlight. [...] Our operation only made things a little whiter by day, and the sunsets were sometimes more red than before. Quite beautiful on certain days. But mostly things looked the same. **The sunlight we deflected to space was said to be about a fifth of one percent of the total incoming.** Very important crucial stuff, but it's not really possible to see a difference that small. **Global effect was said to be like Pinatubo's eruption in 1991, or some said a double Pinatubo.** The total release was taken to the stratosphere in several thousand individual missions. We had a fleet of only two hundred planes, so we went up scores of times, spread out over seven months.

Global CO₂ emissions will peak in 2023

Global CO₂ emissions could peak as soon as 2023, IEA reveals

Global energy-related CO₂ emissions, billion tonnes



← 2023
IEA* NZE**
report

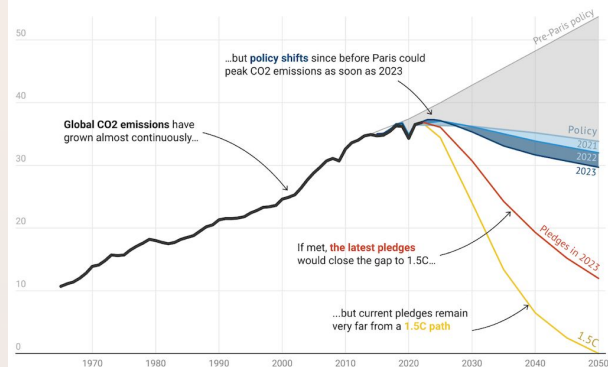
* International Energy Agency
** Net-Zero Emissions by 2050 Scenario

Global CO₂ emissions will peak in 2023

~~2022~~ ~~2021~~

Global CO2 emissions could peak as soon as 2023, IEA reveals

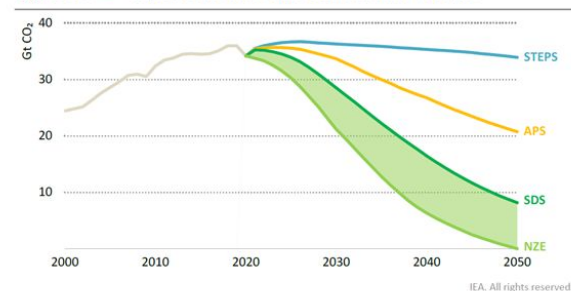
Global energy-related CO2 emissions, billion tonnes



← 2023
IEA * NZE**
report

2021 IEA
NZE/APS†
report →

Figure 1.4 ▶ CO₂ emissions in the WEO-2021 scenarios over time



IEA. All rights reserved.
The APS pushes emissions down, but not until after 2030; the SDS goes further and faster to be aligned with the Paris Agreement; the NZE delivers net zero emissions by 2050

* International Energy Agency
** Net-Zero Emissions by 2050 Scenario
† Announced Pledges Scenario

Global CO₂ emissions will peak in 2023

~~2022~~ ~~2021~~ ~~2020~~ ~~2019~~

Global CO₂ emissions could peak as soon as 2023, IEA reveals

Global energy-related CO₂ emissions, billion tonnes

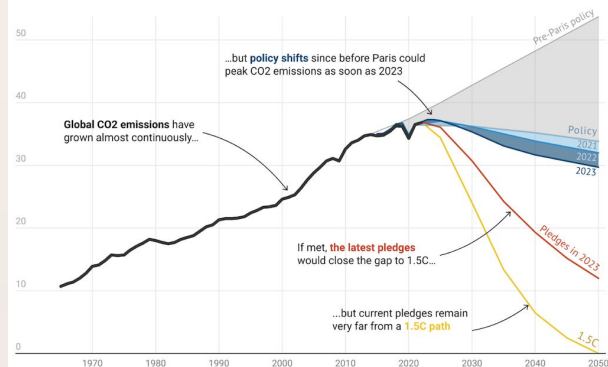
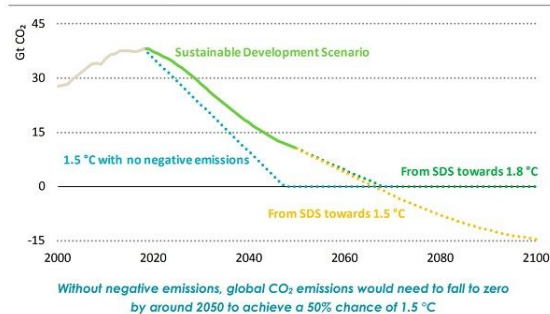


Figure 2.27 ▶ Emissions trajectories for total CO₂ emissions in the Sustainable Development Scenario and to limit warming to 1.5 °C



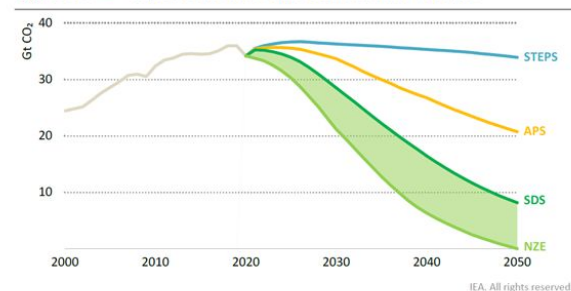
← 2023
IEA * NZE**
report

2021 IEA
NZE/APS†
report →

← 2019
IEA SDS‡
report

* International Energy Agency
** Net-Zero Emissions by 2050 Scenario
† Announced Pledges Scenario
‡ Sustainable Development Scenario

Figure 1.4 ▶ CO₂ emissions in the WEO-2021 scenarios over time



The APS pushes emissions down, but not until after 2030; the SDS goes further and faster to be aligned with the Paris Agreement; the NZE delivers net zero emissions by 2050

Global CO₂ emissions will peak in 2023

~~2022~~ ~~2021~~ ~~2020~~ ~~2019~~ ~~2018~~ ~~2017~~ ~~2016~~

Global CO₂ emissions could peak as soon as 2023, IEA reveals

Global energy-related CO₂ emissions, billion tonnes

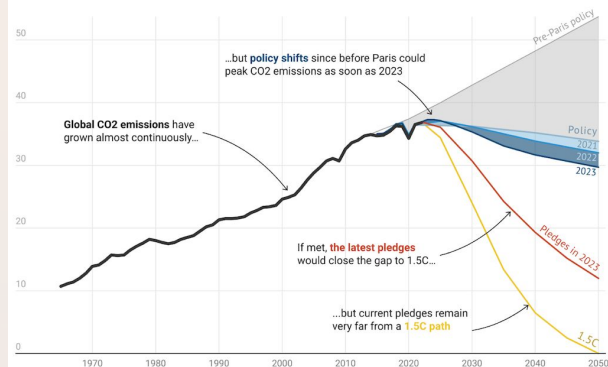
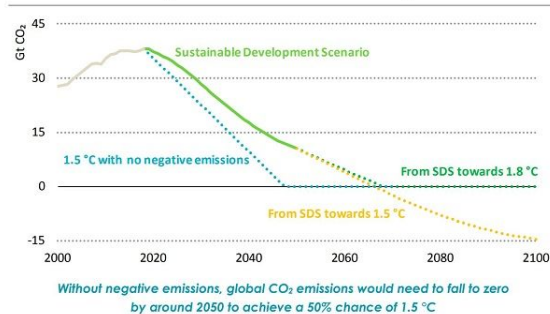


Figure 2.27 Emissions trajectories for total CO₂ emissions in the Sustainable Development Scenario and to limit warming to 1.5 °C



← 2023
IEA* NZE**
report

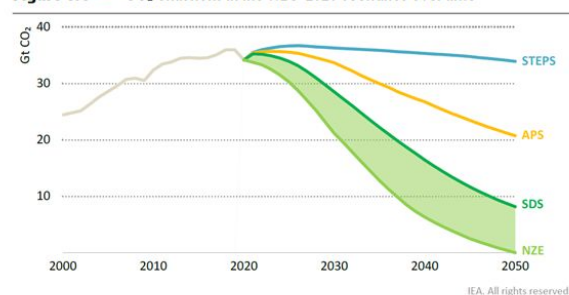
2021 IEA
NZE/APS[†]
report →

← 2019
IEA SDS[‡]
report

2016-2019
IEA SDS
reports →

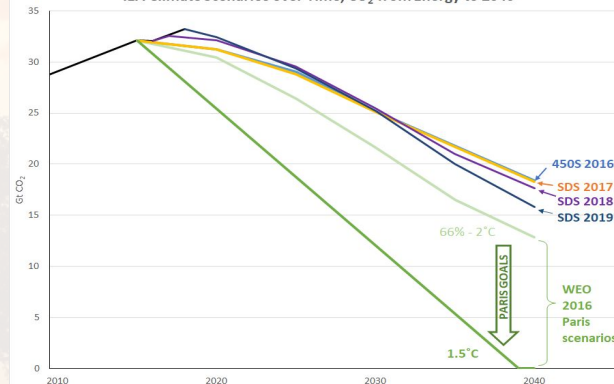
* International Energy Agency
** Net-Zero Emissions by 2050 Scenario
† Announced Pledges Scenario
‡ Sustainable Development Scenario

Figure 1.4 CO₂ emissions in the WEO-2021 scenarios over time



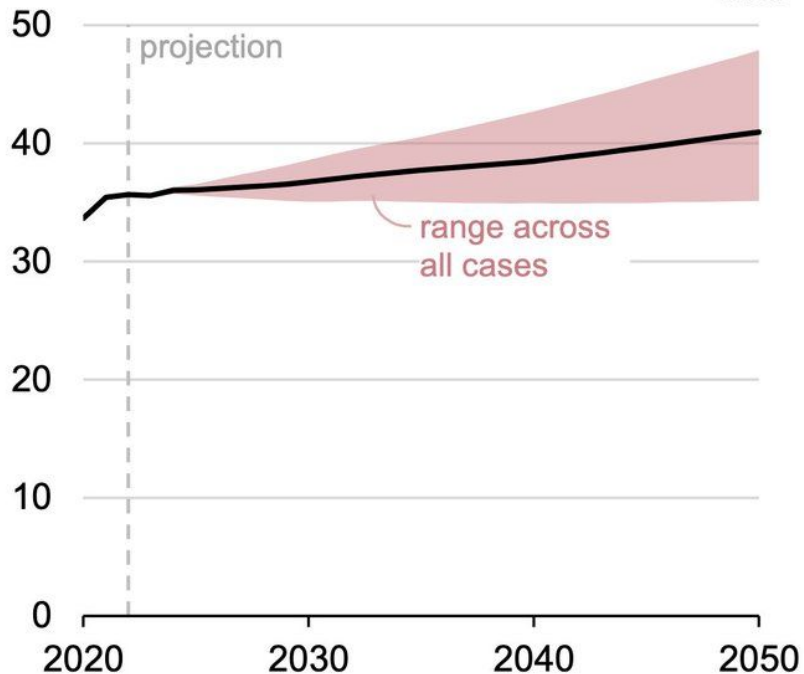
The APS pushes emissions down, but not until after 2030; the SDS goes further and faster to be aligned with the Paris Agreement; the NZE delivers net zero emissions by 2050

IEA Climate Scenarios over Time, CO₂ from Energy to 2040



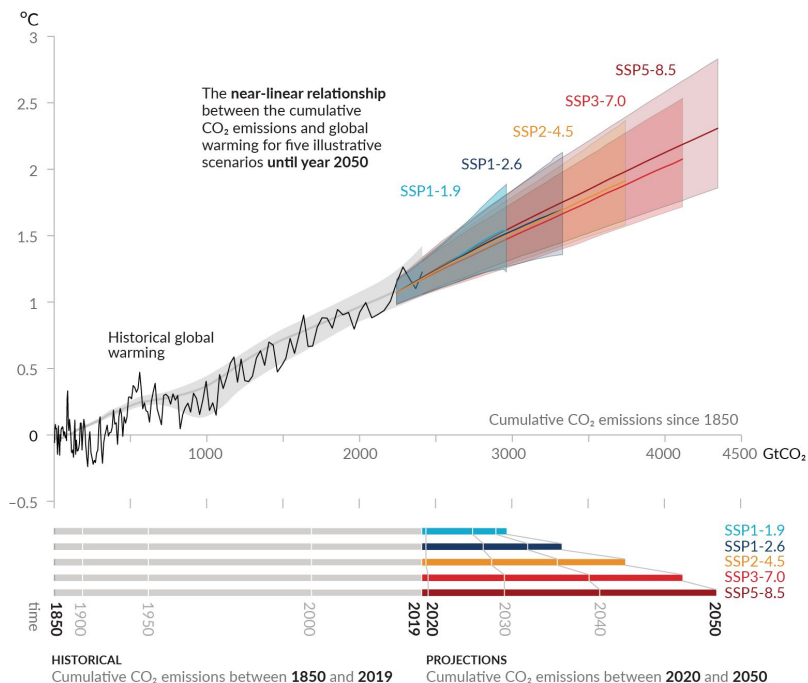
...maybe things don't get better

Energy-related CO₂ emissions, world billion metric tons



Every tonne of CO₂ emissions adds to global warming

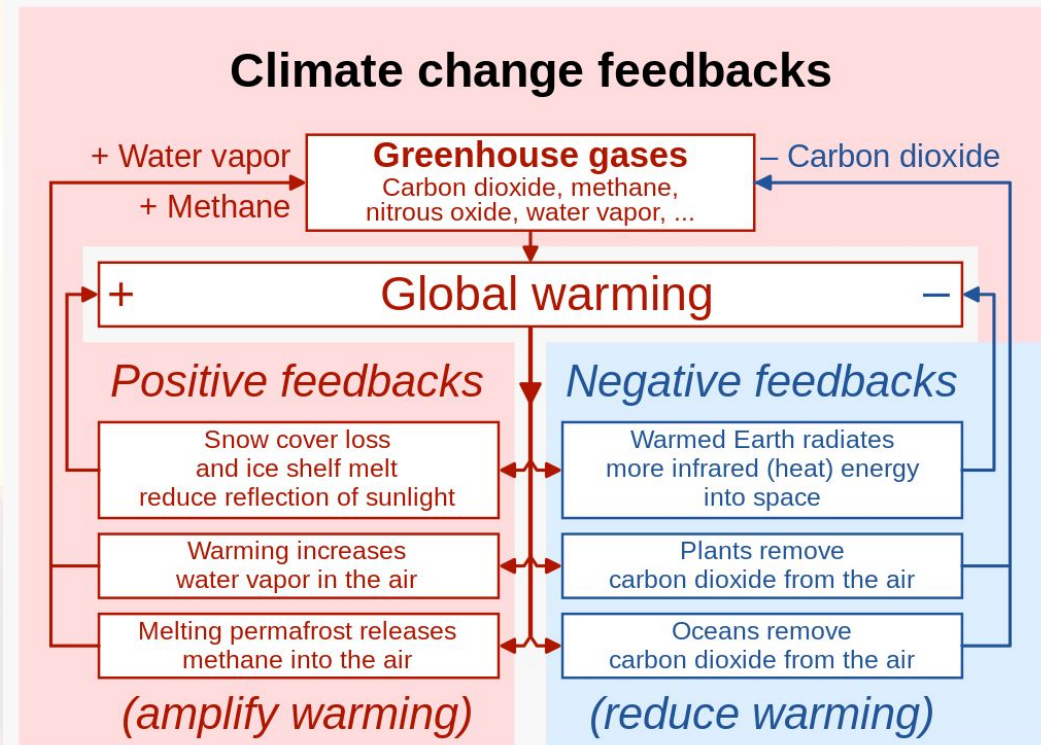
Global surface temperature increase since 1850–1900 (°C) as a function of cumulative CO₂ emissions (GtCO₂)



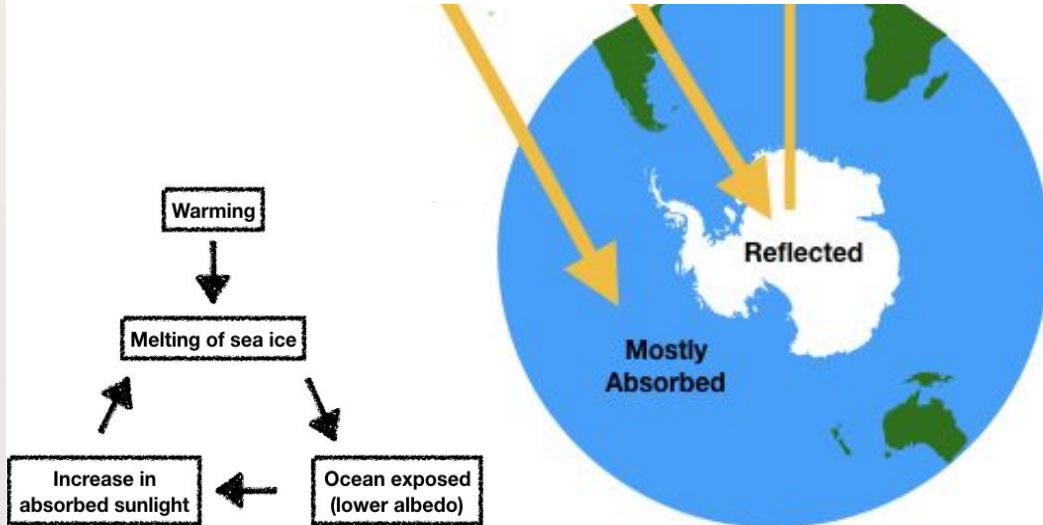
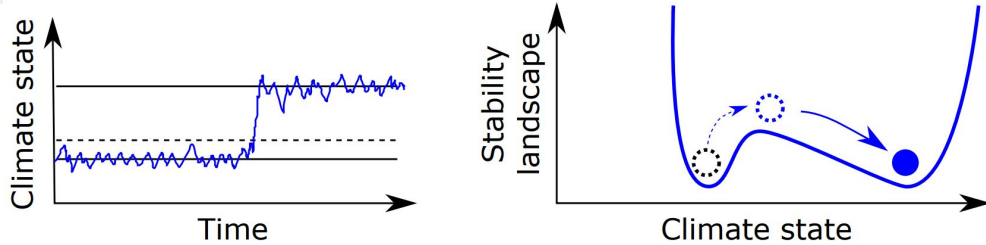
Future cumulative CO₂ emissions differ across scenarios and determine how much warming we will experience.

Climate Feedback Loops

feedback loops
can be **positive**
(self-reinforcing)
or **negative**
(balancing)



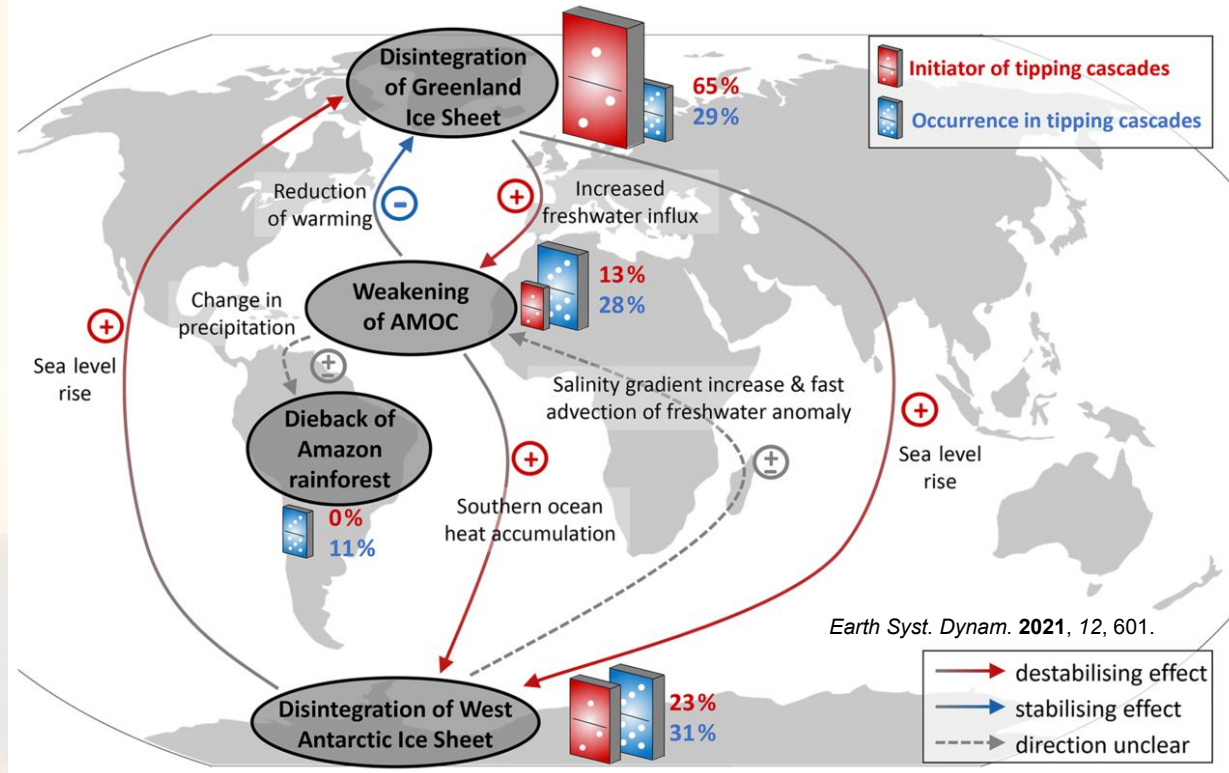
Climate Tipping Points



tipping points are **rapid** and often **irreversible** changes to the planetary system due to **positive feedback loops**

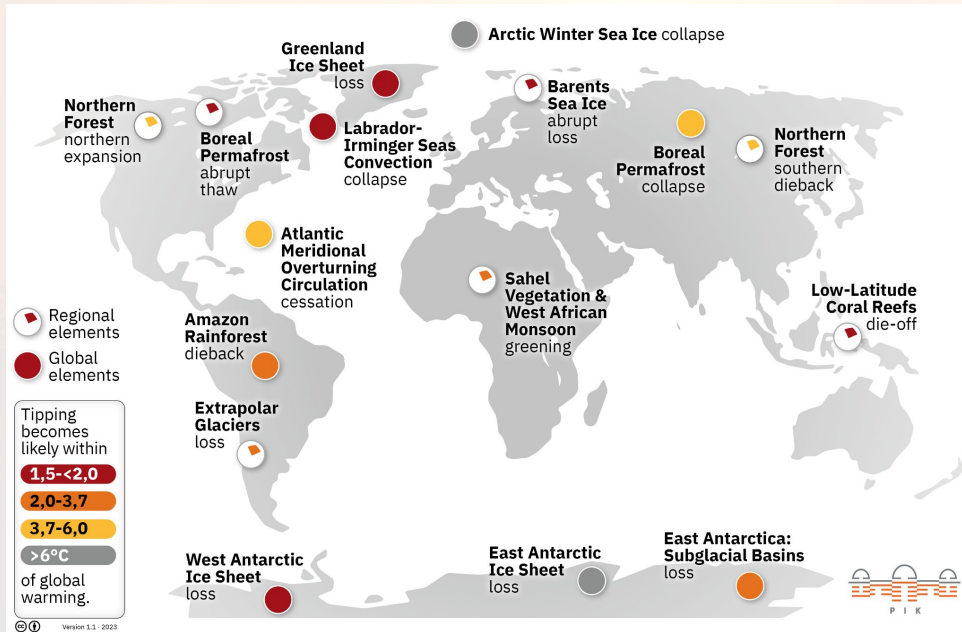
Tipping Point Cascades

passing one tipping point risks a 'domino effect' inducing a **cascade** of tipping points



Tipping Point Cascades

there are *so many* possible tipping points



the uncertainty is *ridiculously* high (almost unquantifiable)

ARCTIC WINTER SEA ICE COLLAPSE
BOREAL FOREST NORTHERN EXPANSION
GREENLAND ICE SHEET COLLAPSE
BARENTS SEA ICE COLLAPSE
BOREAL PERMAFROST COLLAPSE

HOW FAR WOULD YOU GO TO PREVENT A CIVILIZATION-ENDING EXTINCTION EVENT?

OVERTURNING CIRCULATION COLLAPSE
SAHEL / WEST AFRICAN MONSOON GREENING
AMAZON
LOW-LATITUDE CORAL REEFS DIE-OFF

WHAT ABOUT A 50% CHANCE OF AN EVENT?

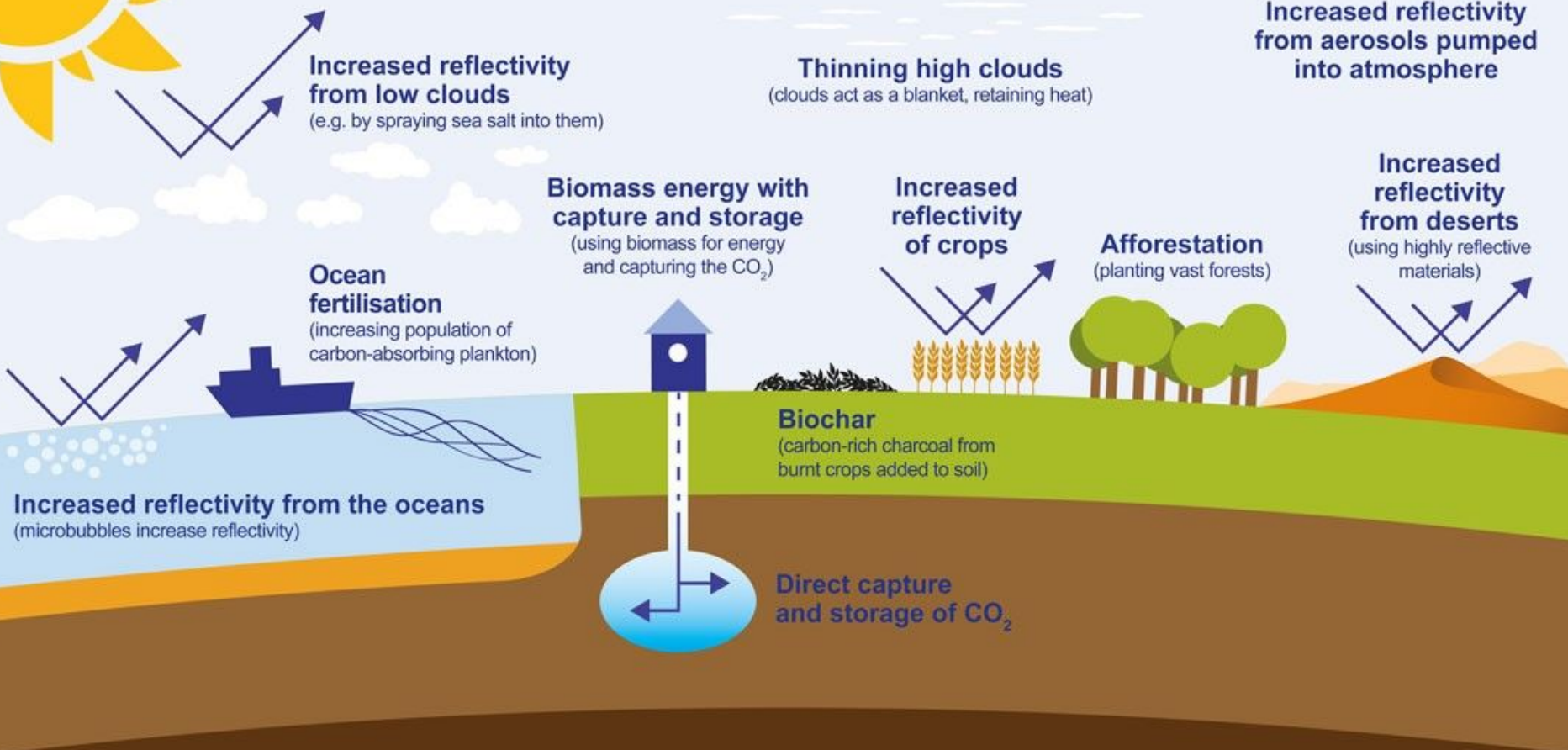
MOUNTAIN GLACIERS LOSS
WEST ANTARCTIC ICE SHEET COLLAPSE
A 10% CHANCE?
A 1% CHANCE?
EAST ANTARCTIC ICE SHEET COLLAPSE
EAST ANTARCTIC SUBGLACIAL BASINS COLLAPSE

GLOBAL WARMING THRESHOLDS

○ <2°C ◆ 2-4°C ▲ ≥4°C

Science 2022, 377, eabn7950.

GEOENGINEERING PROPOSALS



Geoengineering

Carbon Dioxide Removal

(CDR / “negative emissions”)

- ❖ Direct-air capture (DAC)
- ❖ Enhanced weathering (EWR)
- ❖ Biomass carbon removal (BECCS/BiCRS)
- ❖ Pyrolytic carbon removal (biochar, PyCCS)
- ❖ Afforestation / desert greening
- ❖ Ocean carbon removal (DOC, OAE, etc.)

Solar Radiation Management

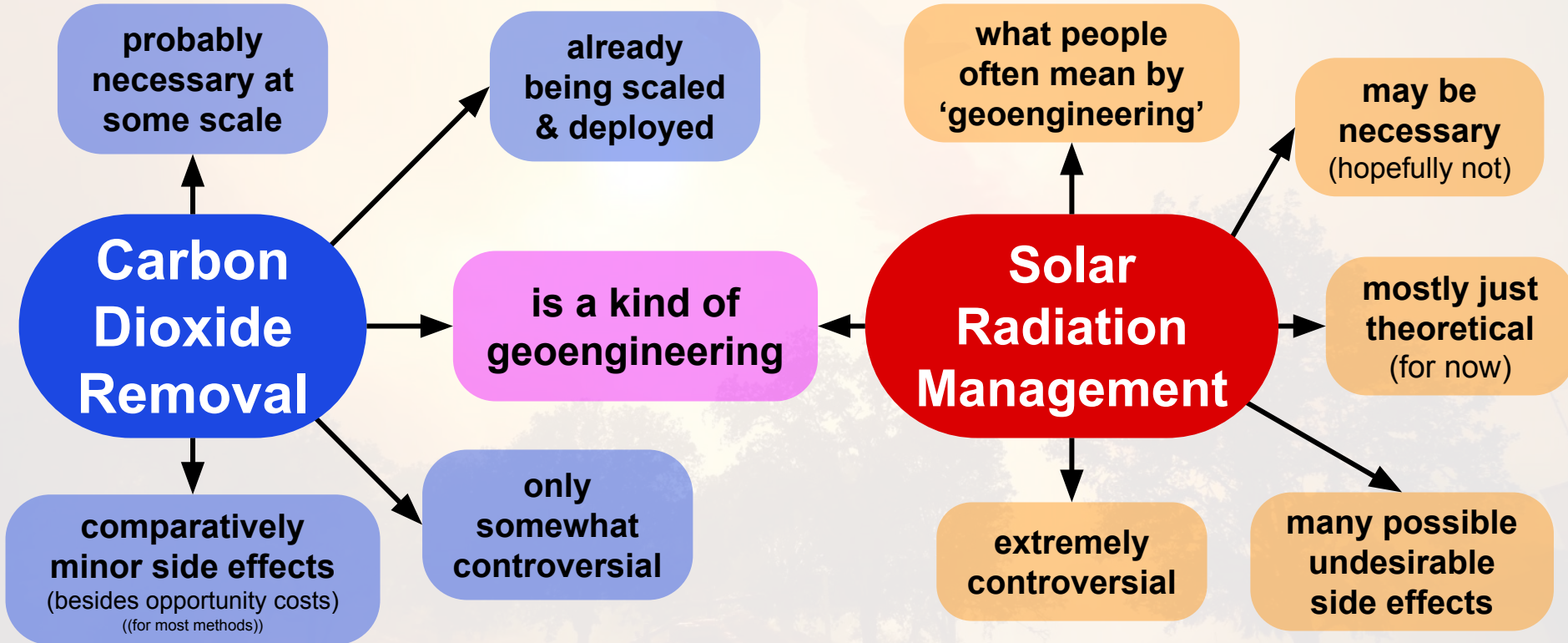
(SRM / “solar geoengineering”)

- ❖ Stratospheric aerosol dispersion
- ❖ Cirrus cloud thinning
- ❖ Marine cloud brightening
- ❖ Orbital mirror deployment

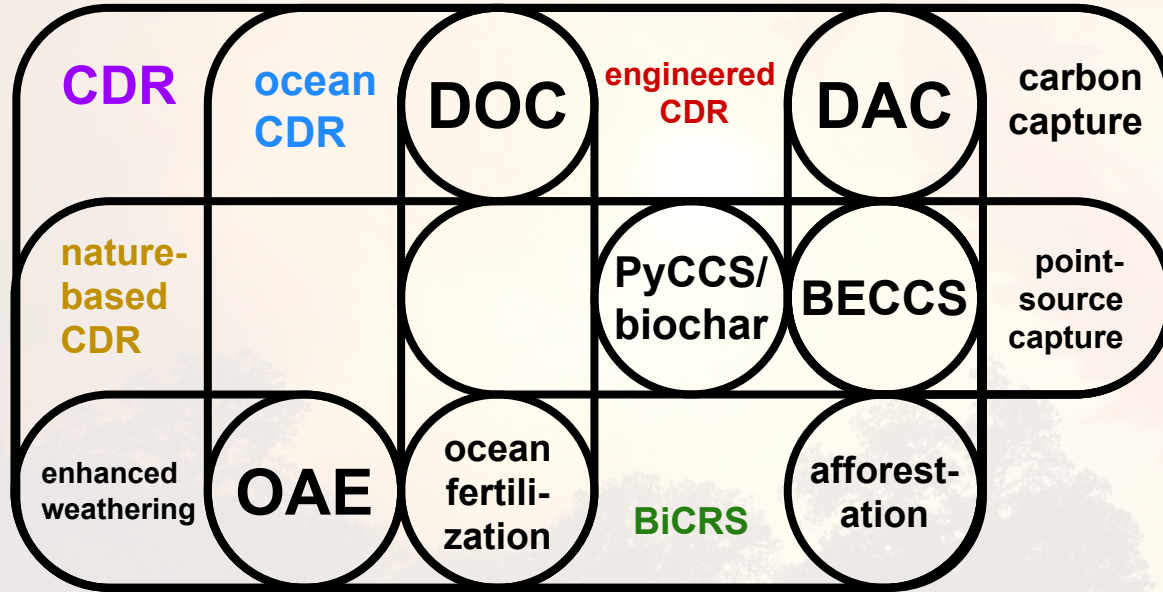
Others

- ❖ Surface albedo modification
- ❖ Glacier stabilization
- ❖ Coastal engineering
- ❖ Other, even dumber ideas

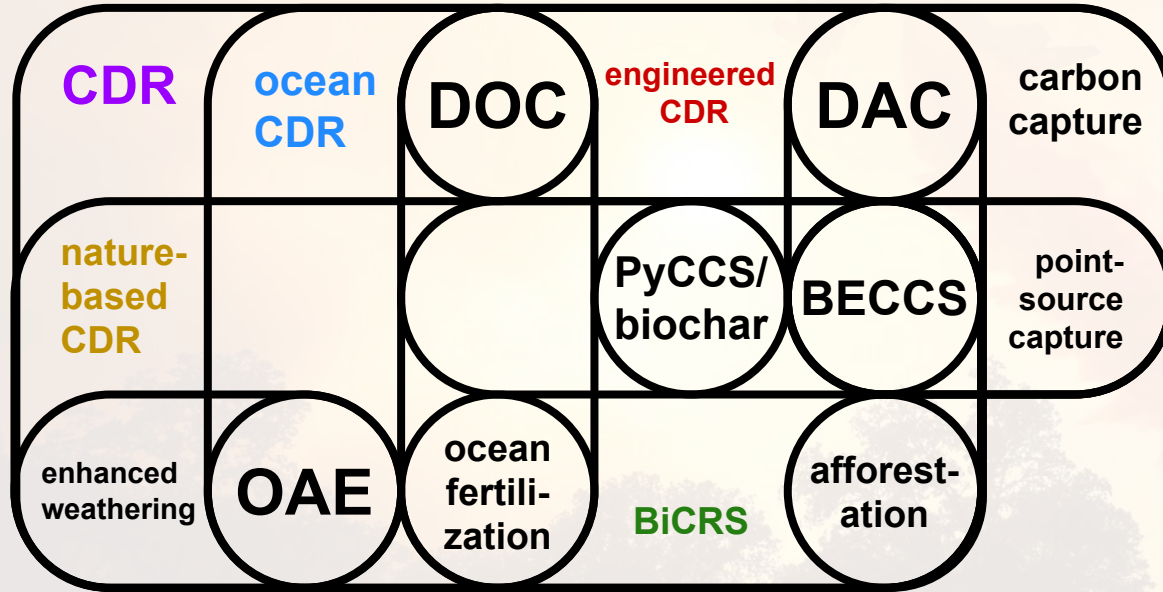
i know this is confusing



Every CDR Technology in One Simple Venn Diagram

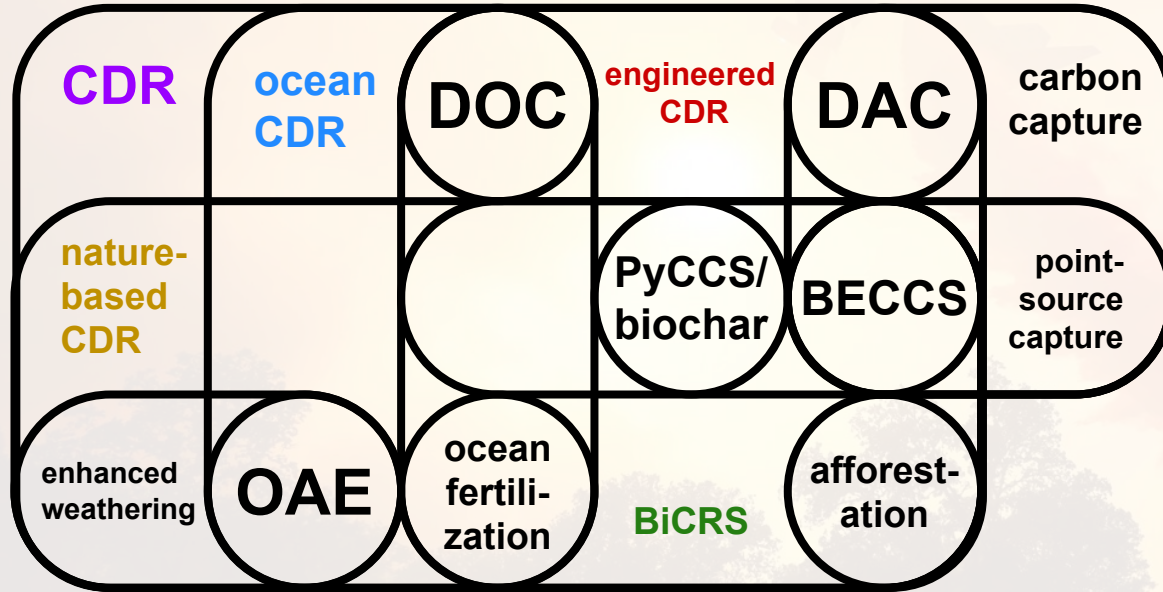


Every* CDR Technology in One Simple Venn Diagram



* does not actually include every CDR technology

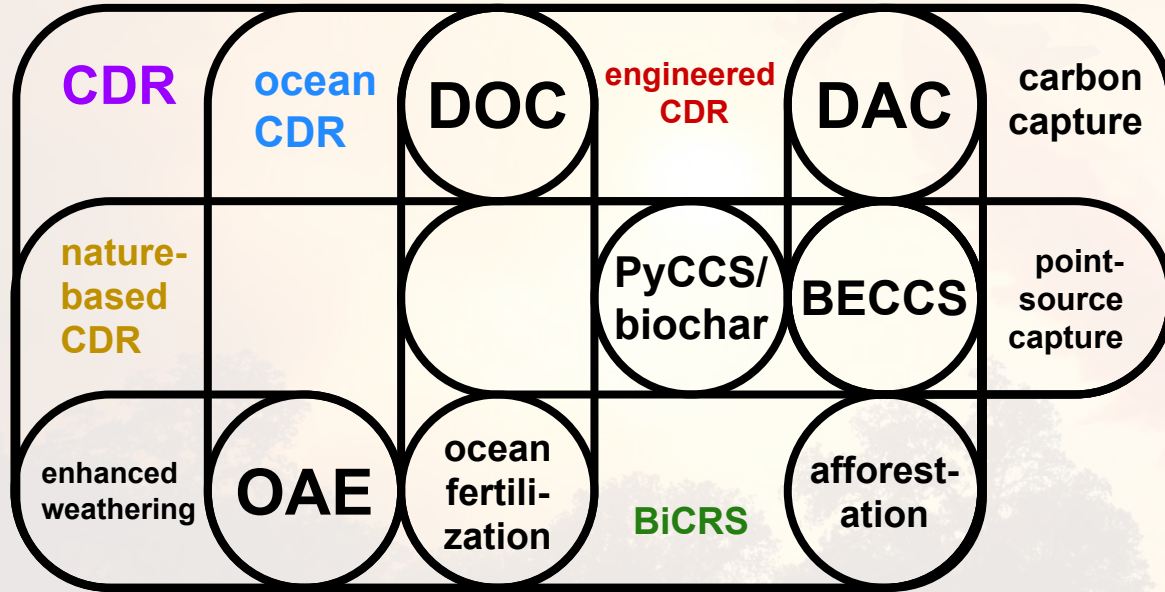
Every* CDR Technology in One Simple† Venn Diagram



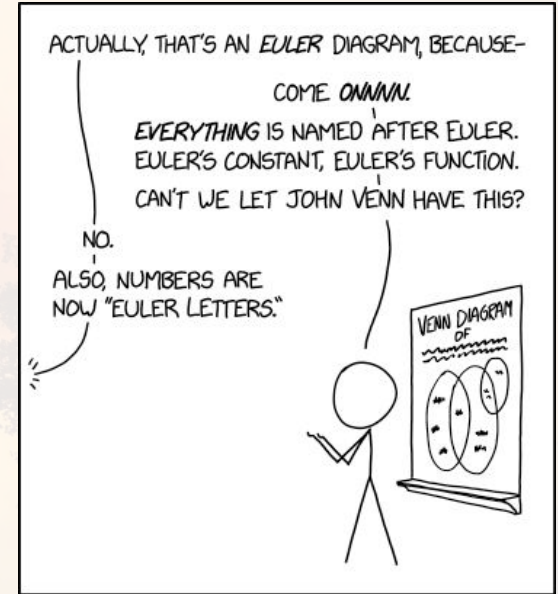
* does not actually include every CDR technology

† really not all that simple

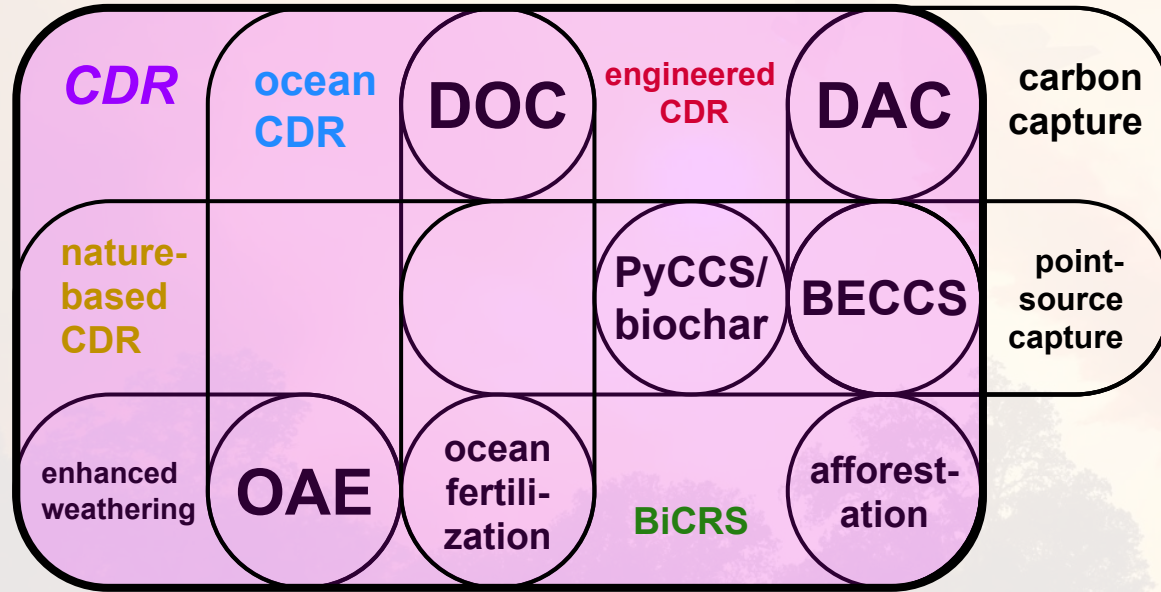
Every* CDR Technology in One Simple† Venn‡ Diagram



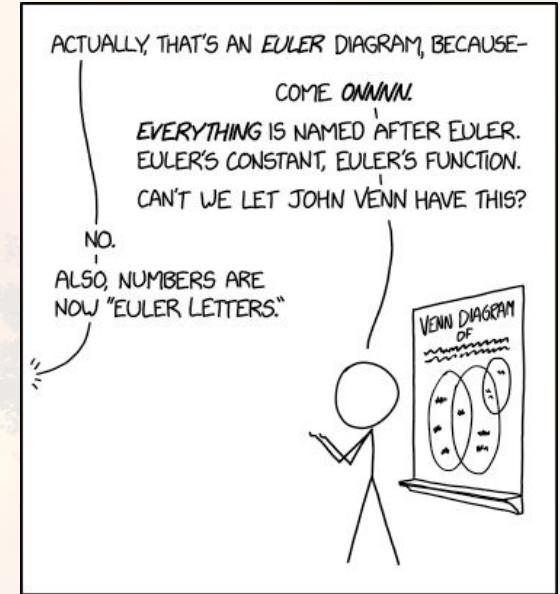
- * does not actually include every CDR technology
- † really not all that simple
- ‡ technically this is considered an “Euler diagram”



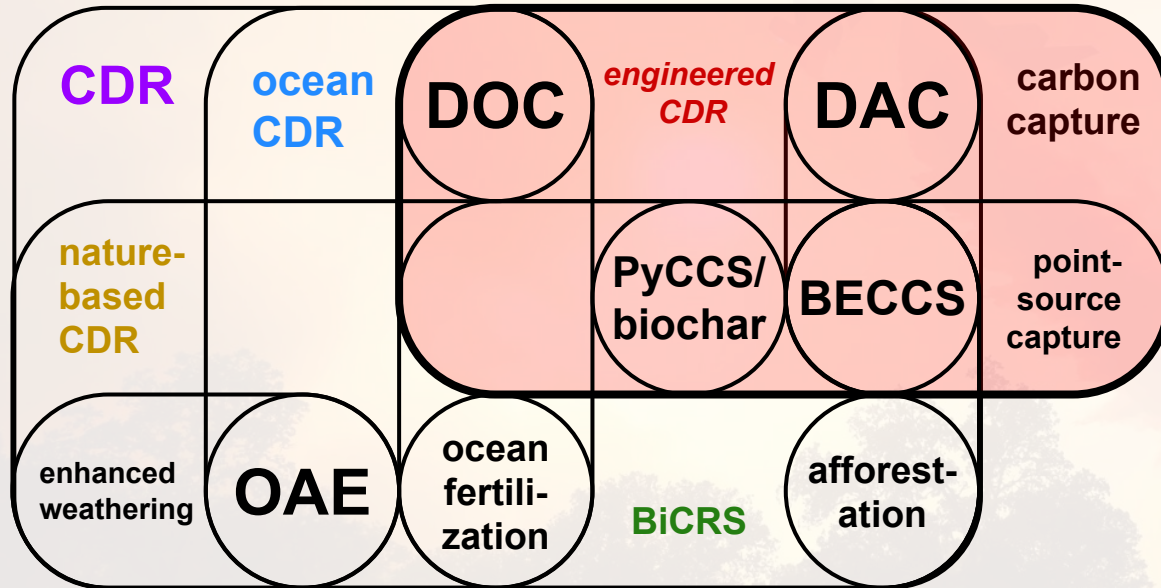
Every* CDR Technology in One Simple† Venn‡ Diagram



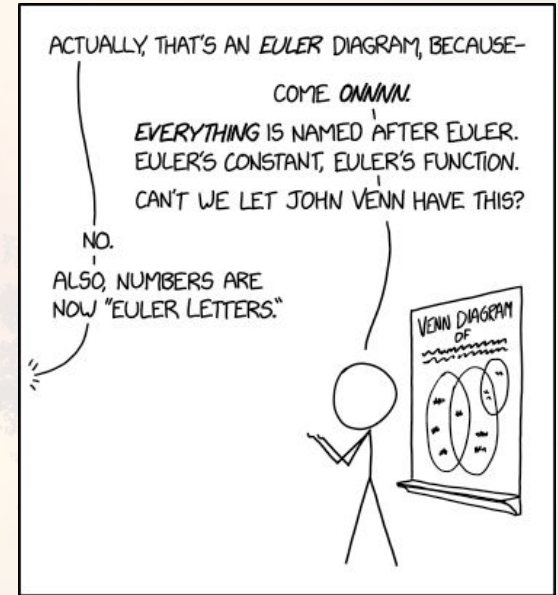
- * does not actually include every CDR technology
- † really not all that simple
- ‡ technically this is considered an "Euler diagram"



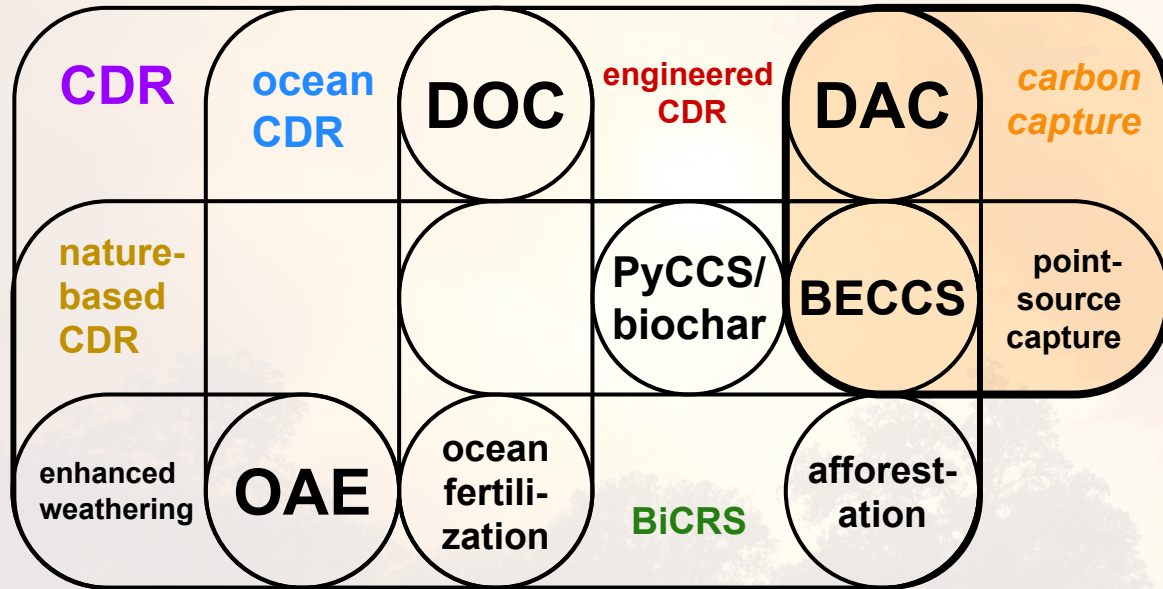
Every* CDR Technology in One Simple† Venn‡ Diagram



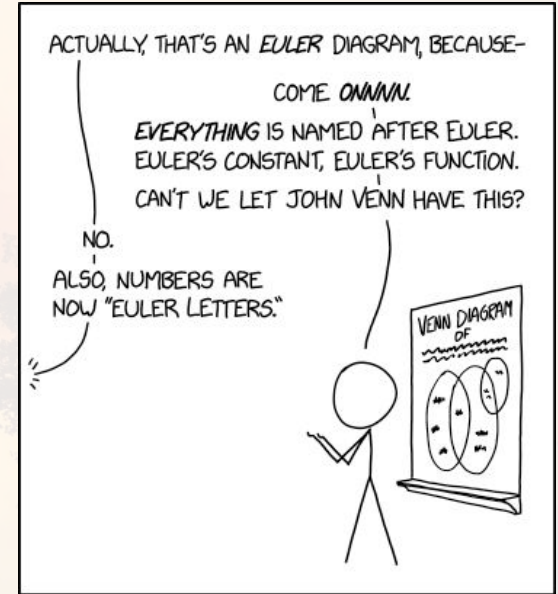
- * does not actually include every CDR technology
- † really not all that simple
- ‡ technically this is considered an "Euler diagram"



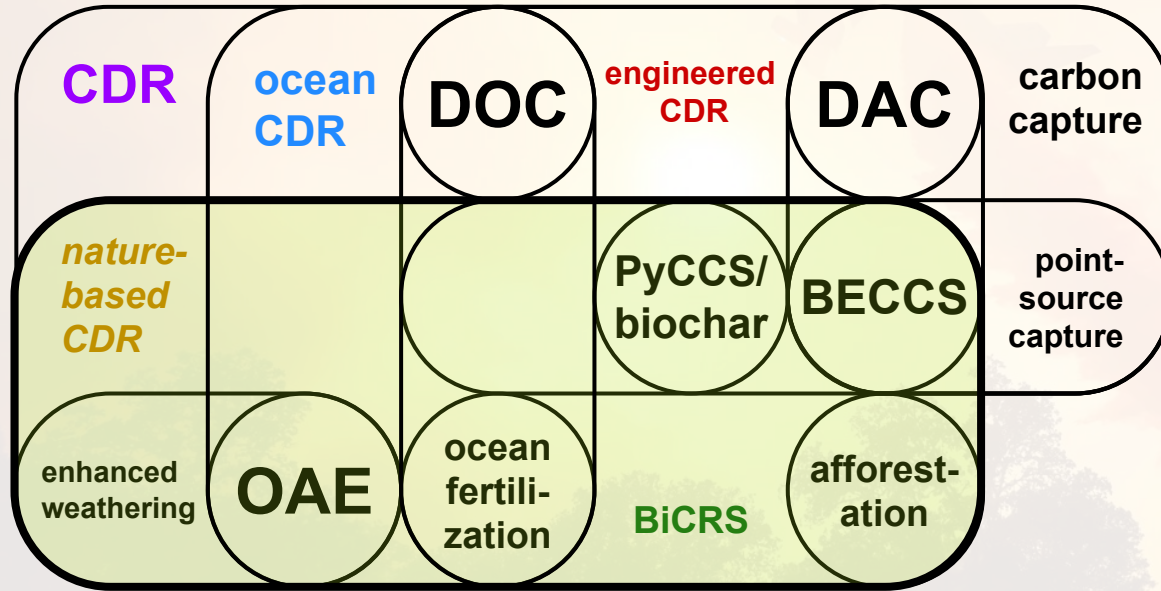
Every* CDR Technology in One Simple† Venn‡ Diagram



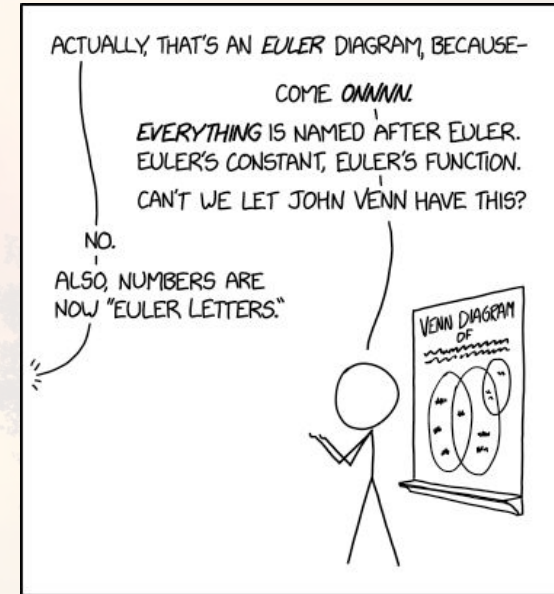
- * does not actually include every CDR technology
- † really not all that simple
- ‡ technically this is considered an “Euler diagram”



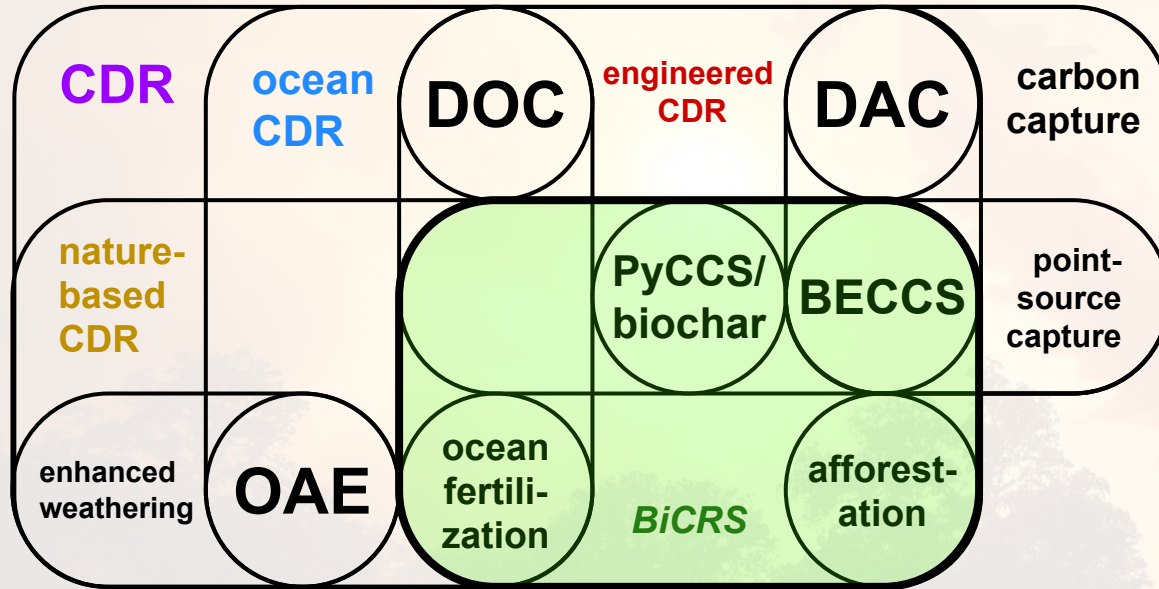
Every* CDR Technology in One Simple† Venn‡ Diagram



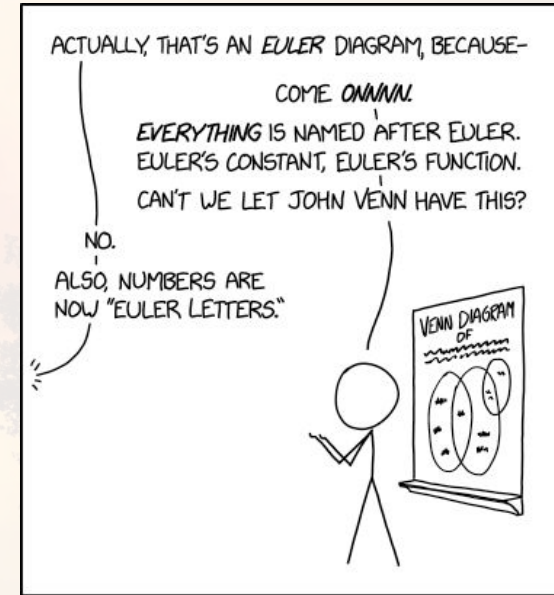
- * does not actually include every CDR technology
- † really not all that simple
- ‡ technically this is considered an "Euler diagram"



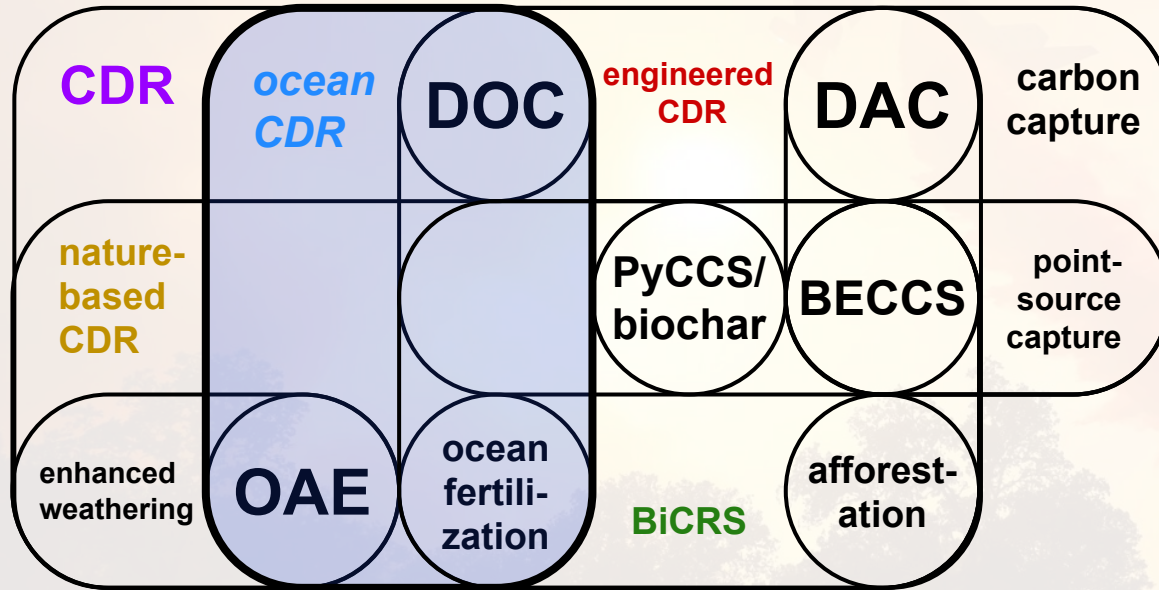
Every* CDR Technology in One Simple† Venn‡ Diagram



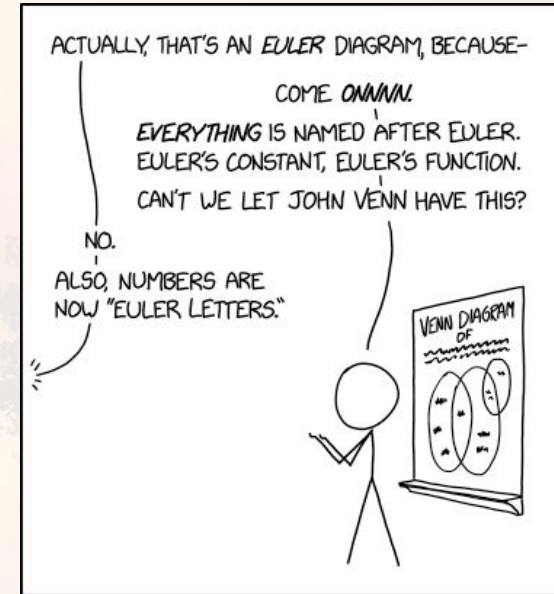
- * does not actually include every CDR technology
- † really not all that simple
- ‡ technically this is considered an "Euler diagram"



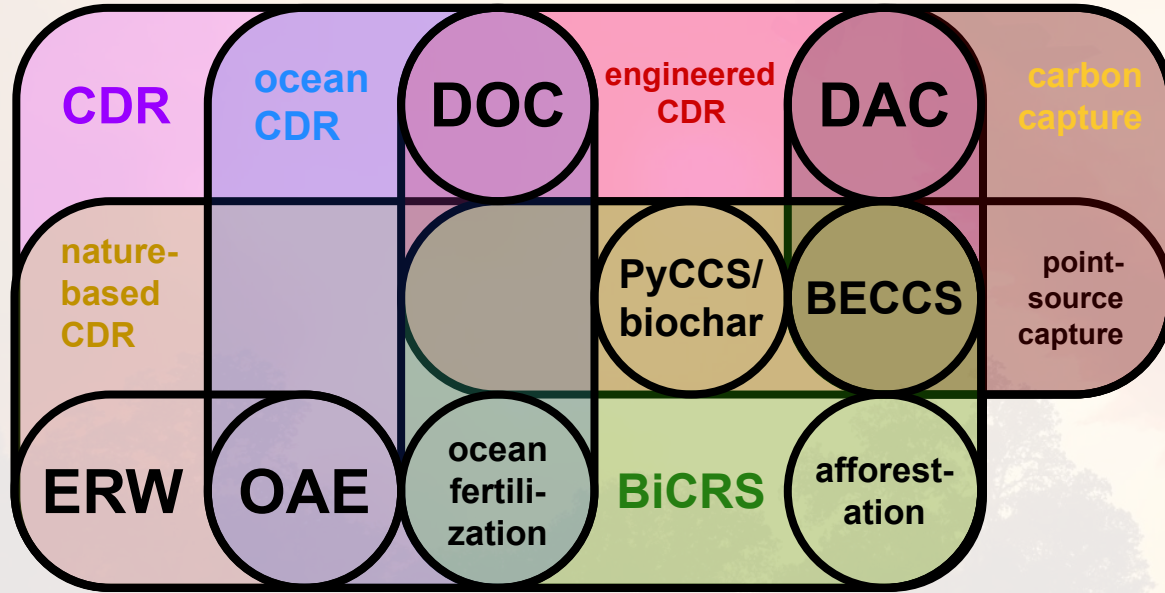
Every* CDR Technology in One Simple† Venn‡ Diagram



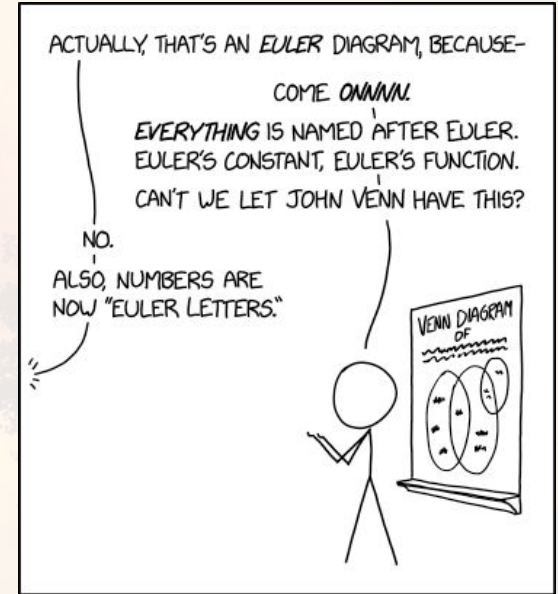
- * does not actually include every CDR technology
- † really not all that simple
- ‡ technically this is considered an “Euler diagram”



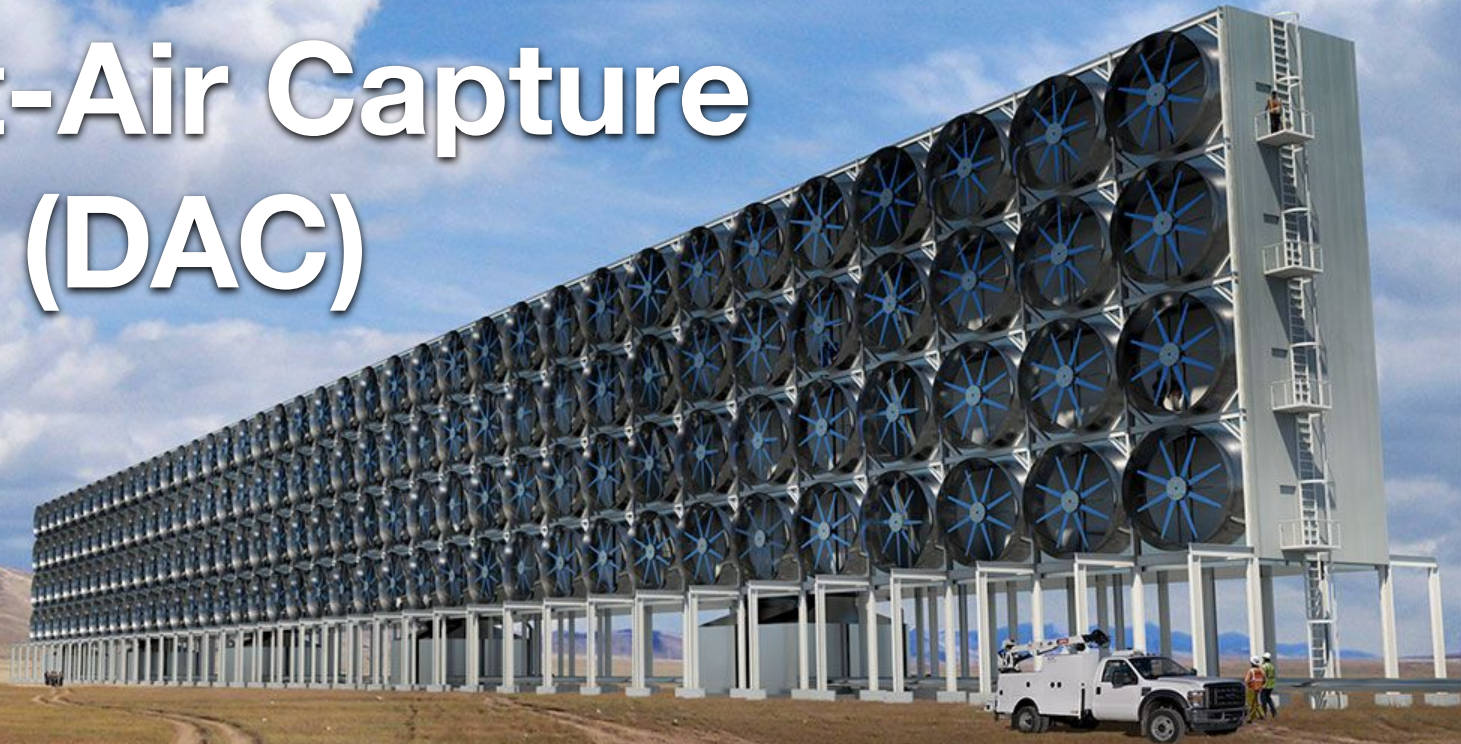
Every* CDR Technology in One Simple† Venn‡ Diagram



- * does not actually include every CDR technology
- † really not all that simple
- ‡ technically this is considered an “Euler diagram”



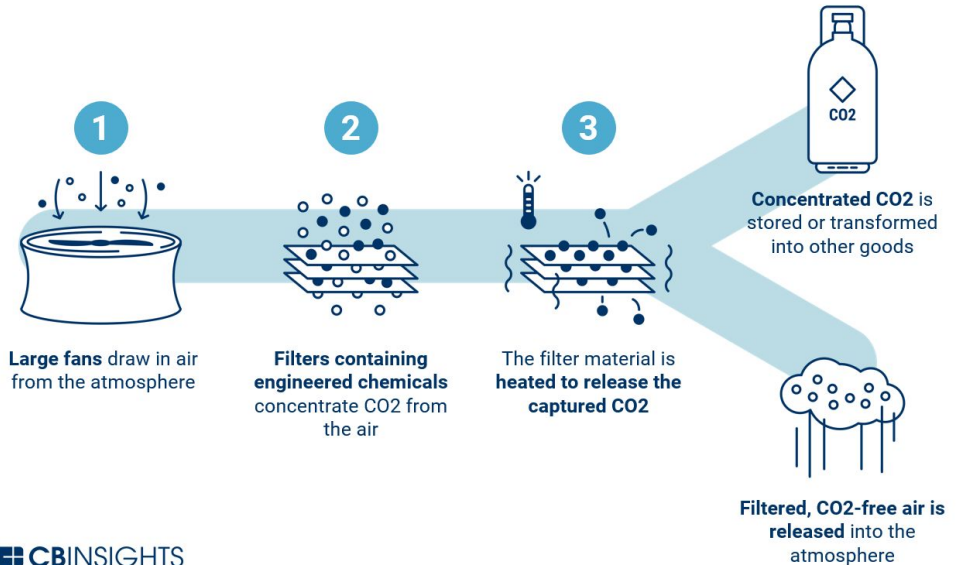
Direct-Air Capture (DAC)



Direct-Air Capture (DAC)

- literally just a big machine to filter CO₂ out of the air
- needs energy (\$\$\$) to run fans, regenerate filters

How direct air capture works



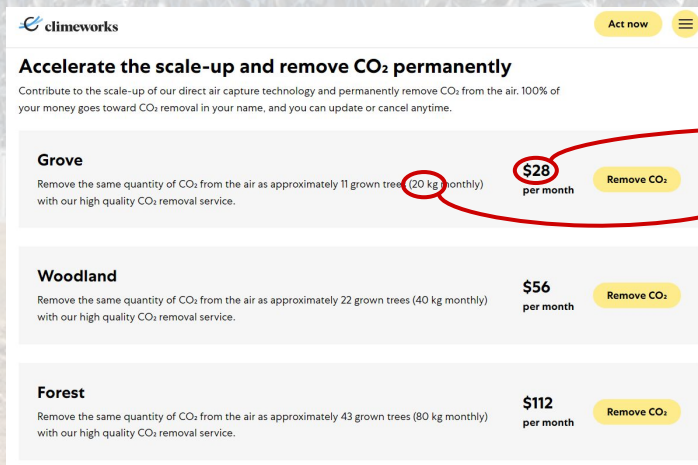
Direct-Air Capture (DAC)

Pros:

- + already being scaled & deployed
- + no real negative side effects
- + it just works!

Cons:

- so expensive!



The screenshot shows the Climevents website interface. At the top, there is a navigation bar with the Climevents logo and an 'Act now' button. Below the navigation bar, a headline reads 'Accelerate the scale-up and remove CO₂ permanently'. A sub-headline states: 'Contribute to the scale-up of our direct air capture technology and permanently remove CO₂ from the air. 100% of your money goes toward CO₂ removal in your name, and you can update or cancel anytime.' The main content area features three rows of options, each with a title, description, price, and a 'Remove CO₂' button. The 'Grove' option is highlighted with red circles around the price '\$28 per month' and the quantity '(20 kg monthly)'. The 'Woodland' option has a price of '\$56 per month' and a quantity of '(40 kg monthly)'. The 'Forest' option has a price of '\$112 per month' and a quantity of '(80 kg monthly)'. Red arrows point from the '\$28' and '(20 kg monthly)' in the Grove row to a handwritten calculation on the right side of the slide.

Option	Price	Quantity
Grove	\$28 per month	20 kg monthly
Woodland	\$56 per month	40 kg monthly
Forest	\$112 per month	80 kg monthly

$$\begin{aligned} & \frac{\$28}{20 \text{ kg CO}_2} \times \frac{1000 \text{ kg}}{1 \text{ tonne}} \\ &= \frac{\$1400}{\text{tCO}_2} \end{aligned}$$

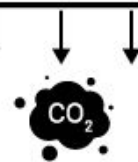
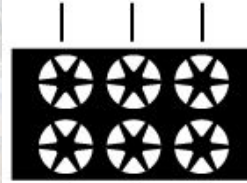
Point-Source Capture

- Just like DAC but filters CO_2 from industrial waste streams (i.e. smokestacks)
- More CO_2 from a smokestack than air
 - easier to capture

2 APPROACHES TO CAPTURING CARBON

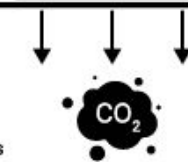
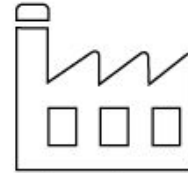
Direct air capture

CO_2 is directly captured from atmosphere and sequestered underground or used in other processes.



Point source capture

CO_2 is captured from industrial waste streams such as power plants and sequestered underground or used in other processes.



As of July 13, 2022.
Source: Climeworks

Point-Source Capture

Pros:

- + cheaper than DAC (per CO₂ molecule)
- + retrofit solution to decarbonize hard-to-abate heavy industries

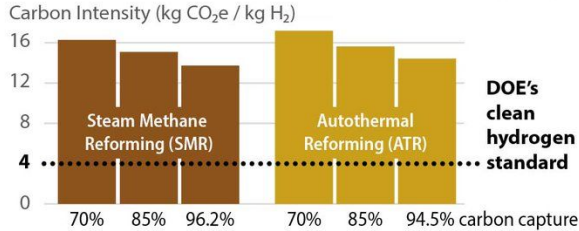
Cons:

- “avoided emissions”, not “negative emissions”
- ~90% efficient at best
- high CapEx, unclear value proposition
- precludes transition from fossil fuels

Point-Source Capture

Blue Hydrogen: Clean in Theory But Not Reality

Realistic assumptions for CO₂ capture rates, methane emissions and other factors reveal blue H₂ will be very dirty

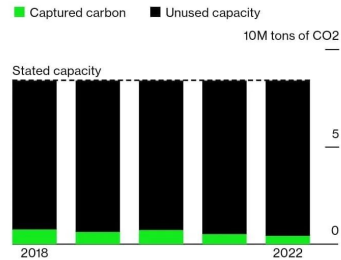


Sources: DOE GREET model, IEEFA analysis

IEEFA

Uncaptured Carbon

Only a small fraction of the CO₂-capturing capacity at the Century plant has ever been used



October 25, 2023 | Updated: 6 days

Occidental Petroleum Quietly Abandons Biggest Carbon Capture Plant

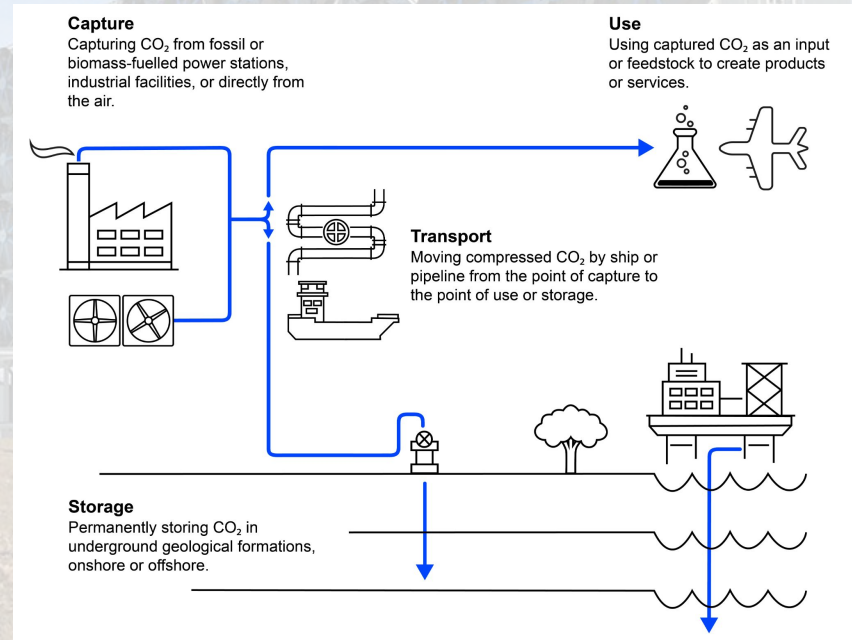
By Jennifer L



"While carbon dioxide emissions are lower, fugitive methane emissions for blue hydrogen are higher than for gray hydrogen because of an increased use of natural gas to power the carbon capture."

What Happens to the CO₂?

- **Utilization / Use**
 - CO₂ is used directly or converted to products
- **Sequestration / Storage**
 - CO₂ is injected underground and hopefully stays there



What Happens to the CO₂?

- Inflation Reduction Act § 45Q defines tax credits for CCUS:

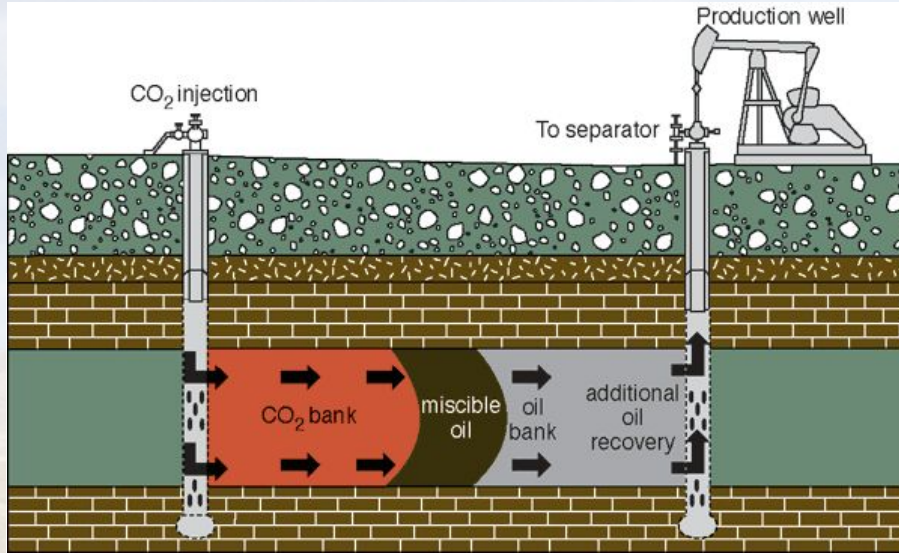
	utilized	sequestered
point-source	\$60/tCO ₂	\$85/tCO ₂
direct-air	\$130/tCO ₂	\$180/tCO ₂

uses for CO₂:

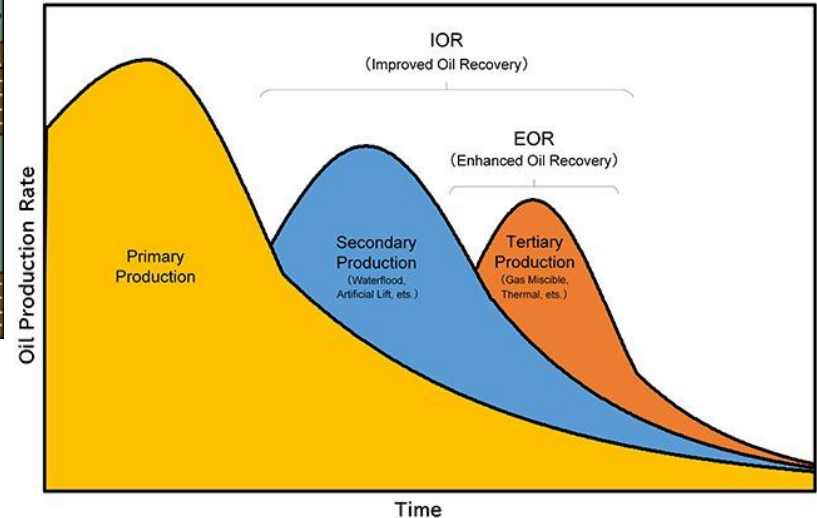
- food & beverage (e.g. seltzer, beer)
- synfuels (e.g. SAF)

...but that's not the #1 use of captured CO₂:

the primary use of CO₂ is drilling oil



EOR: Enhanced Oil Recovery



(i) used by the taxpayer as a tertiary injectant in a qualified enhanced oil or natural gas recovery project and disposed of by the taxpayer in secure geological storage, or

(ii) utilized by the taxpayer in a manner described in subsection (f)(5).

Enhanced Rock Weathering (ERW)

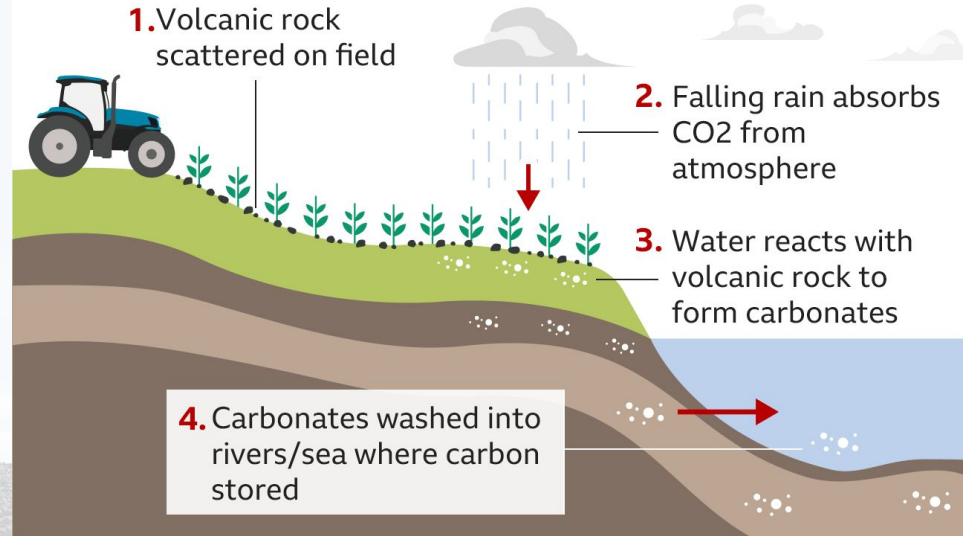


Enhanced Rock Weathering (ERW)

- some kinds of rock (silicates, basalts, olivine) naturally absorb CO₂ and turn into carbonates
 - mine em, grind em up, let em rip



How enhanced rock weathering works



Source: BBC research, Getty Images

Enhanced Rock Weathering (ERW)

Pros:

- + comparatively cheap (est. ~\$150/tCO₂)
- + more than enough silicates in the crust to scale globally

Cons:

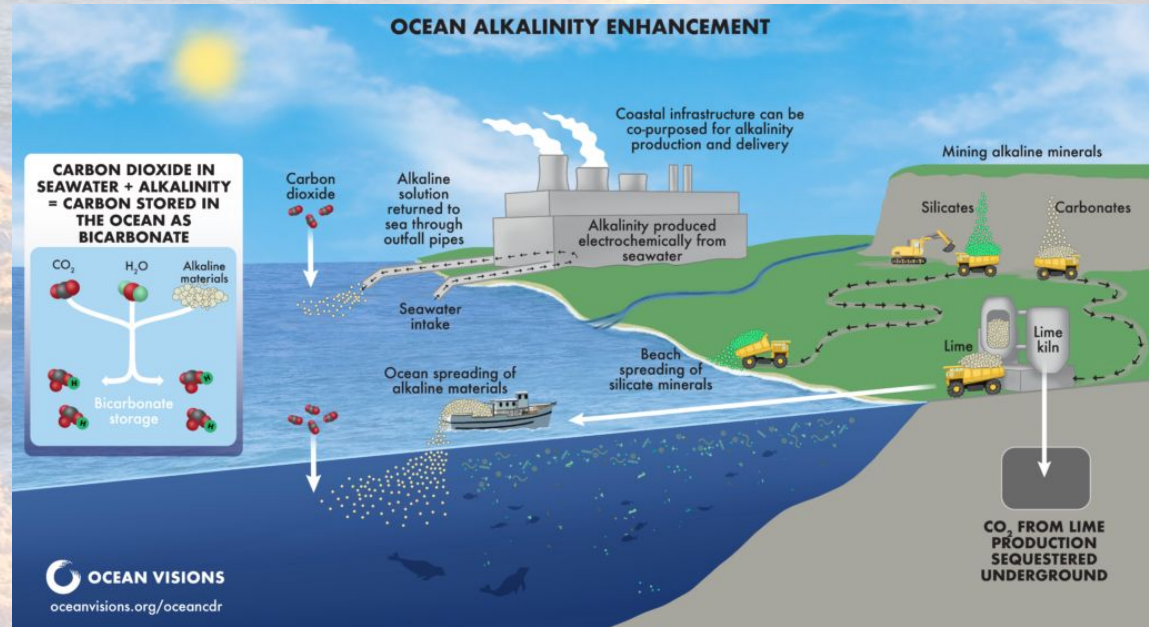
- difficult to quantify total carbon removed
 - risk of heavy metal leaching into soil, water
 - have to mine, grind rock
 - can be extremely slow
-

Ocean Alkalinity Enhancement (OAE)



Ocean Alkalinity Enhancement (OAE)

- grind up the silicates and scatter them in the ocean



Ocean Alkalinity Enhancement (OAE)

Pros:

- + probably even cheaper than ERW (est. ~\$50/tCO₂)
- + could counteract ocean acidification

Cons:

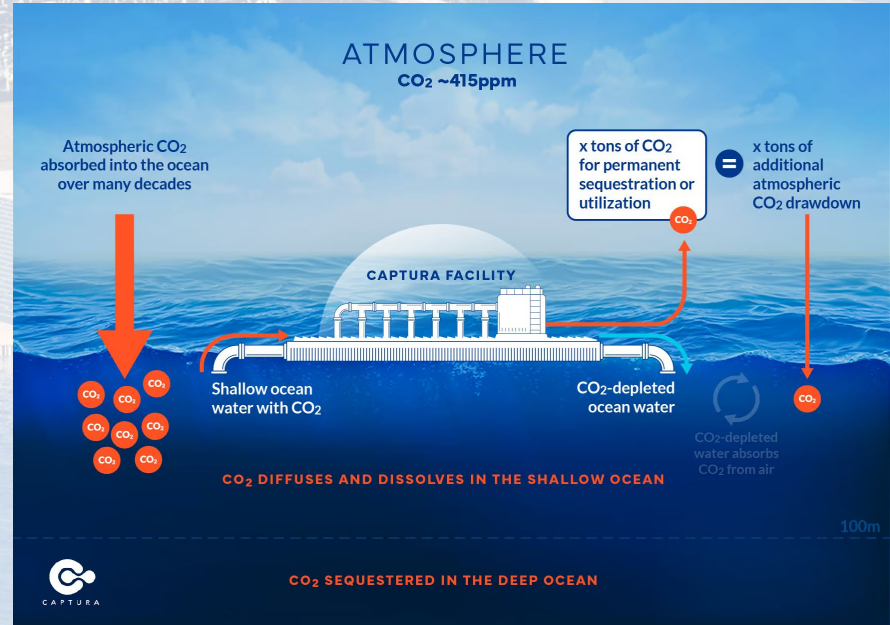
- difficult to quantify total carbon removed
- heavy metal leaching directly into ocean
- have to mine, grind rock
- the ocean is big and scary



Direct Ocean Capture (DOC)

Direct Ocean Capture (DOC)

- extract dissolved CO_2 gas from ocean water
- decarbonized seawater reabsorbs atmospheric CO_2



Direct Ocean Capture (DOC)

Pros:

- + more energy-efficient & cheaper than DAC
- + probably minimal negative side effects
- + CO₂ is a potential revenue stream

Cons:

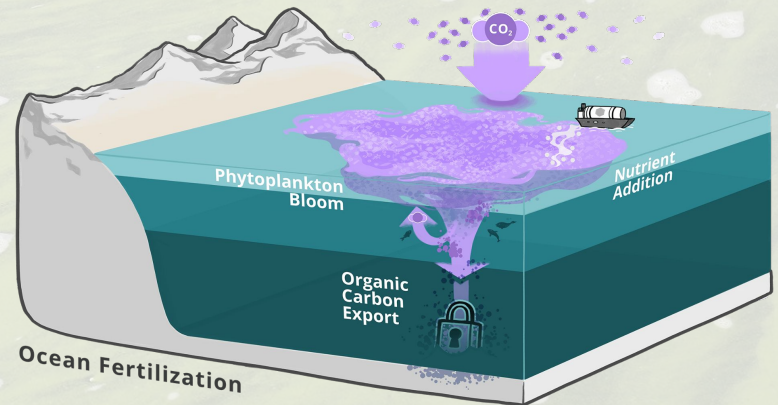
- still have to sequester or utilize the CO₂
- remote ocean location makes both more costly

Ocean Fertilization



Ocean Fertilization

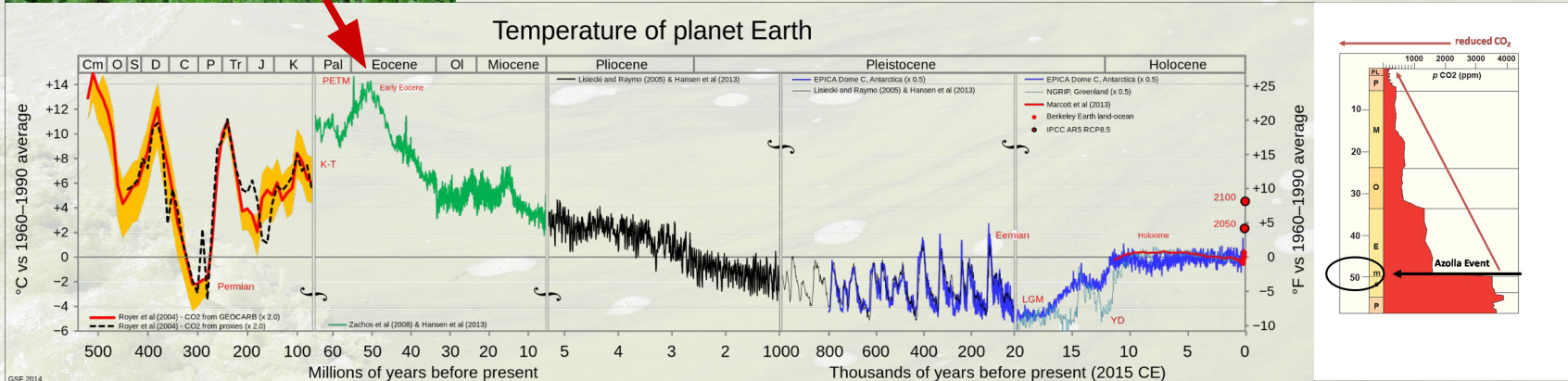
- photosynthetic microalgae (phytoplankton) are often resource-limited in Fe, N, P, etc.
- add nutrients to induce ocean algal bloom (eutrophication)
- plankton suck up CO_2 , sink to bottom of sea



Ocean Fertilization: The Azolla Event



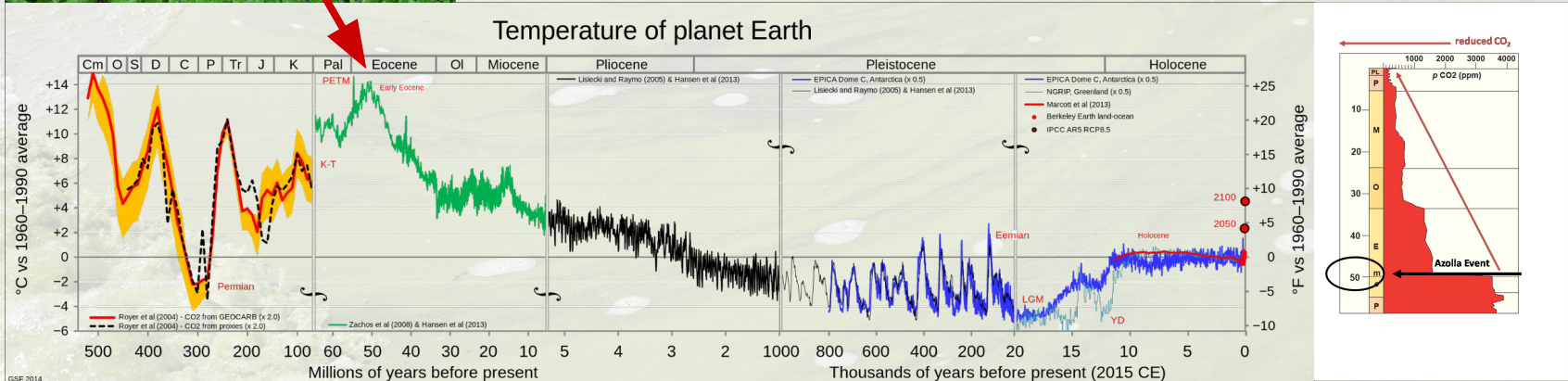
- This has (probably) happened before!



Ocean Fertilization: The Azolla Event



- This has (probably) happened before!
 - 50 m.y.a. the oceans filled up with *Azolla* ferns that sucked up all the CO₂, sunk to the seafloor, and ended hothouse earth



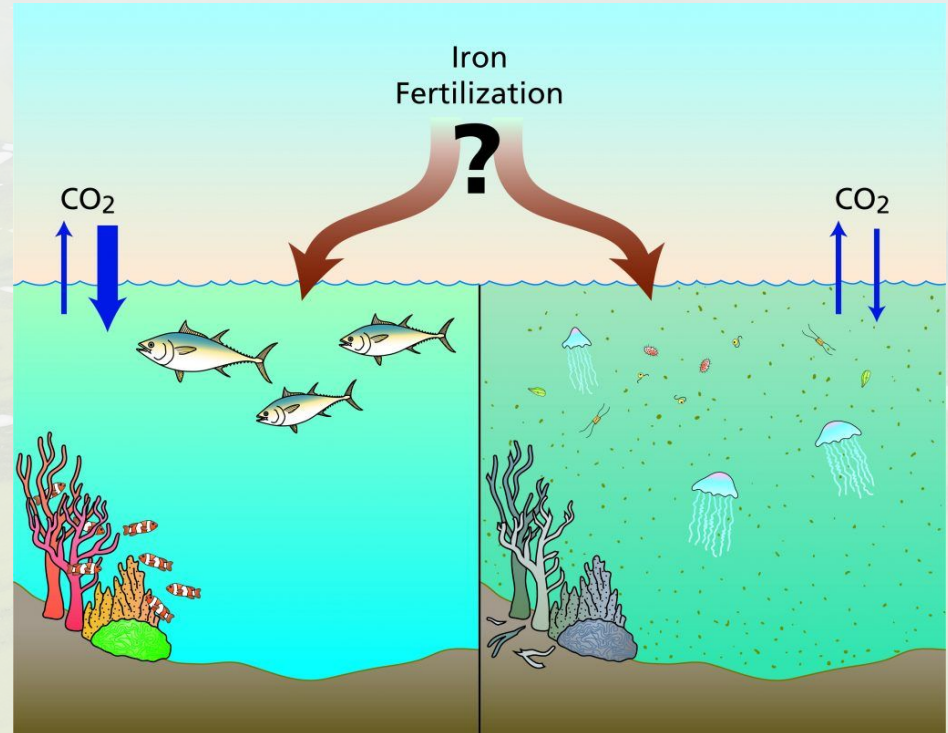
Ocean Fertilization

Pros:

- + good enough for the early Cretaceous

Cons:

- carbon sequestration may be temporary (upwelling)
- might fuck up the entire ocean ecosystem, whoops



Biomass Carbon Removal & Storage (BiCRS):

**Bioenergy + Carbon
Capture & Storage
(BECCS)**

Afforestation

**Biochar Carbon Removal
(BCR)**

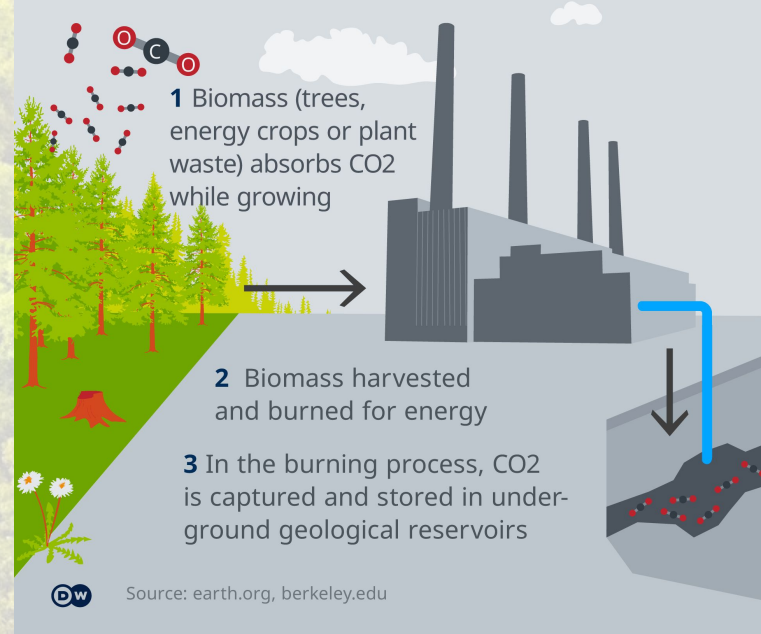
AKA

**Pyrogenic Carbon Capture
& Storage (PyCCS)**

Bioenergy + Carbon Capture & Storage (BECCS)

- Combine bioenergy with point-source carbon capture

Bioenergy with carbon capture and storage (BECCS)



Bioenergy + Carbon Capture & Storage (BECCS)

Pros:

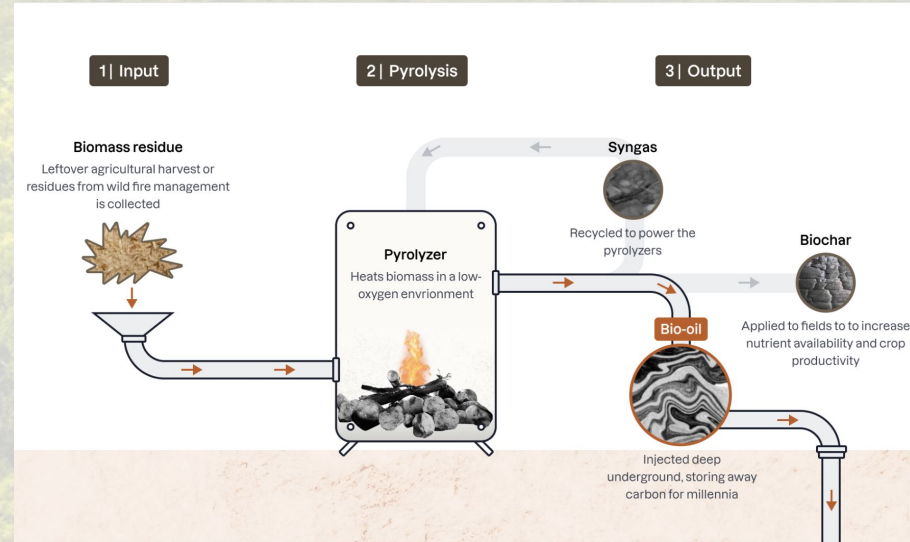
- + carbon-negative energy generation!
- + point-source capture is easier than DAC

Cons:

- high land & water use
- competition w/ food crops
- associated costs & risks of CO₂ sequestration

Biochar Carbon Removal (BCR) AKA Pyrogenic Carbon Capture & Storage (PyCCS)

- pyrolyze plant biomass into solid biochar or liquid bio-oil
- spread biochar on fields, inject bio-oil into ground



Biochar Carbon Removal (BCR) AKA Pyrogenic Carbon Capture & Storage (PyCCS)

Pros:

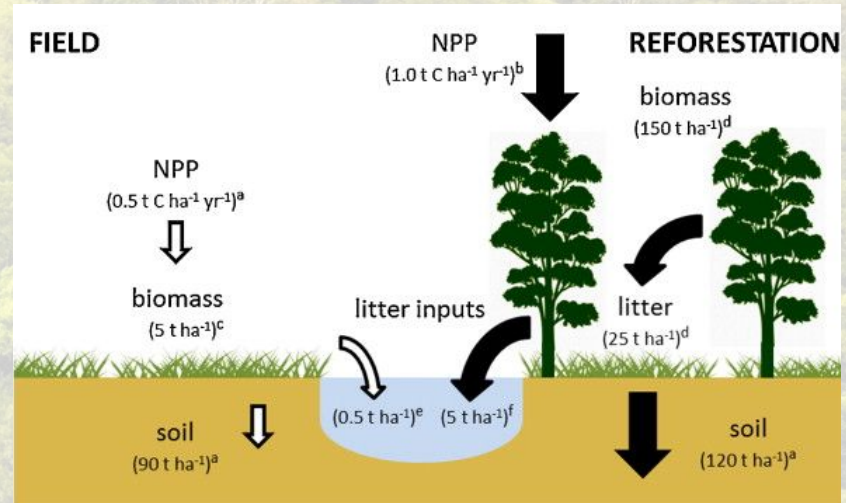
- + solid, liquid C are much stabler sequestration than CO₂ injection
- + can use waste biomass
- + biochar is probably good for soil health

Cons:

- pyrolysis is inefficient, energy-intensive
- limited scalability to just bio-waste pyrolysis
- bio-oil is not very useful

Afforestation

- what if you grew a forest
- that'd be pretty cool



Afforestation

Pros:

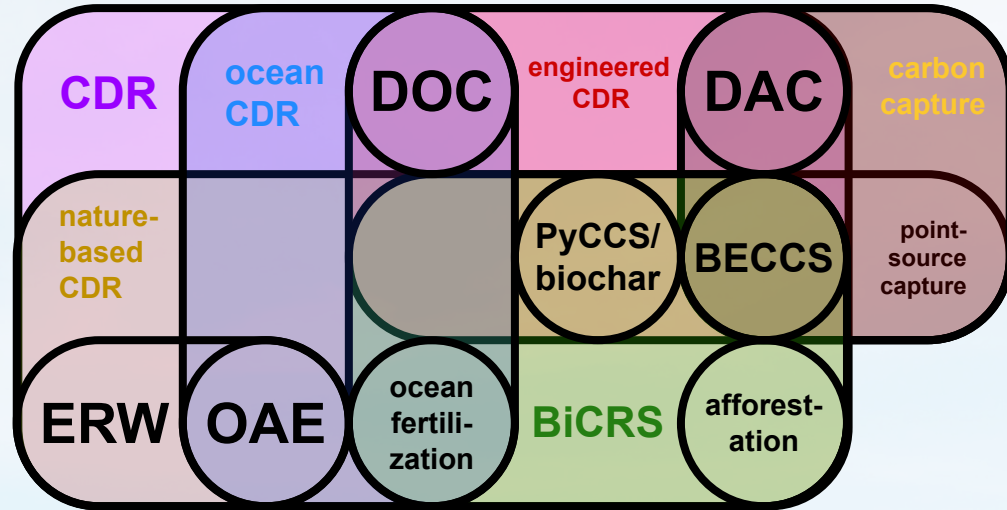
- + it's a forest (:
- + ecosystem benefits
- + fights desertification

Cons:

- not all that land-efficient
- competition w/ food & bioenergy crops
- difficult to quantify total carbon removed

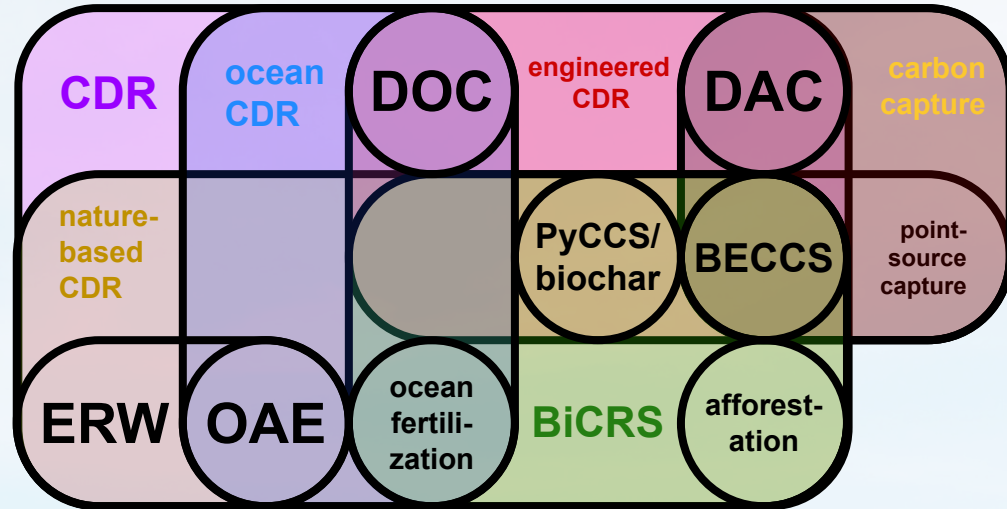
What are the commonalities?

- capturing CO₂ takes energy
 - there are always costs (financial and opportunity)
- the carbon has to go *somewhere*



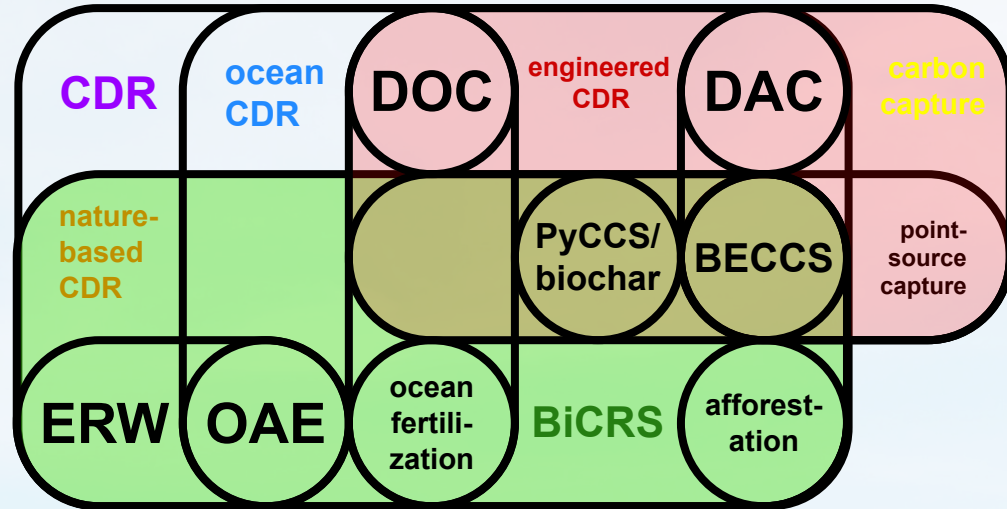
What are the differences?

- How much does it cost?
- How is the C stored?
- How scalable is it?
- How measurable is the carbon drawdown?
- Are there other risks?



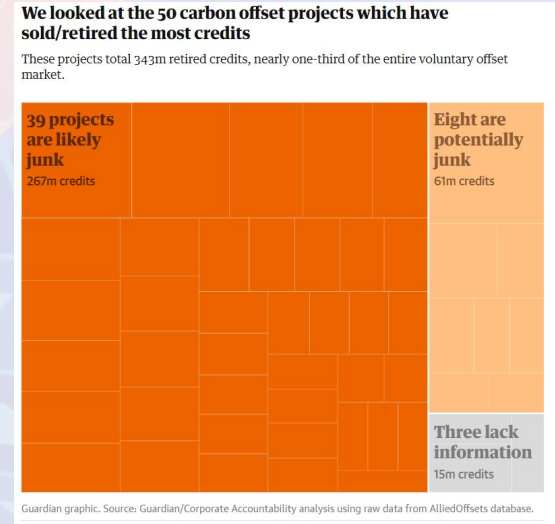
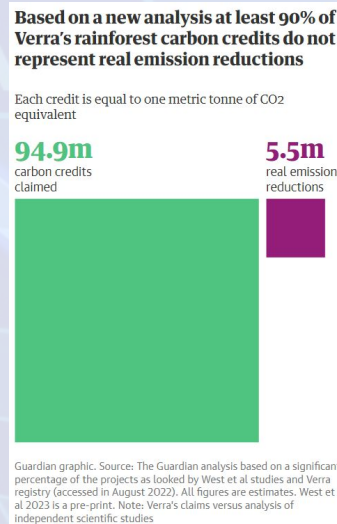
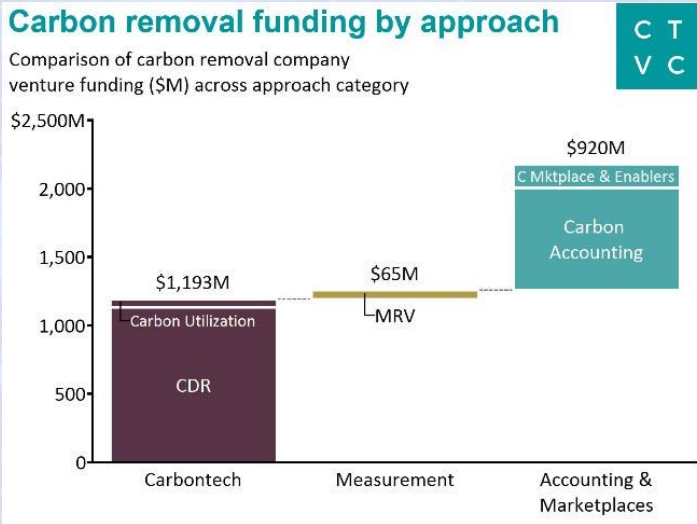
What are the differences?

- How much does it cost?
- How is the C stored?
- How scalable is it?
- How measurable is the carbon drawdown?
- Are there other risks?



Measurement, Reporting, Verification

- Carbon removal is only as good as the proof that it removed CO₂ from the atmosphere



Geoengineering

Carbon Dioxide Removal

(CDR / “negative emissions”)

- ❖ Direct-air capture (DAC)
- ❖ Enhanced weathering (EWR)
- ❖ Biomass carbon removal (BECCS/BiCRS)
- ❖ Pyrolytic carbon removal (biochar, PyCCS)
- ❖ Afforestation / desert greening
- ❖ Ocean carbon removal (DOC, OAE, etc.)

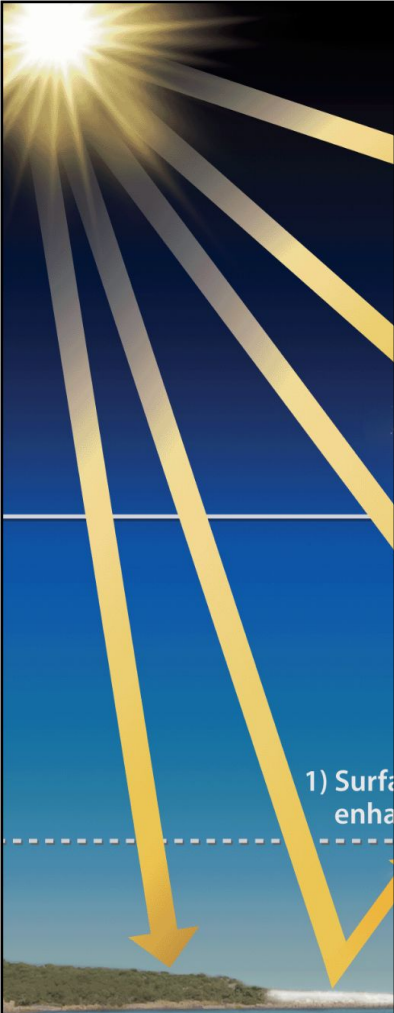
Solar Radiation Management

(SRM / “solar geoengineering”)

- ❖ Stratospheric aerosol dispersion
- ❖ Cirrus cloud thinning
- ❖ Marine cloud brightening
- ❖ Orbital mirror deployment

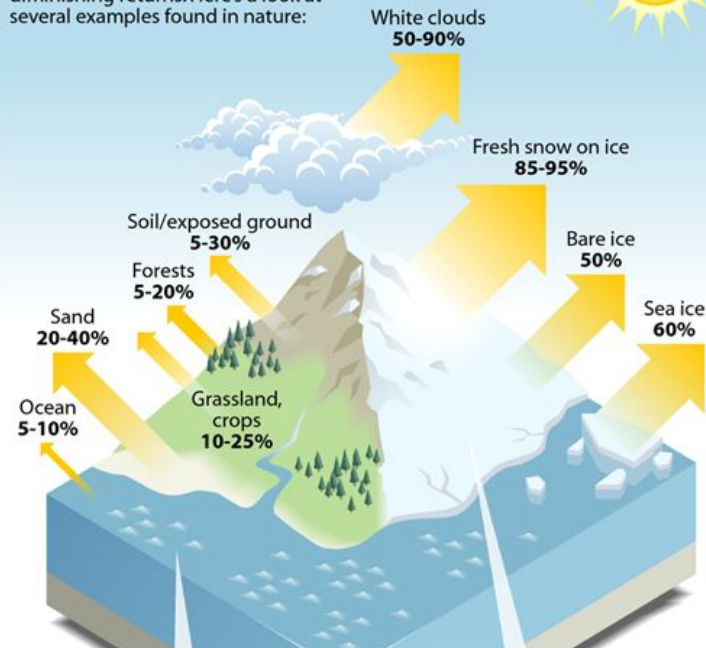
Others

- ❖ Surface albedo enhancement
- ❖ Glacier stabilization
- ❖ Coastal engineering
- ❖ Other, even dumber ideas



Keeping Things Cool: The Albedo Effect

The albedo effect — the reflectivity of sunlight on various surfaces — is important in keeping the Earth cool. Clean, white clouds and fresh snow and ice reflect the most sunlight, while exposed land, water and vegetation have diminishing returns. Here's a look at several examples found in nature:



OCEANS

The oceans act as a heat sink, absorbing nearly all sunlight and reflecting barely a tenth back (at zenith). Warm water hastens the melting of icebergs and ice floes. Oceans expand as they warm, resulting in rising sea levels.

ARCTIC

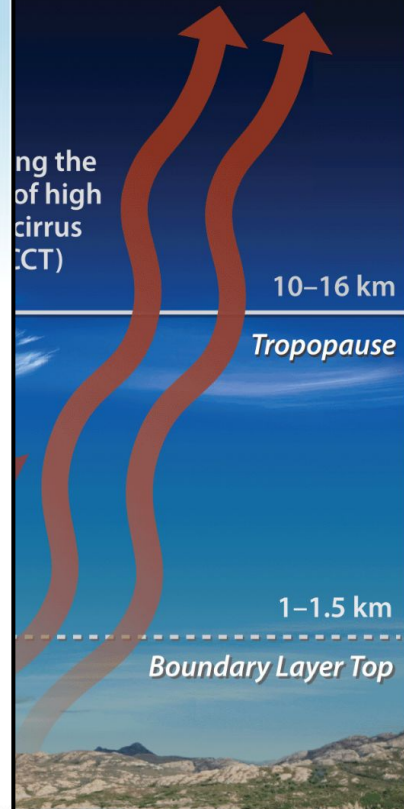
The more snow and ice there is, the less heat is absorbed. But as reduced snowfalls and snow pack leave more ground exposed, more heat is absorbed, exacerbating snow melt.

Note: Illustration is diagrammatic and not to scale.

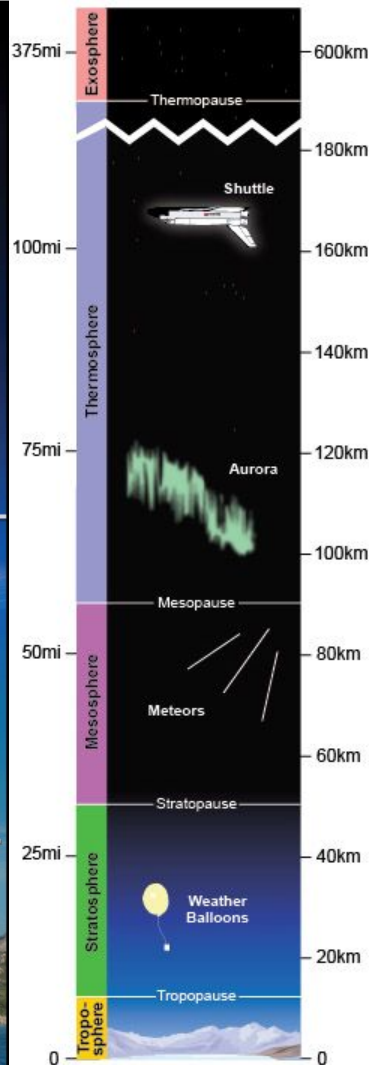
SOURCE: InsideClimate News research

PAUL HORN / InsideClimate News

Solar Climate Intervention Methods



tion of longwave radiation



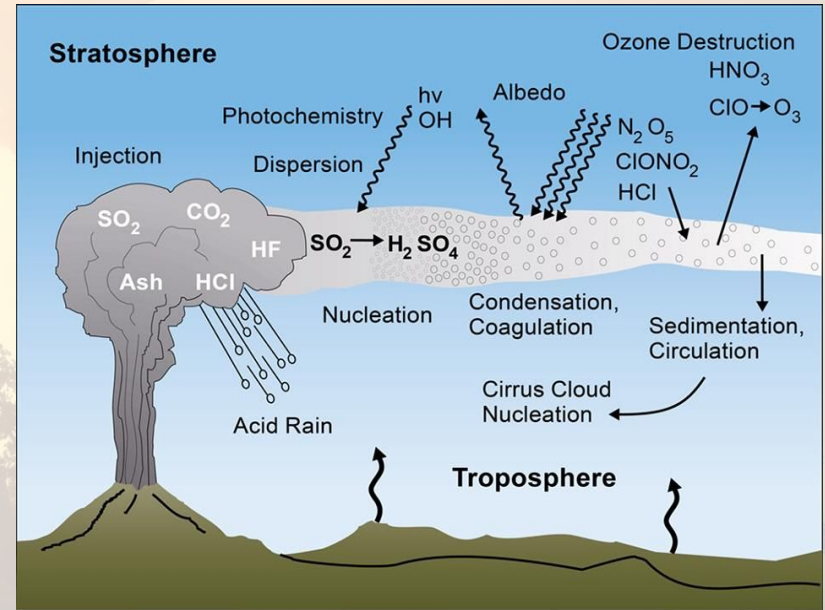
Altering reflection of

Stratospheric Aerosol Injection (SAI)



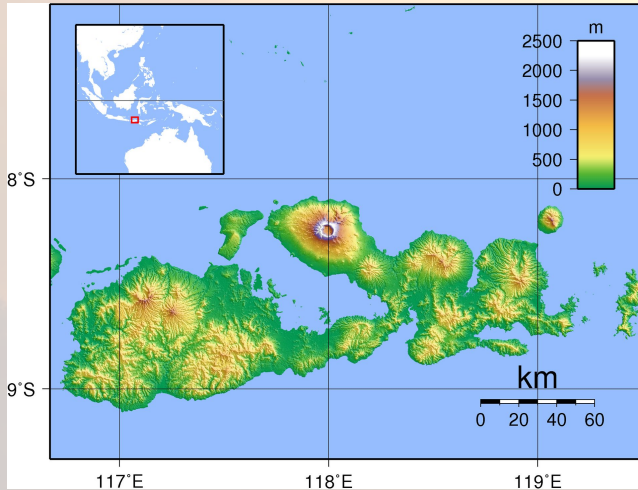
Stratospheric Aerosol Injection (SAI)

- SO_2 is dispersed in stratosphere
- SO_2 forms clouds of sulfuric acid, H_2SO_4
- H_2SO_4 clouds are reflective (high albedo)



Stratospheric Aerosol Injection (SAI)

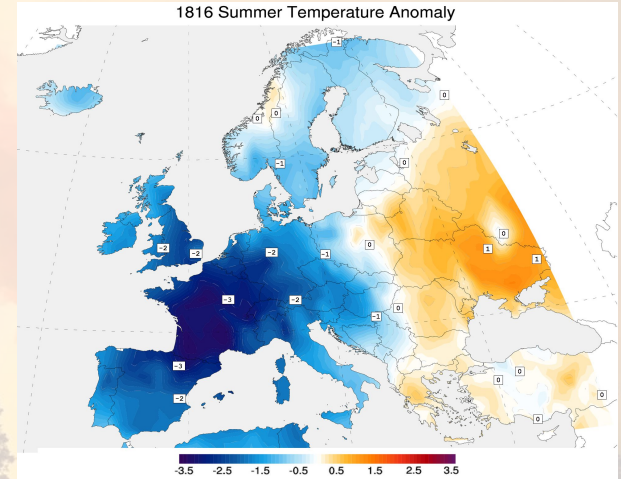
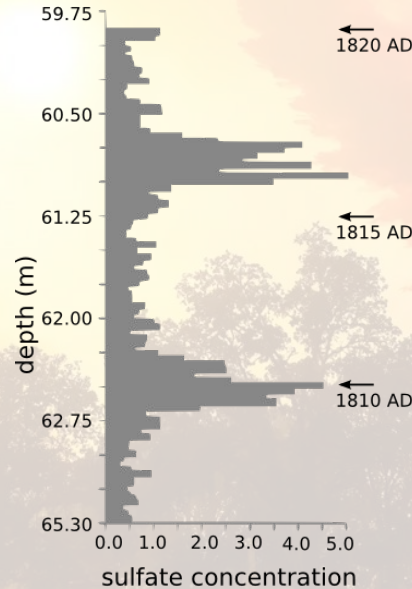
- literally a man-made volcanic winter



Indonesia

April-July 1815

Mt. Tambora erupts



Europe

1816

“The Year Without a Summer”

Stratospheric Aerosol Injection (SAI)

Pros:

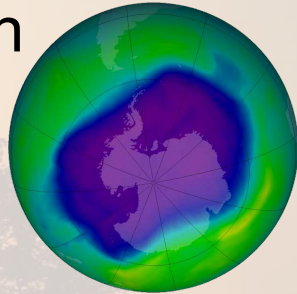
- + comparatively cheap
- + say what you will
(and i'm about to)
but it will almost
certainly lower average
global temperatures

Cons:

- many, many undesirable
side effects
 - exact magnitude of effect
is very hard to estimate
 - termination shock
(it's as bad as it sounds)
-

Stratospheric Aerosol Injection: Risks

- Asian/African monsoon cycle disruption
 - 1783 Laki eruption (Iceland) caused famines in Japan, Egypt, India
- Sulfate deposition (acid rain)
- Reduced cloudiness → regional warming
- Polar stratospheric ozone depletion
 - Antarctic ozone hole hasn't healed, would reopen

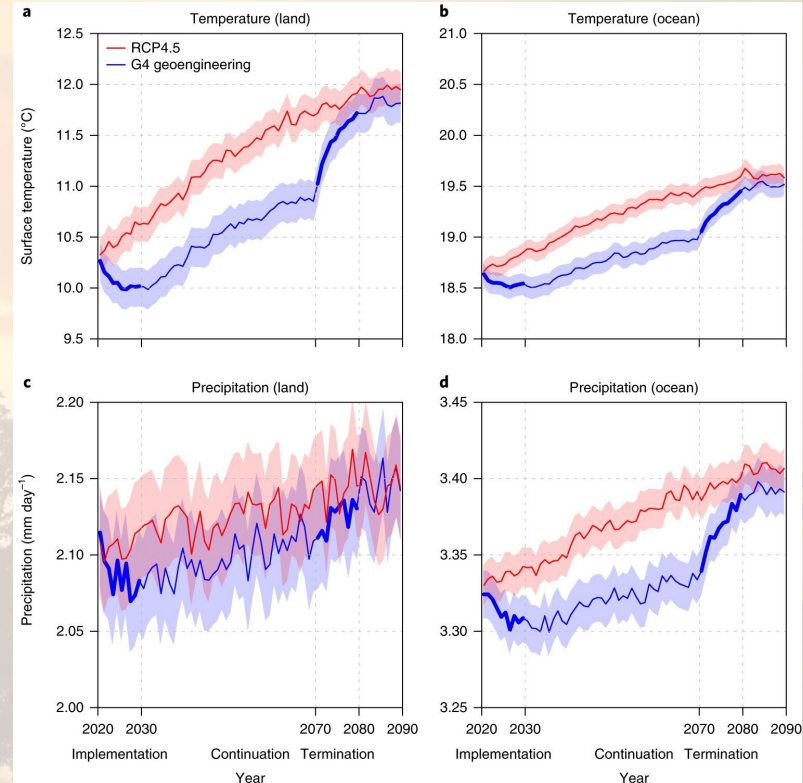


Stratospheric Aerosol Injection: Uncertainties

- Secondary effects on greenhouse gases:
 - Increased lifetime of atmospheric methane
 - Increase in stratospheric water vapor
 - Variable effect on cirrus cloud formation
 - Nonlinear relationship with injection quantity
 - $2\times$ as much $\text{SO}_2 \neq 2\times$ as much cooling
 - Very sensitive to latitude/altitude of injection
 - Risk of undershooting OR overshooting target
-

Termination Shock

➤ if you stop injecting SO_2 *all* the warming you avoided comes back within 1-2 years



Make Sunsets

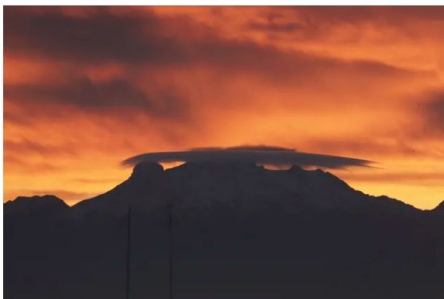
- startup doing unlicensed aerosol injections

Mexico cracks down on solar geoengineering, forcing startup to pause operations

PUBLISHED WED, JAN 18 2023-4:26 PM EST | UPDATED WED, JAN 18 2023-4:41 PM EST

CLIMATE / ENVIRONMENT / SCIENCE

Mexico bans solar geoengineering experiments after startup's field tests



/ The startup tried to launch sulfur dioxide into the stratosphere from Baja California, and now, the government of Mexico is cracking down.

By [Justine Calma](#), a science reporter covering the environment, climate, and energy with a decade of experience. She is also the host of the [Hell or High Water](#) podcast.

Jan 18, 2023, 1:59 PM EST | [7 Comments](#) / [7 New](#)



FIRST SAI DEPLOYMENT IN THE USA

Cowboy Geoengineering

- Make Sunsets is:
 - Luke Iseman
(BS Economics, Penn)
 - Andrew Song
(BS Economics, NYU)
- No meteorologists
- No detection or MRV
 - “Our customers don’t care about that”



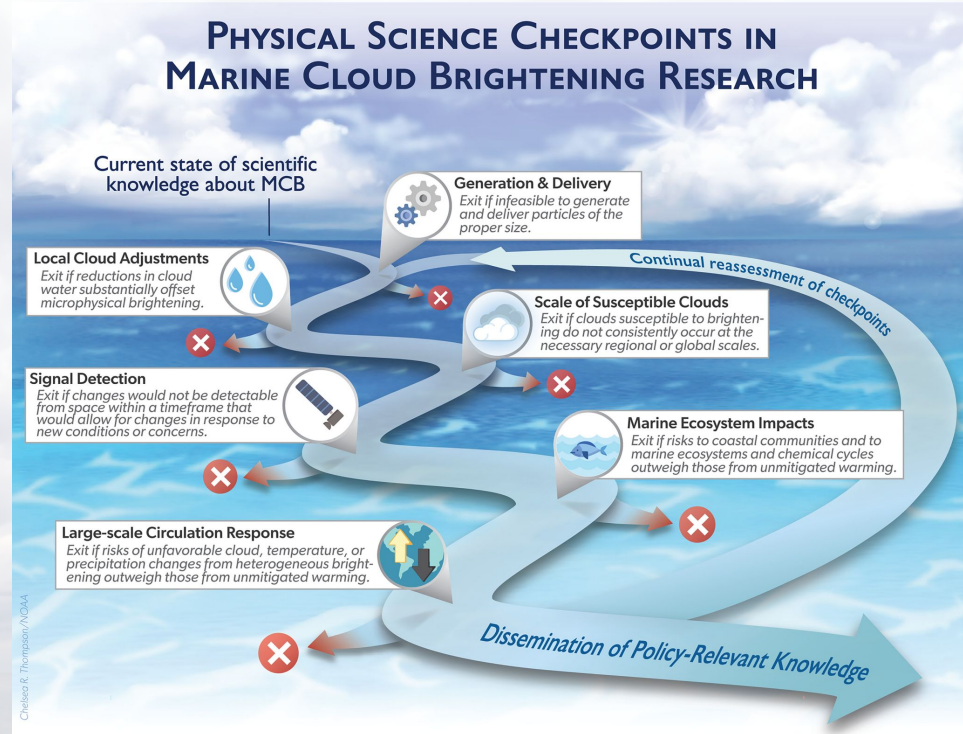
Luke Iseman and Andrew Song use a grill to burn sulfur powder and capture the smoke in a plastic bag. Balazs Gardi for TIME

A wide-angle photograph of a vast ocean under a sky filled with numerous small, white, puffy clouds. The clouds are densely packed and appear to be illuminated from below, possibly by the sun, creating a bright, hazy atmosphere. The horizon line is visible in the lower third of the image, with a faint outline of land in the distance. The overall scene is serene and atmospheric.

Marine Cloud Brightening (MCB)

Marine Cloud Brightening (MCB)

- have ships spray a mist of seawater into marine clouds
 - sea salt particulate helps condensation
 - brighter, more reflective clouds



Marine Cloud Brightening (MCB)

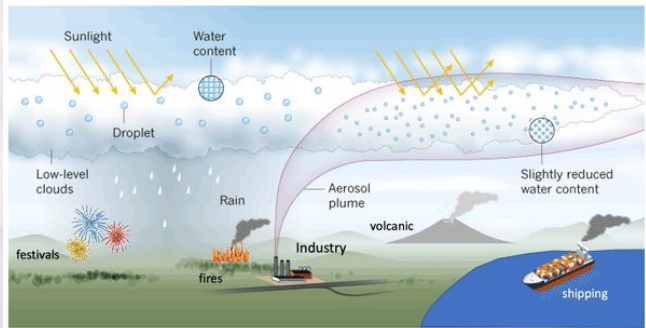
Pros:

- + more benign than SAI
- + rapid climatic response (weeks) vs. SAI (years)
- + quite likely to work (maybe already happening)

Cons:

- not very well-understood
 - more expensive than SAI
 - effects fairly localized (regional cooling)
 - unclear ecosystem effects
 - termination shock, still
-

Accidental Maritime Geoengineering



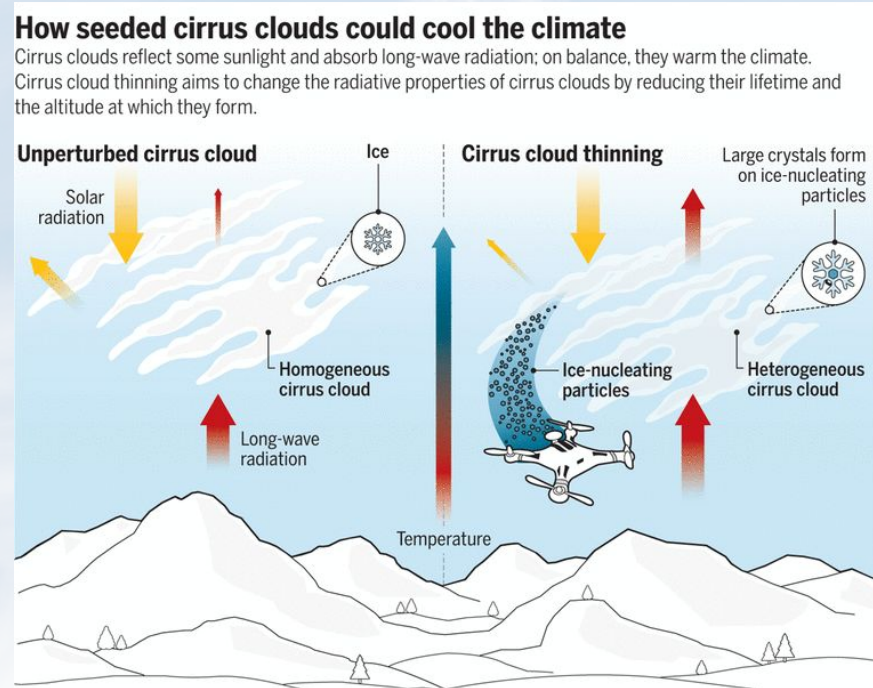
New regulations from the International Maritime Organization (IMO) **limiting sulfur emissions from the shipping industry** are expected to have large benefits in terms of public health but may come with an undesired side effect: **acceleration of global warming as the climate-cooling effects of ship pollution on marine clouds are diminished**. Previous work has found a substantial decrease in the detection of ship tracks in clouds after the IMO 2020 regulations went into effect [...] we confidently detect a reduction in the magnitude of cloud droplet effective radius decreases within the shipping corridor and **find evidence for a reduction in the magnitude of cloud brightening as well**.

The background of the image is a clear blue sky filled with soft, wispy white cirrus clouds. The clouds are scattered and have a delicate, feathery appearance. The text is centered in the upper half of the image.

Cirrus Cloud Thinning (CCT)

Cirrus Cloud Thinning (CCT)

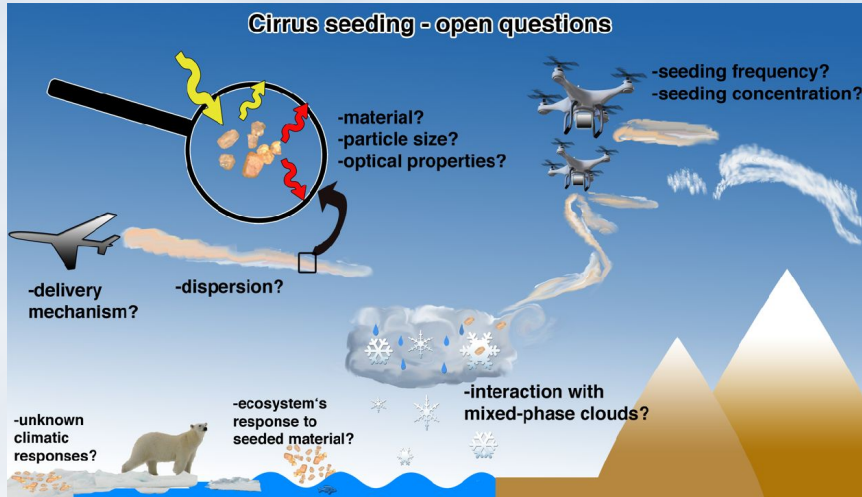
- Cirrus clouds (wispy, high-altitude) have a net warming effect
 - unlike other clouds, trap more heat than they reflect
 - seed cirrus with aerosols to reduce warming effect



Cirrus Cloud Thinning (CCT)

Pros:

+ probably safer than SAI



Cons:

- ...might cause warming lol
 - really not well-understood
- unclear effects on precipitation (rainfall)
- termination shock is really just kinda intrinsic to SRM

A large, dark, triangular space mirror is shown in orbit above Earth. The mirror is composed of many smaller, reflective panels and is mounted on a central structure. The Earth's surface, including the Mediterranean Sea and surrounding landmasses, is visible in the background. The text "Space Mirrors" is overlaid in large white letters.

Space Mirrors



SPACE MIRRORS

- just put a big-ass mirror in orbit?
- stop overthinking it



SPACE MIRRORS

Pros:

- + definitely would work (with enough mirrors)
- + minimal ecosystem risks
- + would be *extremely* funny

Cons:

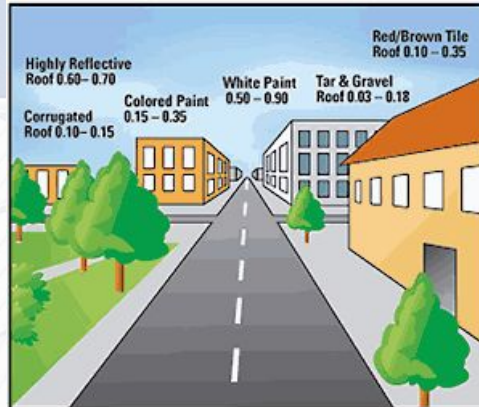
- dear god, how much would this cost
 - emissions footprint of launching that many satellites might be large
 - do you even hear yourself
-

Surface Albedo Modification



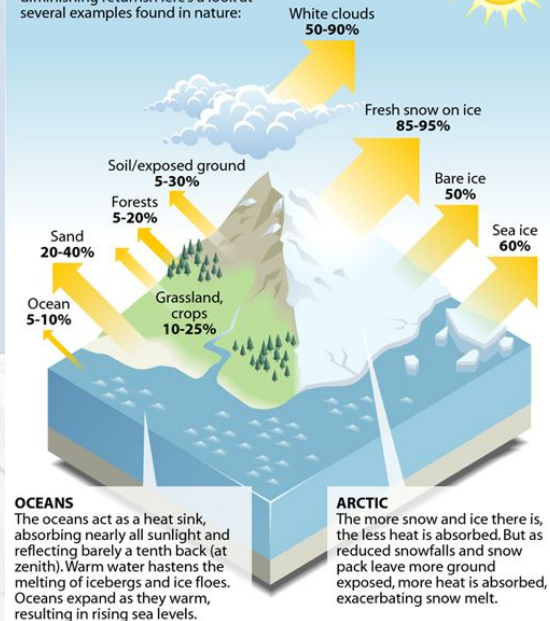
Surface Albedo Modification

- Just paint your roof white!
- Not geoengineering, according to the IPCC



Keeping Things Cool: The Albedo Effect

The albedo effect — the reflectivity of sunlight on various surfaces — is important in keeping the Earth cool. Clean, white clouds and fresh snow and ice reflect the most sunlight, while exposed land, water and vegetation have diminishing returns. Here's a look at several examples found in nature:



Note: Illustration is diagrammatic and not to scale.

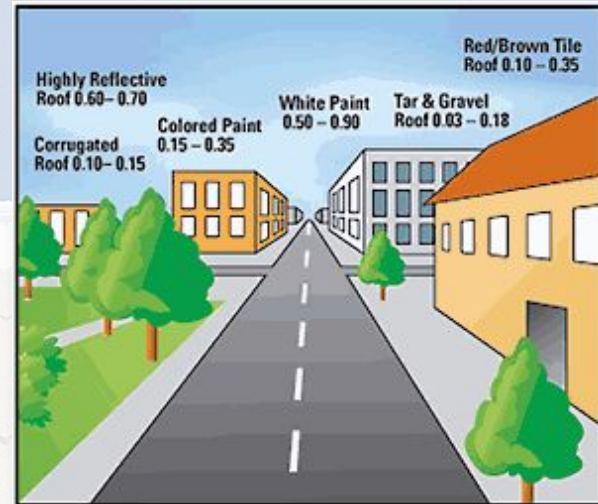
Surface Albedo Modification

Pros:

- + negligible side effects
- + lower heating bills
- + definitely works
- + mitigates urban heat island effect

Cons:

- really not enough by itself



Geoengineering

Carbon Dioxide Removal

(CDR / “negative emissions”)

- ❖ Direct-air capture (DAC)
- ❖ Enhanced weathering (EWR)
- ❖ Biomass carbon removal (BECCS/BiCRS)
- ❖ Pyrolytic carbon removal (biochar, PyCCS)
- ❖ Afforestation / desert greening
- ❖ Ocean carbon removal (DOC, OAE, etc.)

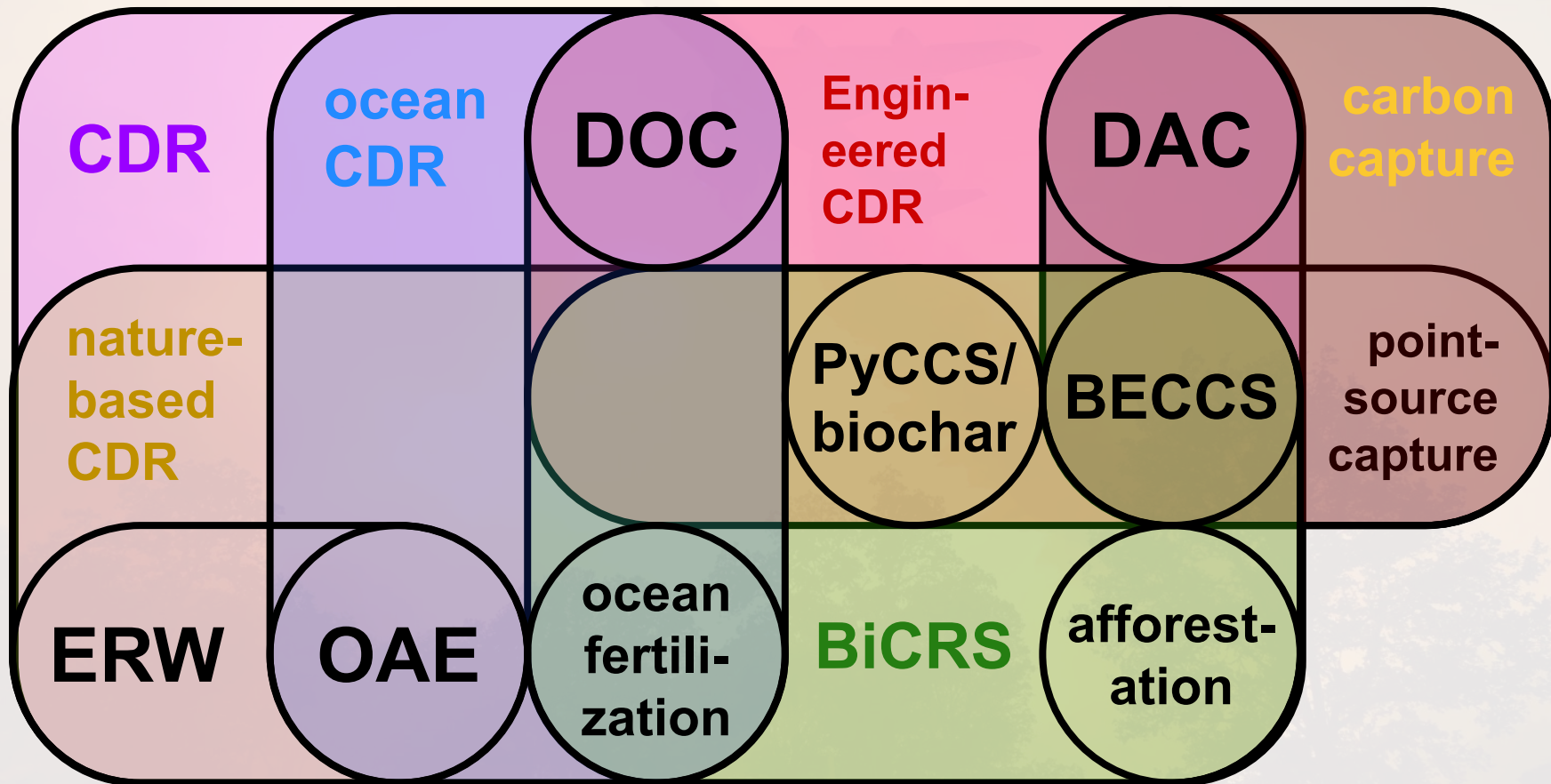
Solar Radiation Management

(SRM / “solar geoengineering”)

- ❖ Stratospheric aerosol dispersion
- ❖ Cirrus cloud thinning
- ❖ Marine cloud brightening
- ❖ Orbital mirror deployment

Others

- ❖ Surface albedo enhancement
- ❖ Glacier stabilization
- ❖ Coastal engineering
- ❖ Other, even dumber ideas



ARCTIC WINTER SEA ICE COLLAPSE
BOREAL FOREST NORTHERN EXPANSION
GREENLAND ICE SHEET COLLAPSE
BARENTS SEA ICE COLLAPSE
BOREAL PERMAFROST COLLAPSE

HOW FAR WOULD YOU GO TO PREVENT A CIVILIZATION-ENDING EXTINCTION EVENT?

OVERTURNING CIRCULATION COLLAPSE
SAHEL / WEST AFRICAN MONSOON GREENING
AMAZON
LOW-LATITUDE CORAL REEFS DIE-OFF

WHAT ABOUT A 50% CHANCE OF AN EVENT?

MOUNTAIN GLACIERS LOSS
WEST ANTARCTIC ICE SHEET COLLAPSE
A 10% CHANCE?
A 1% CHANCE?
EAST ANTARCTIC ICE SHEET COLLAPSE
EAST ANTARCTIC SUBGLACIAL BASINS COLLAPSE

GLOBAL WARMING THRESHOLDS

○ <2°C ◆ 2-4°C ▲ ≥4°C

Discussion Questions

- What role does CDR play in reaching net-zero?
 - What metrics should we optimize for?
 - What kinds of CDR should we use?
 - Who should decide if/when SRM is deployed?
 - What kinds of SRM are we willing to tolerate?
 - How should a global community regulate / oversee SRM?
 - Does climate alarmism / doomerism increase affinity to radical / high-risk solutions?
-