Earth's Climate: Past, Present and Future
OLLI South Spring 2017:

week 8 (May 18th)

Paul Belanger

Solutions – part B:
The Ultimate Primary Focus: Energy and Sequestration of CO2

A low-carbon footprint snowplow

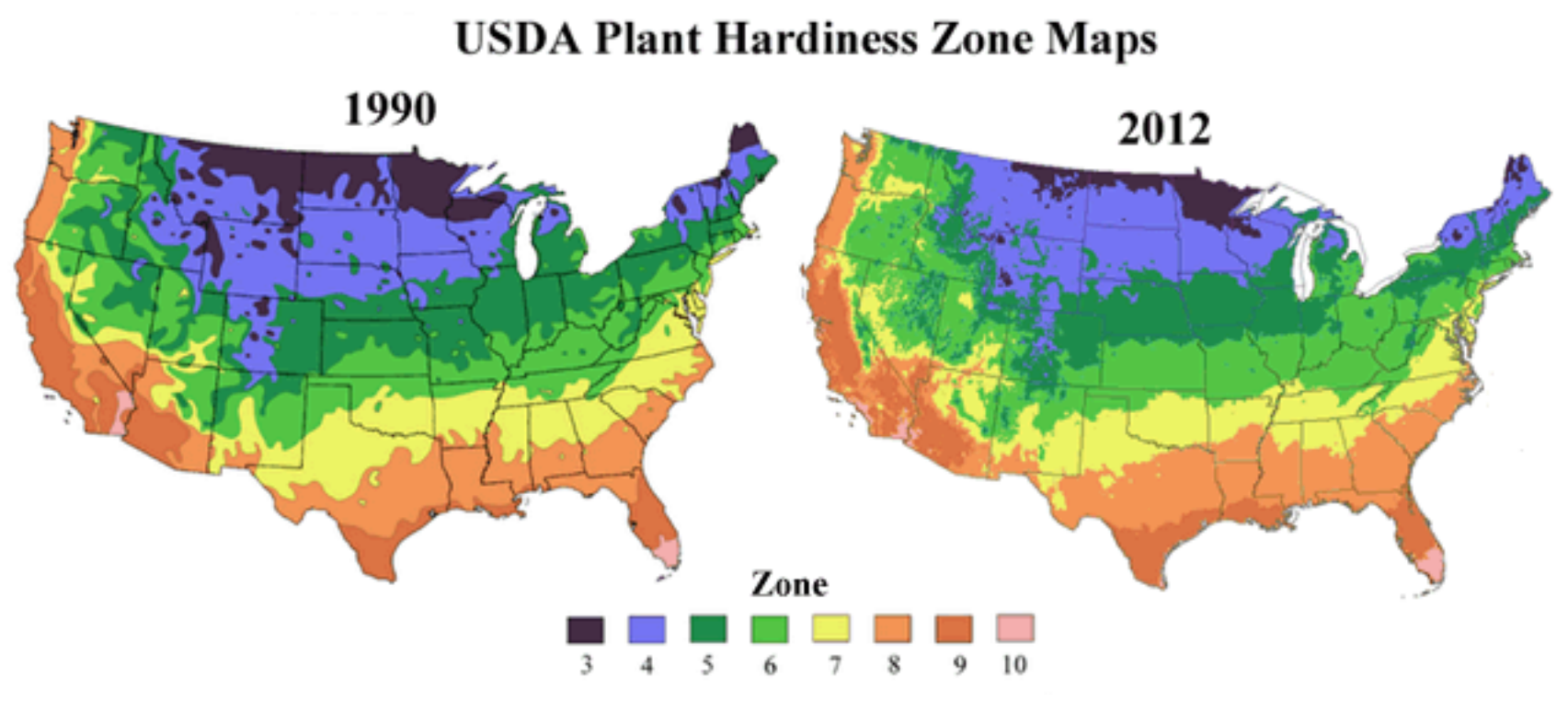
Another low-carbon footprint snowplow

Announcements

Compare next slides

- In particular notice the difference between 2012 and 2015 – 3 YEARS!

Plants and Animals are Responding to a Warming Climate
1990 vs. 2012



Spring is springing forward: Spring events, like bird and butterfly migrations, flower blooming times, and frog mating, have been advancing by about three days per decade over the past 30 years.

Source: Jeong et al., 2011, "Phenology shifts at start vs. end of growing season in temperate vegetation over the Northern Hemisphere for the period 1982–2008"

https://www.arborday.org/media/zones.cfm

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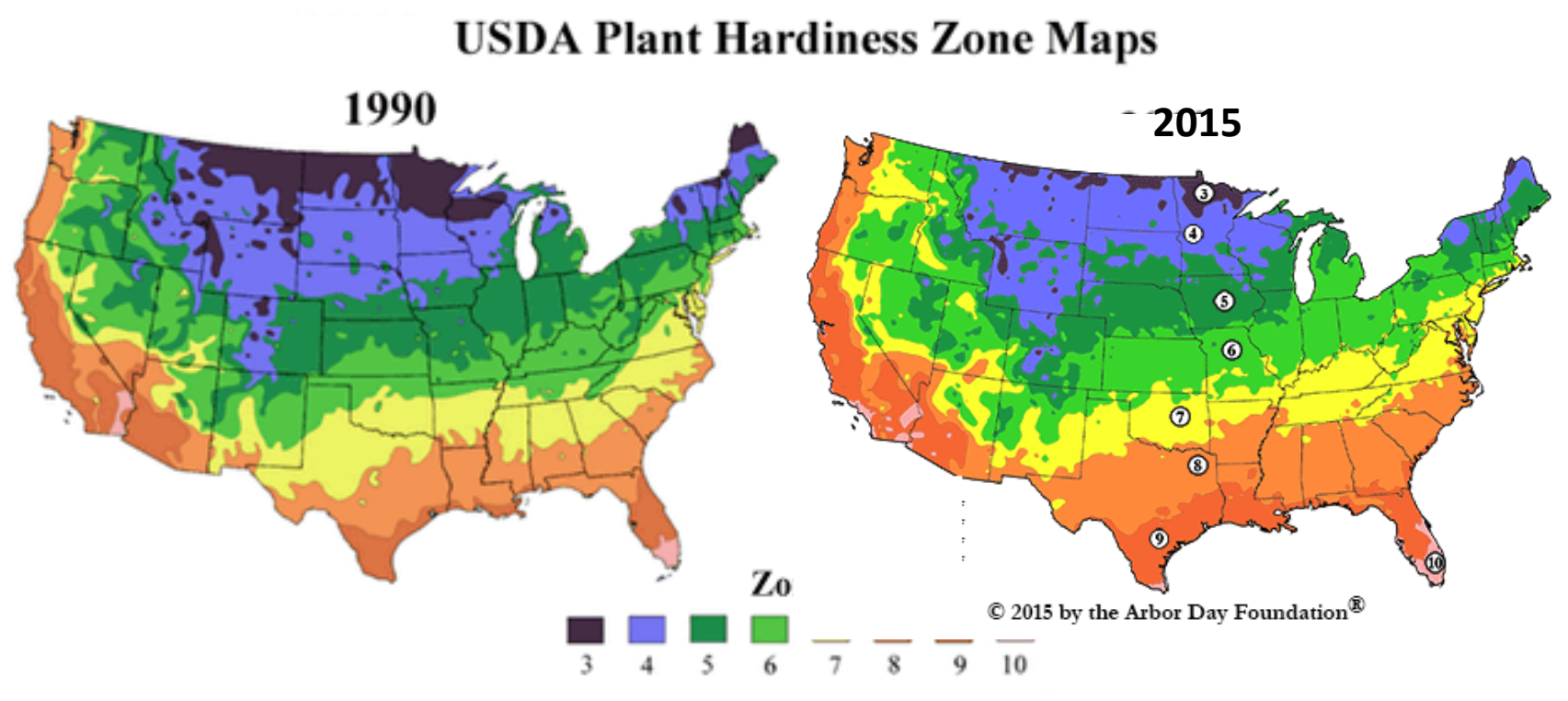

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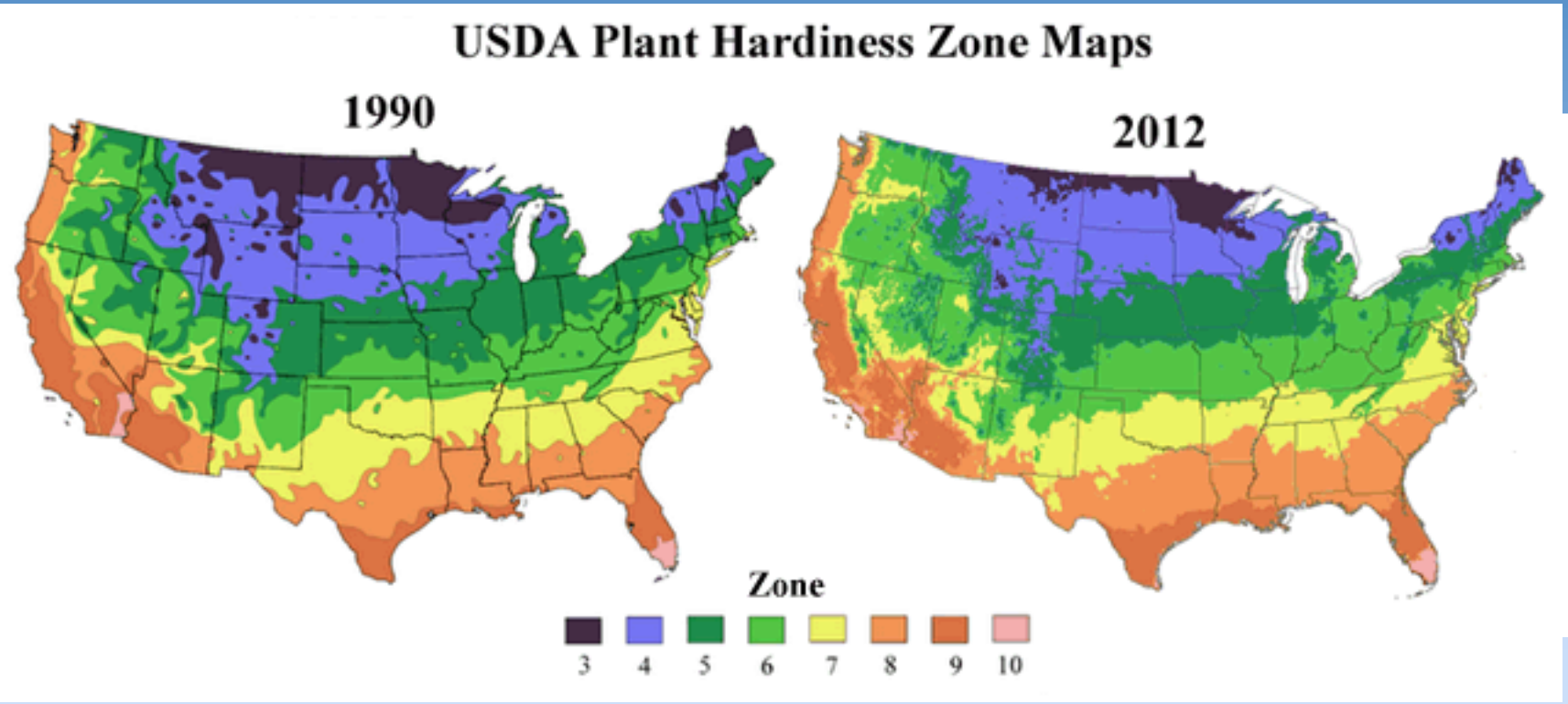

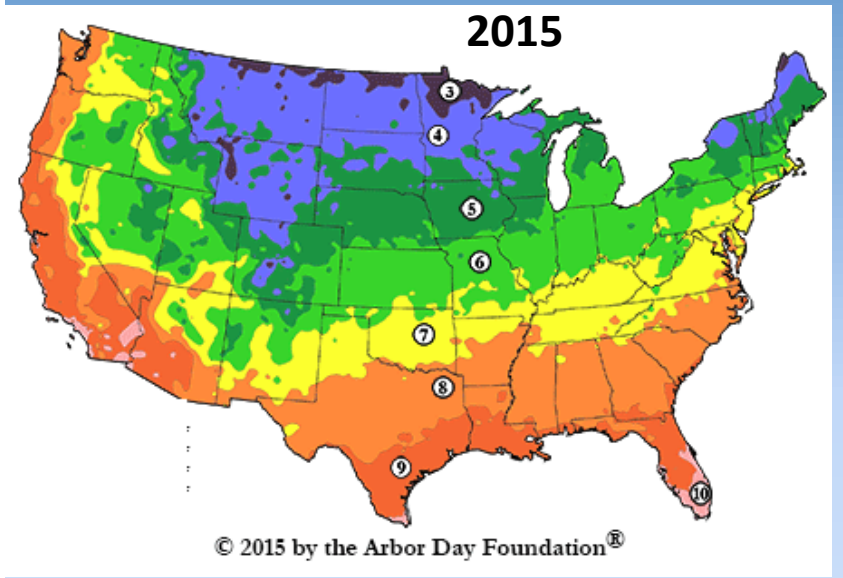

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Earth's Climate: Past, Present and Future
OLLI South Spring 2017 -
Last week 7 – May 11th
covered:

Solutions – part A

1. Economics
   - of doing nothing (solely adapting) vs. the economics of mitigation
   - Actuality: it WILL be a combination
2. Capitalism, GDP/growth based economics vs. "Herman Daly" economics (no-growth/steady-state)
3. Solutions? Paradigm shift? From we can't/too expensive to WE CAN
4. There is promise, but at what cost? (One might be surprised).
   - Energy
   - Mitigation – Agricultural revolution/biofuels: Biochar for Carbon Dioxide Removal (CDR)

Colorado changes in renewable energy

- Didn't cover:
- I refer you to various slides:
  - week 5 (slides 78-80) and
  - Week 6 PART B: SEE http://denverclimatestudygroup.com/wp-content/uploads/2014/07/Belanger-OLLI-WEST-wk6-PART-B-storage-and-grid-options.pdf
  - from my OLLI West class on web page http://denverclimatestudygroup.com/?page_id=24
- And I also refer to you my April 7th OLLI west talk:

  - http://denverclimatestudygroup.com/wp-content/uploads/2014/07/Belanger-April-7th-lecture.pdf Especially slides 85 to the end (parts about jobs, NREL, etc.)

Colorado Wind Development

STATE WIND FACTS

Wind Projects

- **Installed wind capacity:** 3,026 MW
- **State rank for installed wind capacity:** 10th
- **Number of wind turbines:** 1,913
- **State rank for number of wind turbines:** 8th
- **Wind projects online:** 25 (Projects over 10 MW: 17)
- **Wind capacity under construction:** 76 MW
- **Wind capacity in advanced development:** 600 MW

Current Wind Generation

For the 12 month period ending October 2016, wind energy provided 16.87% of all in-state electricity production.

- **Equivalent number of homes powered by wind:** 846,000

Wind Generation Potential

The DOE Wind Vision Scenario projects that Colorado could produce enough wind energy by 2030 to power the equivalent of average American homes.

- **Land based technical wind potential at 80 m hub height**: 274,353 MW
- **Land based technical wind potential at 110 m hub height**: 262,878 MW (Source: NREL)

Environmental Benefits

Generating wind power creates no emissions and uses virtually no water.

- **2015 annual state water consumption savings*:** 4.4 billion gallons
- **2015 equivalent number of water bottles saved:** 33.1 billion
- **2015 annual state carbon dioxide (CO_2) emissions avoided:** 8.0 million metric tons
- **2015 equivalent cars worth of emissions avoided:** 1.7 million

*Based on national average water consumption factors for coal and gas plants

Source: AWEA

This week, May 18th : Solutions – part B continued

5. Geoengineering:
   - Solar Radiation Management (SRM) and
   - Carbon Dioxide Removal (CDR)
6. Biochar vs. BECCS solutions SEE MY BIOCHAR LINK IN OTHER PAGES: http://denverclimatestudygroup.com/?page_id=28
7. Efficiency – the single quickest way to reduce:
   - What NREL is doing: Efficiency, Solar, wind, other
8. Other strategies:
   - CCL – carbon fee/dividend
   - Cap and trade?
9. Gloom and Doom? NO! IT'S A CHALLENGE, and humanity has always been challenged and we are an adaptable species that has met the challenge over and over again!

However – POTENTIAL big game changers in Energy and Carbon Dioxide Removal

1. Energy – from fusion
2. Mitigation in the form of carbon dioxide removal (CDR), agricultural changes and biofuels

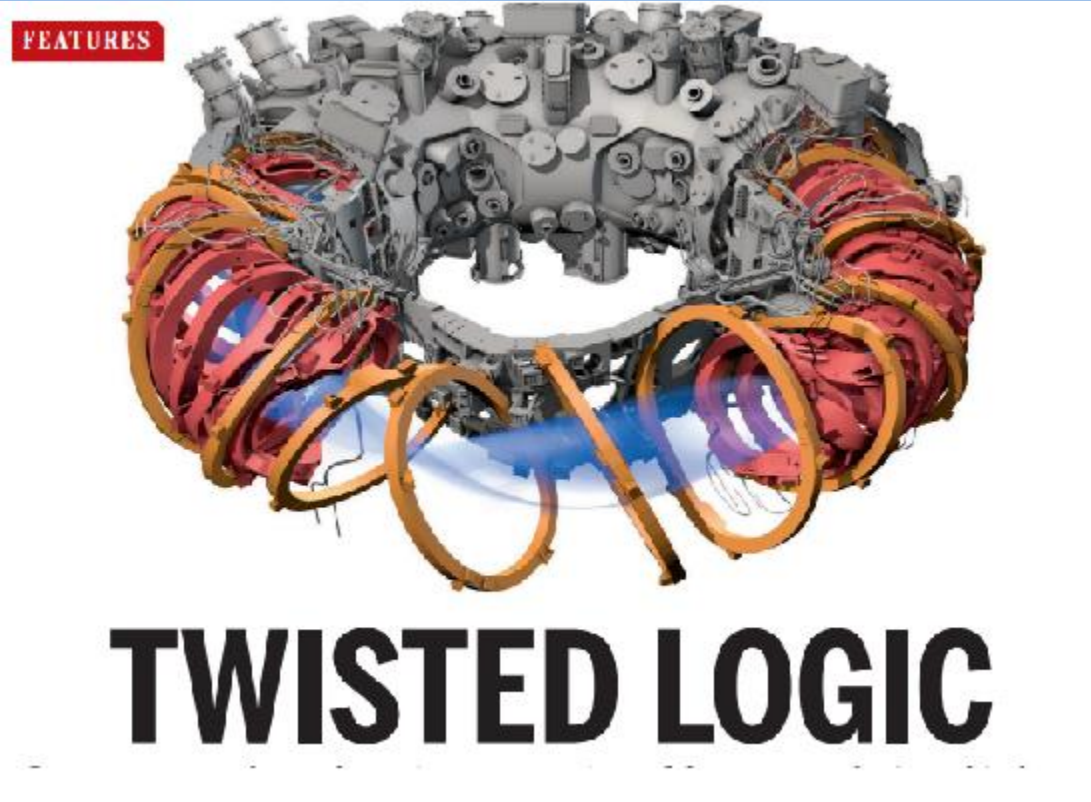
1. Energy – from fusion

Lockheed Martin Compact Fusion breakthrough?

- http://www.lockheedmartin.com/us/products/compact-fusion.html
- http://aviationweek.com/blog/high-hopes-can-compact-fusion-unlock-new-power-space-and-air-transport
- http://aviationweek.com/fusion-podcast

1. More on Fusion:

Fusion article in Science: Twisted Logic [Science-2015-Clery-369-7]

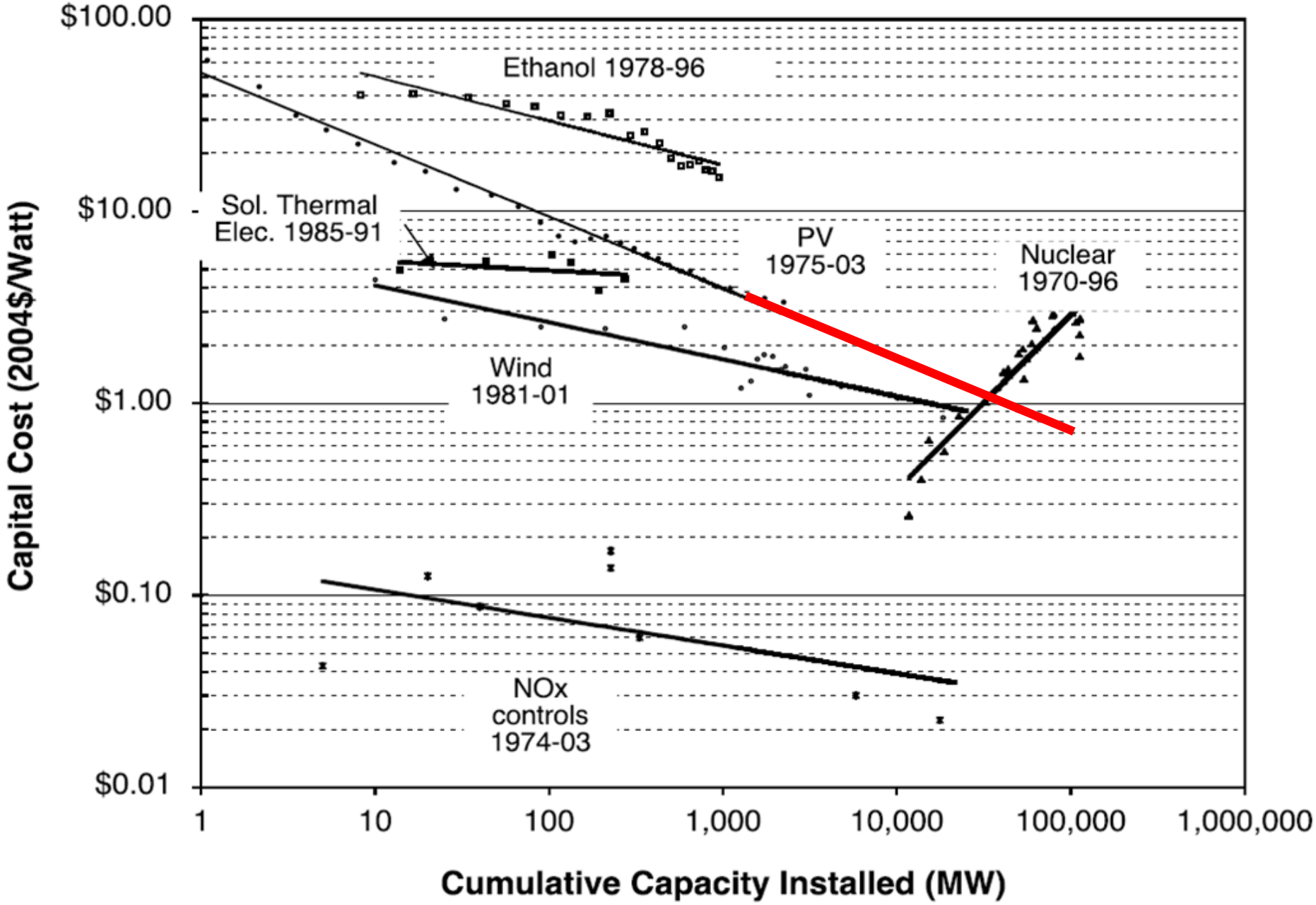


Will we ever get there?

- **Fusion reactors: Not what they're cracked up to be**
  - http://thebulletin.org/fusion-reactors-not-what-they%E2%80%99re-cracked-be10699
  - State not able to replicate Sun
  - State Tritium cannot be fully replenished
  - Huge parasitic power consumption
  - Some forms (deuterium-tritium) do have radiation damage and waste
  - Etc.

BUT
WE MAY NOT NEED IT?

- 2 REASONS:
  - COST/Renewables cheaper
  - Backup Storage and Expanded Grid (or NOT) make Baseload NOT necessary



https://carbonremoval.wordpress.com/

https://carbonremoval.files.wordpress.com/2014/12/energy-learning-curves.png

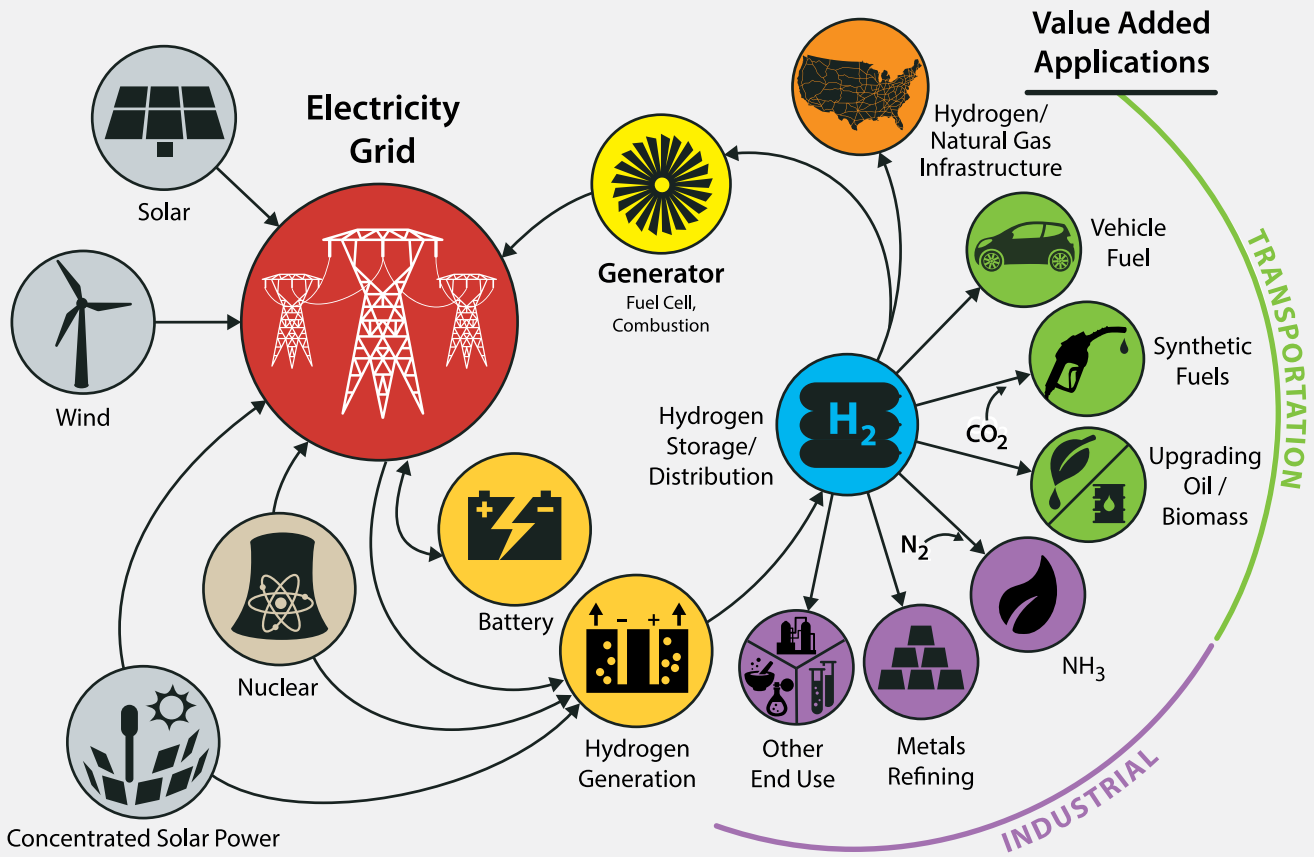
BACKUP AND/OR GRID

- Balanced power is necessary:
  - not too much, not too little
- SOLUTION – EITHER:
  - Backup:
    - Battery,
    - Compressed Air,
    - Re-pumped Hydro,
    - H_2 (this can be 2-way for excess power or needed power)
    - Rubber Bands, etc.
  - Grid

Future Energy System – Commodity H_2

SEE: Ramping Up Solar to Power the World - Greg Wilson, NREL:
https://www.youtube.com/watch?v=7CDPHxcnq4c&t=9s

Future H_2 at Scale Energy System



WHY HYDROGEN?

- Hydrogen is an ideal clean energy carrier—connecting diverse energy sources to diverse applications
- It can play a unique and critical role in addressing many of the energy sector's greatest challenges

TODAY'S ENERGY SYSTEM

- Renewable energy—particularly wind and solar—offer great promise but have challenges associated with variable and concurrent generation
- Options to achieve deep decarbonization while meeting society's multi-sector energy demands are limited, particularly in the industrial and transportation sectors

FUTURE H_2 AT SCALE ENERGY SYSTEM

- Connects low-carbon energy sources to all of the energy sectors
- Uses carbon-free, renewable inputs to service all of society's energy needs, in particular the difficult to decarbonize sectors of industry and transportation
- Does not compete with other options—rather, it enables increased renewable penetration
- Can decrease 45% of all U.S. carbon emissions by 2050

NREL NATIONAL RENEWABLE ENERGY LABORATORY | ENERGY SYSTEMS INTEGRATION FACILITY
U.S. DEPARTMENT OF ENERGY

The ESIF helps NREL contribute to the U.S. Department of Energy's and our nation's energy goals by providing the R&D capabilities needed to collaborate with private industry, academia, government, and public entities on utility-scale projects focused on solving issues in relation to grid integration of renewable energy and other efficiency technologies.

Ken Regelson videos

- CRES YouTube: Many videos on
  - https://www.youtube.com/channel/UCr81EUb2qVJVfmmlJMxEHVw/videos
- Energy Should Be web page: http://energyshouldbe.org/
  - Why Storage is Key for a Renewable Energy Future: https://www.youtube.com/watch?v=Yc_hULwykvQ&t=14s
  - **To Allow Lots of Renewables, Baseload Coal & Nuclear Must Go: https://youtu.be/deWtgpheDJM**
  - Etc.

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Solutions – part B

5. Geoengineering:
   - Solar Radiation Management (SRM) and
   - Carbon Dioxide Removal (CDR)
6. Biochar vs. BECCS solutions SEE MY BIOCHAR LINK IN OTHER PAGES:

7. Efficiency – the single quickest way to reduce:
   - What NREL is doing: Efficiency, Solar, wind, other
8. Other strategies:
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Part A: Geoengineering

Geoengineering:

1. Solar Radiation Management (SRM) and
2. Carbon Dioxide Removal (CDR) / Greenhouse Gas (GHG) Capture
   - Focus on: Biochar vs. Bio-Energy with Carbon Capture and Storage (BECCS) solutions
   - Direct Air Capture (DAR) also in this category
   - Reducing Enteric Methane (BURPED stomach gases from Ruminants) too
   - SEE MY BIOCHAR web page LINK: http://denverclimatestudygroup.com/?page_id=28

Extras to investigate outside of class

SEE February 15, 2016 discussion on EEE tab:
http://denverclimatestudygroup.com/?page_id=683

- **National Academy of Science (NAS) Climate Intervention: Preface and links (Click here); detailed reports below:**
  - **NATIONAL ACADEMY OF SCIENCES (NAS) ONLINE: *CLIMATE INTERVENTION: REFLECTING SUNLIGHT TO COOL EARTH* (2015), AT HTTP://WWW.NAP.EDU/READ/18988;**
  - **AND *CLIMATE INTERVENTION:* CARBON DIOXIDE REMOVAL AND RELIABLE SEQUESTRATION (2015), AT HTTP://WWW.NAP.EDU/READ/18805.**

Terminology

- No terminology is going to be complete
- Despite NAS efforts Geoengineering as a term is still currently the most common term used

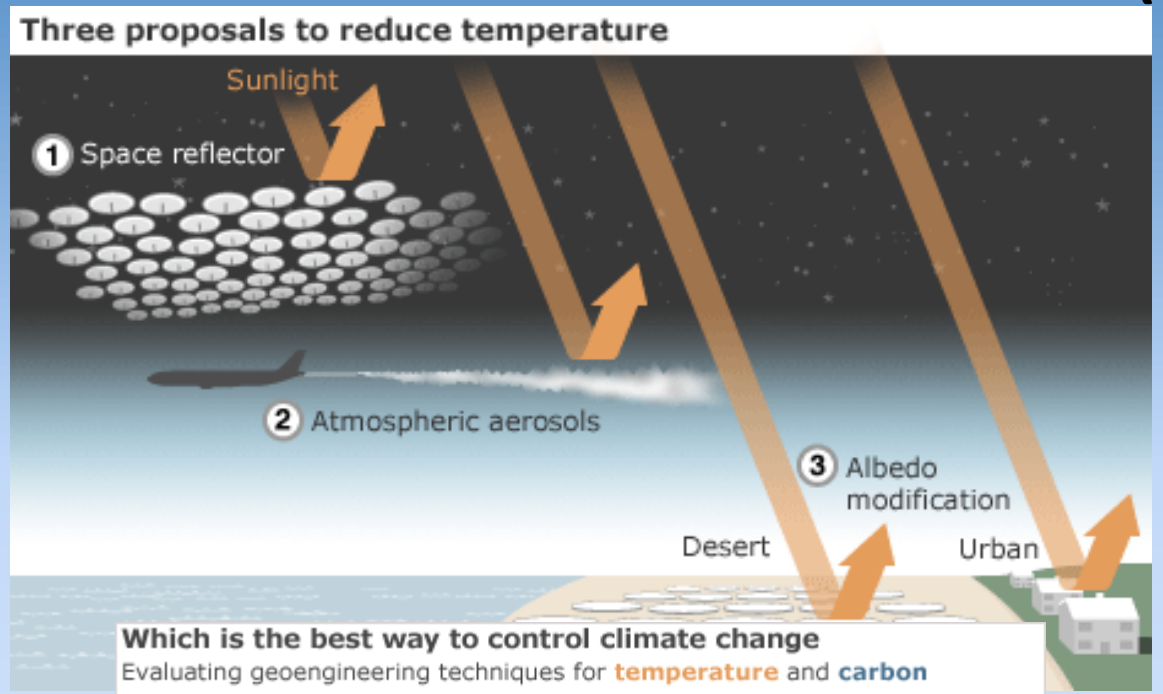
Extras to investigate outside of class

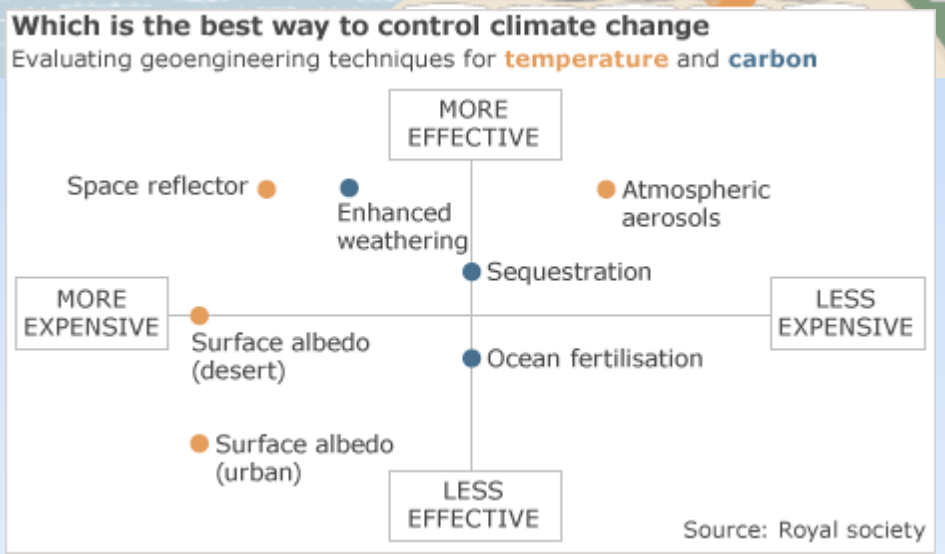
IPCC Assessment report-5 (AR5); Working Group III (WGIII): Mitigation

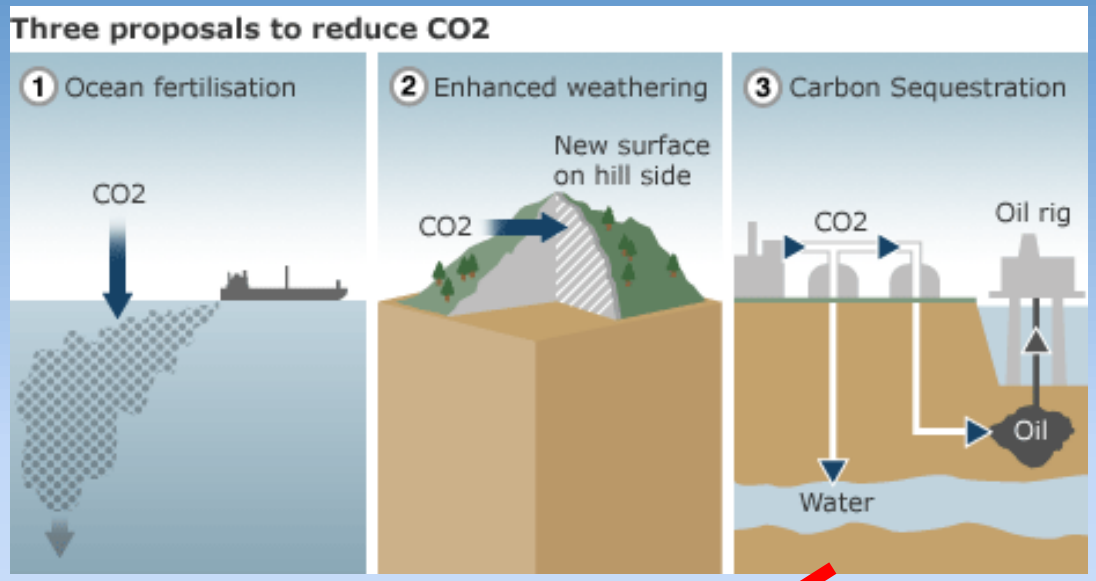
- WGIII_AR5_Presentation or in PDF format
- wg3_ar5_summary-for-policymakers_approved
- Video – the geoengineering dilemma 4.5 7.3 minutes
  https://www.futurelearn.com/courses/climate-change-challenges-and-solutions/1/steps/3297
- Are Ideas to cool the planet realistic

  http://news.bbc.co.uk/2/hi/technology/8338853.stm

Solar Radiation Management vs. Carbon dioxide Removal (SRM VS. CDR)







Biochar & Beccs

- https://en.wikipedia.org/wiki/Biochar
- https://en.wikipedia.org/wiki/Bio-energy_with_carbon_capture_and_storage

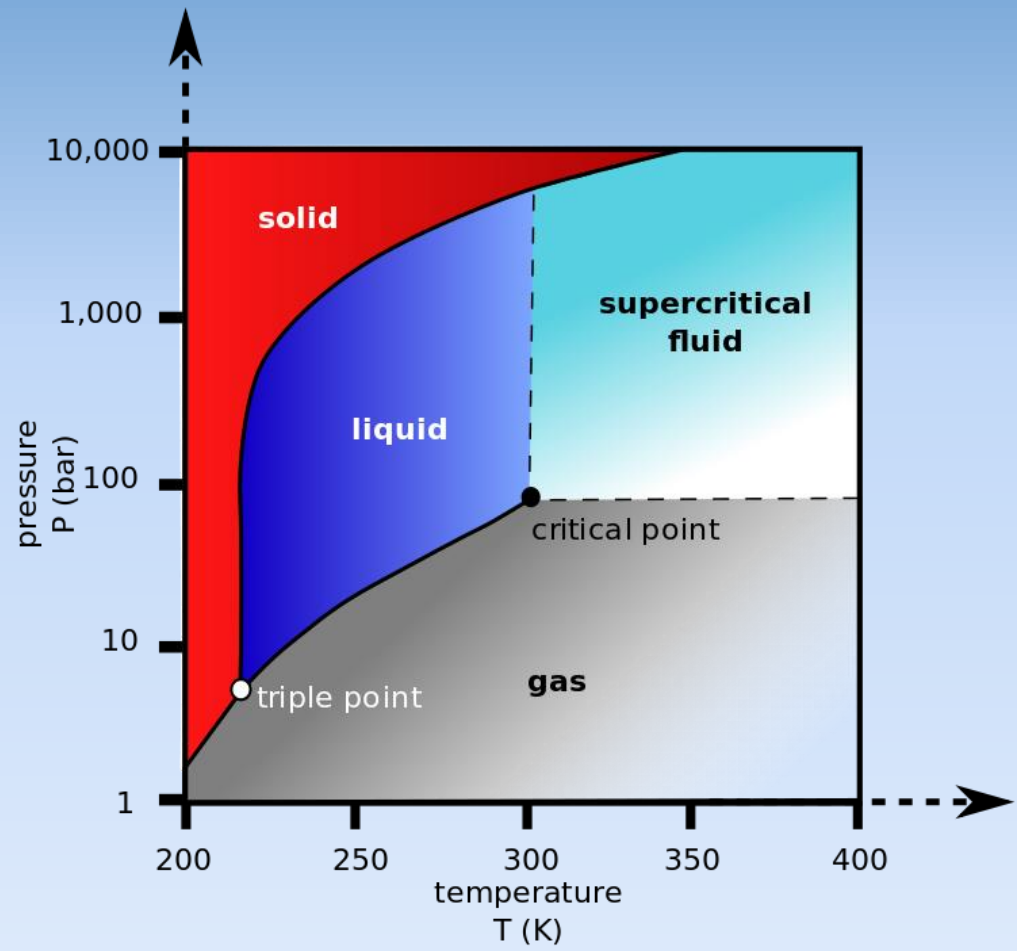
Royal Society

Additional

- SRM
  - Cloud Brightening to increase Earth's Albedo (reflectivity) also investigated
- CDR
  - Ocean fertilization with Iron to create algal blooms that sink to the sea floor:
    - https://en.wikipedia.org/wiki/Ocean_fertilization
  - Enhanced weathering: taking unstable mantle minerals, particularly Olivine to lock up Carbon https://en.wikipedia.org/wiki/Enhanced_weathering
  - Carbon Sequestration often ignores the potential of Biochar
  - Carbon Sequestration synonymous with Carbon Negativity

Supercritical CO_2

- See https://en.wikipedia.org/wiki/Supercritical_carbon_dioxide
- Miscible with salt water (saline aquifers)
- it can adopt properties midway between a gas and a liquid. More specifically, it behaves as a supercritical fluid above its critical temperature (304.25 K, 31.10 °C, 87.98 °F) and critical pressure (72.9 atm, 7.39 MPa, 1,071 psi), expanding to fill its container like a gas but with a density like that of a liquid.



Biochar

- Definition: https://en.wikipedia.org/wiki/Biochar
- Biochar tab: http://denverclimatestudygroup.com/?page_id=28

Carbon Dioxide Removal (CDR)

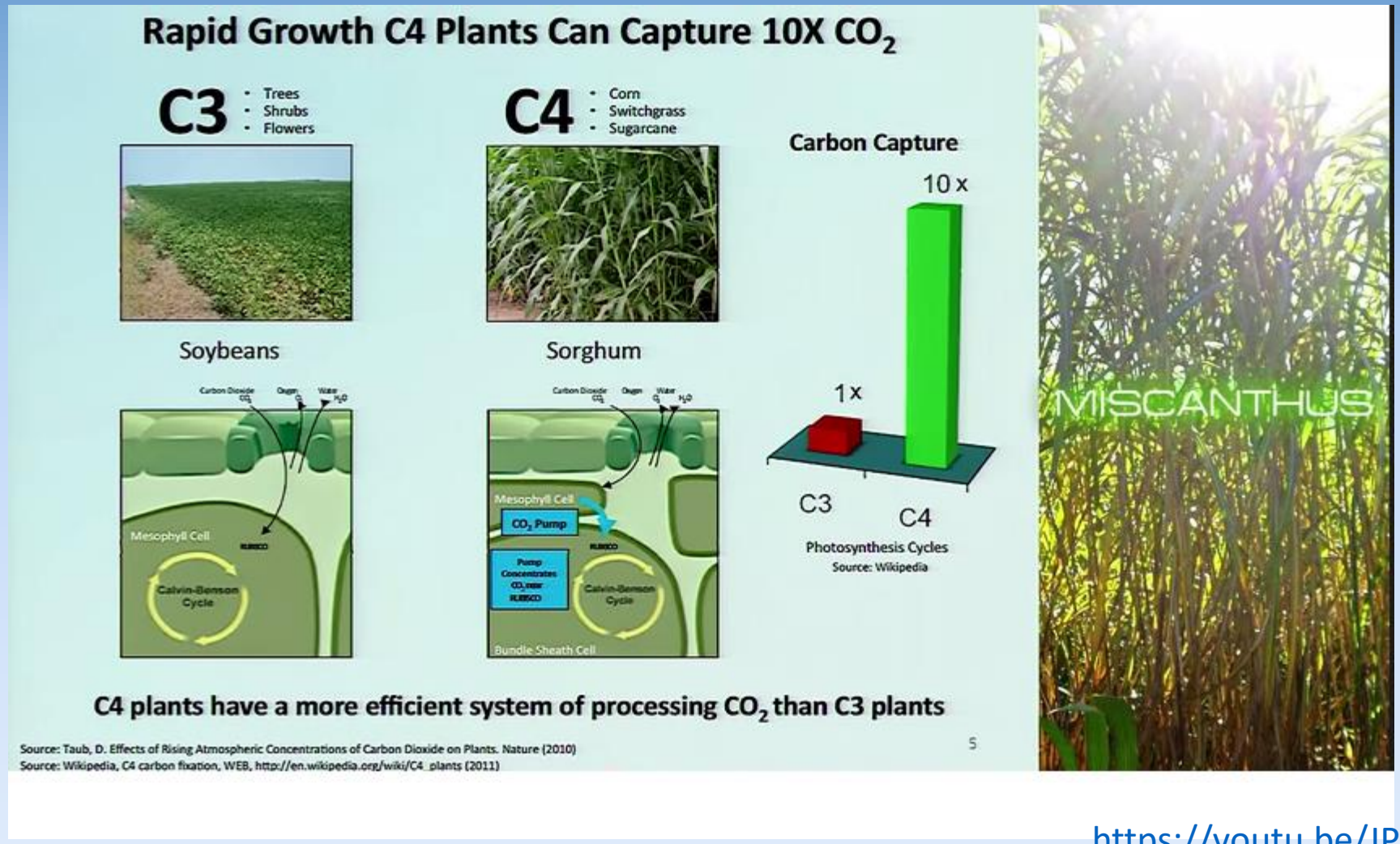
- https://en.wikipedia.org/wiki/Biochar:

"**Biochar** is charcoal used as a soil amendment. Like most charcoal, biochar is made from biomass via pyrolysis. Biochar is under investigation as an approach to carbon sequestration to produce negative carbon dioxide emissions.[1] Biochar thus has the potential to help mitigate climate change via carbon sequestration.[2][3] Independently, biochar can increase soil fertility ofacidic soils (low pH soils), increase agricultural productivity, and provide protection against some foliar and soil-borne diseases.[4] Furthermore, biochar reduces pressure on forests.[5] Biochar is a stable solid, rich in carbon, and can endure in soil for thousands of years.[1]"

Cool Planet - @ 9:00 minutes

- https://youtu.be/JPJsYZLU_sM?t=535

Following slides from Cool Planet Video



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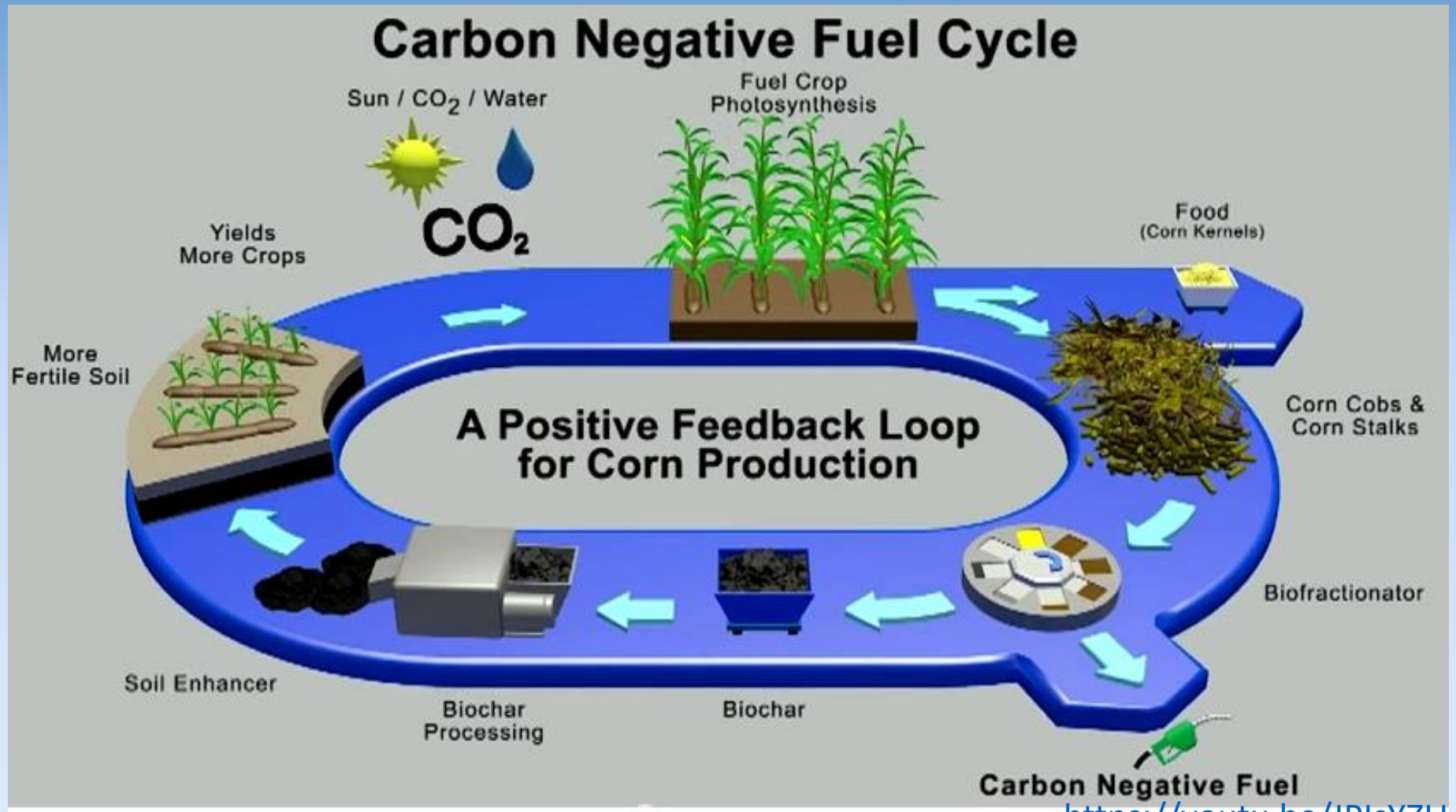
Types of Photosynthesis

- **About C3, C4 and Cam Photosynthesis and Plants:**
- **Photosynthetic efficiency: http://en.wikipedia.org/wiki/Photosynthetic_efficiency**
- **C3 carbon fixation: http://en.wikipedia.org/wiki/C3_carbon_fixation**
- **C4 carbon fixation:http://en.m.wikipedia.org/wiki/C4_carbon_fixation**
- **Summary table comparison: http://www.cropsreview.com/types-of-photosynthesis.html**
- **C3 C4 CAM Photosynthesis video: https://www.youtube.com/watch?v=Yg_pdXzWXVA**

Carbon negative fuel cycle: Biochar and Biofuels



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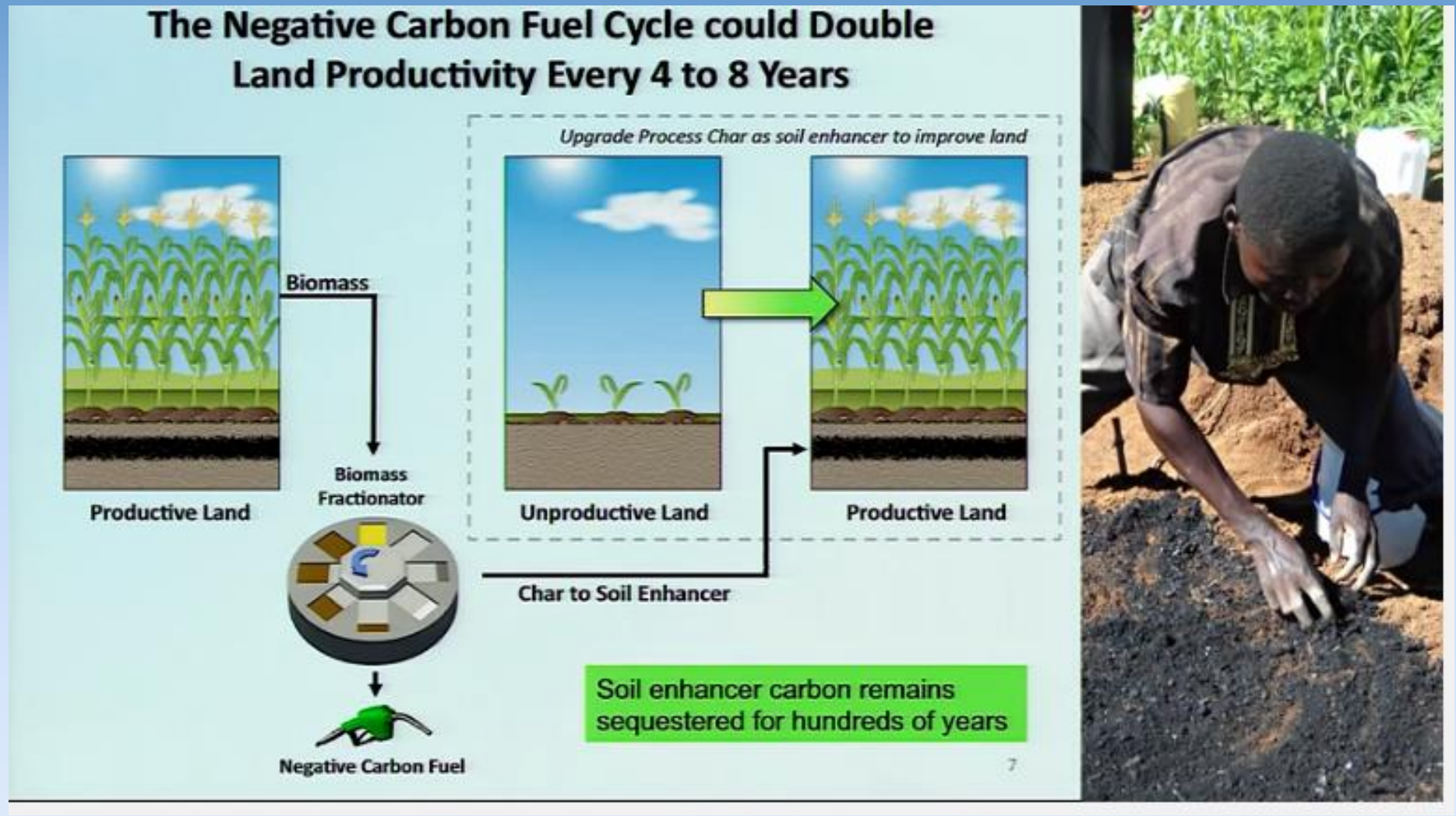
Soil Enhancement



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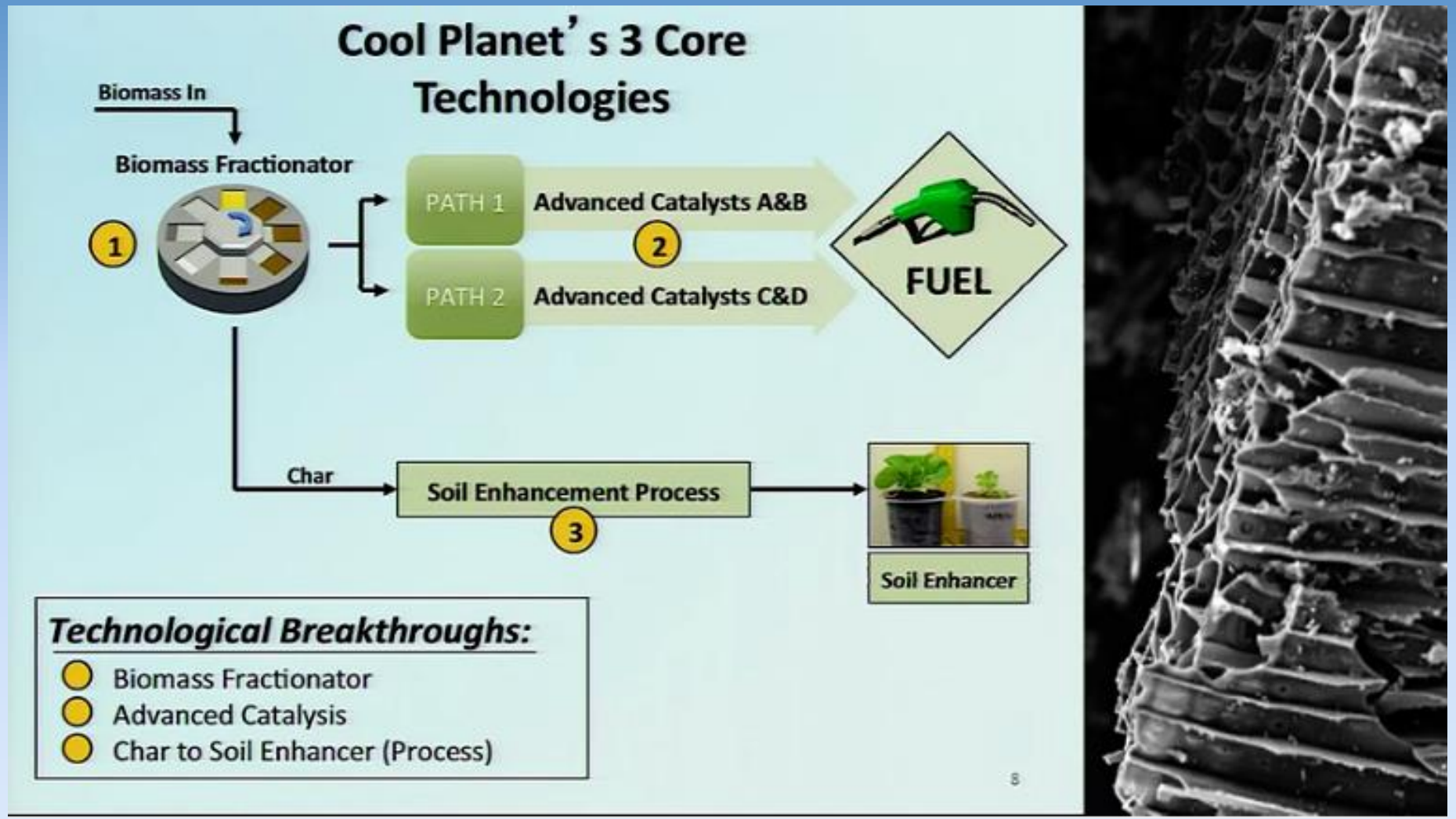
Core Technologies:



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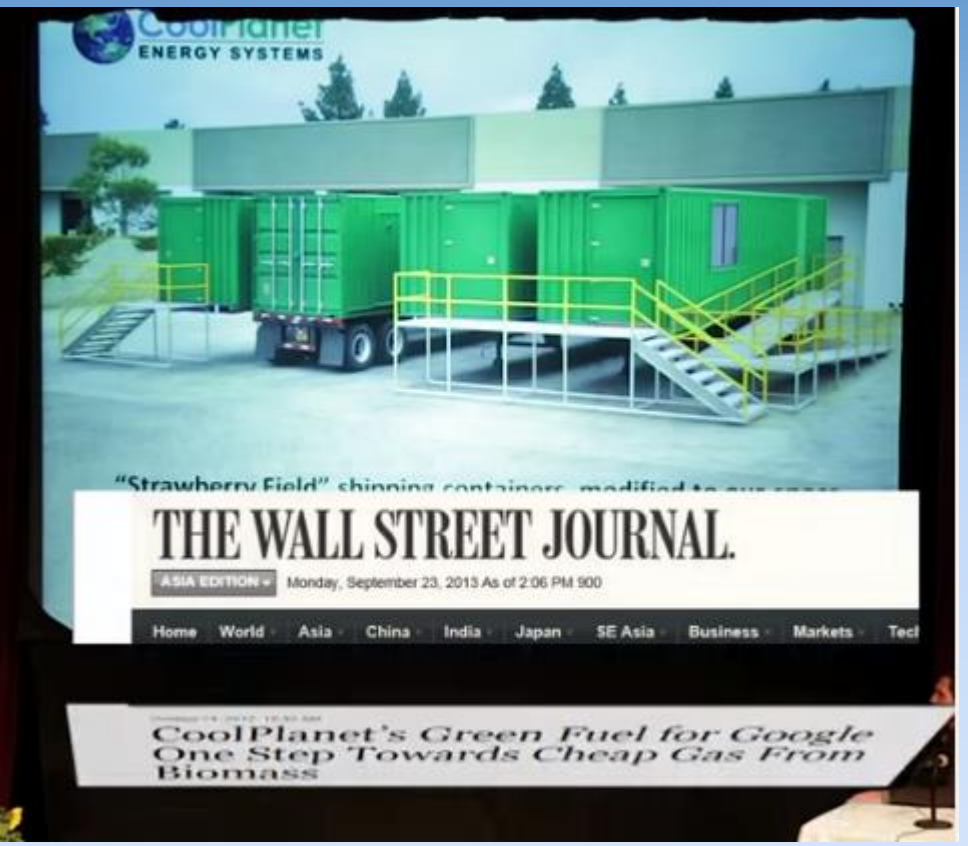
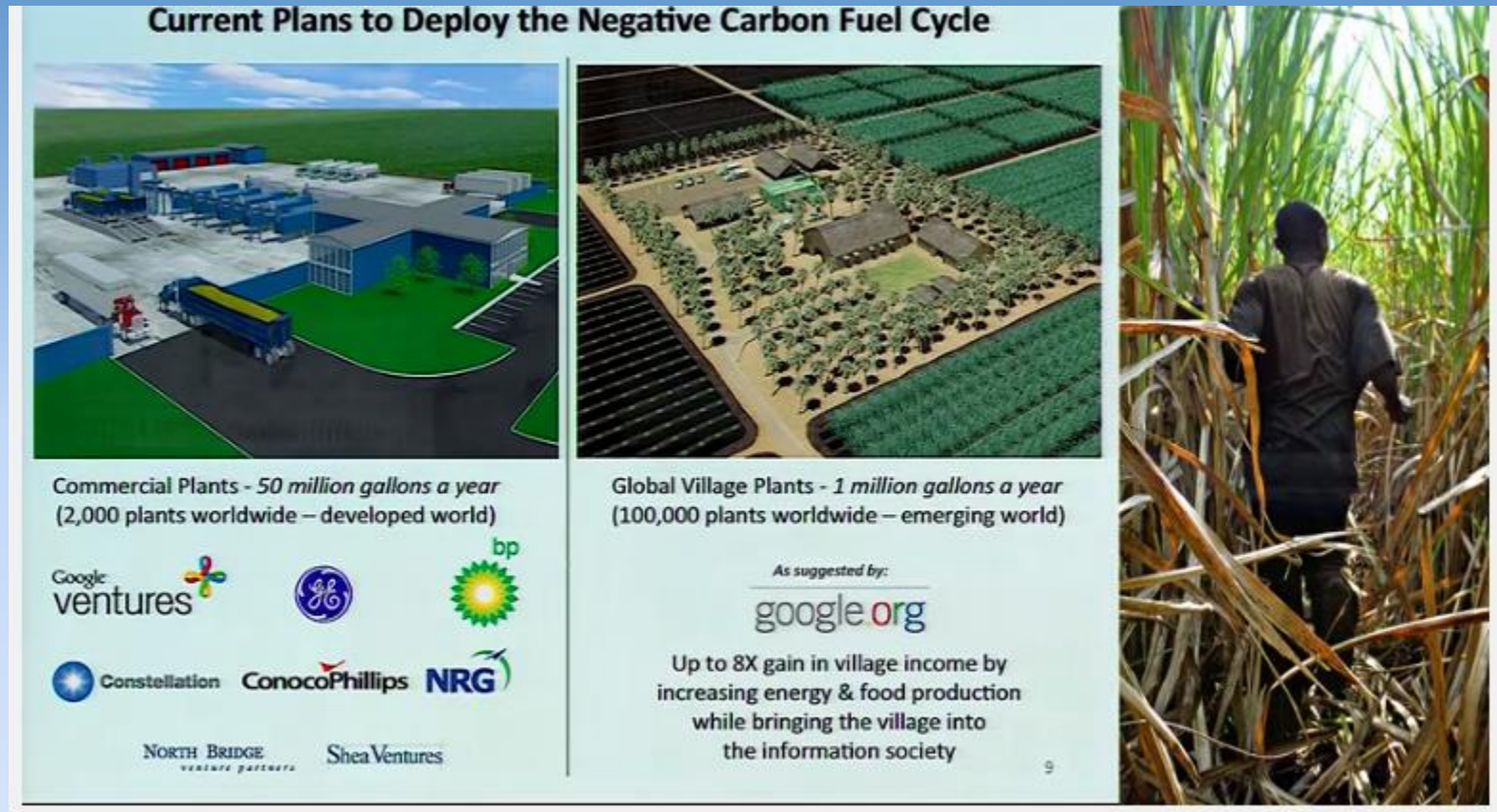
Sponsorships





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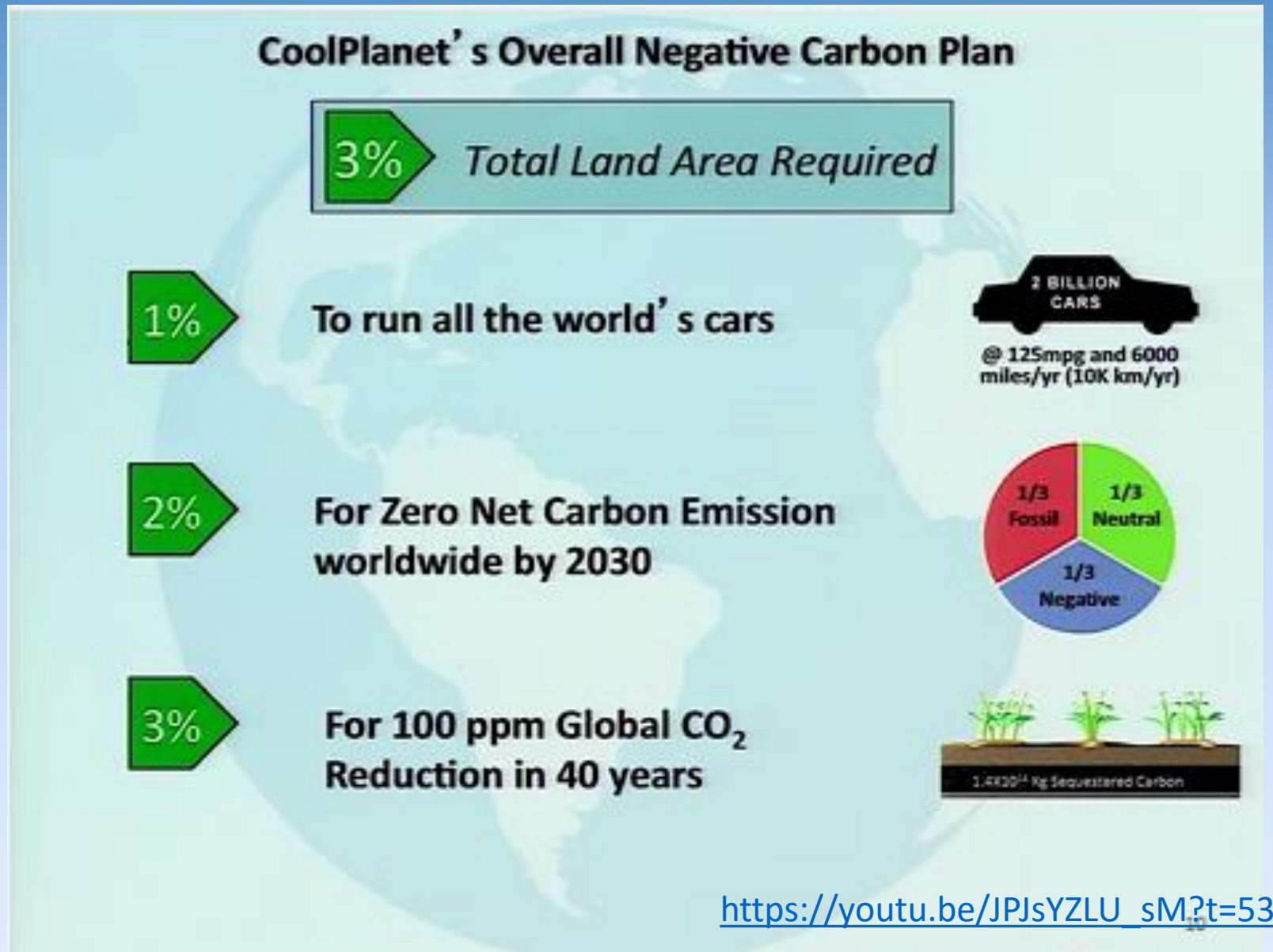
CARBON NEGATIVE BENEFITS:

- Sequester CO2
- create Biofuels



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BIOCHAR

- Ron Larson Presentation MAY 15TH to OLLI West class:
  - BIOCHAR: POLICY AND COMPETION: http://denverclimatestudygroup.com/wp-content/uploads/2014/07/Larson-biochar-PART-B-BIOCHAR2017.pdf

Bio-energy with carbon capture and storage (BECCS)

Bio-energy with carbon capture and storage

- https://en.wikipedia.org/wiki/Bio-energy_with_carbon_capture_and_storage

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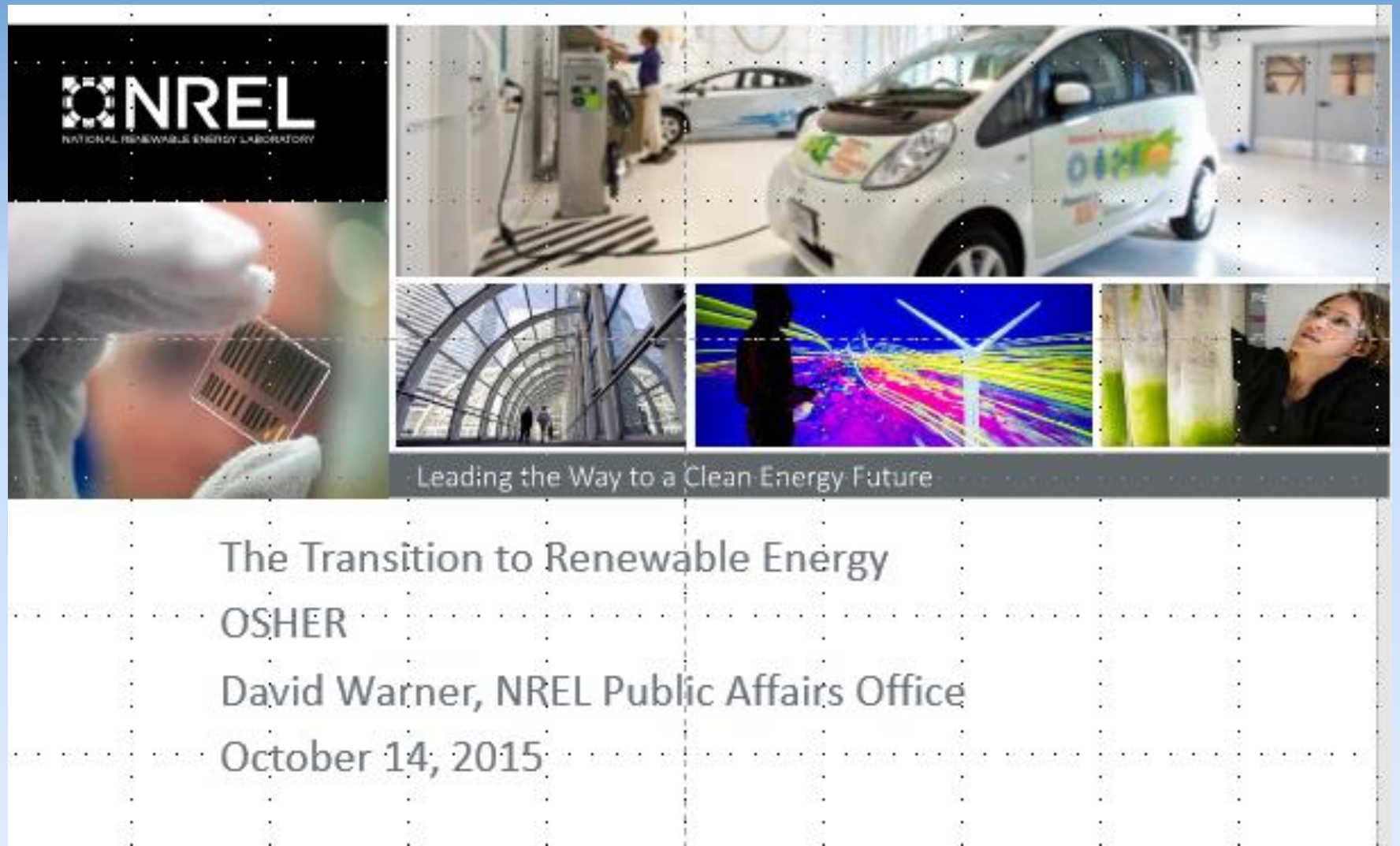
National Renewable Energy Lab: NREL

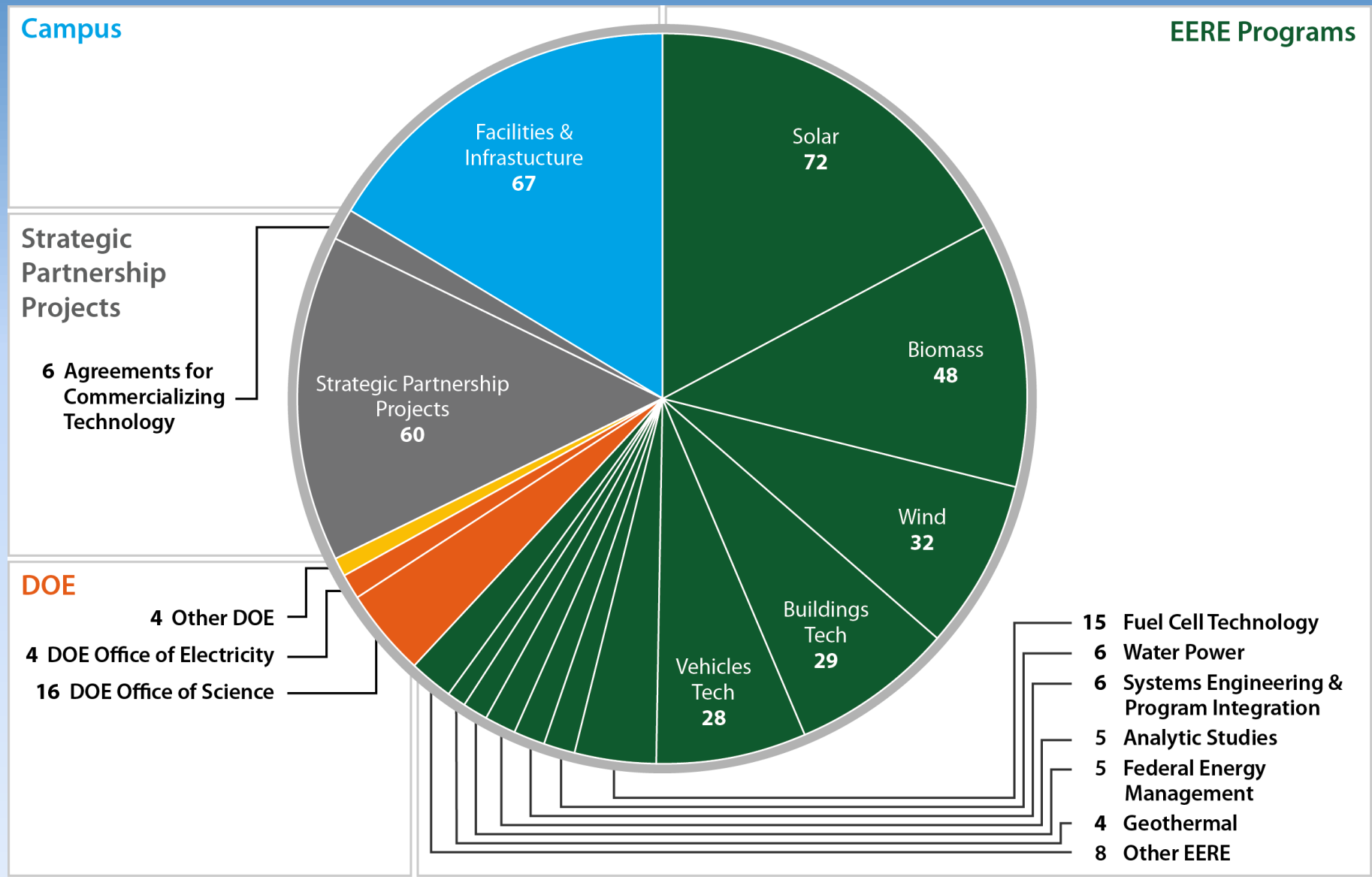
- http://www.nrel.gov/

Go to this 74 slide presentation: TRANSITION TO RENEWABLE ENERGY: OSHER 10.14.15



See What DOE's National Renewable Energy Lab (NREL) is Doing!

- **Go to this 74 slide presentation: TRANSITION TO RENEWABLE ENERGY - OSHER 10.14.15**



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SOLUTIONS

Carbon fee/dividend:

- citizensclimatelobby.org/ccl-applauds-republican-resolution-calling-for-action-on-climate-change/
- http://citizensclimatelobby.org/
- Facebook:
  - CCl – national: https://www.facebook.com/CitizensClimateLobby/?fref=ts
  - CCL-Colorado: https://www.facebook.com/CitizensClimateLobbyDenverChapter/

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IN SUMMARY

1. The world has been getting better

2. **Changes** are happening; **WE NEED TO CHANGE**:
   - 25+ Ways to Reduce Your Carbon Footprint: http://cotap.org/reduce-carbon-footprint/

3. We need to support science and new technologies

25 Charts and Maps that Show the World is Much Better: http://www.vox.com/2014/11/24/7272929/charts-thankful

So – let's not regress; let's continue to improve our world and transition to a new future: A NEW NORMAL

There are few, if any, historical examples of civilizations consciously making sacrifices on behalf of descendants two or more generations removed.

- **In that regard we need a social paradigm shift**

- **Gloom and Doom? NO! IT'S A CHALLENGE, and humanity has always been challenged and we are an adaptable species that has met the challenge over and over again!**
  - http://www.vox.com/2014/11/24/7272929/charts-thankful

25 Charts and Maps that Show the World is Much Better:
http://www.vox.com/2014/11/24/7272929/charts-thankful

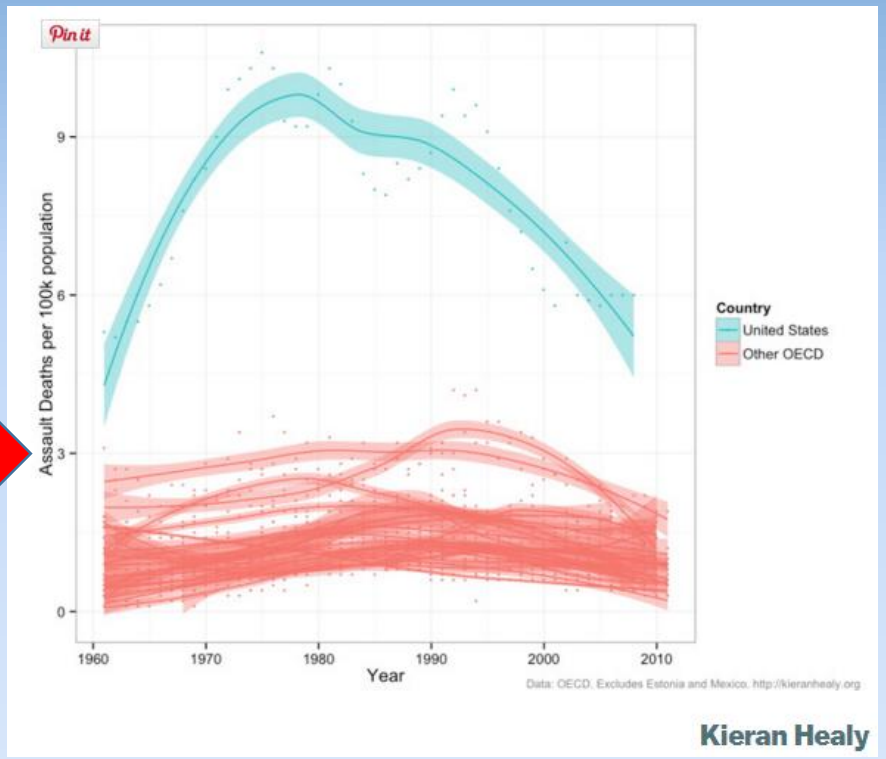
1. ECONOMIC PROGRESS: Extreme poverty has fallen
2. Hunger is falling
3. Child labor in decline
4. More leisure time
5. Income spent on food has plummeted in US
6. Health care: life expectancy is rising
7. Child Mortality is down
8. Death in childbirth is rarer
9. People are getting taller
10. More people have access to malaria bednets

http://www.vox.com/2014/11/24/7272929/charts-thankful

25 Charts and Maps that Show the World is Much Better (cont.):

http://www.vox.com/2014/11/24/7272929/charts-thankful

11. Guinea worm is almost eradicated
12. Teen births in US are down
13. As is smoking
14. War is on the decline
15. Homicide rates are down in Europe
16. And the US too
17. Violent crime declining
18. Rapidly reduce the supply of nuclear weapons
19. More countries are democracies
20. More people going to school longer



25 Charts and Maps that Show the World is Much Better (cont.): http://www.vox.com/2014/11/24/7272929/charts-thankful

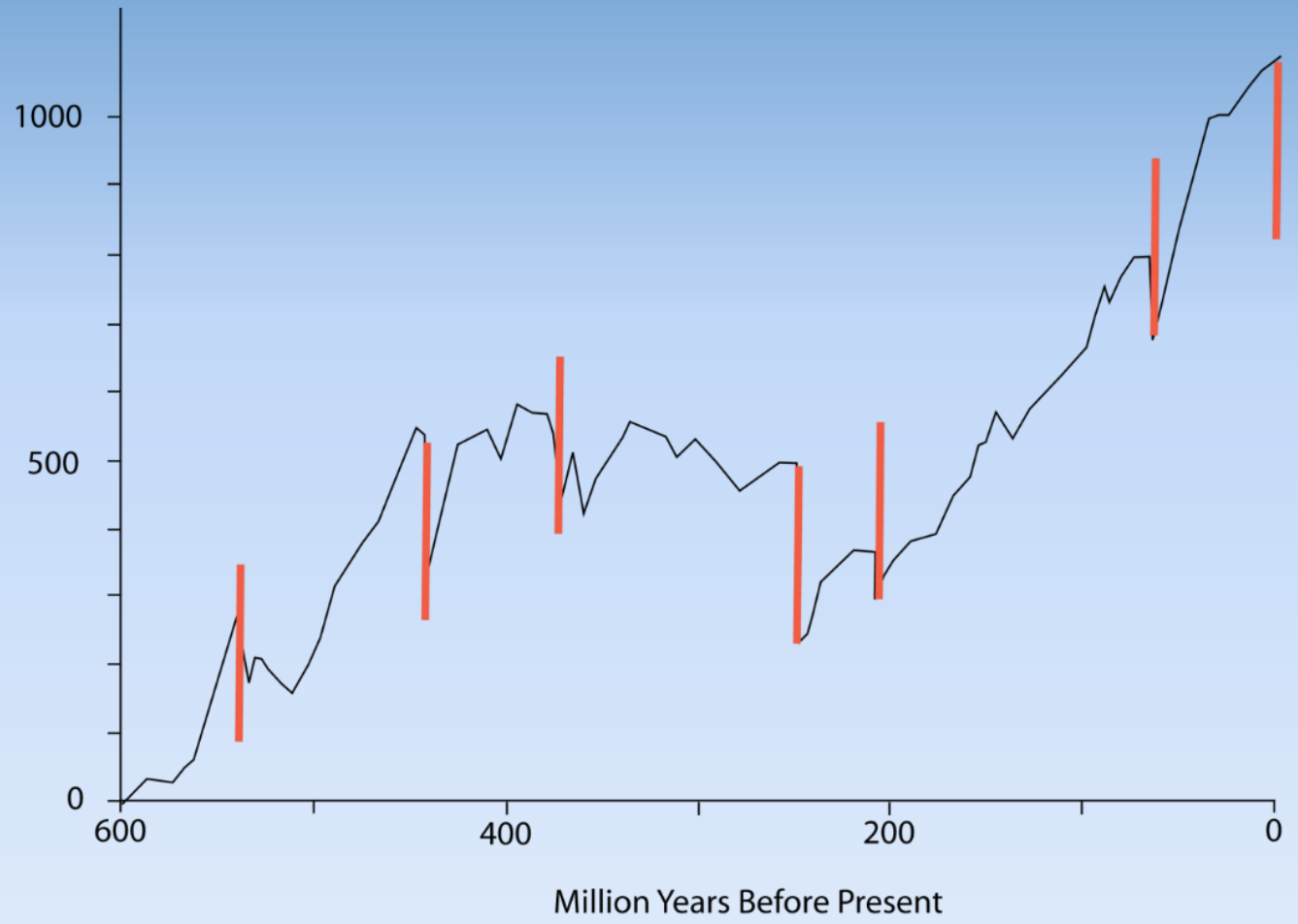
21. Literacy is up as well
22. US unsheltered homeless declined nearly 32% since 2007
23. Moore's law is still going (# transistors on a chip doubling) i.e. greater computer power
24. Access to internet increasing
25. Solar power is getting cheaper

Changes ARE happening

- SEE Bob Raynolds week 4 presentation:

http://denverclimatestudygroup.com/wp-content/uploads/2014/07/Olli-Anthropocene-Oct-2017.pdf

Changes ARE happening: Mass Extinctions

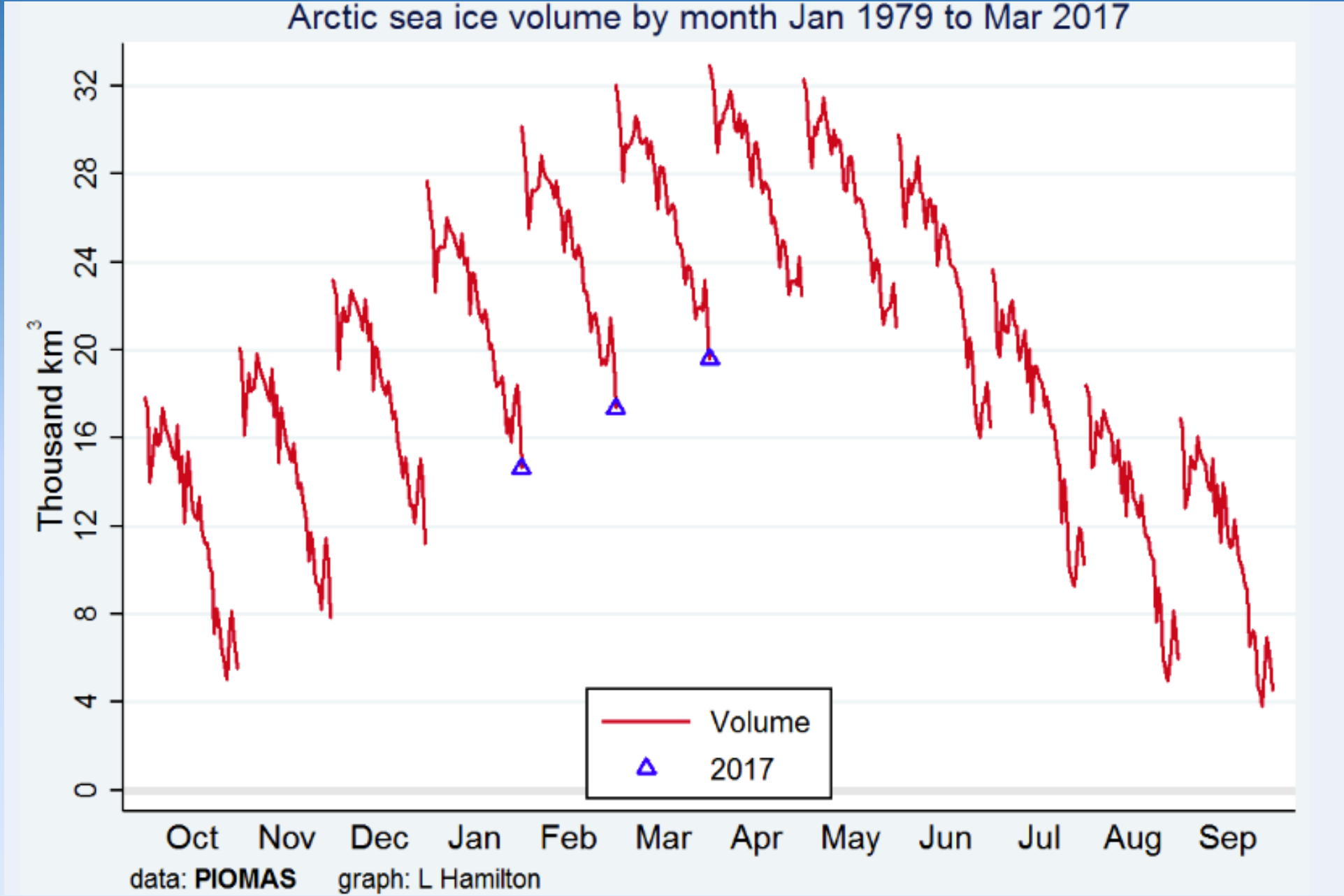


Diversity of marine families

Raup, 1986

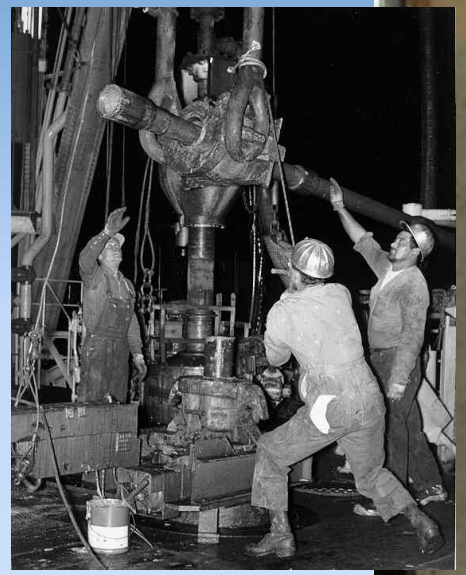
Changes ARE happening

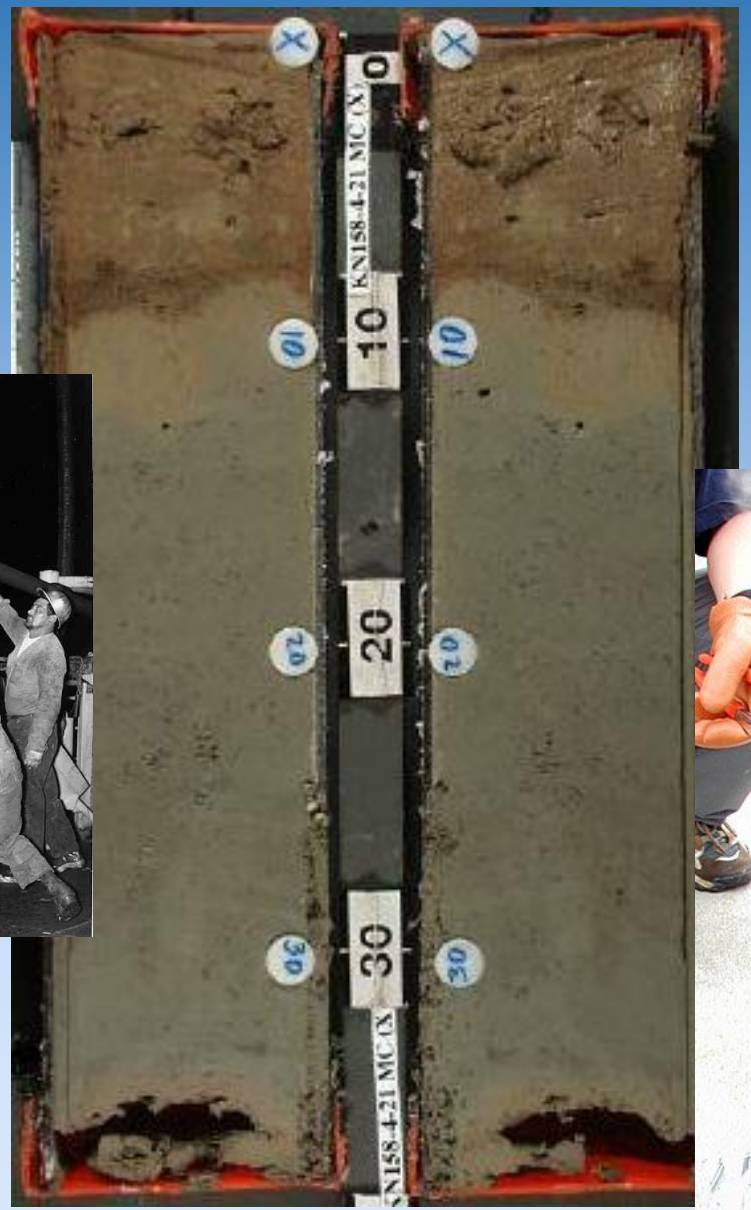
ICE:

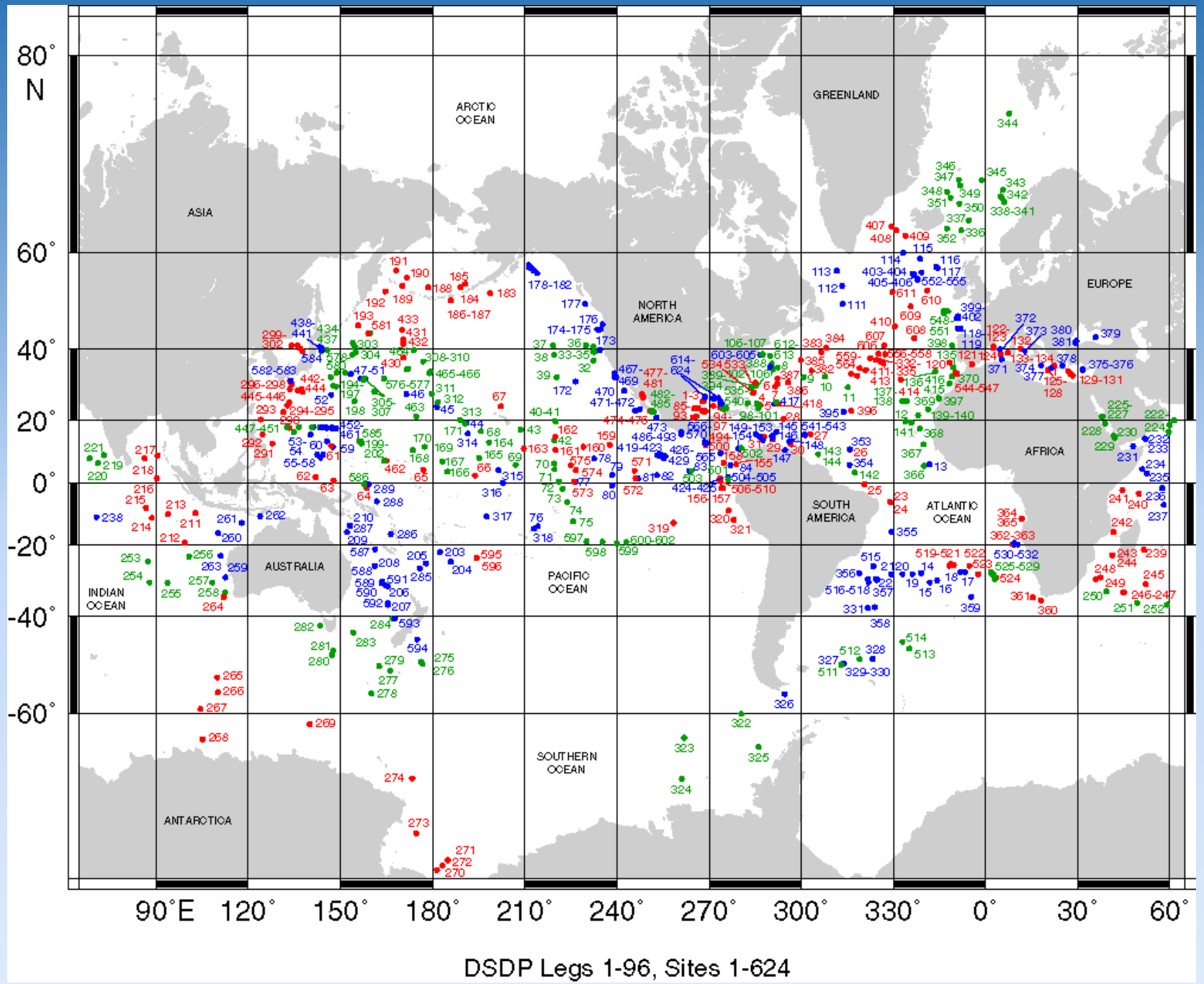


Changes are Happening

MUD



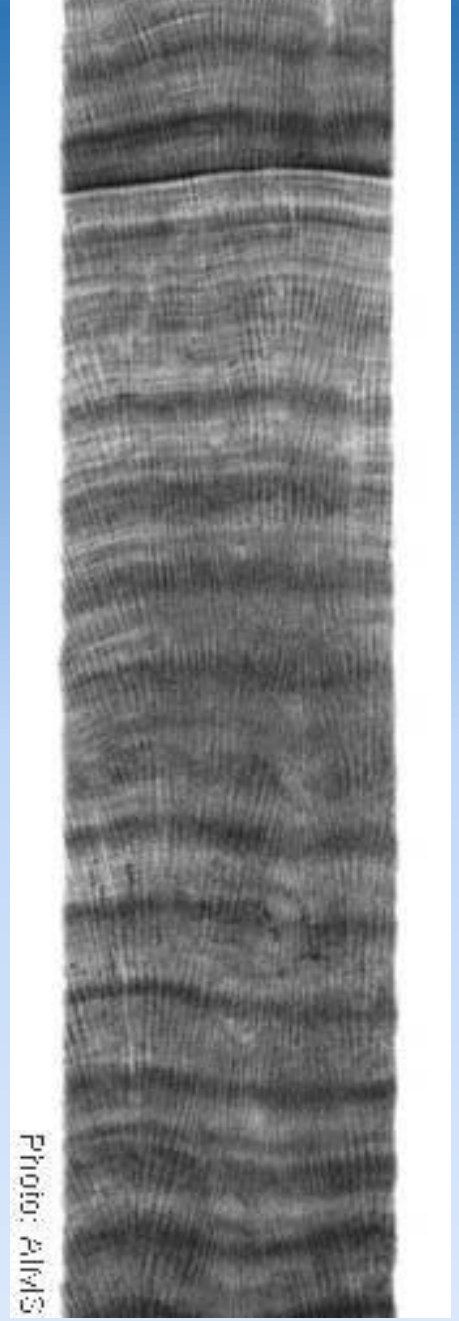

KN158-4-21 MC(X)
0
10
20
30
KN158-4-21 MC(X)



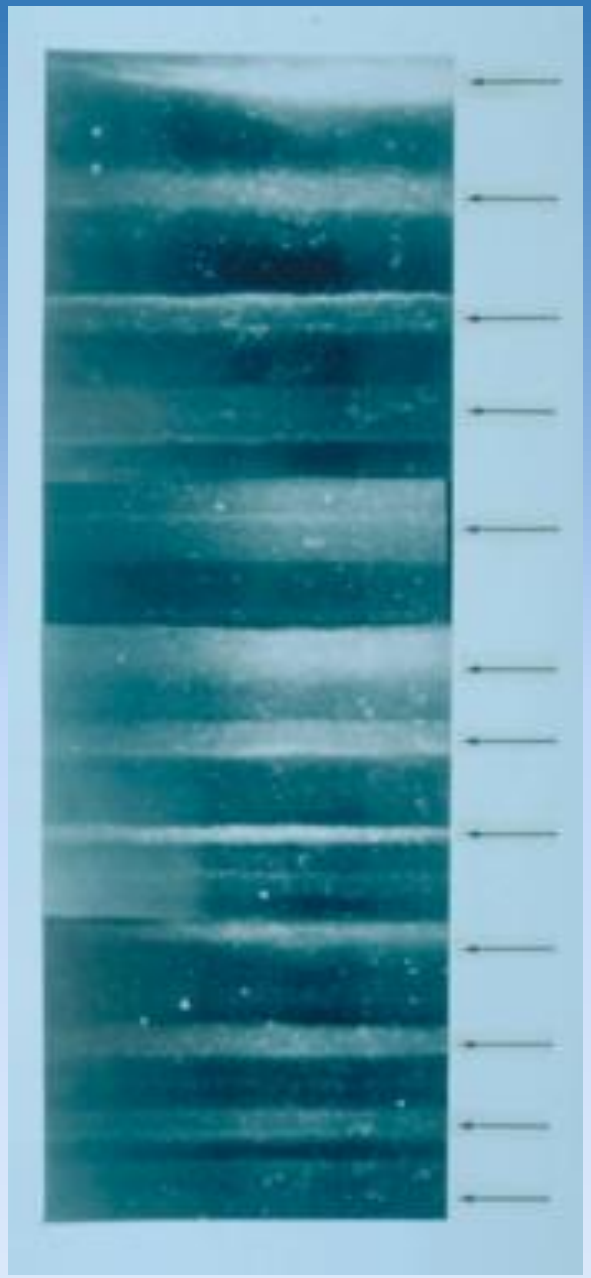
DSDP Legs 1-96, Sites 1-624

Changes are Happening

Caves and Reefs



Coral, Australia



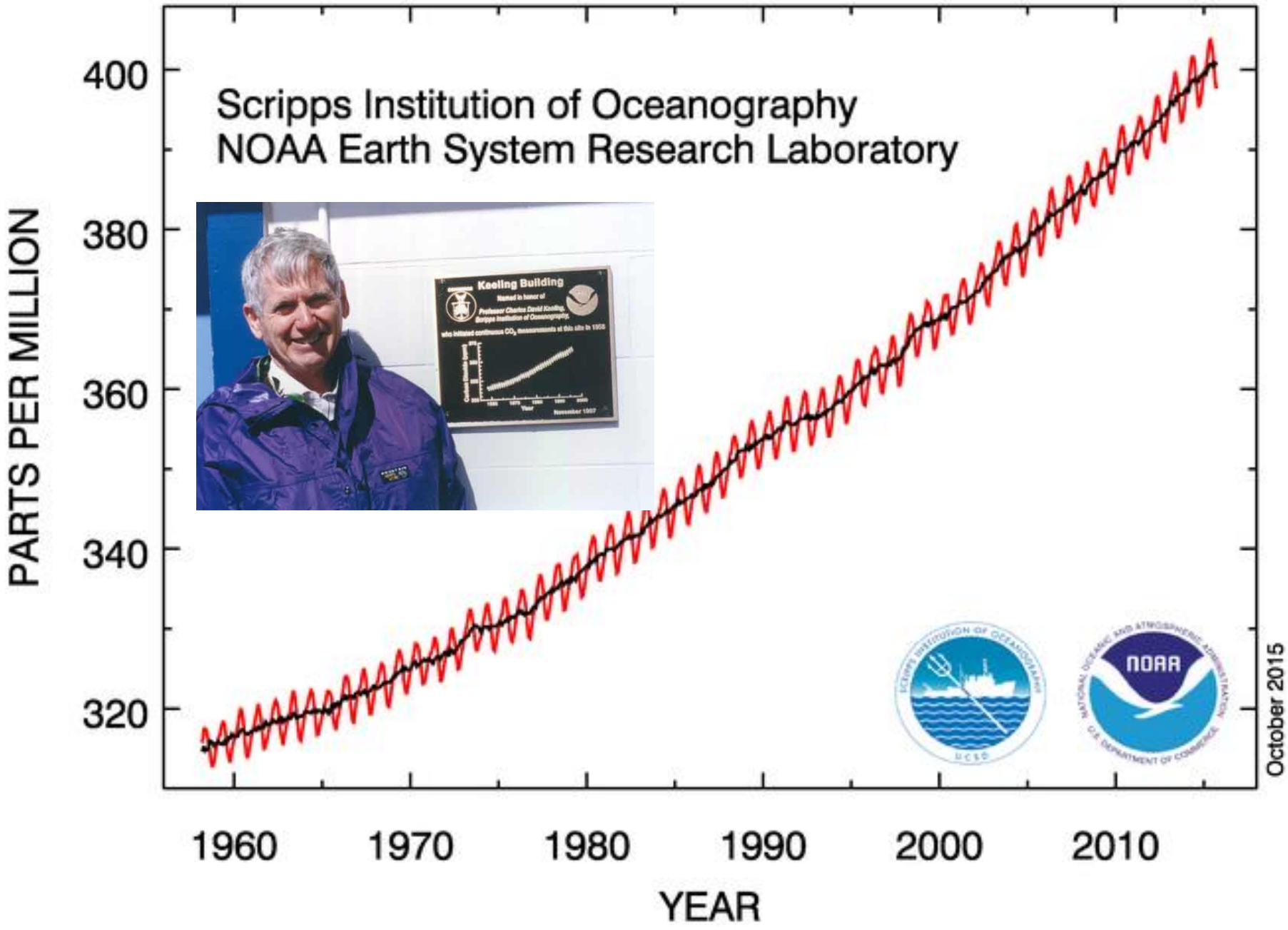
Ice, Greenland

Lake Sediments, Turkey

Changes are Happening

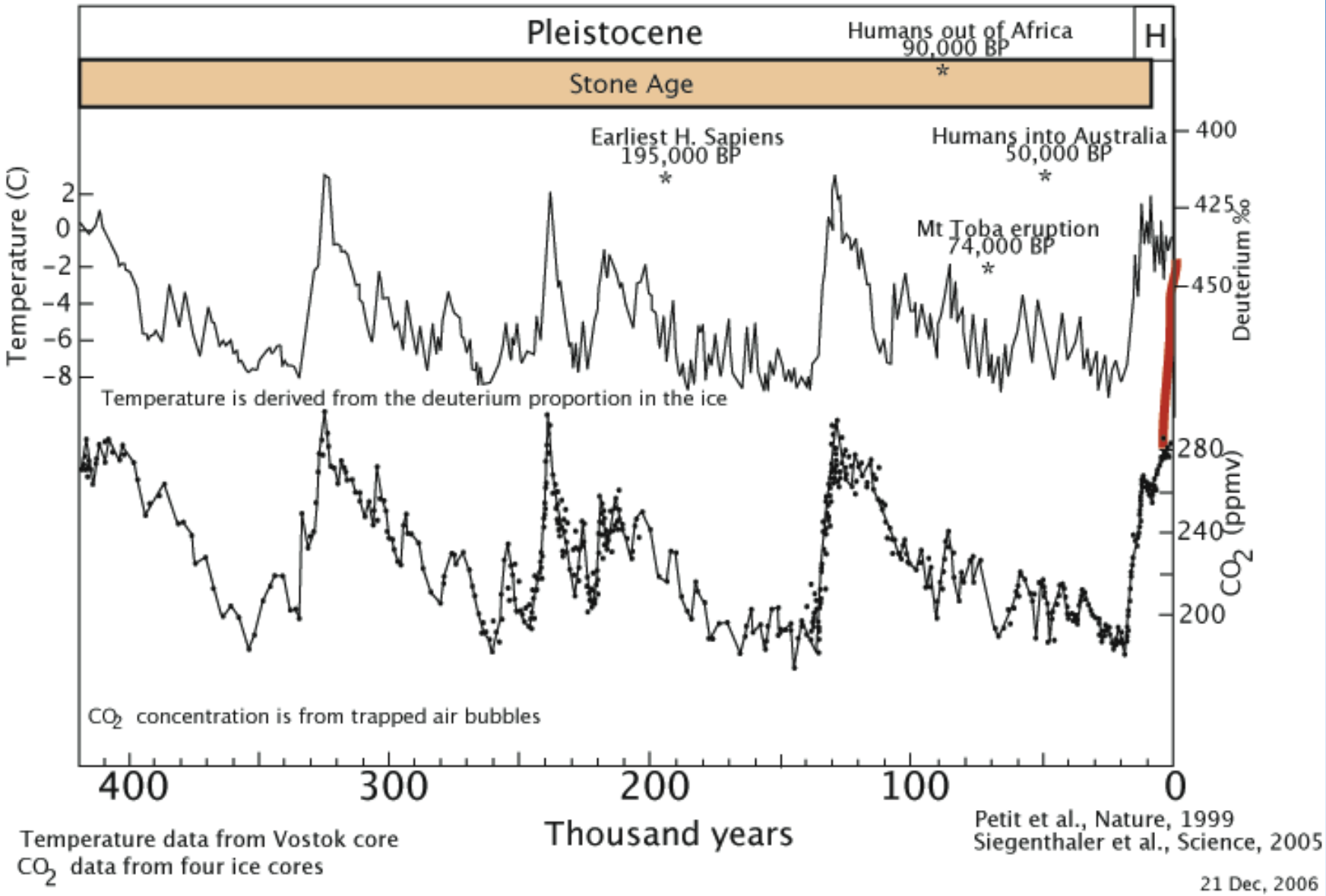
AIR

Atmospheric CO_2 at Mauna Loa Observatory



400,000 years

Antarctic Ice Cores



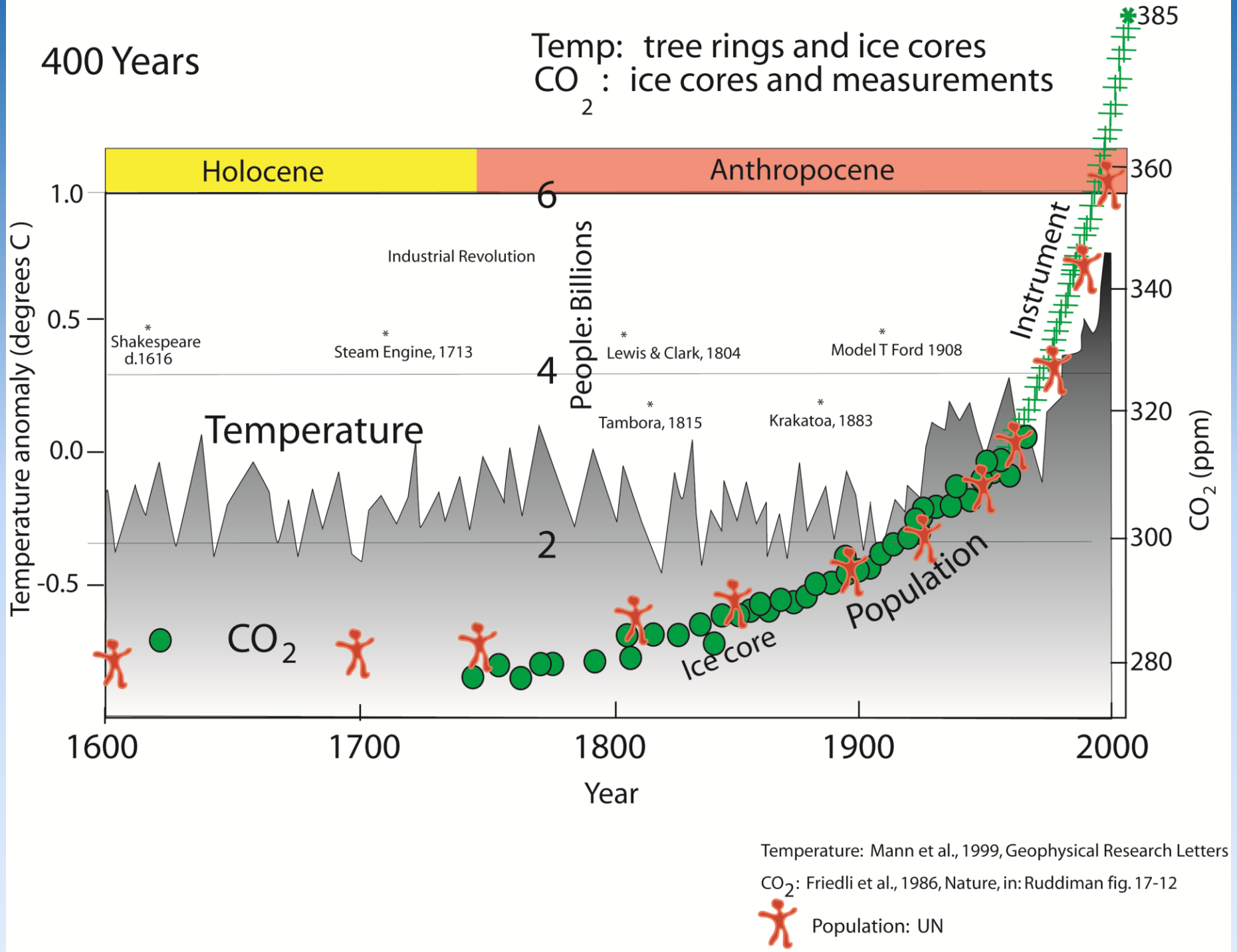
Temperature data from Vostok core
CO_2 data from four ice cores

Petit et al., Nature, 1999
Siegenthaler et al., Science, 2005

21 Dec, 2006

Changes are Happening

POPULATION



Temperature: Mann et al., 1999, Geophysical Research Letters

CO_2: Friedli et al., 1986, Nature, in: Ruddiman fig. 17-12

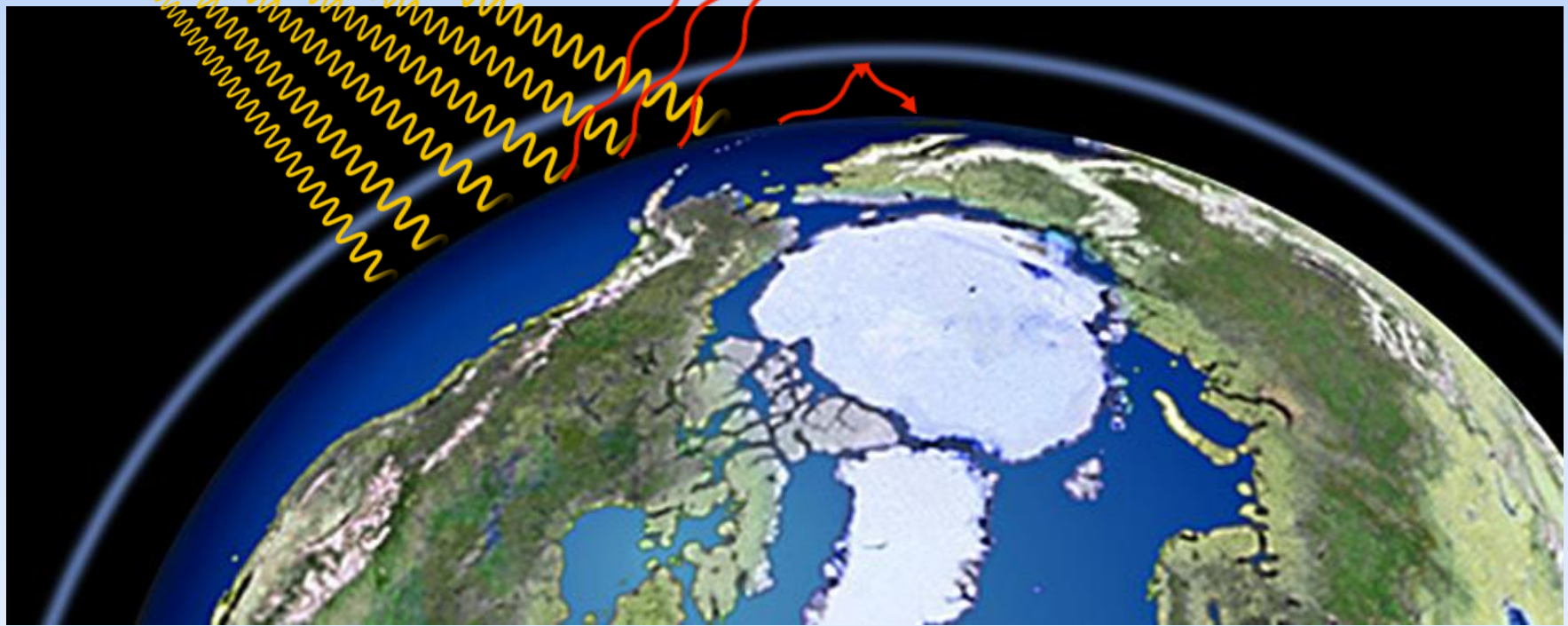
Population: UN

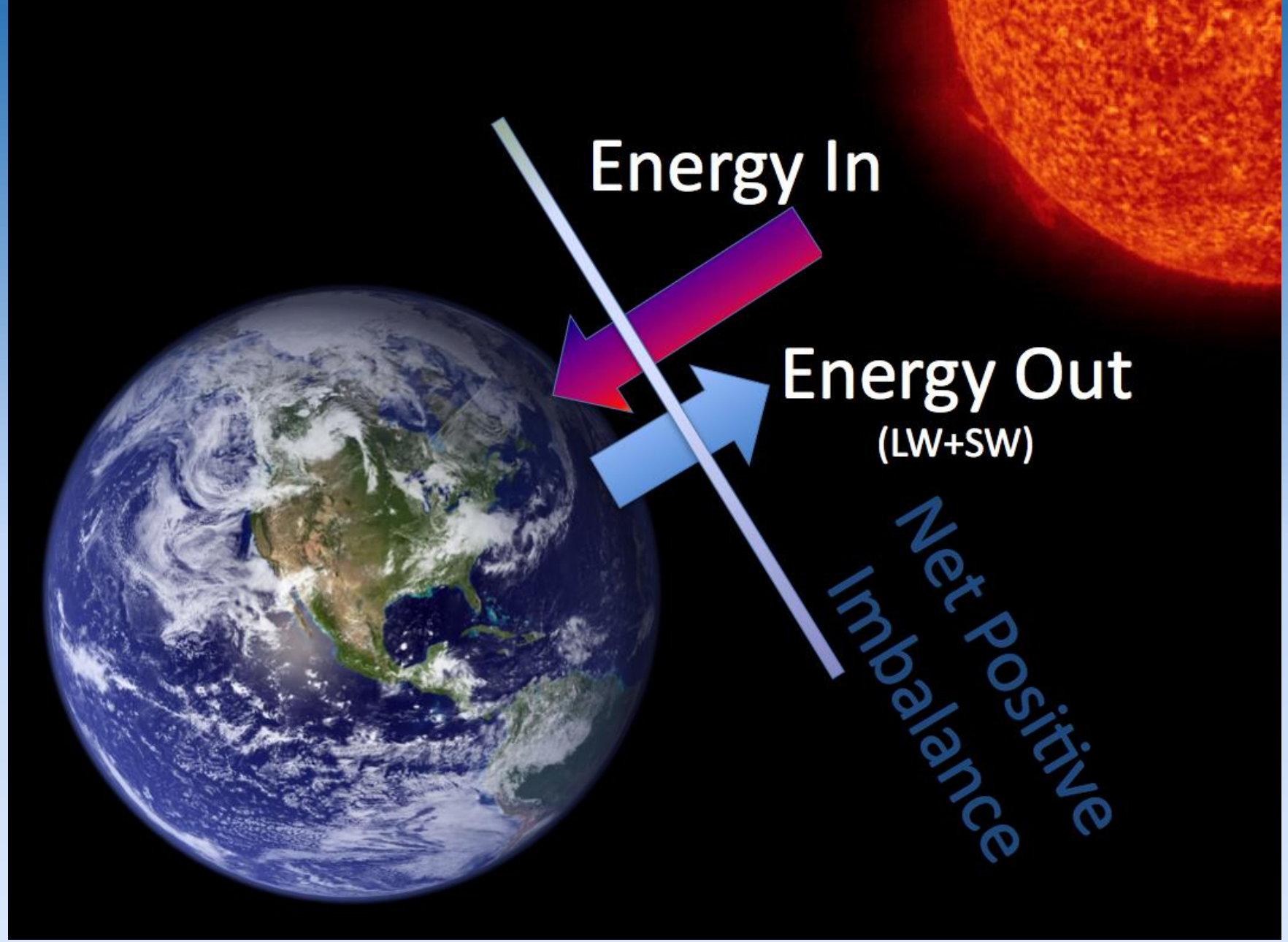
Changes are Happening

GLOBAL WARMING

About 342 w/m2 comes in

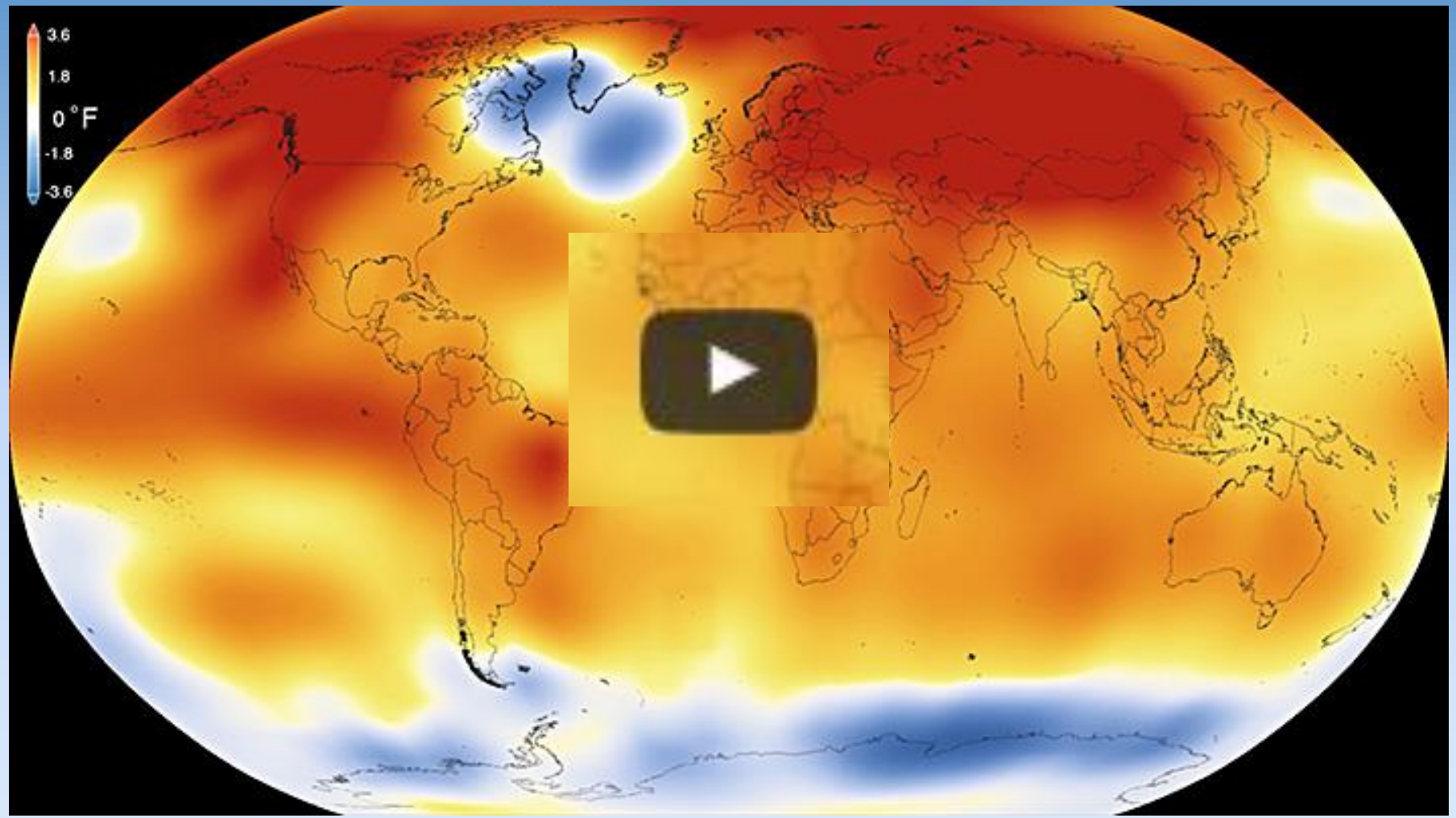
About 341 W/m2 goes out




Energy In
Energy Out
(LW+SW)
Net Positive
Imbalance

Global - Global Temperature Trends: 2015 Summation

Earth's Long-Term Warming Trend, 1880-2015

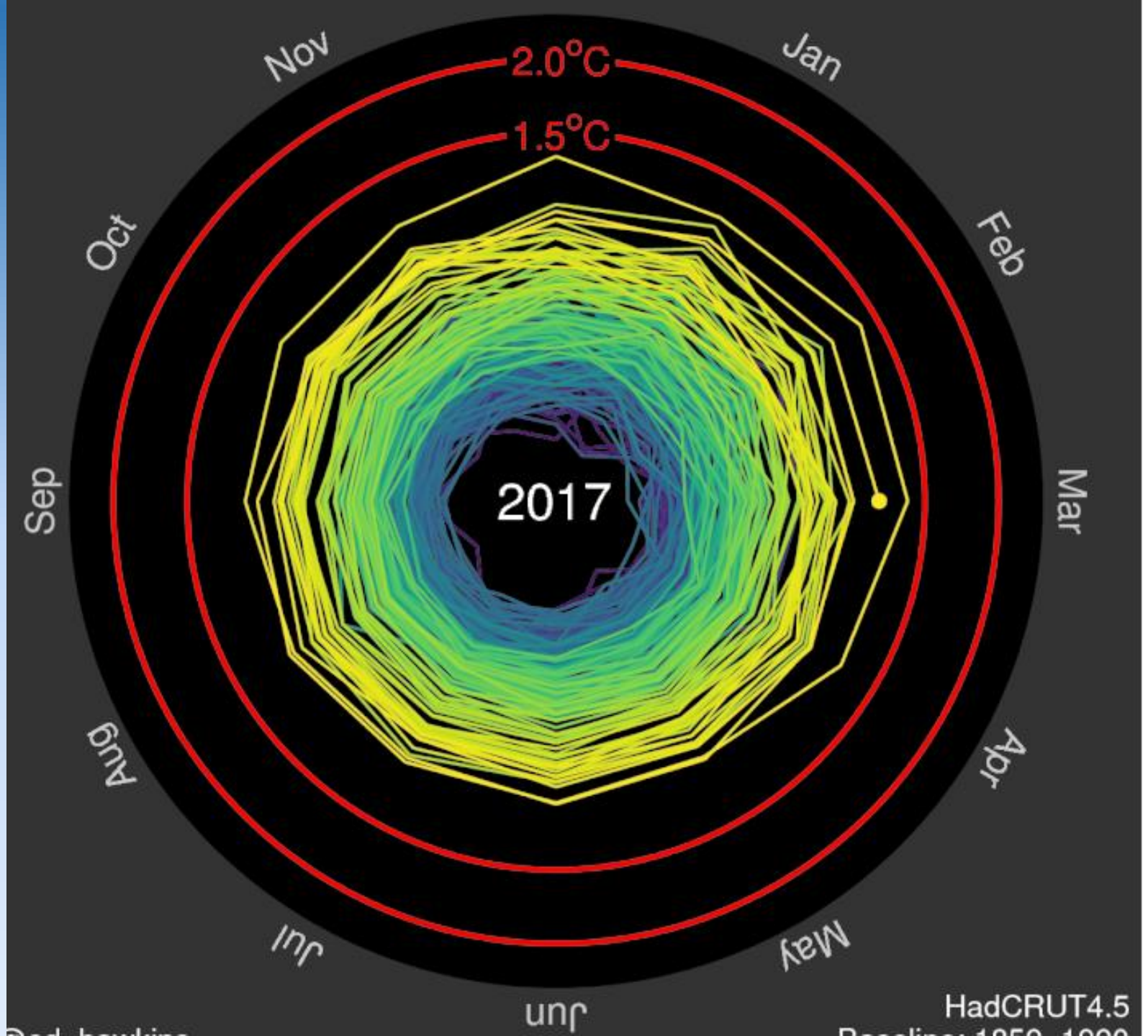


Video link:
https://www.youtube.com/watch?v=gGOzHVUQCw0

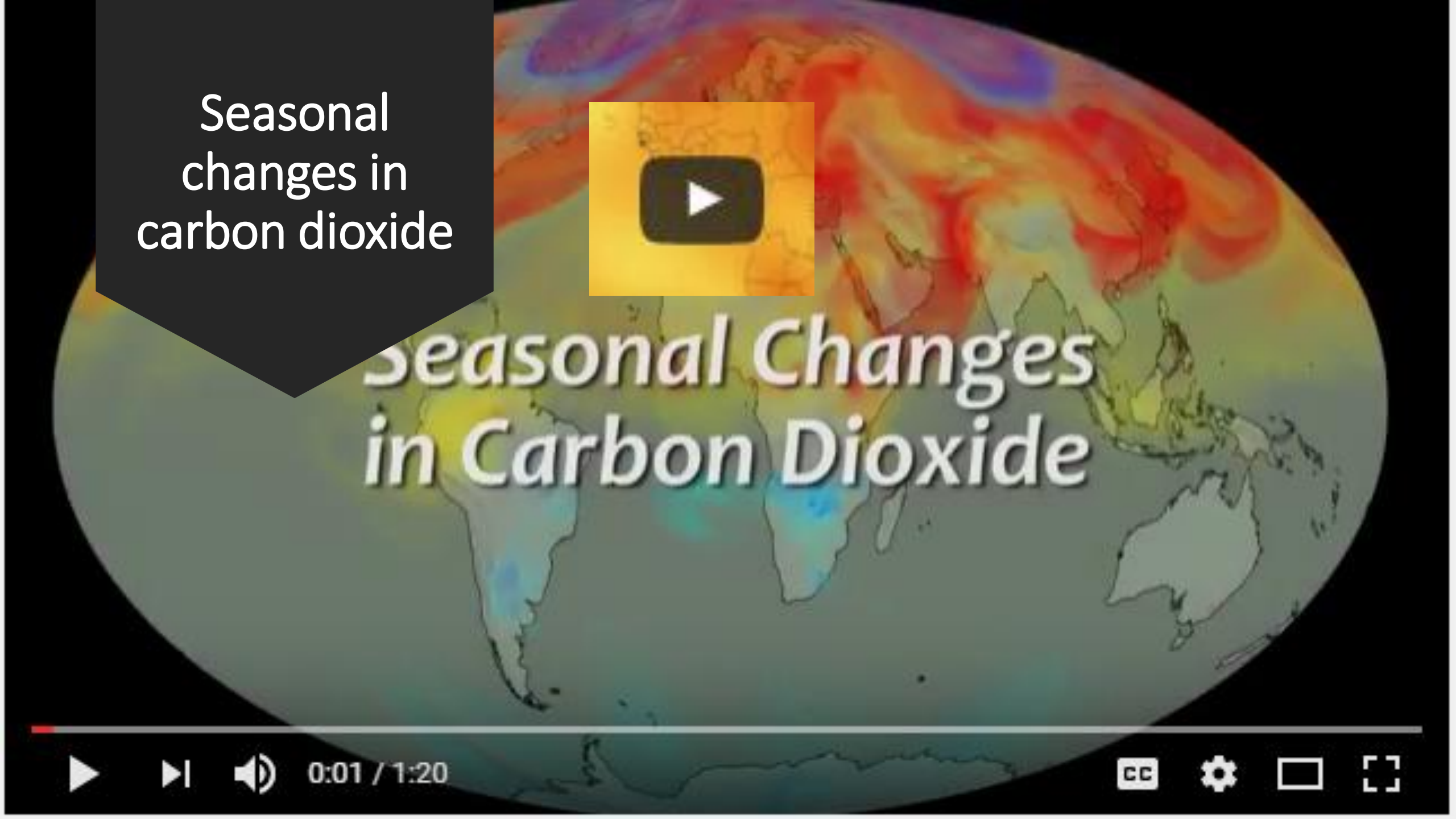
https://www.pmel.noaa.gov/arctic-zone/detect/global-temps.shtml

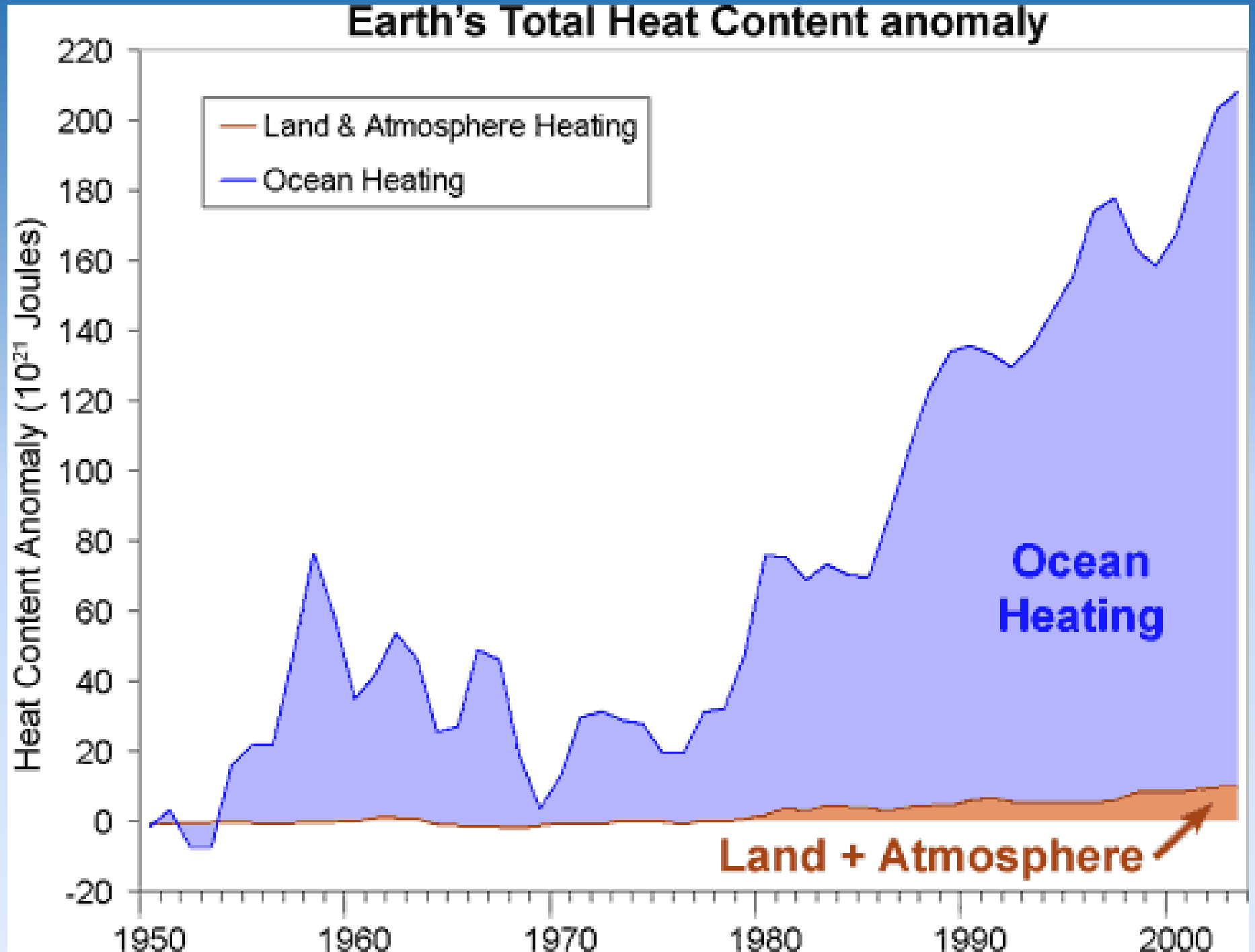
Temperature Spiral

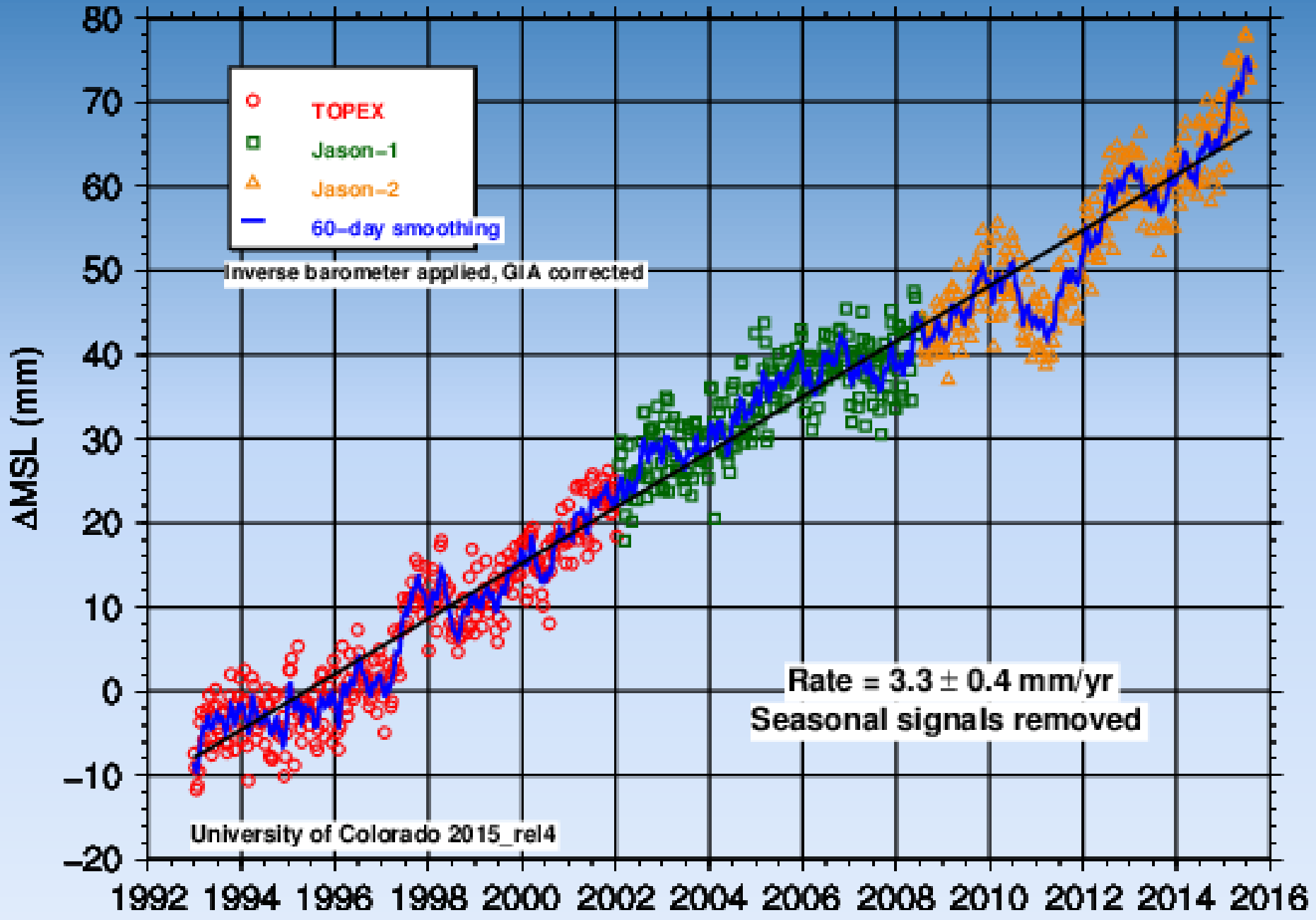
- http://www.climatecentral.org/news/temperature-spiral-turns-1-year-old-21440
- https://www.facebook.com/denverclimatestudygroup/



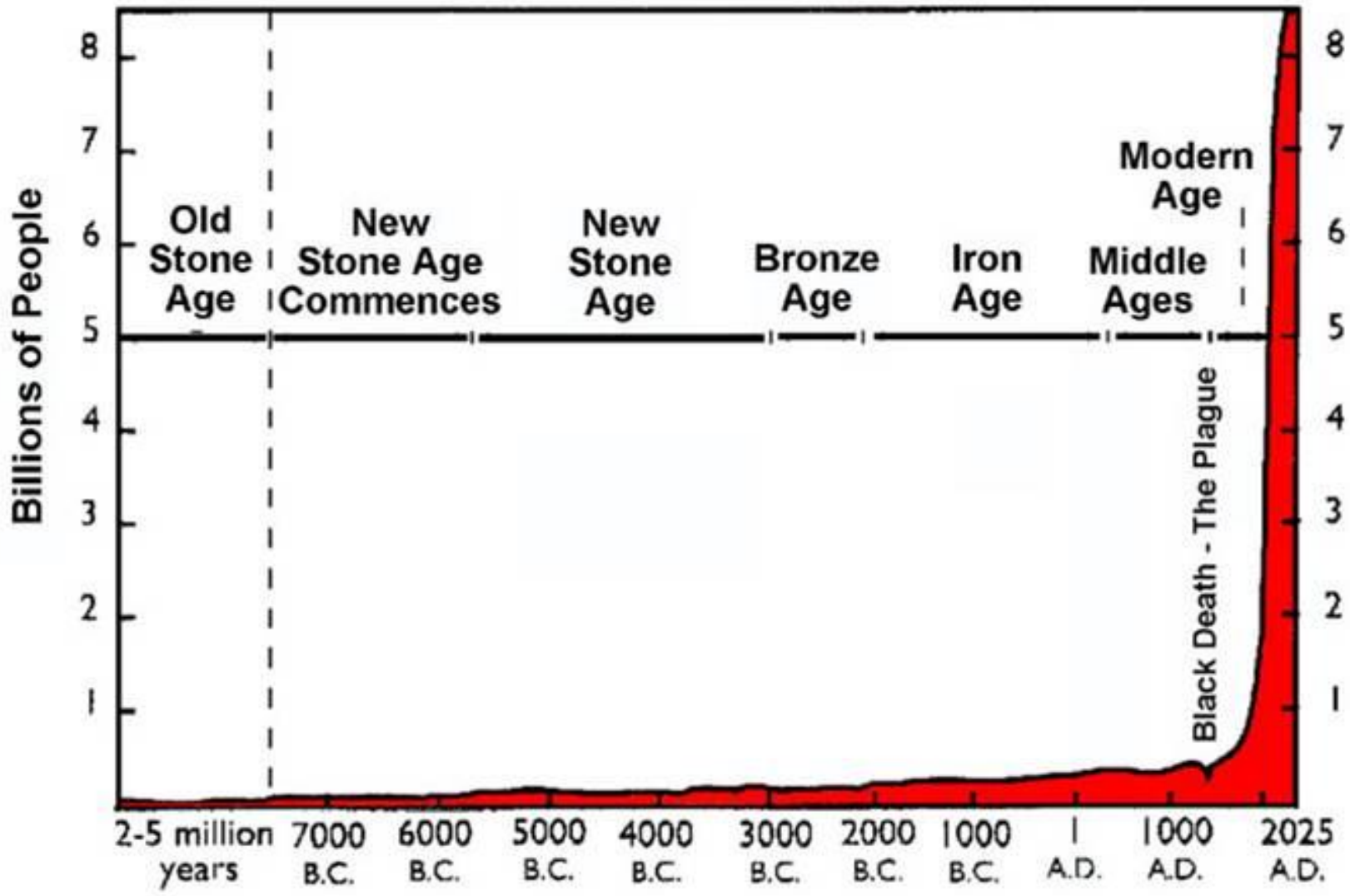
Seasonal changes in carbon dioxide

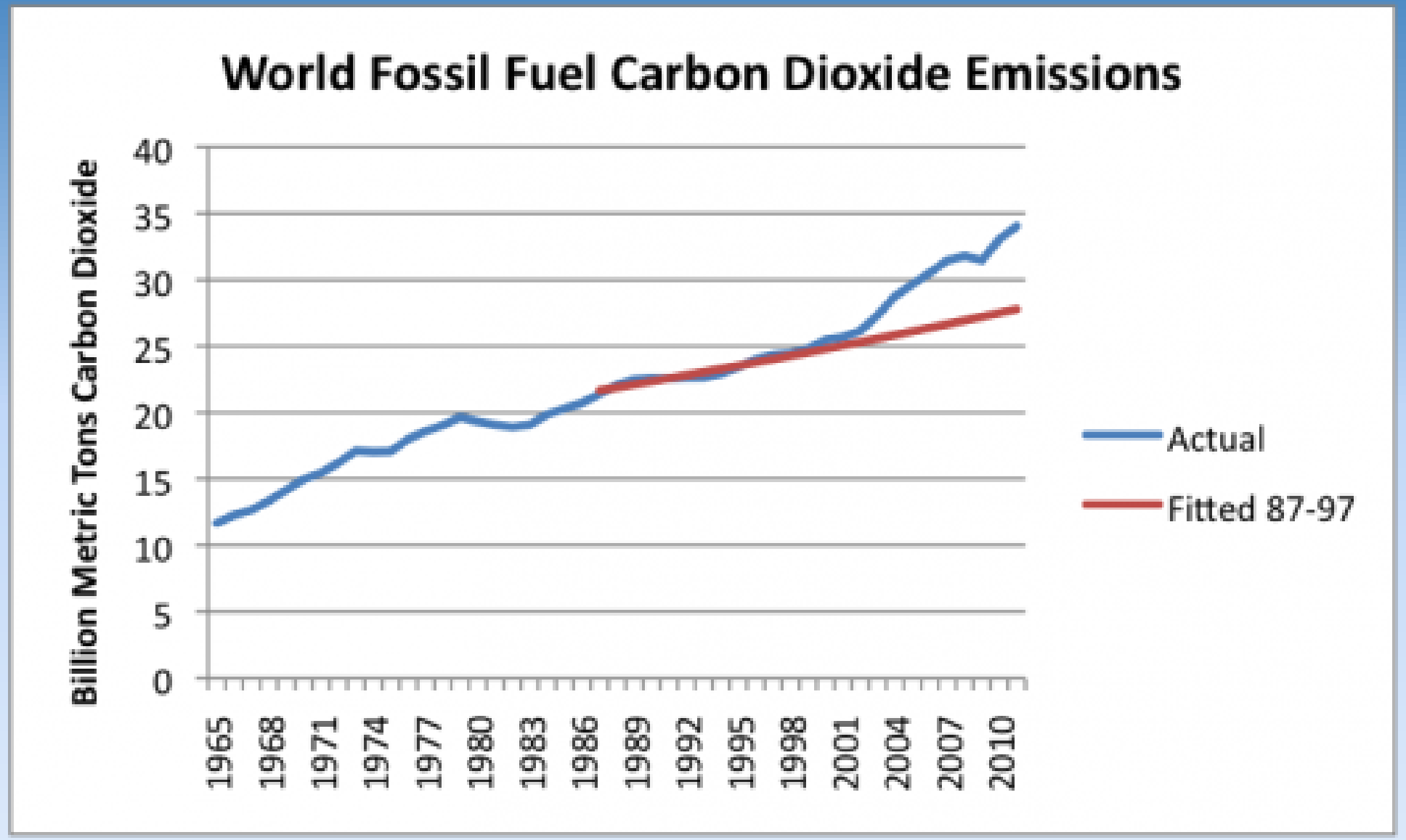



Earth's Total Heat Content anomaly
Land & Atmosphere Heating
Ocean Heating
Heat Content Anomaly (10^{21} Joules)
220
200
180
160
140
120
100
80
60
40
20
0
-20
1950
1960
1970
1980
1990
2000
Ocean Heating
Land + Atmosphere


TOPEX
Jason-1
Jason-2
60-day smoothing
Inverse barometer applied, GIA corrected
ΔMSL (mm)
Rate = 3.3 ± 0.4 mm/yr
Seasonal signals removed
University of Colorado 2015_rel4
80
70
60
50
40
30
20
10
0
-10
-20
1992 1994 1996 1998 2000 2002 2004 2006 2008 2010 2012 2014 2016

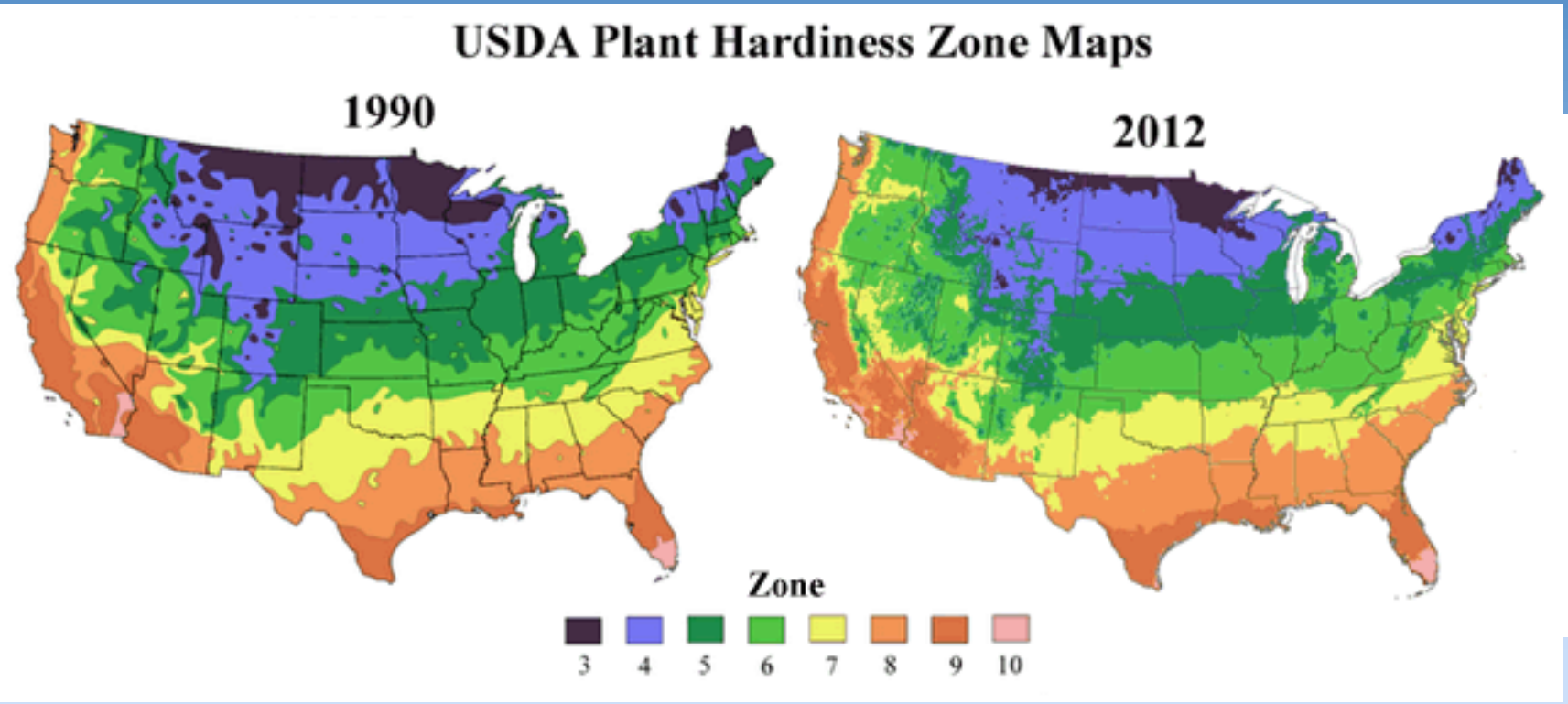
World Population Growth Through History

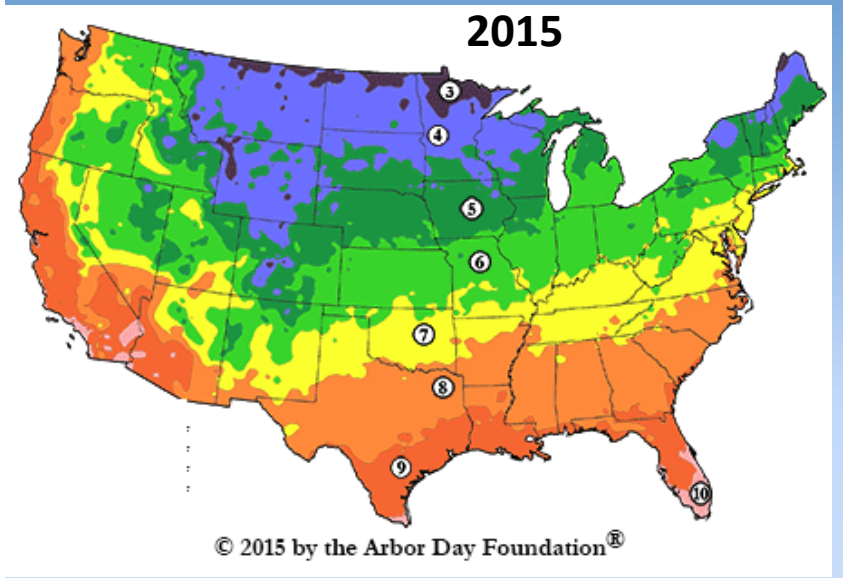



World Fossil Fuel Carbon Dioxide Emissions
Billion Metric Tons Carbon Dioxide
40
35
30
25
20
15
10
5
0
1965
1968
1971
1974
1977
1980
1983
1986
1989
1992
1995
1998
2001
2004
2007
2010
Actual
Fitted 87-97

BP, 2012;

Plants and Animals are Responding to a Warming Climate
1990 vs. 2012





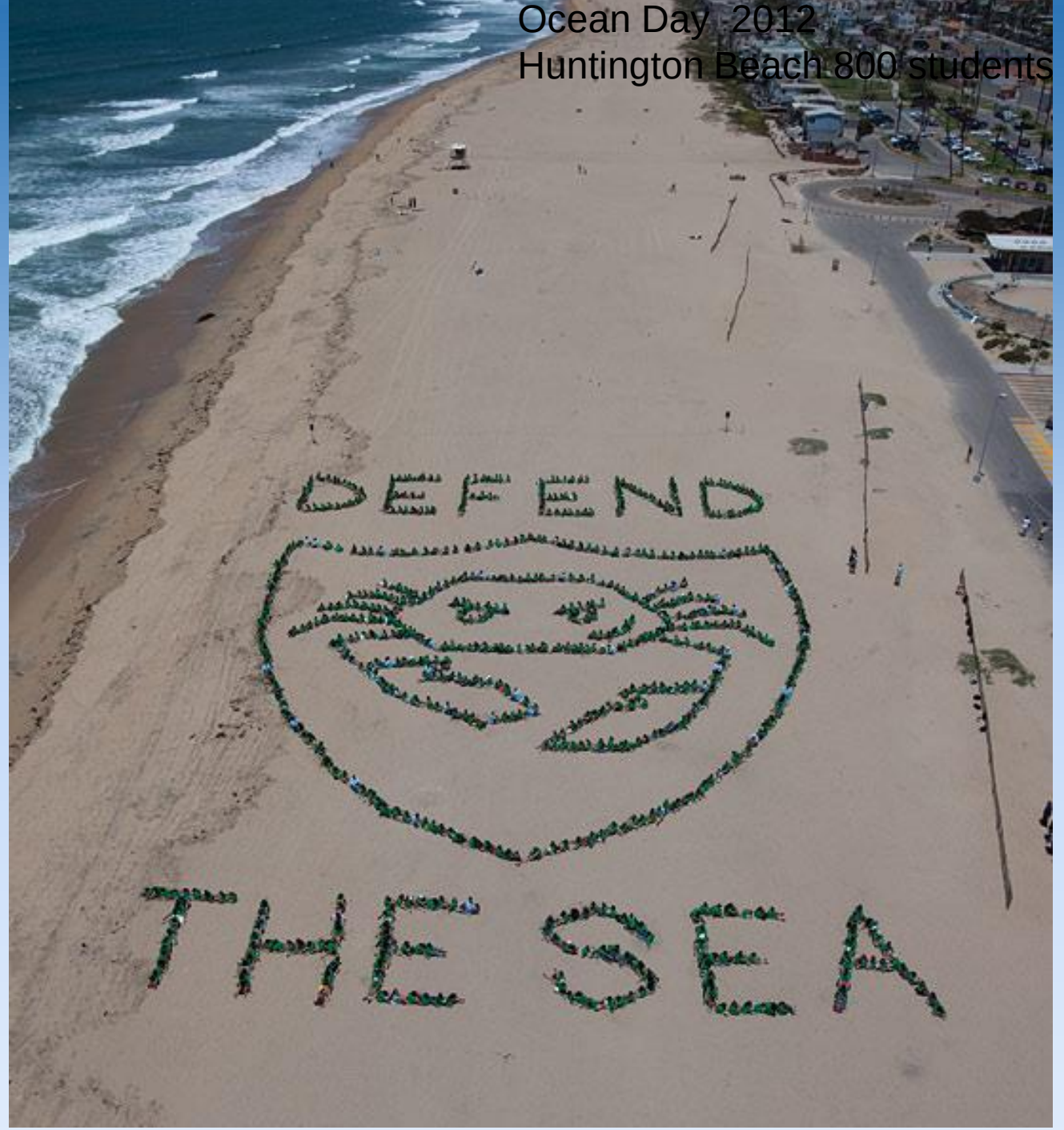
Spring is springing forward: Spring events, like bird and butterfly migrations, flower blooming times, and frog mating, have been advancing by about three days per decade over the past 30 years.

Source: Jeong et al., 2011, "Phenology shifts at start vs. end of growing season in temperate vegetation over the Northern Hemisphere for the period 1982–2008"

https://www.arborday.org/media/zones.cfm

POWER OF THE PEOPLE

Ocean Day 2012
Huntington Beach 800 students



Ocean Day
Dockweiler Beach, LA
5000 students

Museums, Zoos and Your Children will save the World

Climate Experts

- **97 % Climate Scientists say business as usual is NOT safe – should you believe them?**
  - **If 95 of 100 Engineers tell you that IT IS NOT SAFE TO GO FORTH ON THAT BRIDGE – are you going to ignore them?**

YOUTH GET IT!

(dad doesn't)

- https://www.facebook.com/denverclimatestudygroup/

Climate science expert Ivanka Trump to determine the fate of planet Earth. https://t.co/N9Lw7BDvEl

Ivanka Trump to review climate change as US mulls Paris pullout

The president's daughter and adviser will look at the issue as he weighs taking

Neil deGrasse Tyson – he’s not a climate scientist either – and he’s old:
BUT HE GETS IT!

Neil deGrasse Tyson – if I were in charge, I wouldn't be in charge – I would want to inform

- https://www.facebook.com/techinsider/videos/428602874004741/

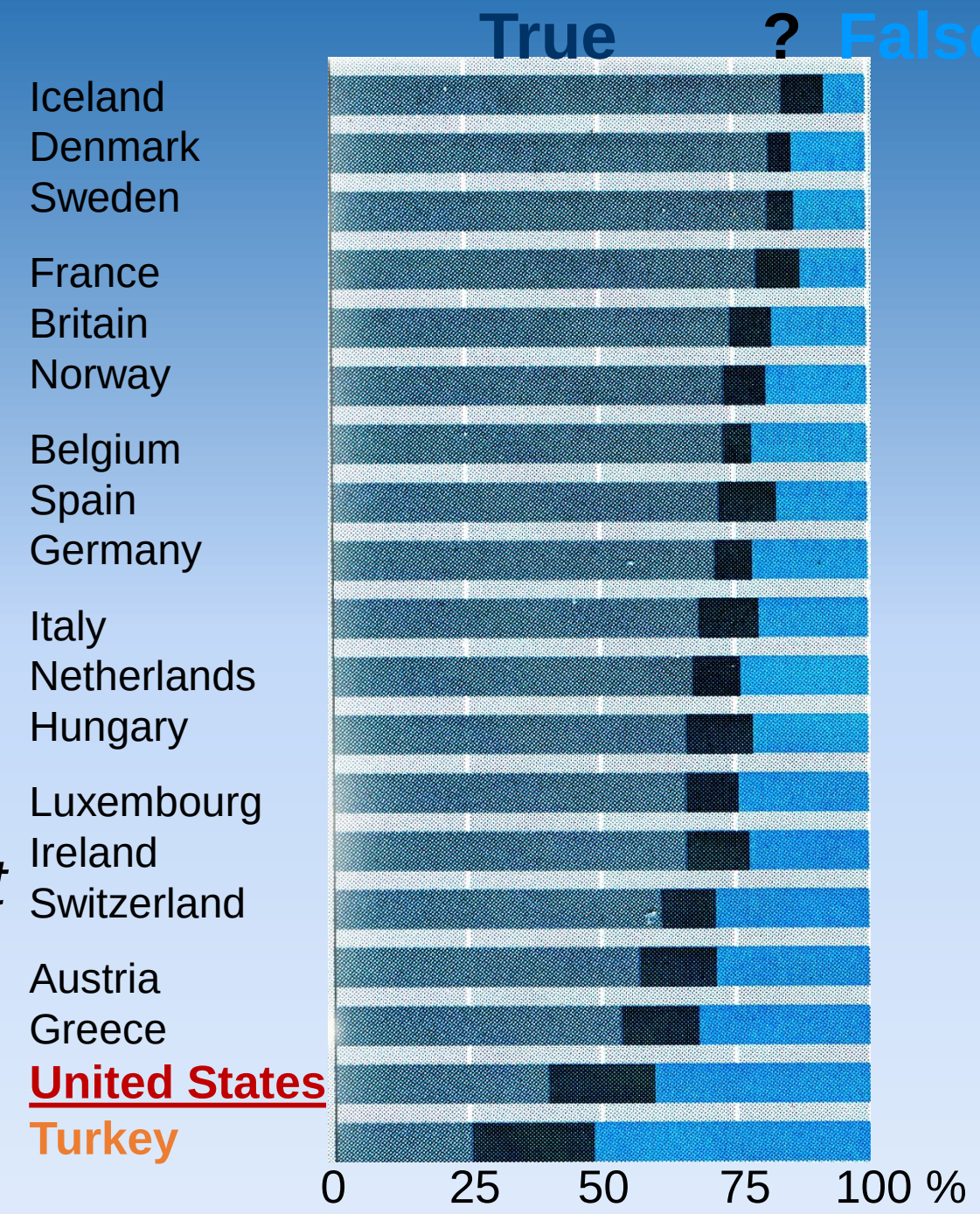
Neil deGrasse Tyson: On climate change deniers

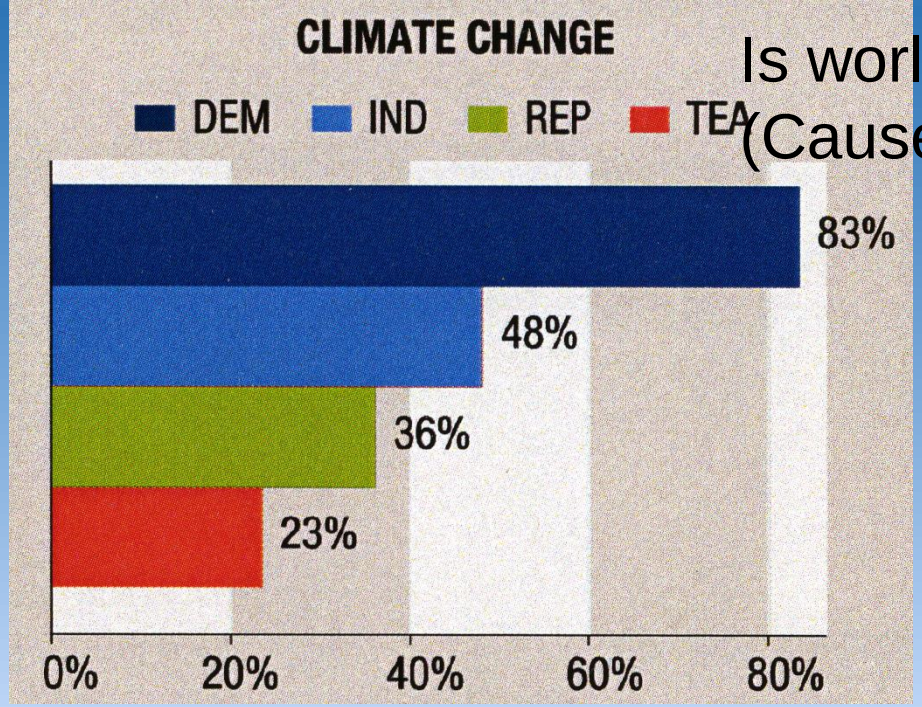
- http://www.cnn.com/videos/tv/2017/05/05/exp-gps-neil-degrasse-tyson-climate-change.cnn

Public acceptance of evolution

Poll by New Scientist, 2006

(2012 Gallup poll found 49% of U.S. responders reject evolution, and another 35% accept it only as divinely steered to produce us)

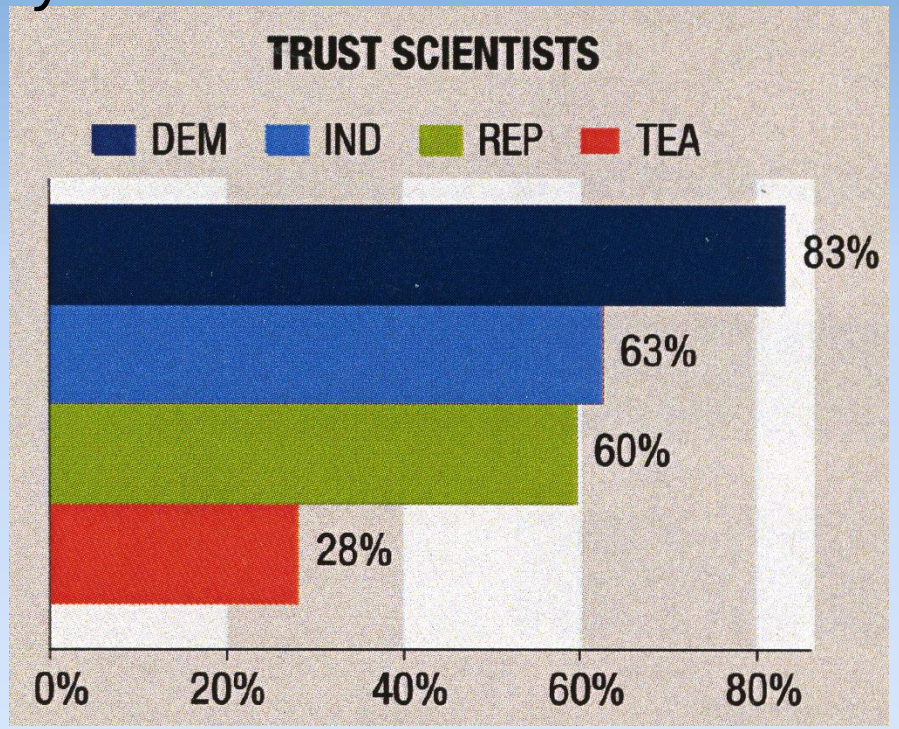


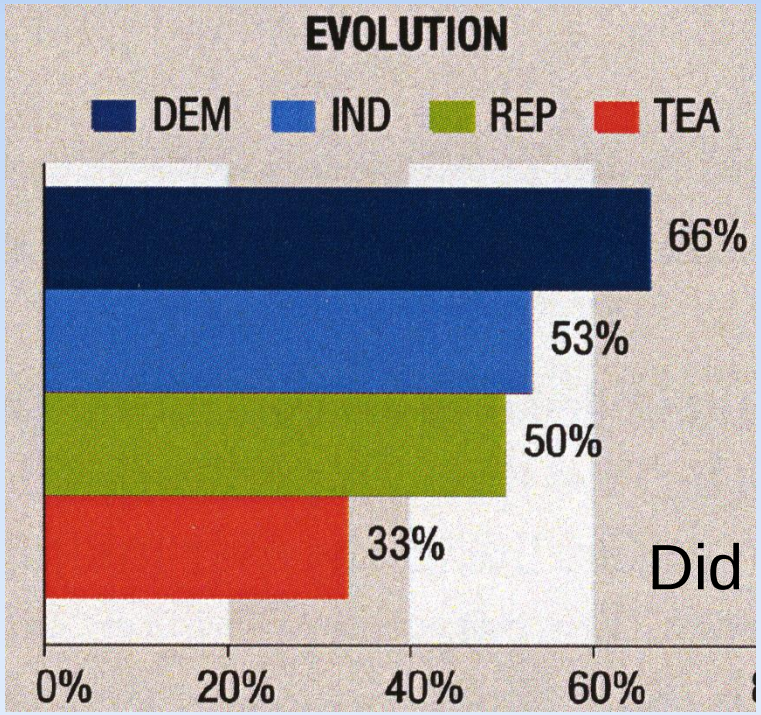


Is world climate warming?
(Cause not specified)

New Hampshire poll,
UNH-Carsey Inst., 2014

Do you trust data from scientists?





Did man evolve?

(L.C. Hamilton, 2014)

CLIMATE

Ted Cruz: 'Climate Change Is Not Science. It's Religion.'

BY SAMANTHA PAGE OCT 30, 2015 11:28AM

IN SUMMARY

1. The world has been getting better
2. Changes are happening
3. We need to support science and new technologies

WE NEED TO SUPPORT GAME CHANGERS; IN PARTICULAR:

1. ENERGY – NON-CARBON sources:
   - RENEWABLES:
     - Photovoltaics (PV)
     - Wind
     - Concentrated Solar Power
2. Storage and/or Expanded Grid
3. Continued subsidy for Conventional Nuclear
4. Possibly FUSION: COMPACT FUSION OF LOCKHEED (CLICK HERE)
   - OR NEW GERMAN REACTOR (CLICK HERE)
   - SOLAR, OTHER NUCLEAR, MODERN GRID, ETC.

WE NEED TO SUPPORT GAME CHANGERS; IN PARTICULAR:

2. **MITIGATION: BIOCHAR as a sequestration agent:** http://denverclimatestudygroup.com/?page_id=28

- ***The potential for land-based biological CO2 removal to lower future atmospheric CO2 concentration-Tim Lenton, University of Exeter - click here***
- ***Sustainable biochar to mitigate global climate change - Woolf,***

Gloom and Doom?

NO! IT’S A CHALLENGE, and humanity has always been challenged and we are an adaptable species that has met the challenge over and over again!

IN SUMMARY

1. The world has been getting better

2. **Changes** are happening; **WE NEED TO CHANGE**:
   - 25+ Ways to Reduce Your Carbon Footprint: http://cotap.org/reduce-carbon-footprint/

3. We need to support science and new technologies
4. GET INVOLVED – keep in touch


Pixdaus

EXTRAS

Naomi Oreskes
Slides excerpted from:

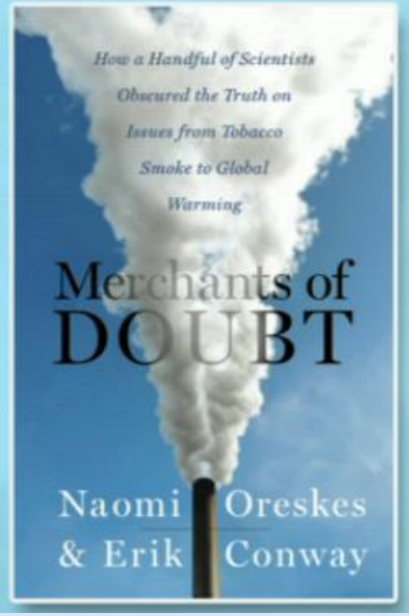
Changing Planet: Past, Present, Future
Lecture 4 – Climate Change: How Do We Know We're Not Wrong?
by Naomi Oreskes, PhD

http://www.hhmi.org/biointeractive/climate-change-how-do-we-know-were-not-wrong

http://media.hhmi.org/hl/12Lect4.html

Implicatory Denial

Rejection of climate science—like acid rain, ozone depletion, tobacco use—was not about science.



It was about its implications.

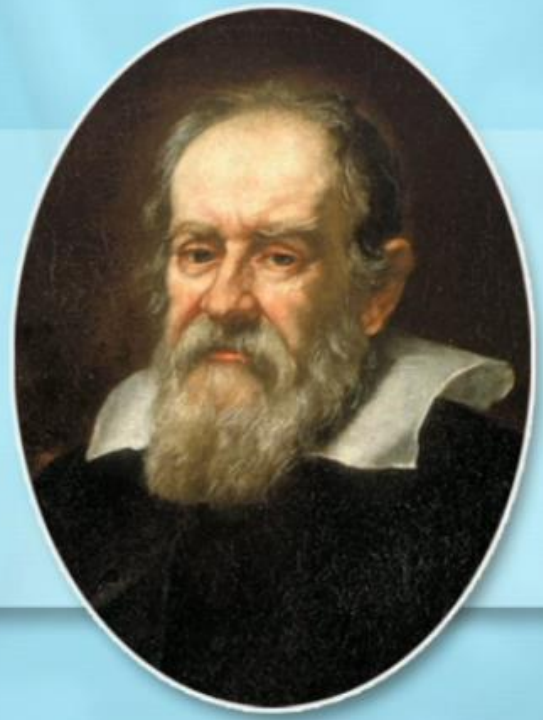
1. Free market capitalism had produced serious problems that the "invisible hand" was not solving.

2. The American way of life might need adjustment.

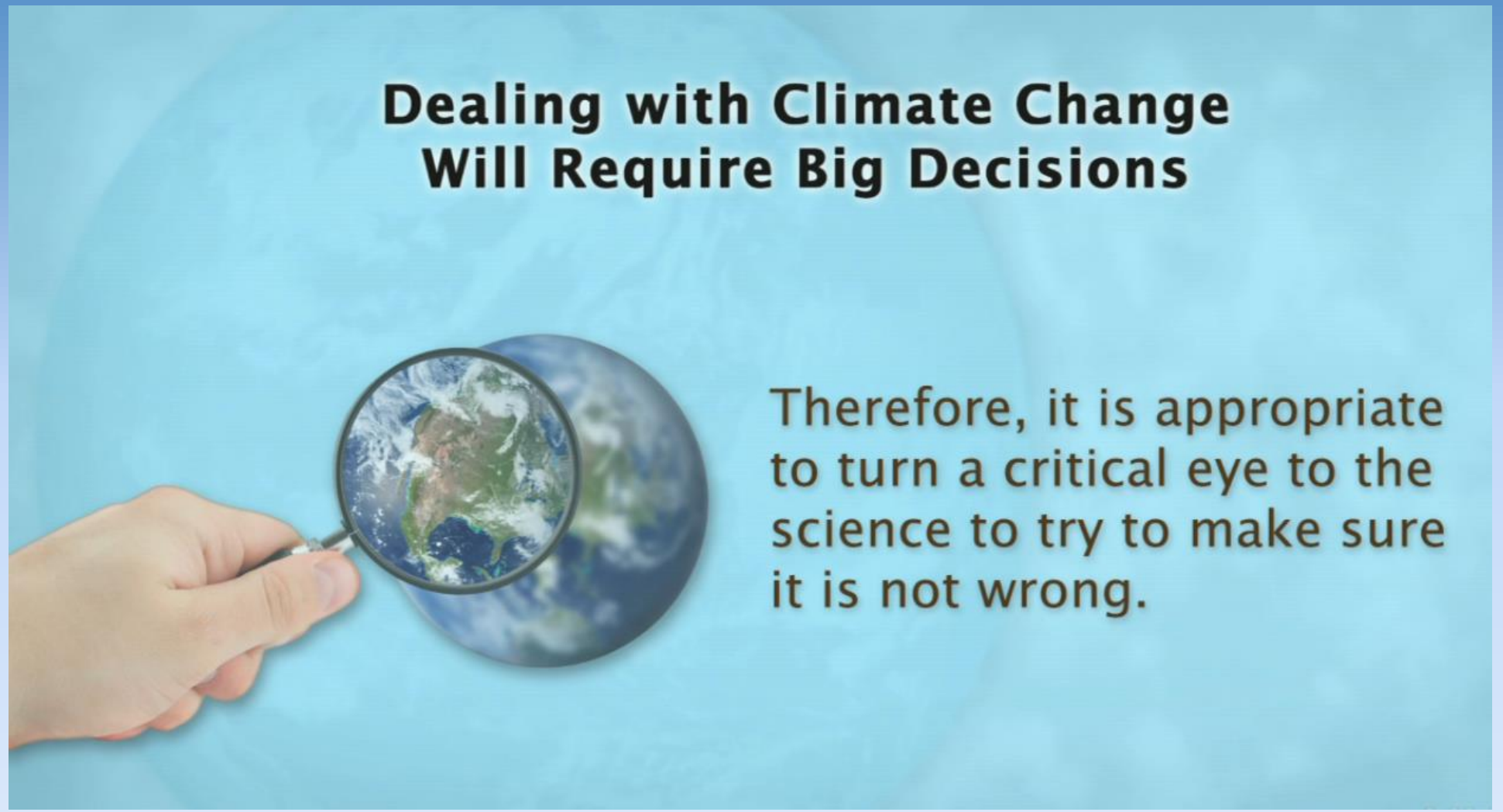
http://media.hhmi.org/hl/12Lect4.html

Catholic Church Rejected Galileo Because They Did Not Like the Implications

Not because his science wasn't right, but because it implied that the Catholic Church wasn't infallible



http://media.hhmi.org/hl/12Lect4.html



http://media.hhmi.org/hl/12Lect4.html

Science Is Falsifiable

This means that if the claim is false, then that can be demonstrated by experiment and/or observation.

Example

Observation:
CO_2 levels are rising

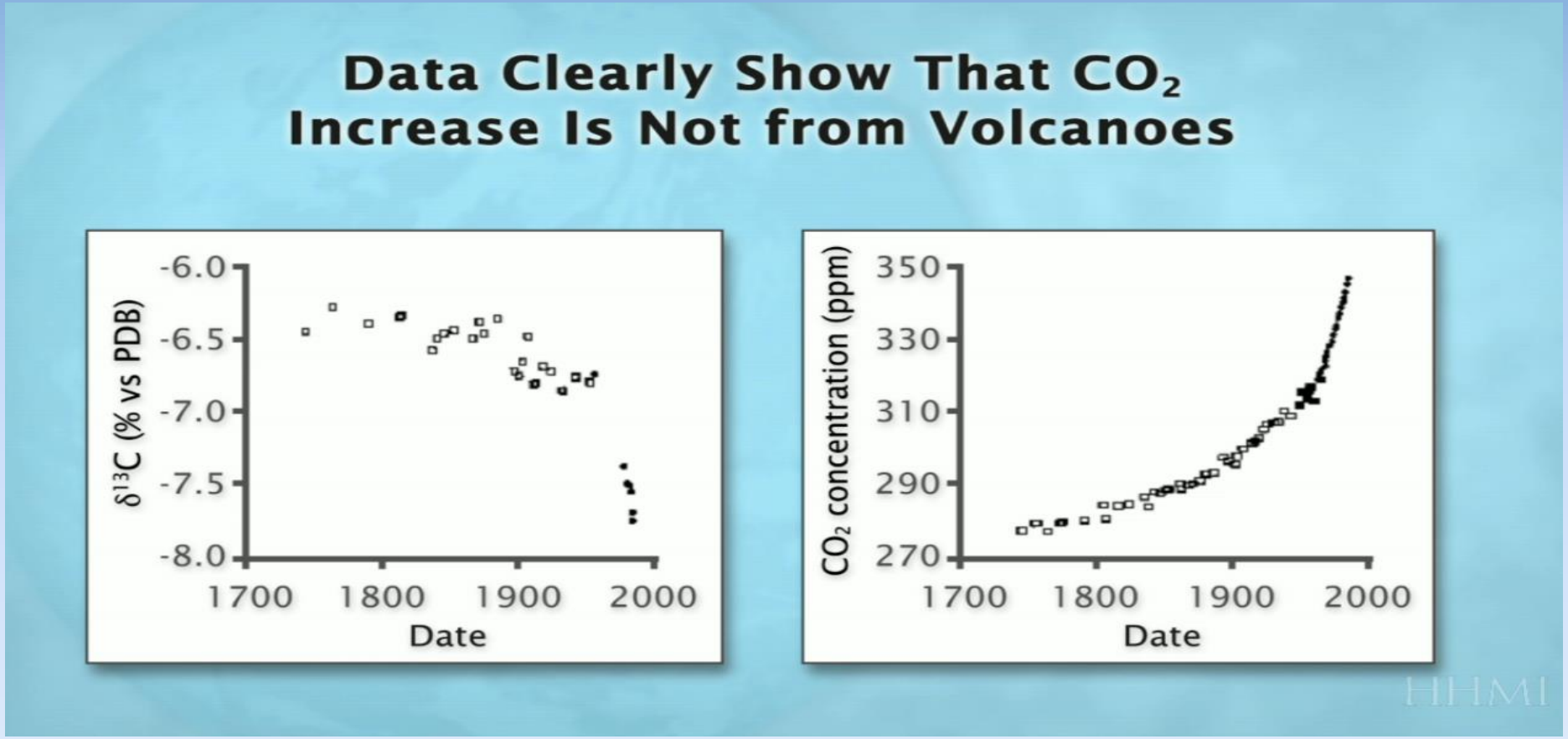
Hypothesis:
Volcanoes are the source of that CO_2

http://media.hhmi.org/hl/12Lect4.html

How to test the hypothesis

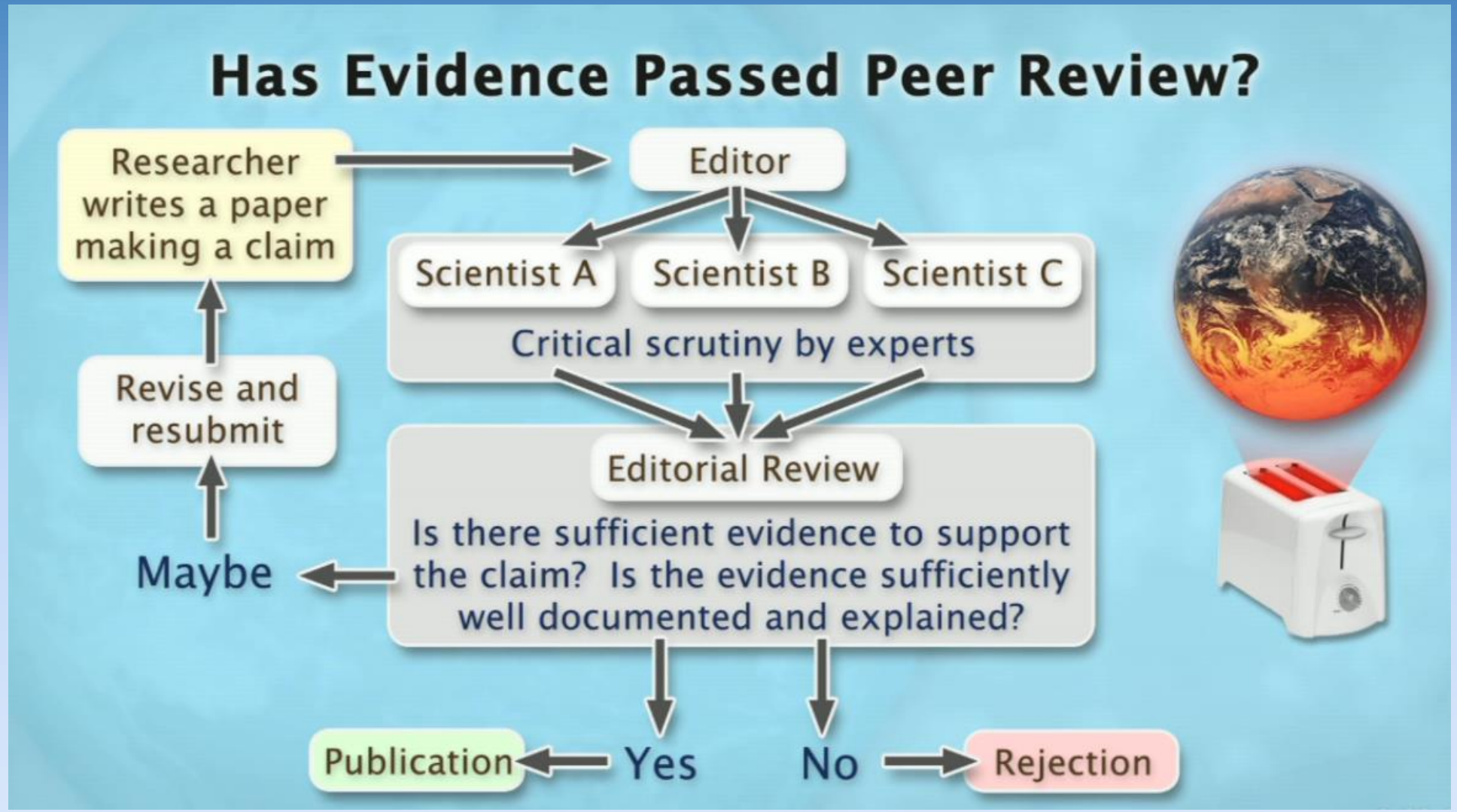
Inorganic CO2 from volcanoes are isotopically more positive; organic matter depleted in C13 = Fossil carbon is negative

"To claim otherwise:
Confused, ignorant or lying"



http://media.hhmi.org/hl/12Lect4.html

How peer review works



http://media.hhmi.org/hl/12Lect4.html

Intergovernmental Panel on Climate Change (IPCC)

Thousands of scientists

195 countries

Open process

An unprecedented level of review and inclusivity

Climate science has passed an unprecedented level of peer review.

http://media.hhmi.org/hl/12Lect4.html

Performance

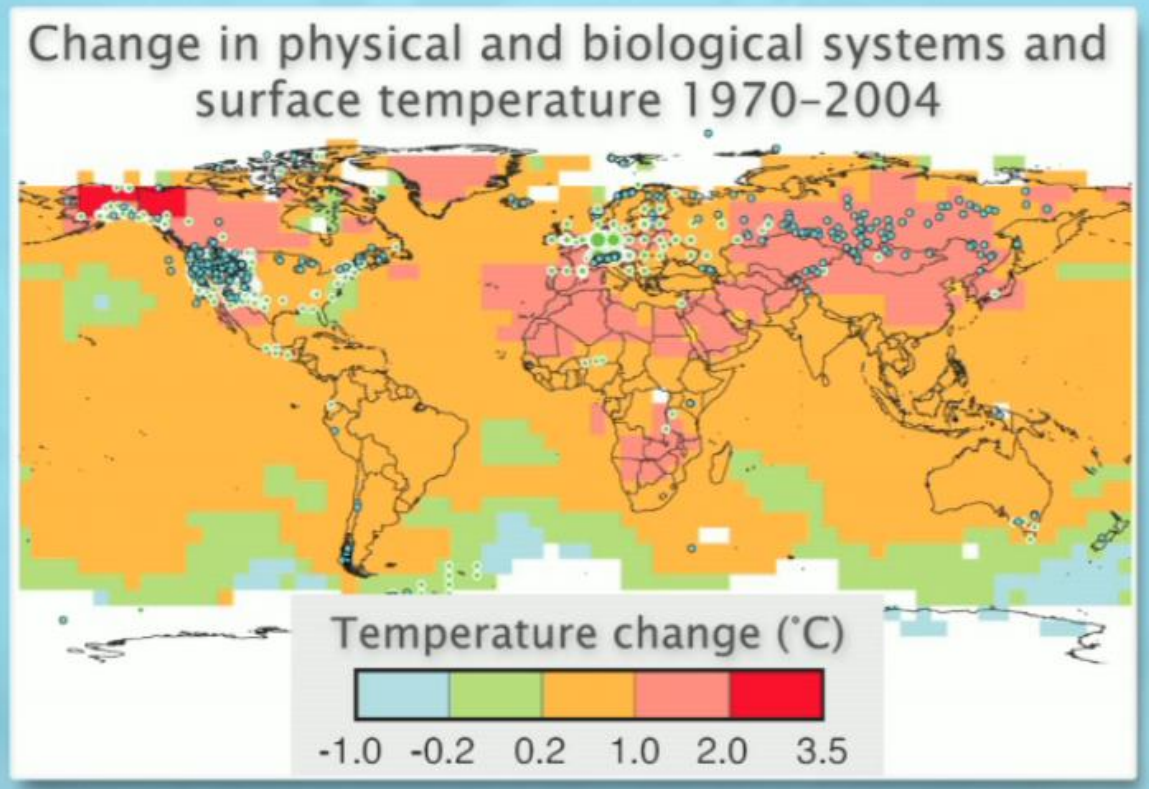
Global climate model
geodesic grid

Climate models are extremely complex systems.

A good model should be consistent with what we see in the real world.

http://media.hhmi.org/hl/12Lect4.html

IPCC Summary: A Vast Number of Observations Fit the Climate Models



Global

Physical	Biological
765 significant observed changes	**28,671** significant observed changes
94% significant changes consistent with warming	**90%** significant changes consistent with warming

http://media.hhmi.org/hl/12Lect4.html

Consensus

ESSAY

BEYOND THE IVORY TOWER

The Scientific Consensus on Climate Change

Naomi Oreskes

This year's essay series highlights the benefits that scientists, science, and technology have brought to society throughout history.

Policy-makers and the media, particularly in the United States, frequently assert that climate science is highly uncertain. Some have used this as an argument against adopting strong measures to reduce greenhouse gas emissions. For example, while discussing a major U.S. Environmental Protection Agency report on the risks of climate change, then-EPA administrator Christine Whitman argued, "No [the report] went through review, there was less consensus on the science and conclusions on climate change" (1). Some corporations whose revenues might be adversely affected by controls on carbon dioxide emissions have also alleged major uncertainties in the science (2). Such statements suggest that there might be substantive disagreement in the scientific community about the reality of anthropogenic climate change. This is not the case.

Without substantial disagreement, scientists find human activities are heating the Earth's surface.

The scientific consensus is clearly expressed in the reports of the Intergovernmental Panel on Climate Change (IPCC). Created in 1988 by the World Meteorological Organization and the United Nations Environmental Programme, IPCC's purpose is to evaluate the state of climate science as a basis for informed policy action, primarily on the basis of peer-reviewed and published scientific literature (3). In its most recent assessment, IPCC states unequivocally that the consensus of scientific opinion is that Earth's climate is being affected by human activities: "Human activities ... are modifying the concentration of atmospheric constituents ... that absorb or scatter radiant energy. ... [M]ost of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations" [p. 21 in (4)].

IPCC is not alone in its conclusions. In recent years, all major scientific bodies in the United States whose members' expertise bears directly on the matter have issued similar statements. For example, the National Academy of Sciences report, *Climate Change Science: An Analysis of Some Key Questions*, begins: "Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise" [p. 1 in (5)]. The report explicitly asks whether the IPCC assessment is a fair summary of professional scientific thinking, and answers yes: "The IPCC's conclusion that most of the observed warming of the last 50 years is likely to have been due to the increase in greenhouse gas concentrations accurately reflects the current thinking of the scientific community on this issue" [p. 3 in (5)].

Others agree. The American Meteorological Society (6), the American Geophysical Union (7), and the American Association for the Advancement of Science (AAAS) all have issued statements in recent years concluding that the evidence for human modification of climate is compelling (8).

The drafting of such reports and statements involves many opportunities for comment, criticism, and revision, and it is not likely that they would diverge greatly from the opinions of the societies' members. Nevertheless, they might downplay legitimate dissenting opinions. That hypothesis was tested by analyzing 928 abstracts, published in refereed scientific journals between 1993 and 2003, and listed in the ISI database with the keywords "climate change" (9).

The 928 papers were divided into six categories: explicit endorsement of the consensus position, evaluations of impacts, mitigation proposals, methods, paleoclimate analysis, and rejection of the consensus position. Of all the papers, 75% fell into the first three categories, either explicitly or implicitly accepting the consensus view; 25% dealt with methods or paleoclimate, taking no position on current anthropogenic climate change. Remarkably, none of the papers disagreed with the consensus position.

Admittedly, authors evaluating impacts, developing methods, or studying paleoclimatic change might believe that current climate change is natural. However, none of those papers argued that point.

This analysis shows that scientists publishing in the peer-reviewed literature agree with IPCC, the National Academy of Sciences, and the public statements of their professional societies. Politicians, economists, journalists, and others may have the impression of confusion, disagreement, or discord among climate scientists, but that impression is incorrect.

The scientific consensus might, of course, be wrong. If the history of science teaches anything, it is humility, and we may can be faulted for failing to act on what is not known. But our grandchildren will surely blame us if they find that we understood the reality of anthropogenic climate change and failed to do anything about it.

Many details about climate interactions are not well understood, and there are ample grounds for continued research to provide a better basis for understanding climate dynamics. The question of what to do about climate change is also still open. But there is a scientific consensus on the reality of anthropogenic climate change. Climate scientists have repeatedly tried to make this clear. It is time for the rest of us to listen.

References and Notes

1. A. C. Revkin, *N. Y. Times*, 19 June 2003, p.1.
2. S. van den Hove, M. Le Menestrel, H.-C. de Bettignies, *Climate Policy* 2 (1), 3 (2002).
3. See www.ipcc.ch/about/about.htm.
4. J. J. McCarthy *et al.*, Eds., *Climate Change 2001: Impacts, Adaptation, and Vulnerability* (Cambridge Univ. Press, Cambridge, 2001).
5. National Academy of Sciences Committee on the Science of Climate Change, *Climate Change Science: An Analysis of Some Key Questions* (National Academy Press, Washington, DC, 2001).
6. American Meteorological Society, *Bull. Am. Meteorol. Soc.* **84**, 508 (2003).
7. American Geophysical Union, www.agu.org/sci_pol/positions/climate2003.html.
8. See www.aaas.org/spp/cstc/news/press/climate.htm.
9. The ISI® (now Thomson ISI) Web of Science® database was searched using the keywords "climate change" for the years 1993–2003. Publication limits were set to "publication year," "publication date," "English," and "article." Publication dates were chosen to ensure that only peer-reviewed papers would be included. Publication delays mean that papers published in 2003 generally would have been submitted in 2002 or earlier. Only papers with abstracts were included. Of 1117 papers identified, 25 were rejected because they were duplicates or abstracts were not available. Two papers were rejected because they were not about climate change.
10. This essay is excerpted from the 2004 George Sarton Memorial Lecture, "Consensus in science: How do we know we're not wrong," presented at the AAAS meeting on 14 February 2004. I am grateful to AAAS and the History of Science Society for their support of this scholarship; to my research assistants S. Lutz and G. Law; and to D. C. Agnew, K. Bellitz, J. R. Fleming, N. T. Greene, N. Lebbon, and K. C. J. Somerville for helpful discussions.

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Review of 928 papers

75% supported the conclusion that anthropogenic climate change was under way

25% focused on paleoclimate or other technical aspects and took no position

No peer-reviewed papers refuted the consensus view

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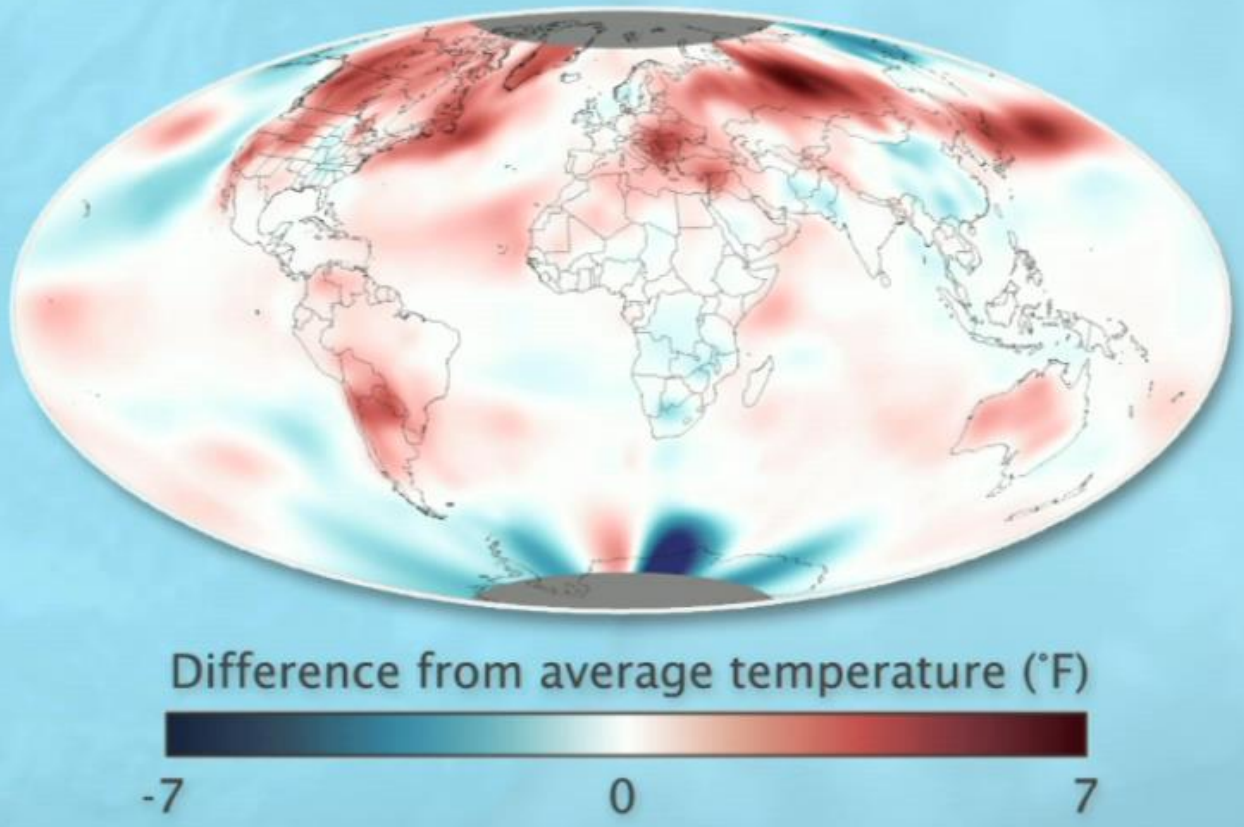
http://media.hhmi.org/hl/12Lect4.html

The Science Is Settled and Passes All the Tests That We Can Subject It To

The globe is warming and the climate is changing.



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