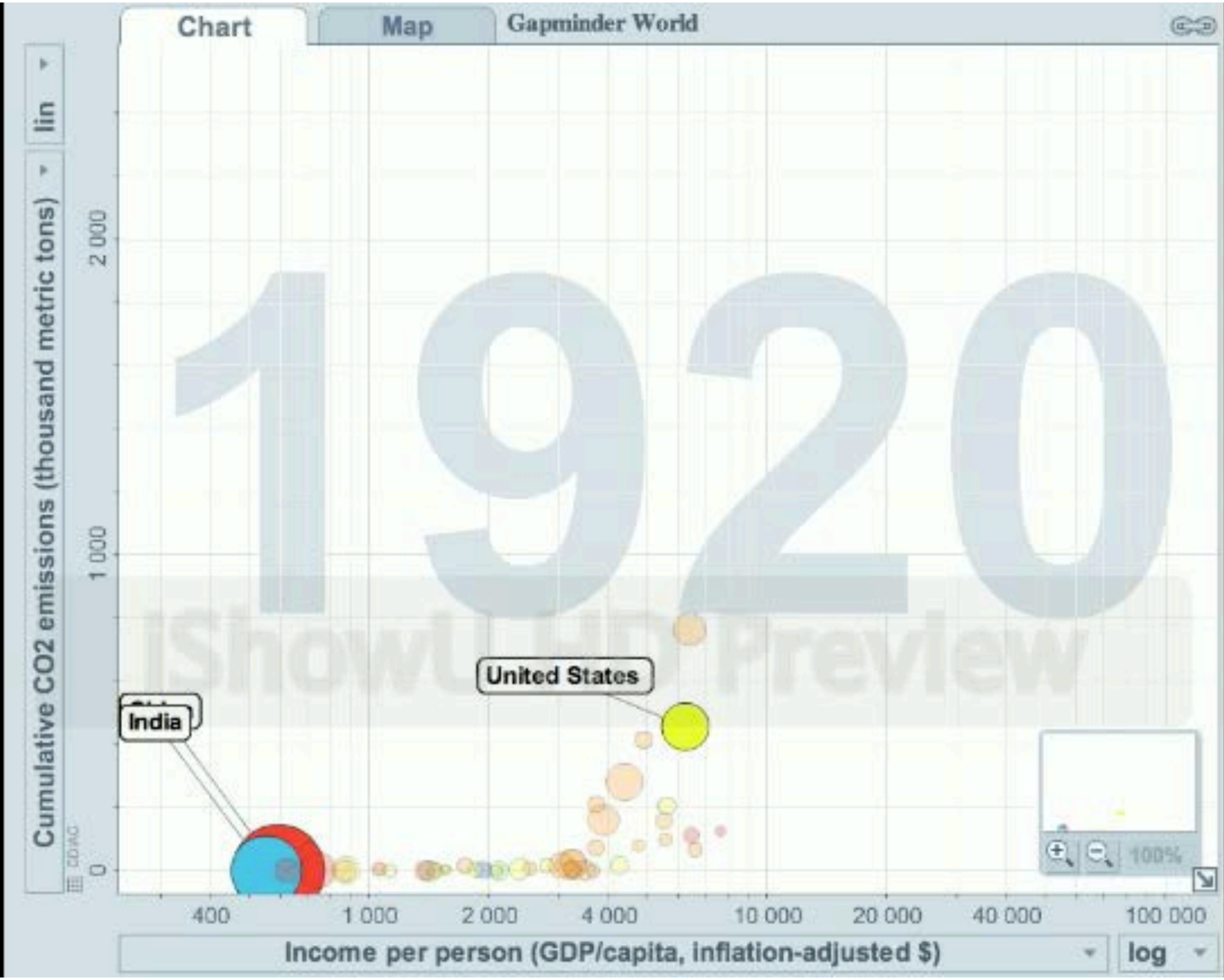
Computational Math and Science

How Mathematics Will Help Save The World

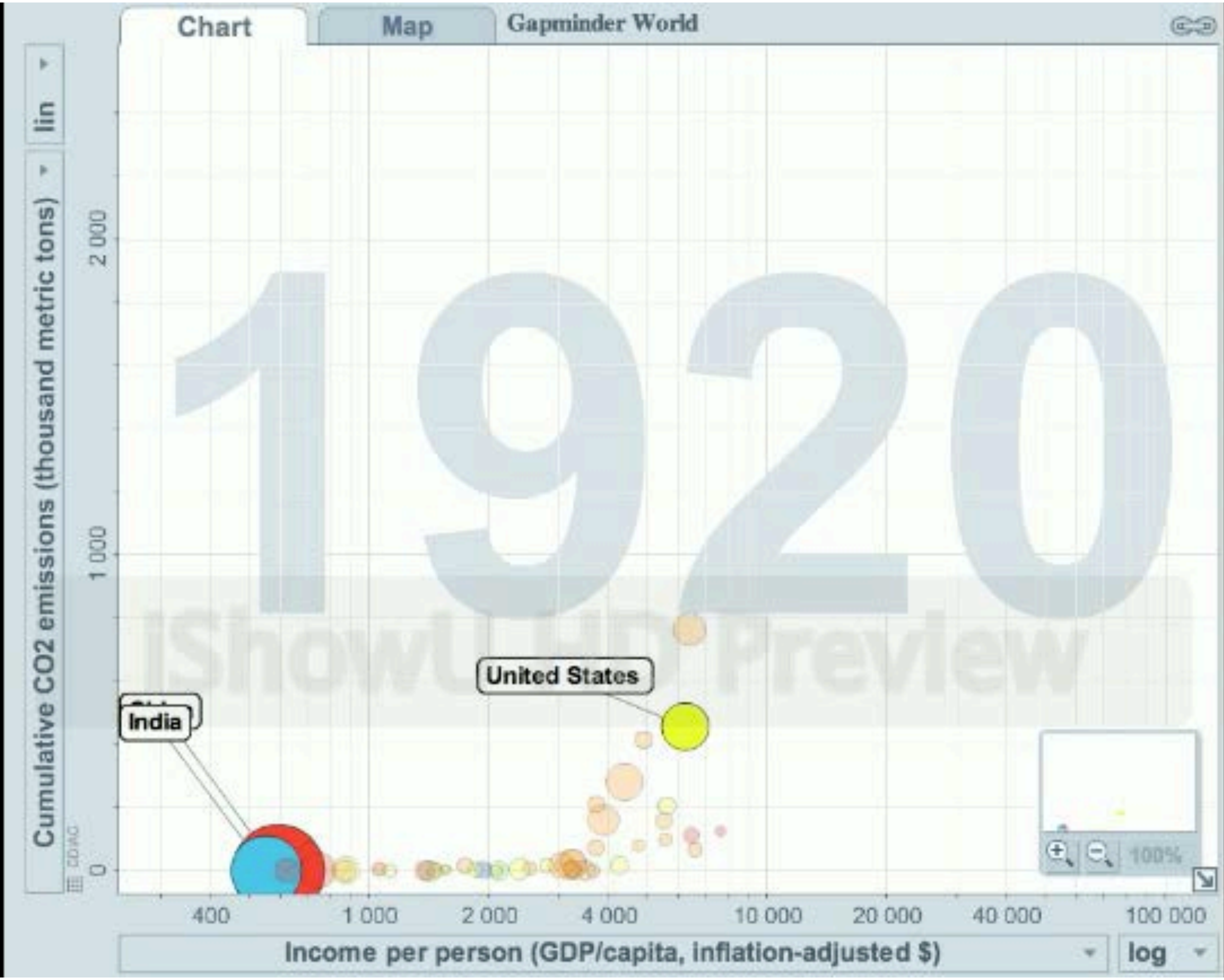
Juan Meza

Professor Applied Mathematics

Dean, School of Natural Sciences, UC Merced



source: gapminder.org



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Let's do an experiment

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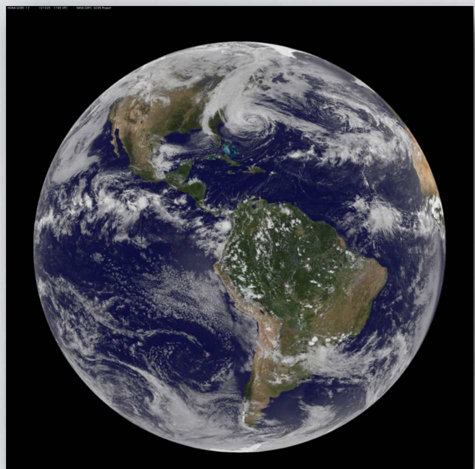

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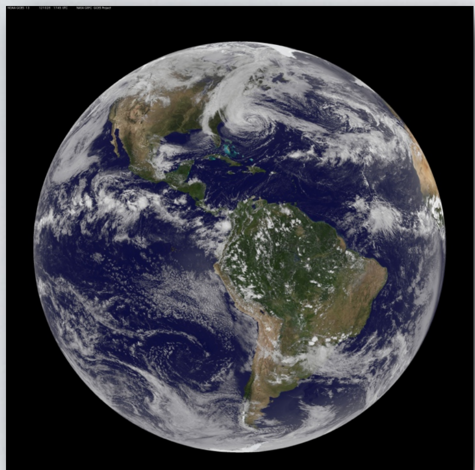

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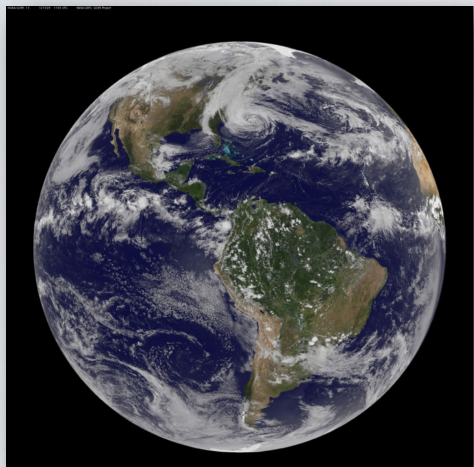

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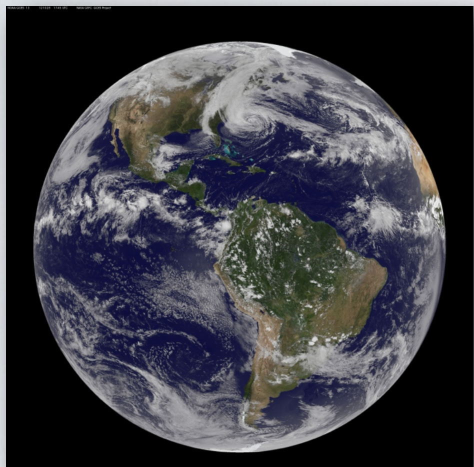

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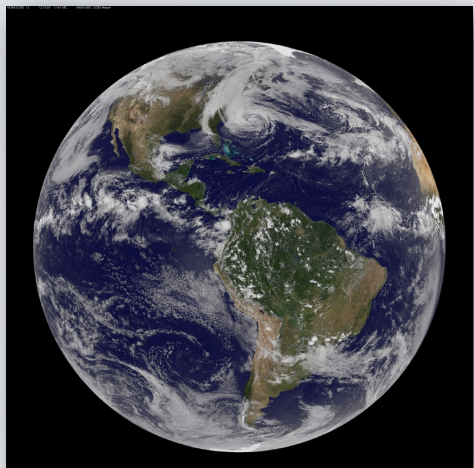

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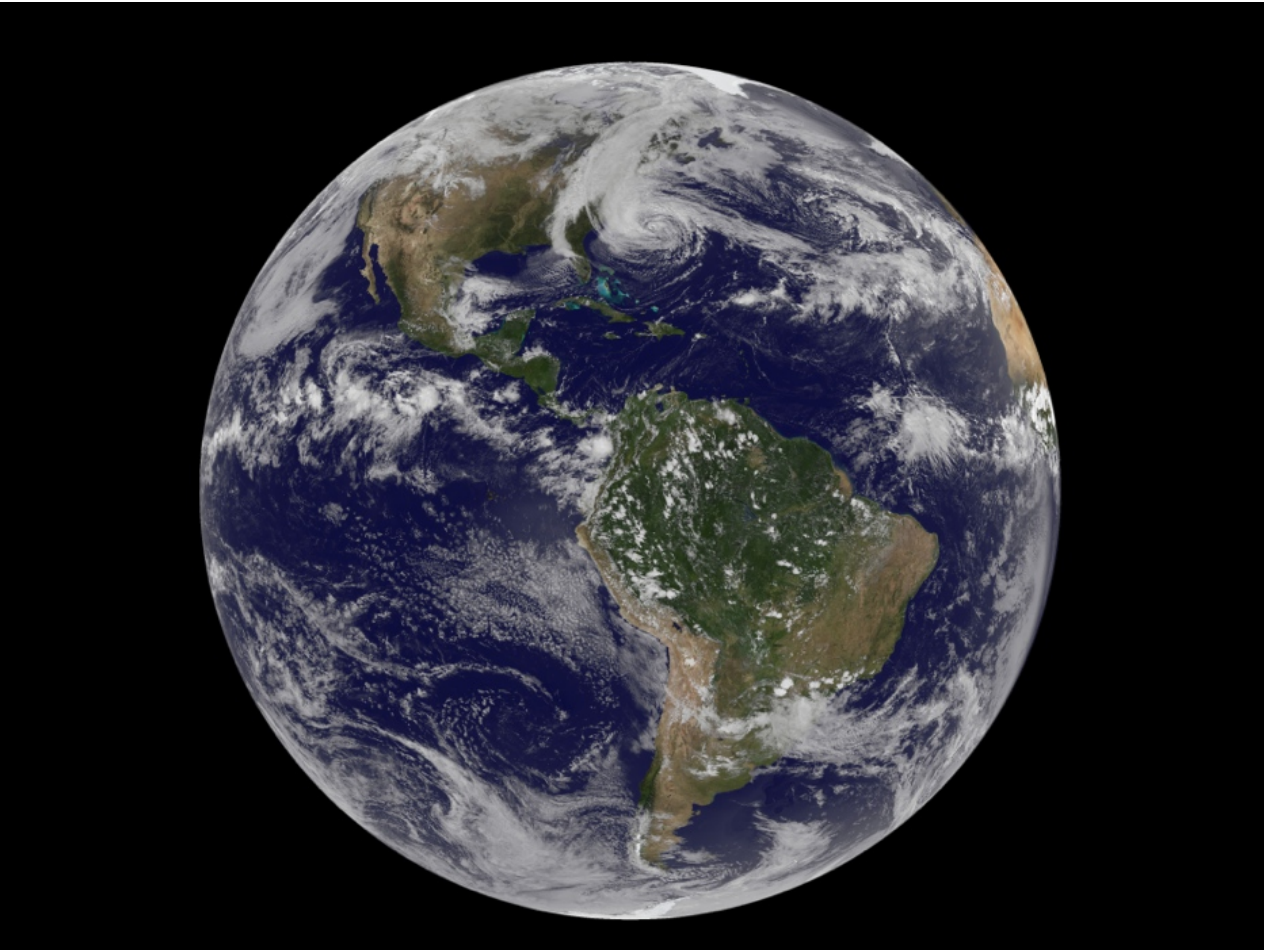
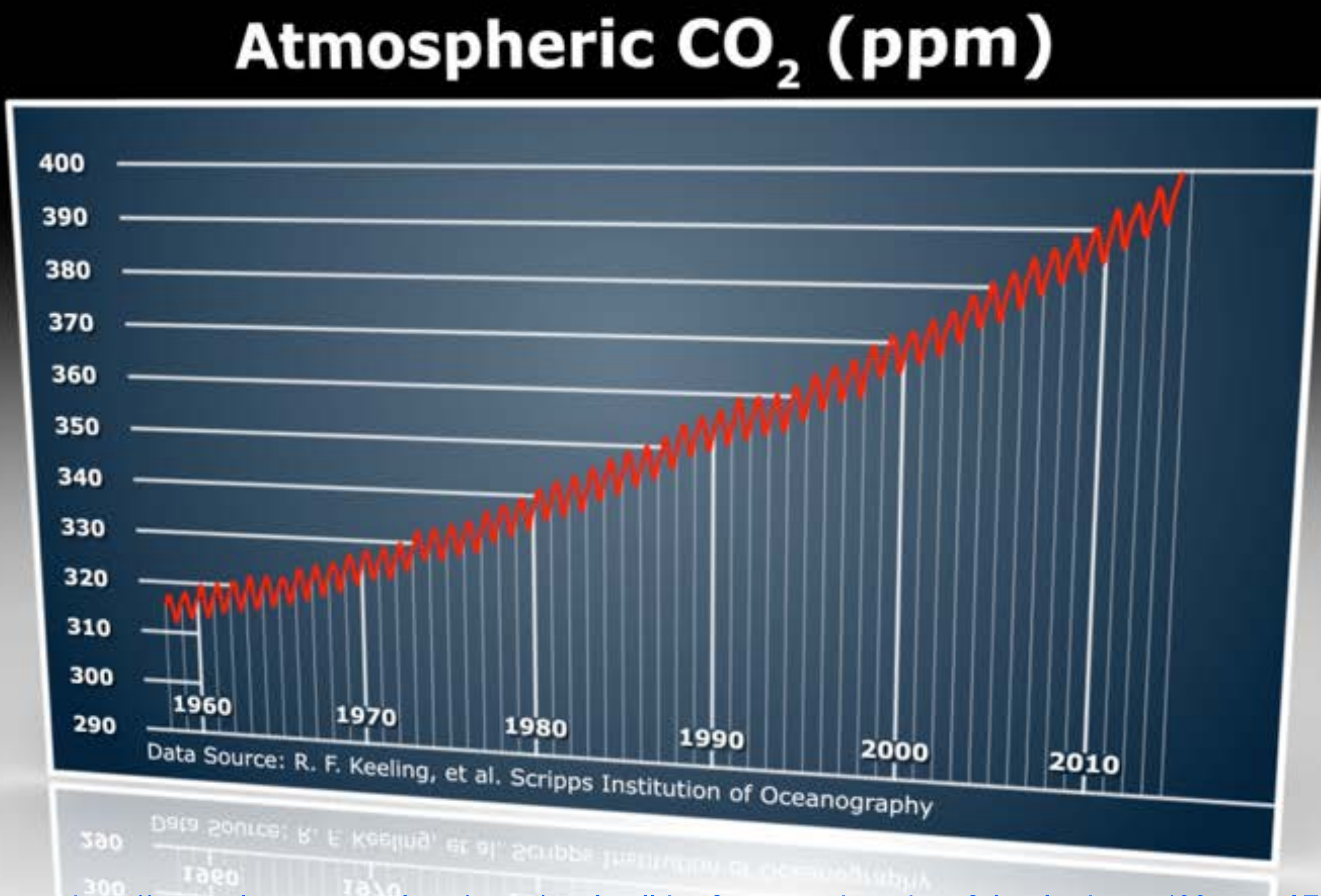
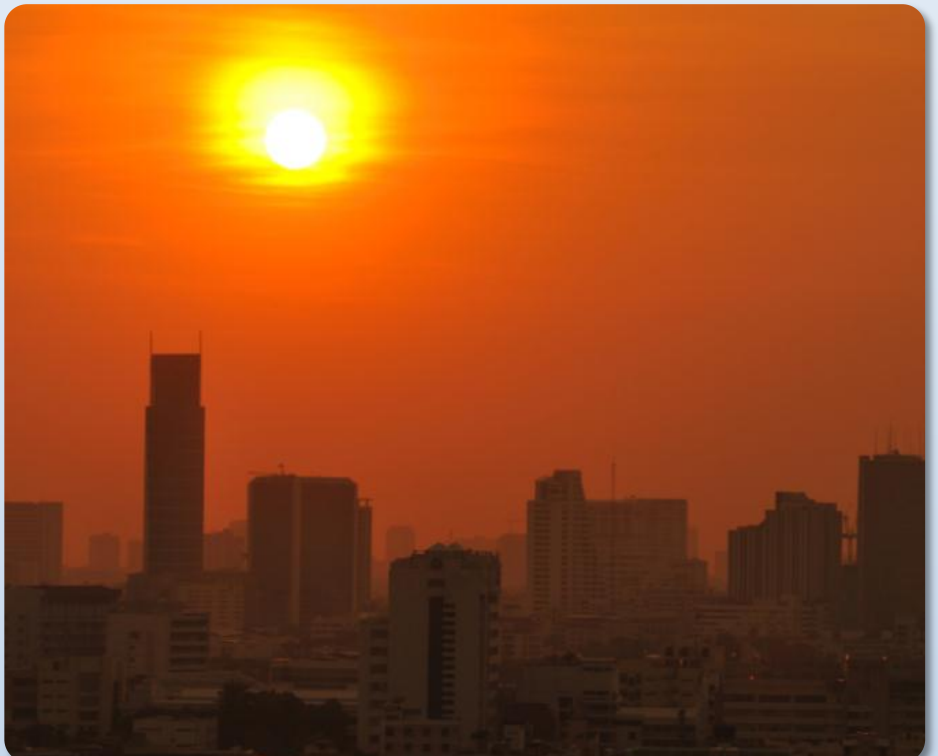


April 2014 Was The First Month With CO2 Levels Above 400 PPM

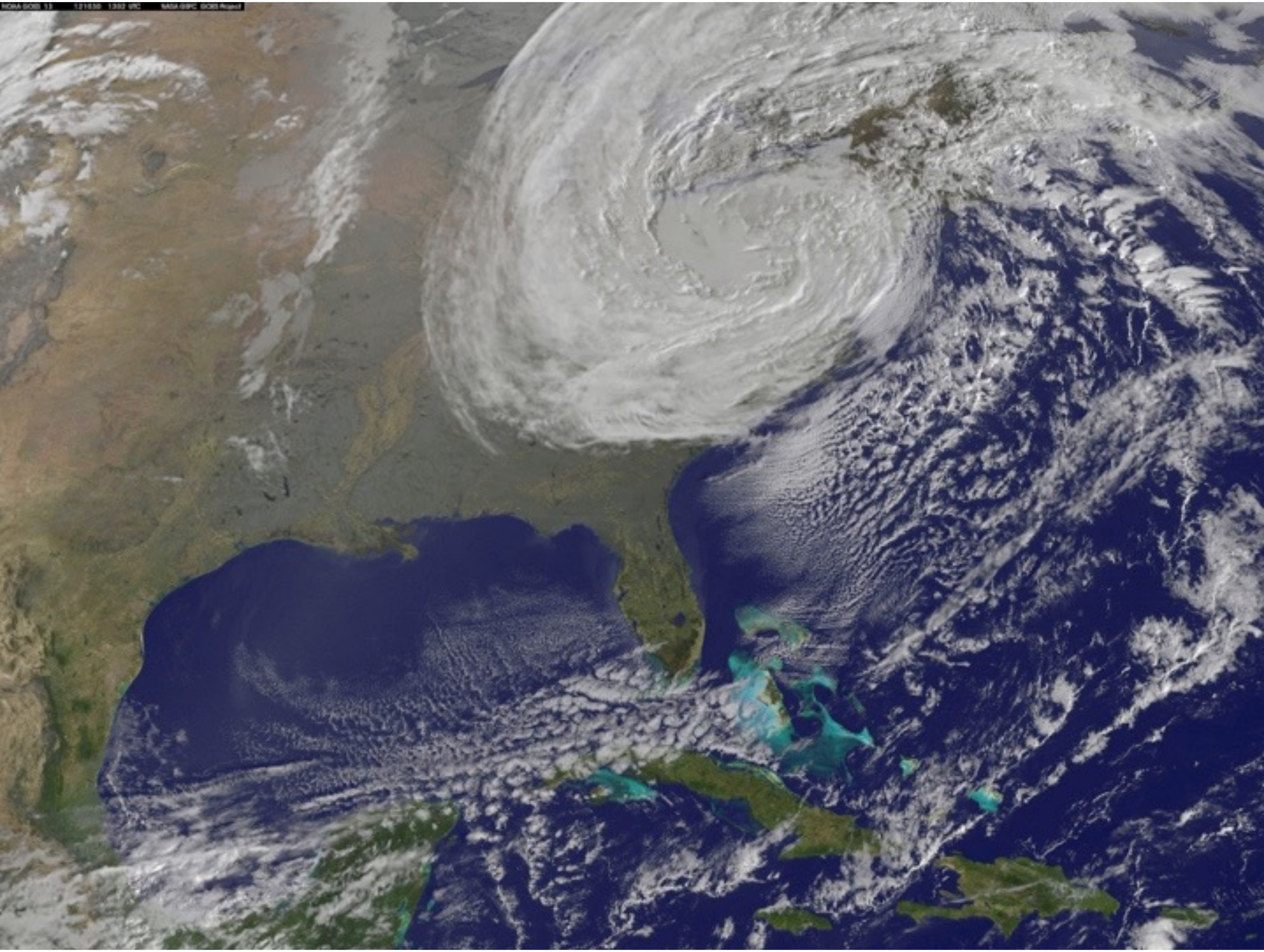


http://www.climatecentral.org/news/april-will-be-first-month-with-co2-levels-above-400-ppm-17331

Since 1950, extreme hot days and heavy precipitation have become more common



There is evidence that anthropogenic influences, including increasing atmospheric greenhouse gas concentrations, have changed these extremes



Managing the risks: hurricanes in the USA and Caribbean

Risk Factors

- population growth
- increasing property value
- higher storm surge with sea level rise

Risk Management/ Adaptation

- better forecasting
- warning systems
- stricter building codes
- regional risk pooling

Projected globally: *likely* increase in average maximum wind speed and associated heavy rainfall (although not in all regions)

Managing the risks: heat waves in Europe

Risk Factors

- lack of access to cooling
- age
- pre-existing health problems
- poverty and isolation
- infrastructure

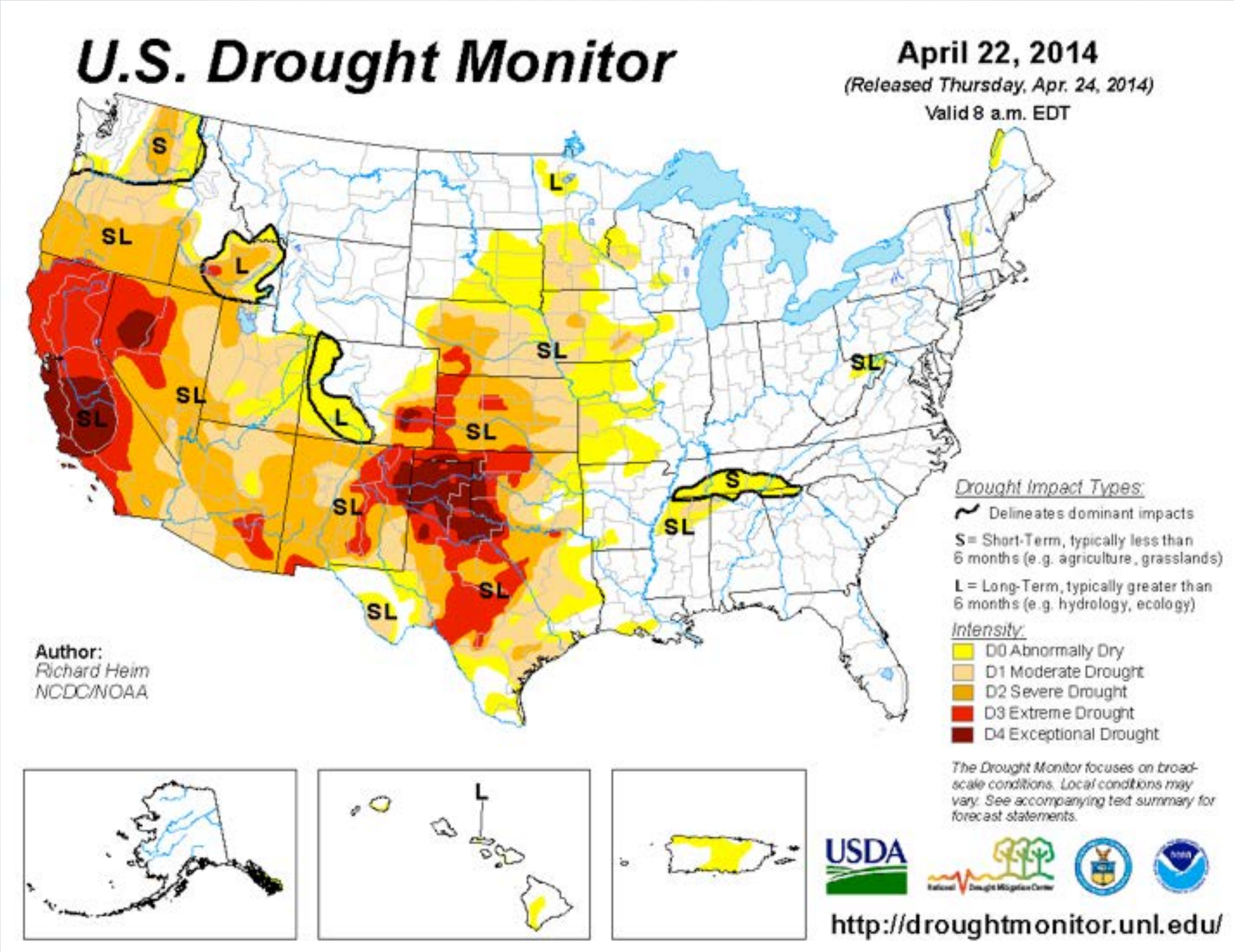
France, August 2003 (over 14,000 dead)

Risk Management/ Adaptation

- cooling in public facilities
- warning systems
- social care networks
- urban green space
- changes in urban infrastructure

Projected: *likely* increase in heat wave frequency and *very likely* increase in warm days and nights across Europe

ipcc INTERGOVERNMENTAL PANEL ON climate change


U.S. Drought Monitor
April 22, 2014
(Released Thursday, Apr. 24, 2014)
Valid 8 a.m. EDT
S
SL
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Drought Impact Types:
Delineates dominant impacts
S = Short-Term, typically less than 6 months (e.g. agriculture, grasslands)
L = Long-Term, typically greater than 6 months (e.g. hydrology, ecology)
Intensity:
D0 Abnormally Dry
D1 Moderate Drought
D2 Severe Drought
D3 Extreme Drought
D4 Exceptional Drought
The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.
Author:
Richard Heim
NCDC/NOAA
USDA
http://droughtmonitor.unl.edu/

U.S. Drought Monitor
California

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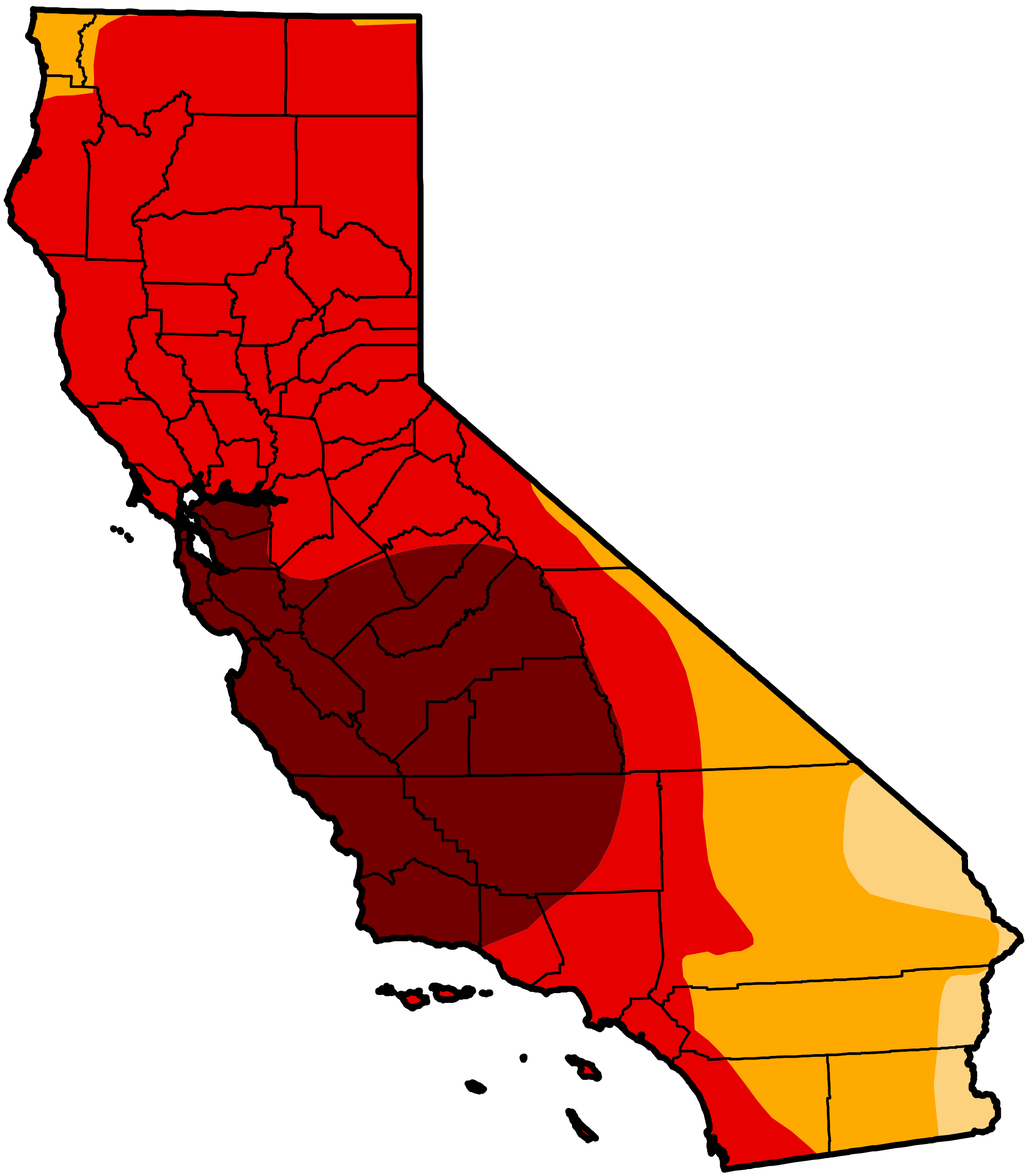

Drought Conditions (Percent Area)

	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	0.00	100.00	100.00	96.01	76.68	24.77
Last Week *4/15/2014*	0.00	100.00	99.80	95.21	68.76	23.49
3 Months Ago *1/21/2014*	1.43	98.57	94.18	89.91	62.71	0.00
Start of Calendar Year *12/31/2013*	2.61	97.39	94.25	87.53	27.59	0.00
Start of Water Year *10/1/2013*	2.63	97.37	95.95	84.12	11.36	0.00
One Year Ago *4/23/2013*	2.84	97.16	63.42	30.00	0.00	0.00

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U.S. Drought Monitor
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April 21, 2015
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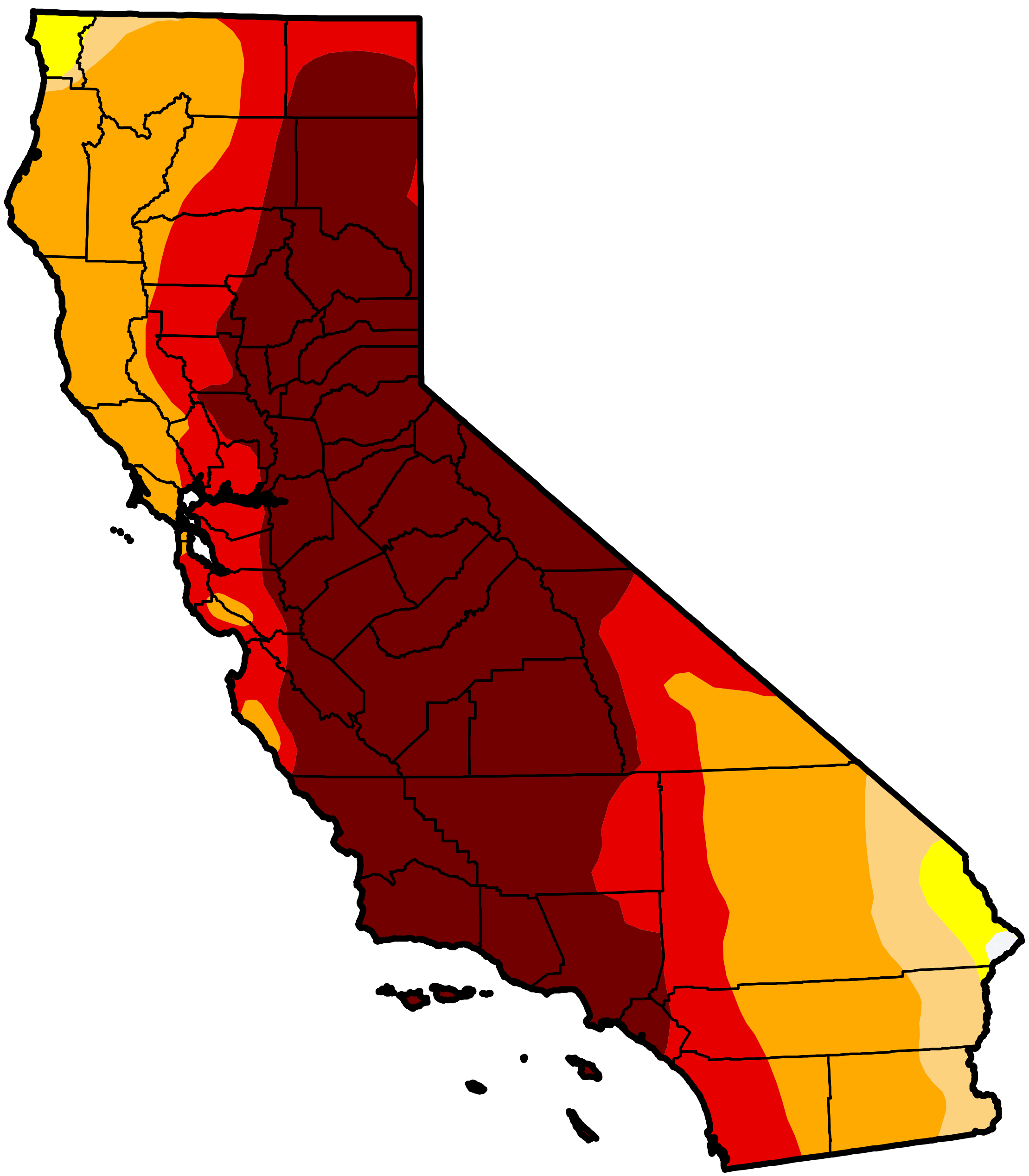

Drought Conditions (Percent Area)

	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	0.14	99.86	98.11	93.44	66.60	46.77
Last Week *4/14/2015*	0.14	99.86	98.11	93.44	66.60	44.32
3 Months Ago *1/20/2015*	0.00	100.00	98.13	94.34	77.52	39.15
Start of Calendar Year *12/30/2014*	0.00	100.00	98.12	94.34	77.94	32.21
Start of Water Year *9/30/2014*	0.00	100.00	100.00	95.04	81.92	58.41
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NOAA/NWS/NCEP/CPC

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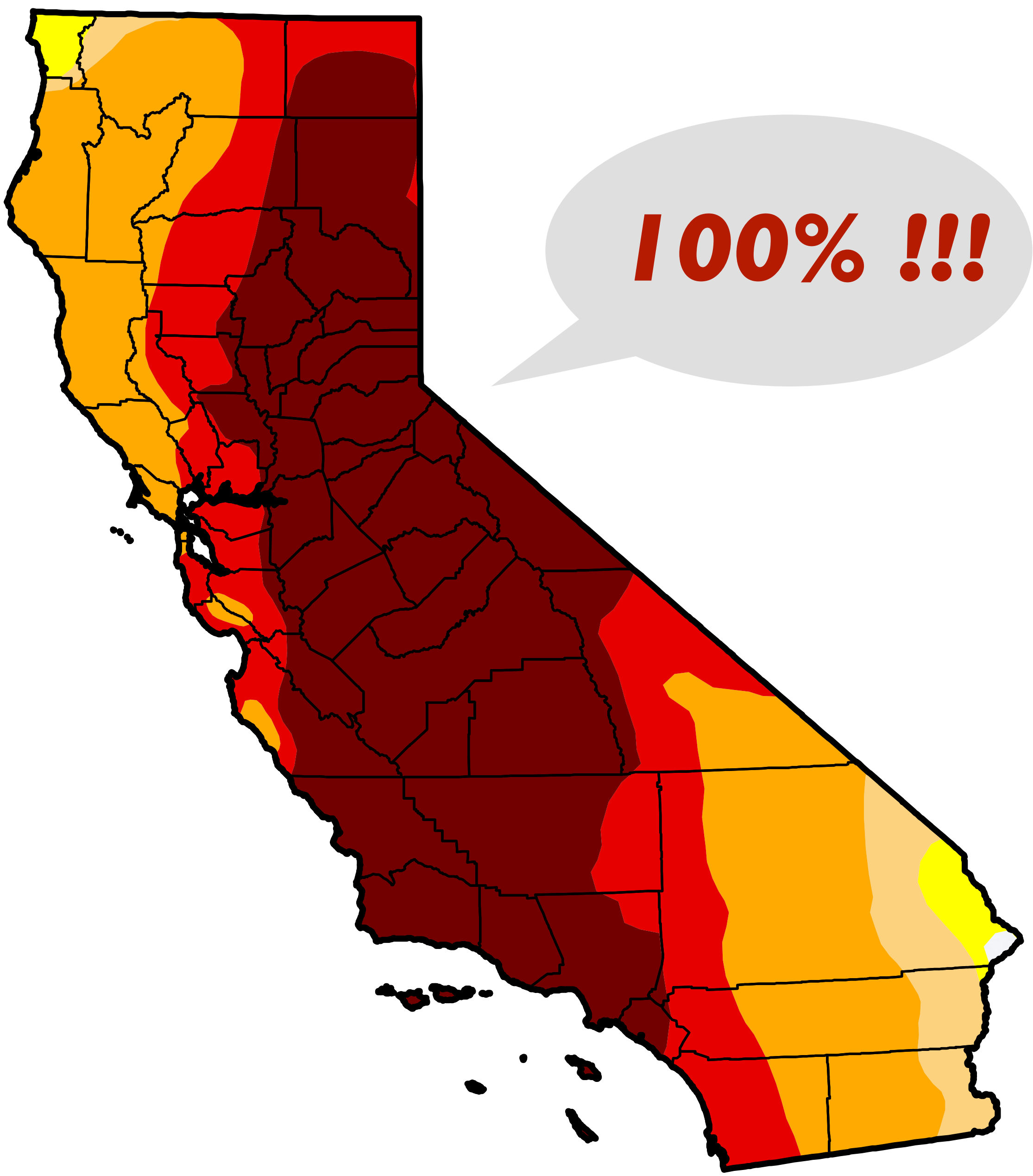

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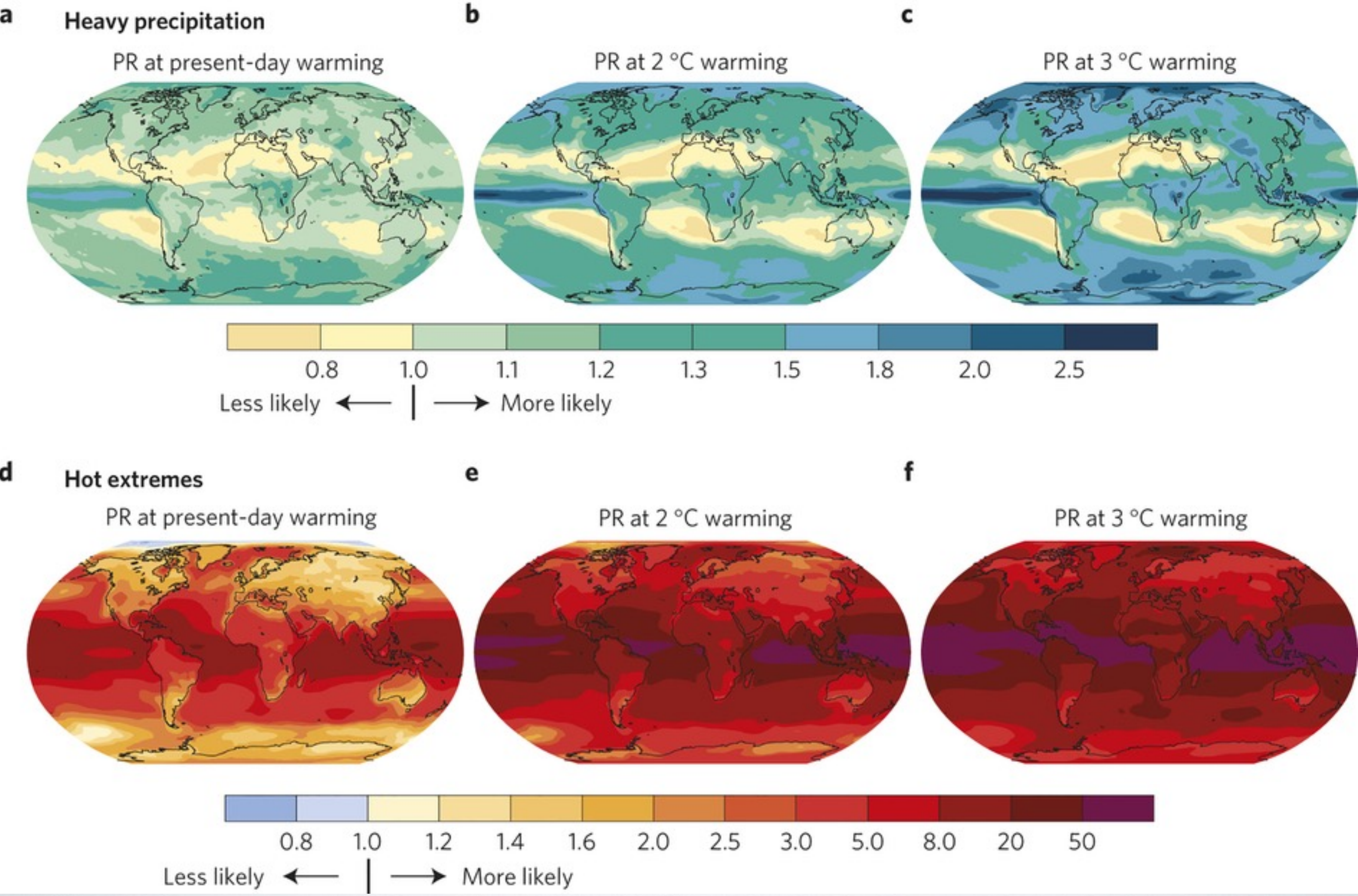
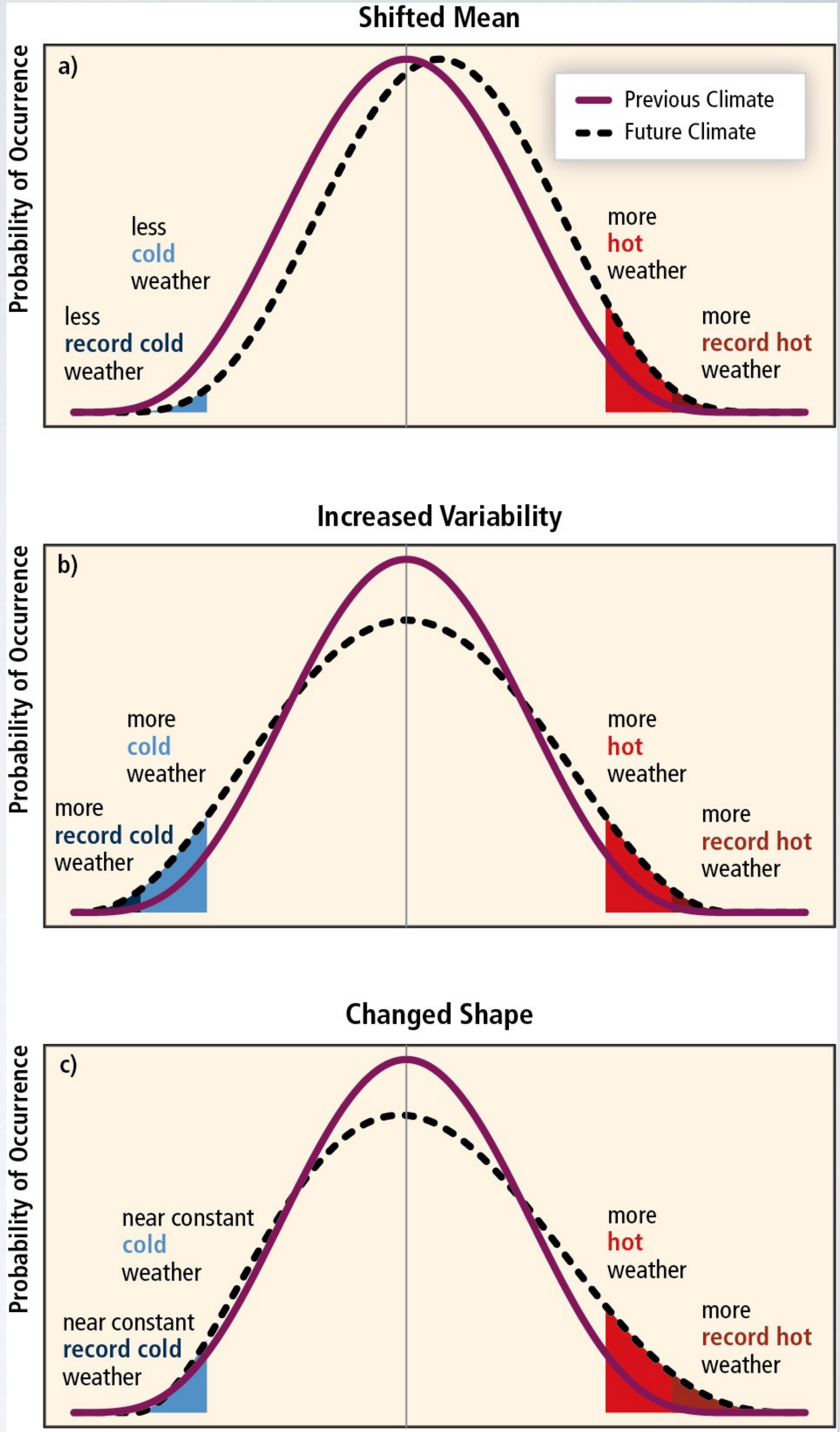


E. M. Fischer* and R. Knutti, Nature Climate Change, 27 April 2015, DOE:10.1038/nclimate2617

- Changing climate leads to changes in extreme weather and climate events
- Extreme events affect agriculture, water, public health, transportation, etc.
- Economic losses can be enormous



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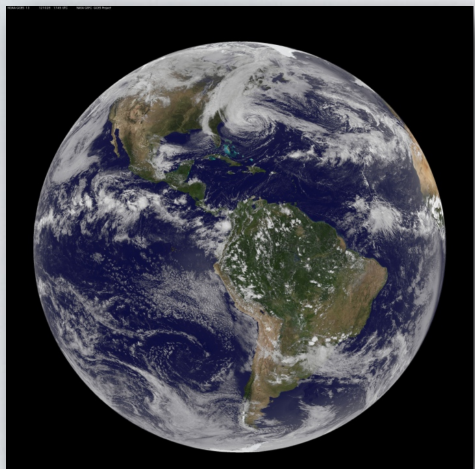 +  = ?

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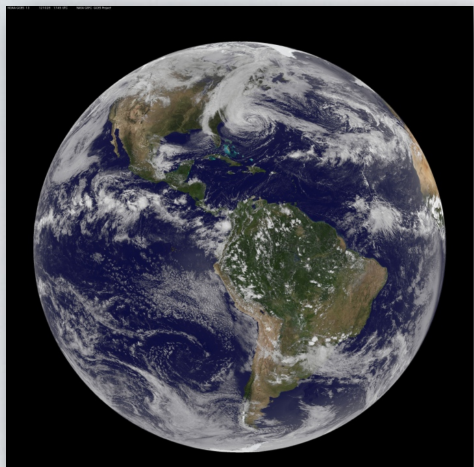

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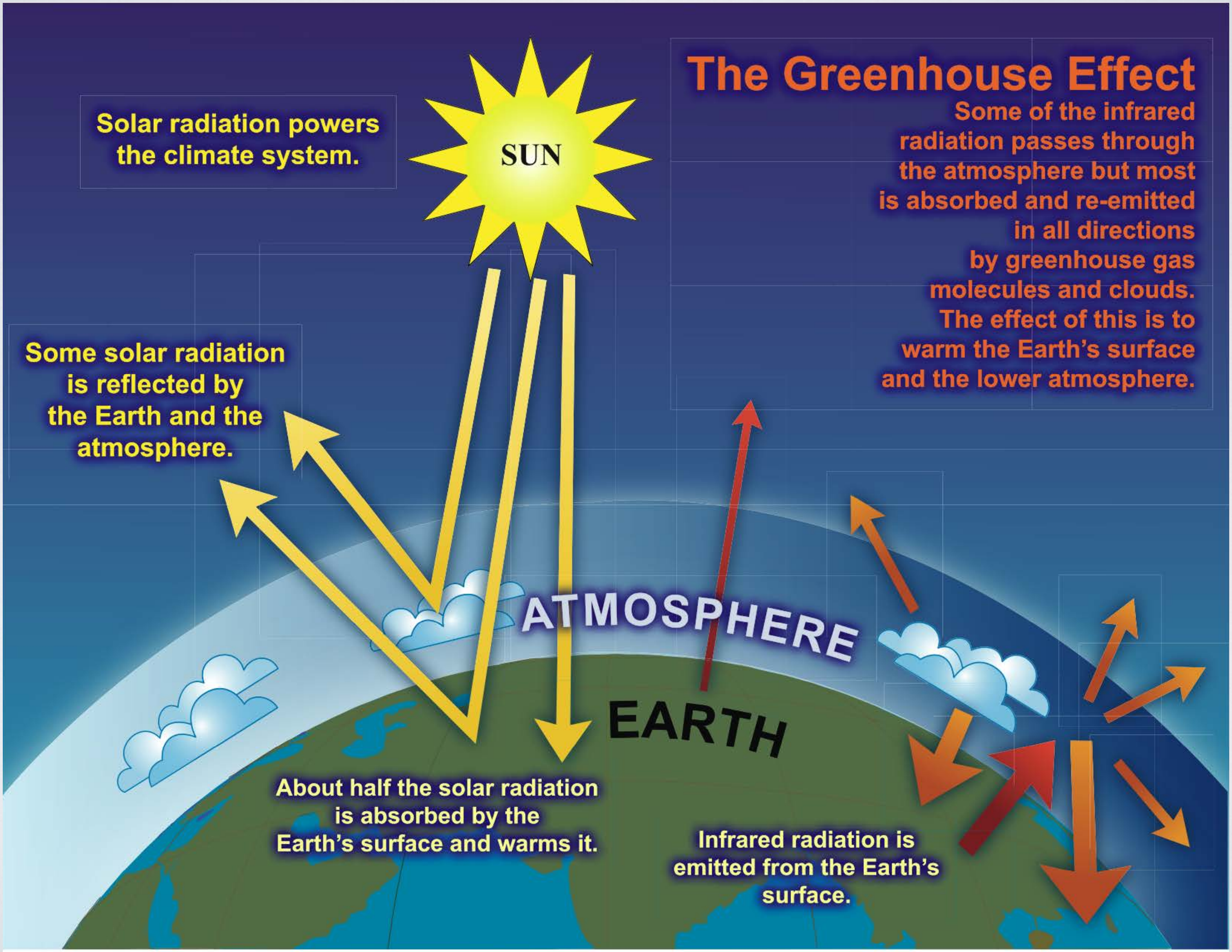
PART II

MATHEMATICS AND COMPUTERS TO THE RESCUE

First Let's Look at the Mathematics

GREENHOUSE EFFECT



FIRST MENTION OF GREENHOUSE EFFECT (1824)

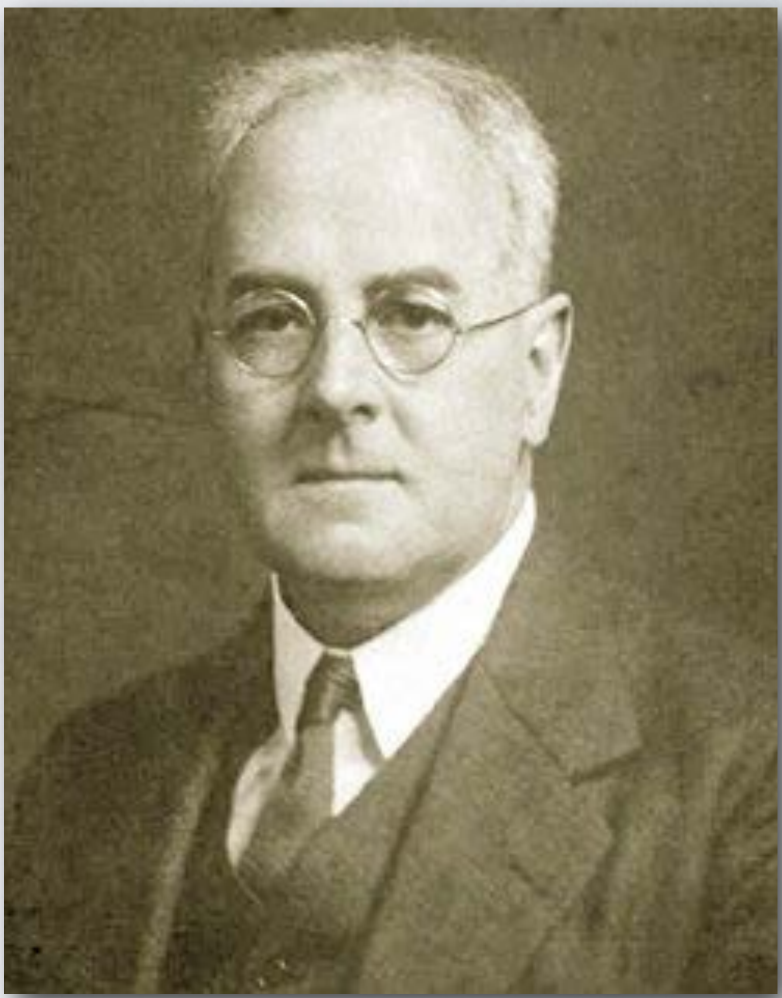
- Fourier developed mathematical theory for the temperature of the terrestrial globe

- "The temperature [of the Earth] can be augmented by the interposition of the atmosphere, because heat in the state of light finds less resistance in penetrating the air, than in repassing into the air when converted into non-luminous heat" (1824)

FOURIER

NUMERICAL WEATHER FORECASTING

- British mathematician Lewis Fry Richardson proposed numerical weather forecasting in 1922
- Computed 1 day weather forecast over a period of 6 weeks,
- While working as the driver of a Quaker ambulance unit in northern France.

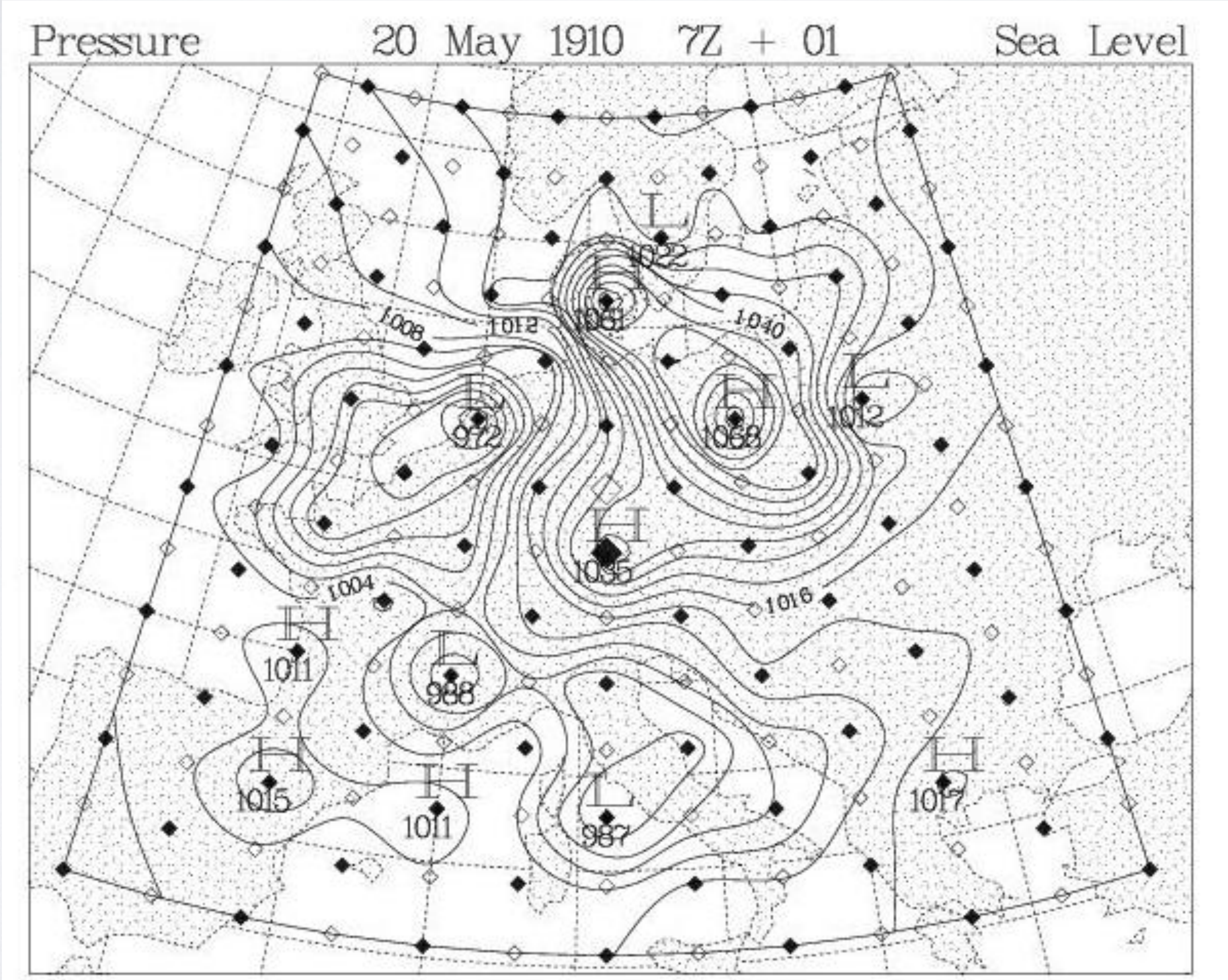


LEWIS FRY RICHARDSON

Fascinating talk by Peter Lynch (University College Dublin) can be found at:
http://www.ncep.noaa.gov/nwp50/Presentations/Tue_06_15_04/Session_1/Lynch_NWP50.pdf

RICHARDSON'S COMPUTATION

Sadly, calculations were unsuccessful, due to numerical problems



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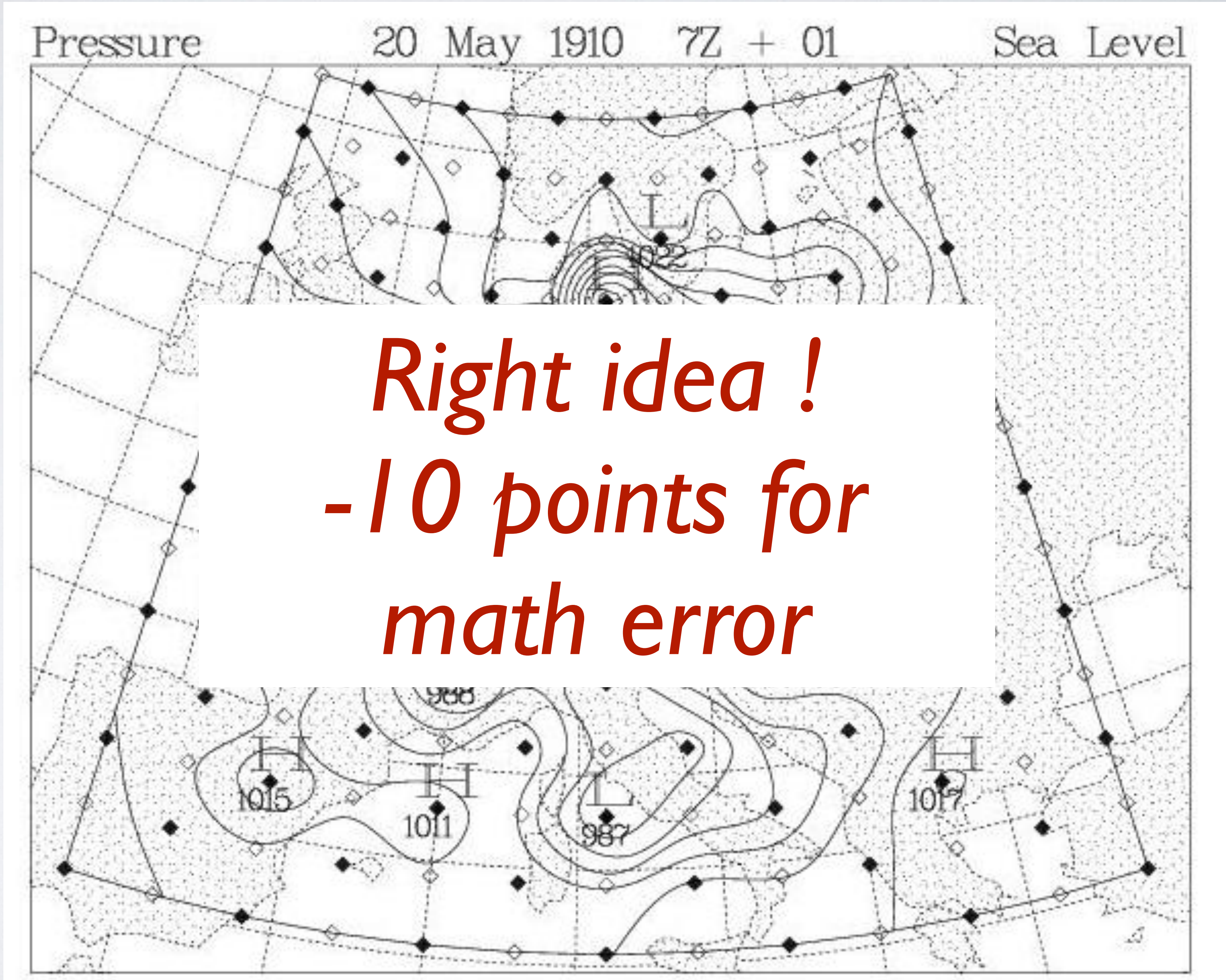


Right idea !
-10 points for math error

PRIMITIVE EQUATIONS FOR ATMOSPHERE

$$\frac{du}{dt} - \left(f + u\frac{\tan\phi}{a}\right)v = -\frac{1}{a\cos\phi}\frac{1}{\rho}\frac{\partial p}{\partial\lambda} + F_\lambda$$

$$\frac{dv}{dt} + \left(f + u\frac{\tan\phi}{a}\right)u = -\frac{1}{\rho a}\frac{\partial p}{\partial\phi} + F_\phi$$

$$g = -\frac{1}{\rho}\frac{\partial p}{\partial z}$$

$$\frac{\partial\rho}{\partial t} = -\frac{1}{a\cos\phi}\left[\frac{\partial}{\partial\lambda}(\rho u) + \frac{\partial}{\partial\phi}(\rho v\cos\phi)\right] - \frac{\partial}{\partial z}(\rho w)$$

$$C_p\frac{dT}{dt} - \frac{1}{\rho}\frac{dp}{dt} = Q$$

$$p = \rho RT$$

PRIMITIVE EQUATIONS FOR ATMOSPHERE

$$\frac{du}{dt} - \left(f + u\frac{\tan\phi}{a}\right)v = -\frac{1}{a\cos\phi}\frac{1}{\rho}\frac{\partial p}{\partial \lambda} + F_\lambda$$

$$\frac{dv}{dt} + \left(f + u\frac{\tan\phi}{a}\right)u = -\frac{1}{\rho a}\frac{\partial p}{\partial \phi} + F_\phi$$

Conservation of momentum

$$g = -\frac{1}{\rho}\frac{\partial p}{\partial z}$$

$$\frac{\partial \rho}{\partial t} = -\frac{1}{a\cos\phi}\left[\frac{\partial}{\partial \lambda}(\rho u) + \frac{\partial}{\partial \phi}(\rho v\cos\phi)\right] - \frac{\partial}{\partial z}(\rho w)$$

Conservation of mass

$$C_p\frac{dT}{dt} - \frac{1}{\rho}\frac{dp}{dt} = Q$$

Conservation of energy

$$p = \rho R T$$

Equation of state

Where do Computers Fit In To the Picture?

Babbage's Difference Engine (1832)

"As soon as an Analytical Engine exists, it will necessarily guide the future course of the science."

http://www.computerhistory.org/babbage/engines/

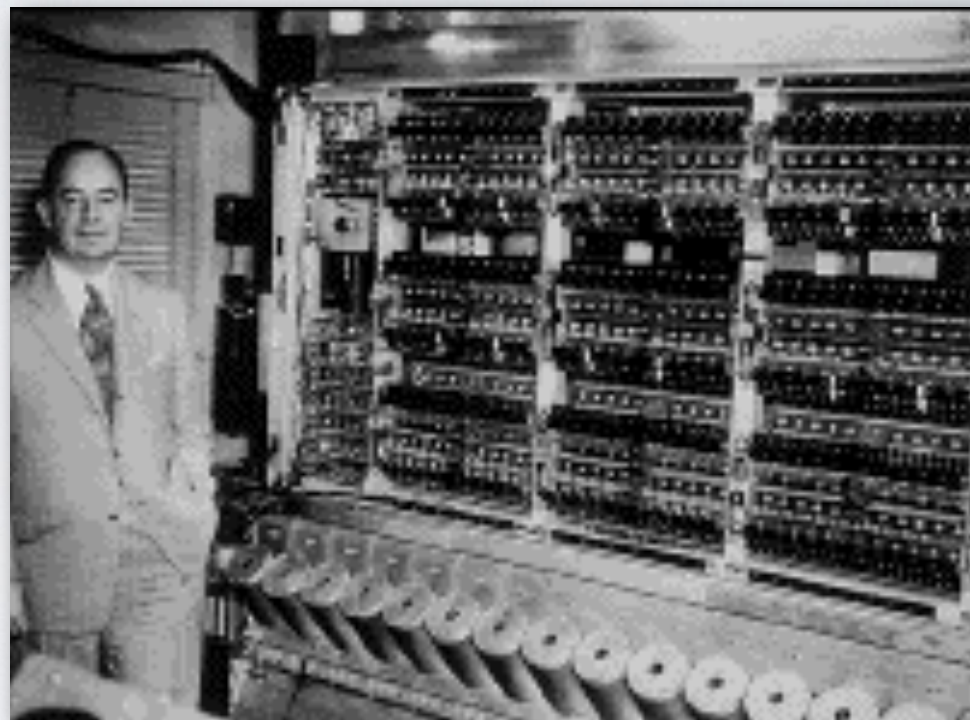
First Computer Programmer

- Described an algorithm for computing Bernoulli numbers on Babbage's Analytical Engine
- Suggested that computers could be used for purposes other than numbers
- Also pointed out a computer "bug" in Babbage's equations

Ada Lovelace

JOHN VON NEUMANN'S METEOROLOGY PROJECT

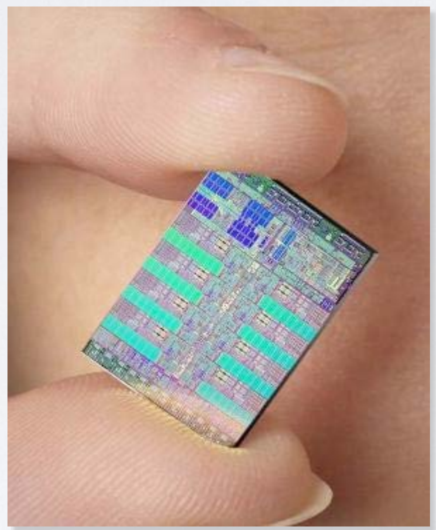
- Recognized numerical weather forecasting as a problem of great importance
- In collaboration with Charney and Fjortoft, they completed the first numerical computer forecast in 1950
- Used ENIAC, first multipurpose electronic digital computer
- Each 24 hour forecast took 24 hours to compute



"If people do not believe that mathematics is simple, it is only because they do not realize how complicated life is."

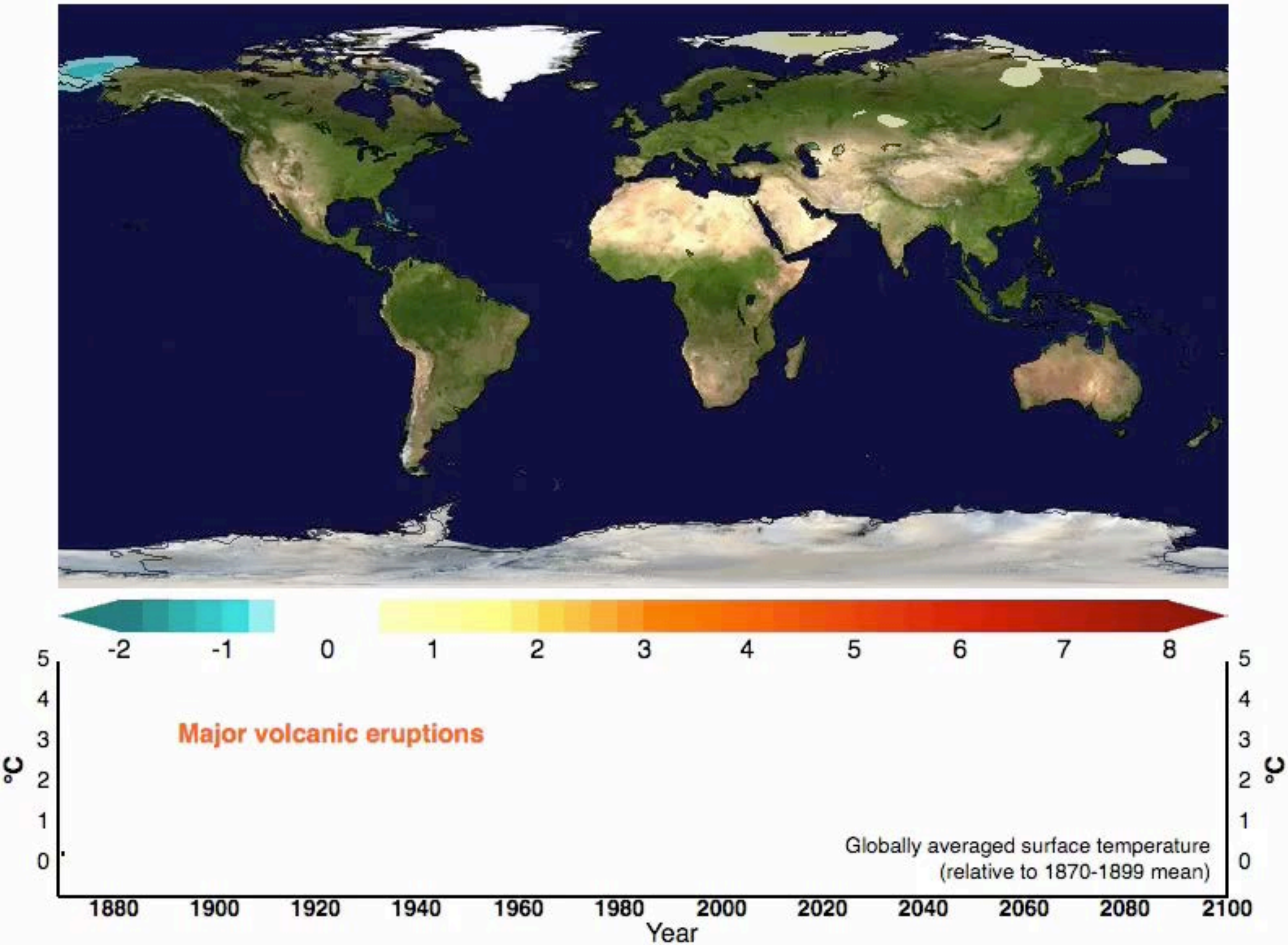
Advances in Computers

33.8 TFlops/s (2014)



200 Billion operations/s
$400 (2005)

400 operations/s, $500K (1946)



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Major volcanic eruptions
°C
Globally averaged surface temperature
(relative to 1870-1899 mean)
1880
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1920
1940
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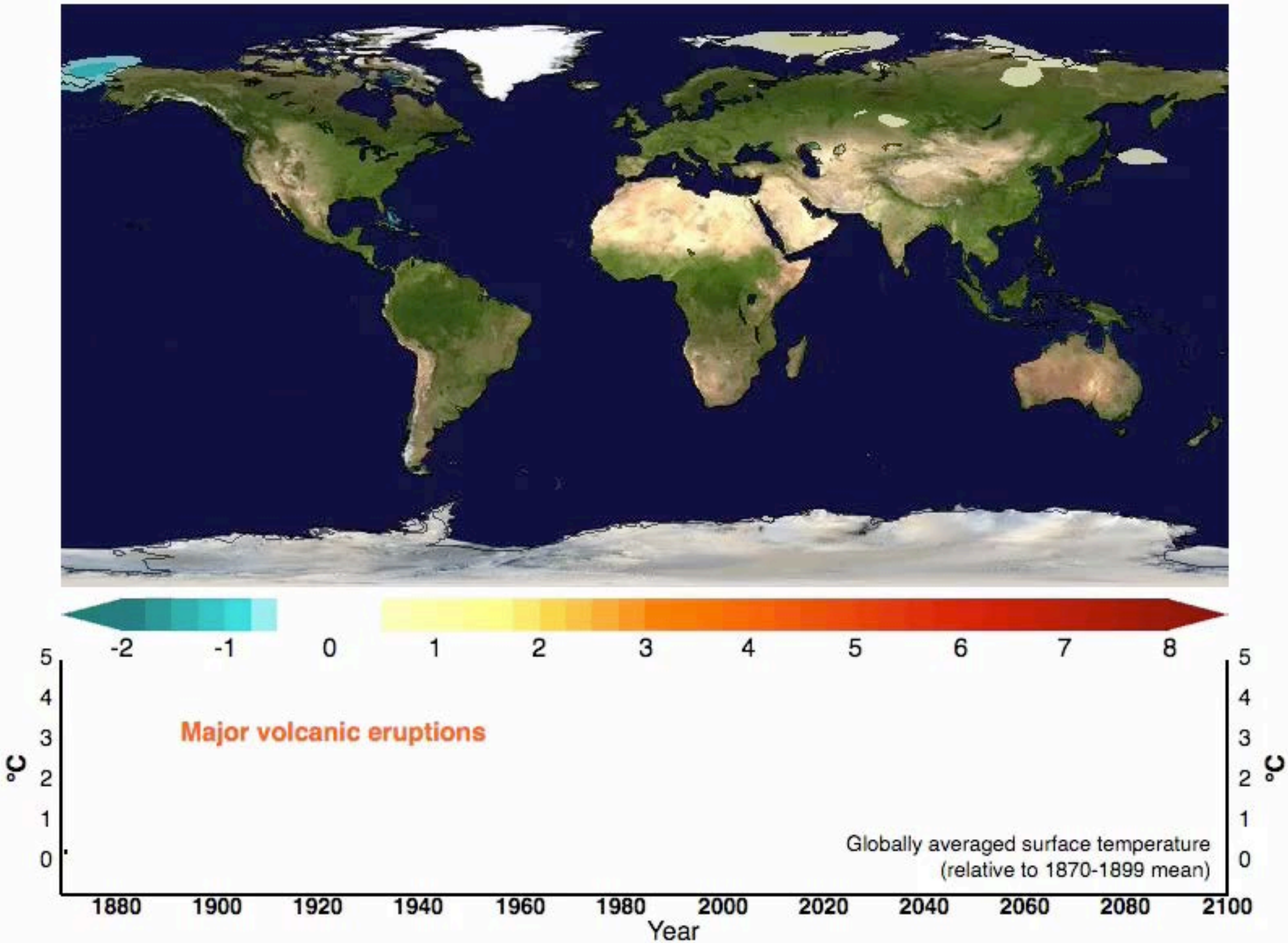
Year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Year

IF BURNING FOSSIL FUELS IS BAD WHAT ARE THE ALTERNATIVES?

Biofuels

Solar Energy

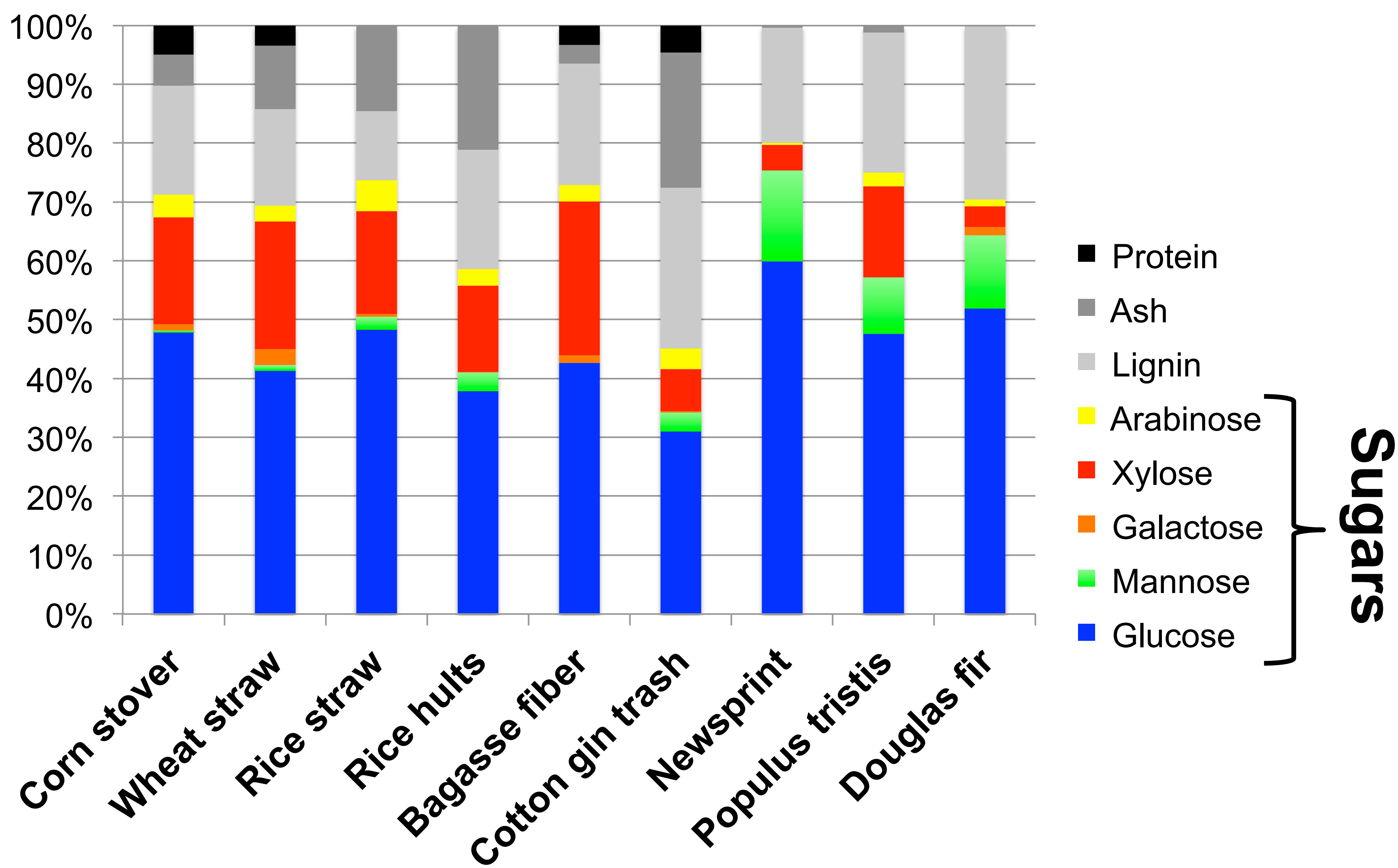
Wind

BIOFUELS

PHOTOGRAPH COURTESY USDA-ARS VIA PNAS

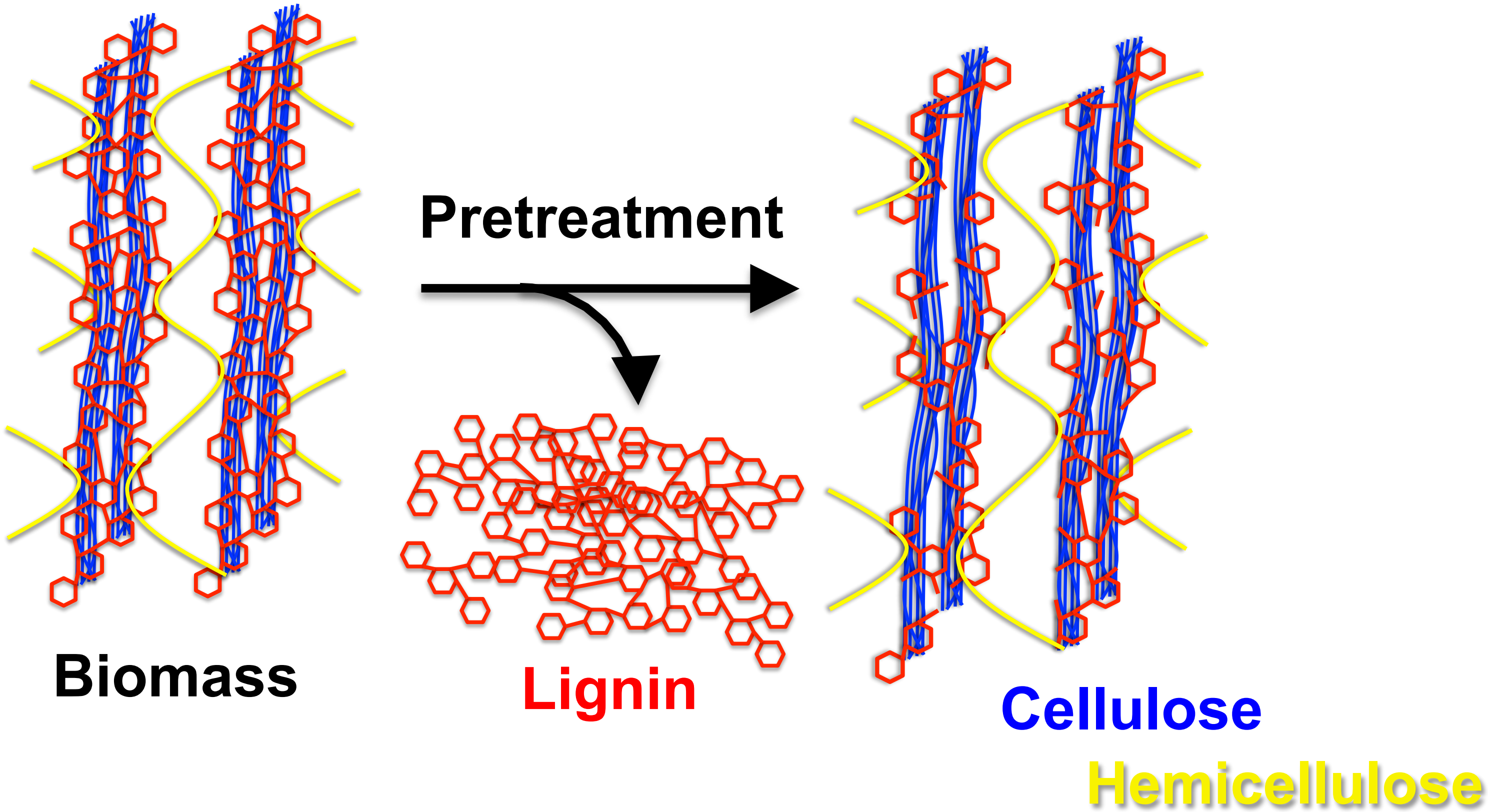
- Idea – Convert sugars in plants into a fuel
- Plants have evolved to be resistant to physical and chemical attack
- If we can understand plant genomics better could we develop better biofuels?

Biomass is predominantly sugar!



Courtesy of Dr. Jay Keasling, LBNL/UCB

BIOFUELS ARE DERIVED FROM THE SUGARS



Courtesy of Dr. Jay Keasling, LBNL/UCB

RENEWABLE TRANSPORTATION FUELS

Perennial plants, such as switchgrass, provide an abundant source of power, generating five times as much energy as they take to grow

Math Can Also be Used to Find Drought Resistant Plants

The loss of harvests in the world's dry areas could have a significant impact on global food security

Researchers are developing mathematical models to identify genetic material that could help improve food crops' resilience to climate change.

SUMMARY

- Math and computers have opened new opportunities in energy, environment, biology
- Many problems still waiting to be studied
- We need more people with new ideas working on these problems

So If Someone Asks You Why You're Studying Math?

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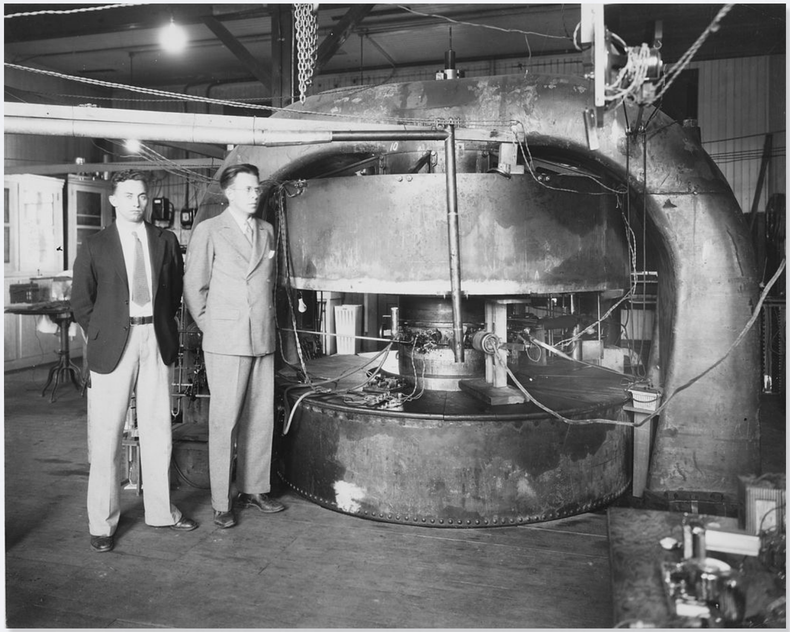
I'm Going To Help Save The World!

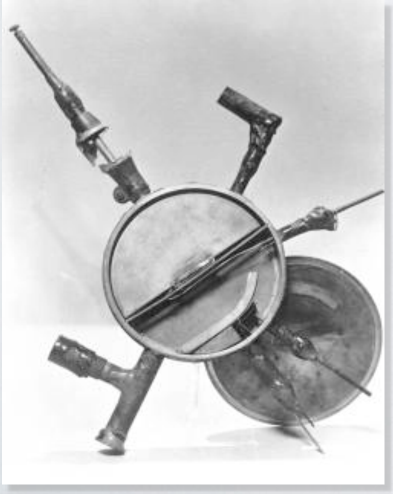
SUPPLEMENTAL MATERIALS

Experimental Science

27 km circumference
7 TeV
$4B US
(2015)

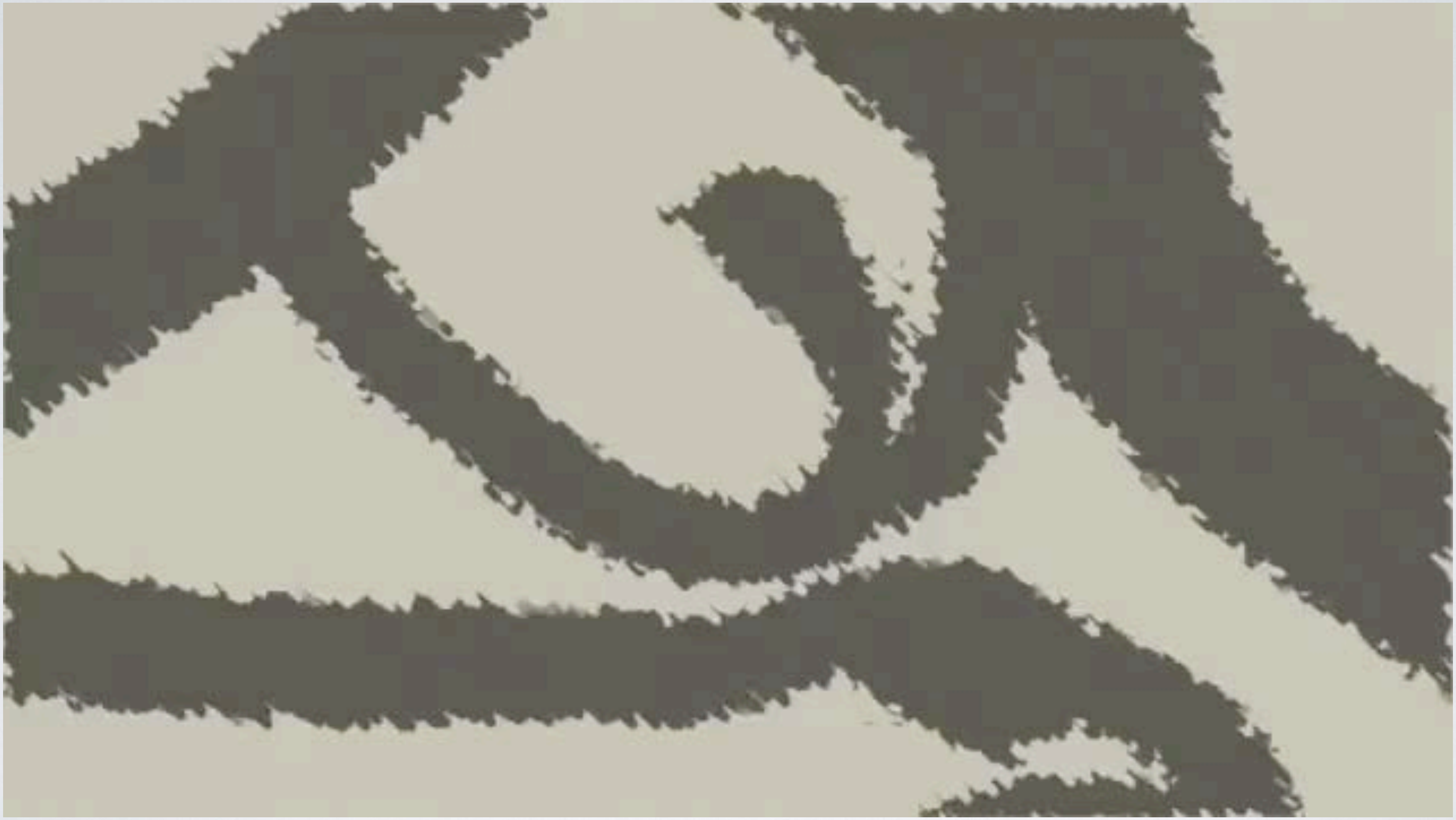


27 inch (1934)



4.5 inches diameter, 80 keV (1931)

Difference between Climate and Weather



https://www.youtube.com/watch?v=e0vj-0imOLw

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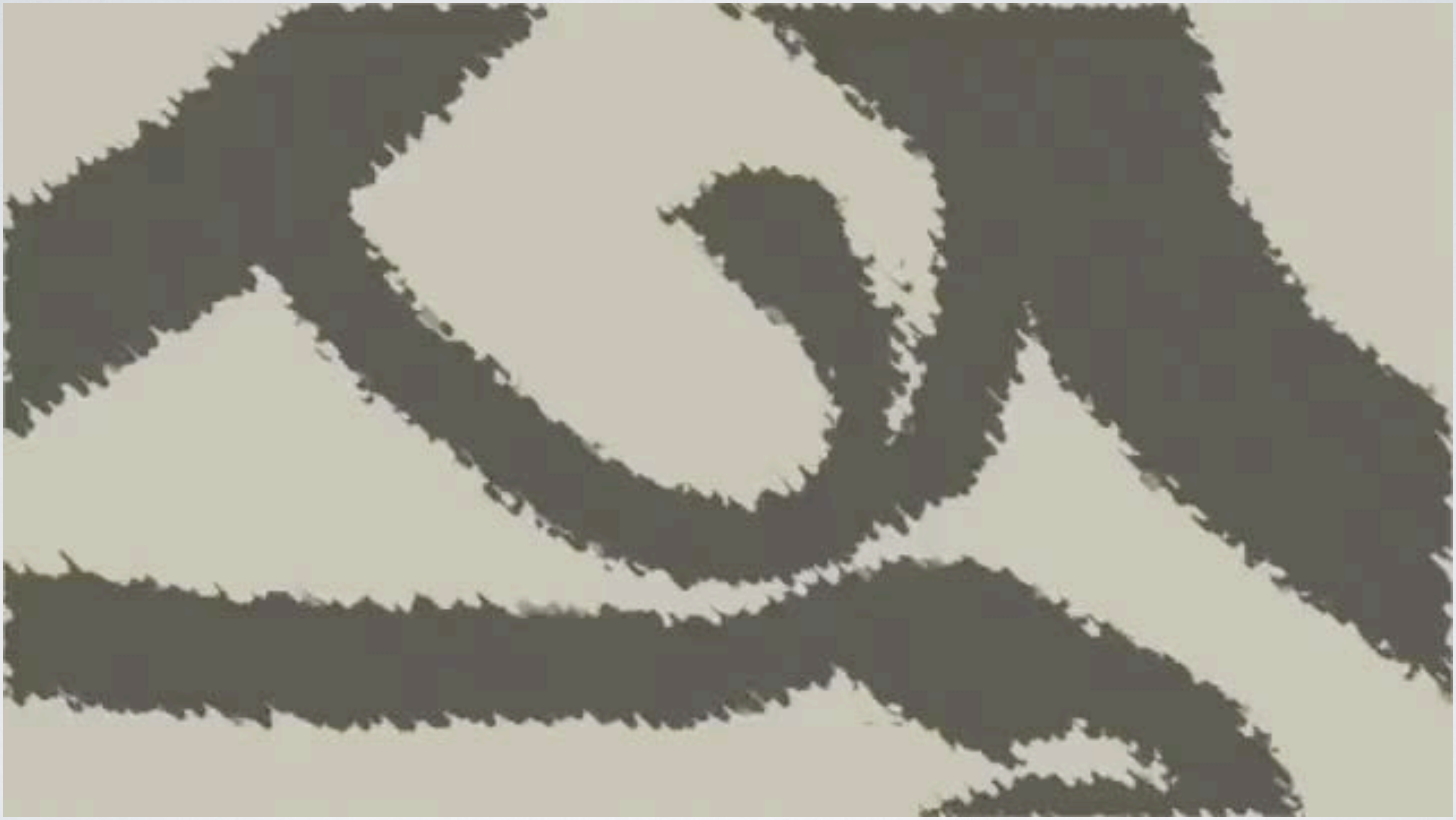
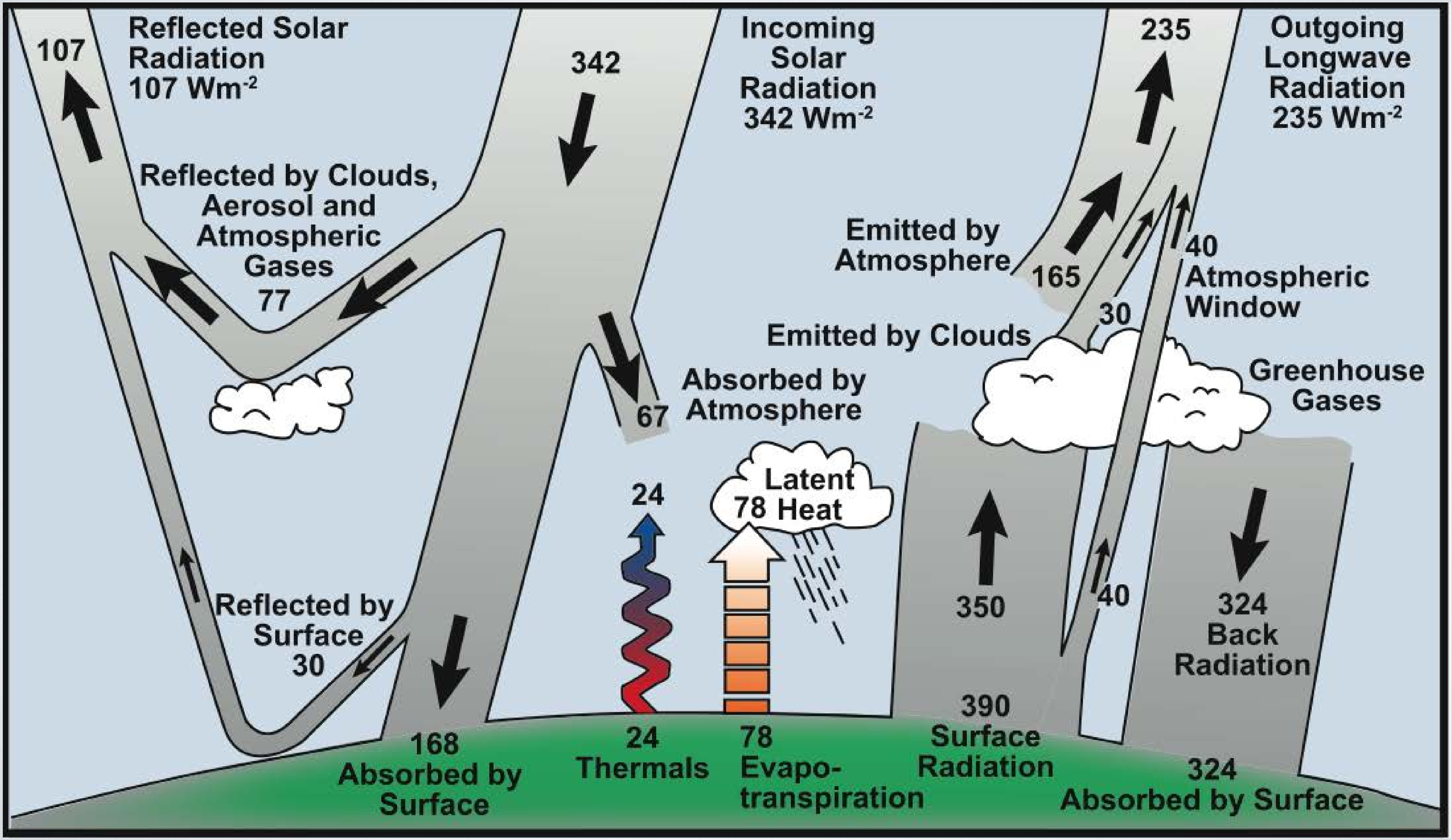


https://www.youtube.com/watch?v=e0vj-0imOLw

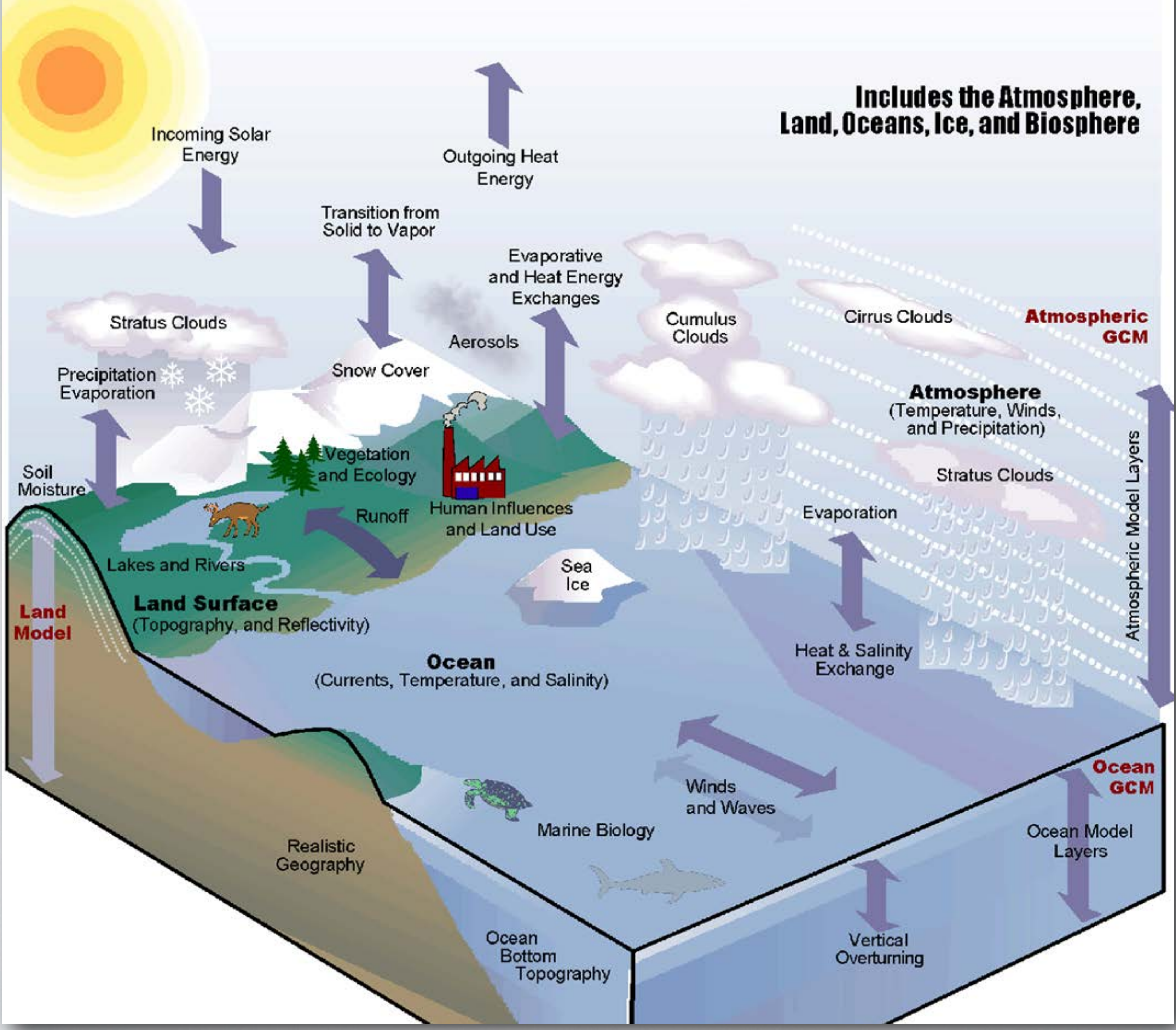
GENERAL CLIMATE

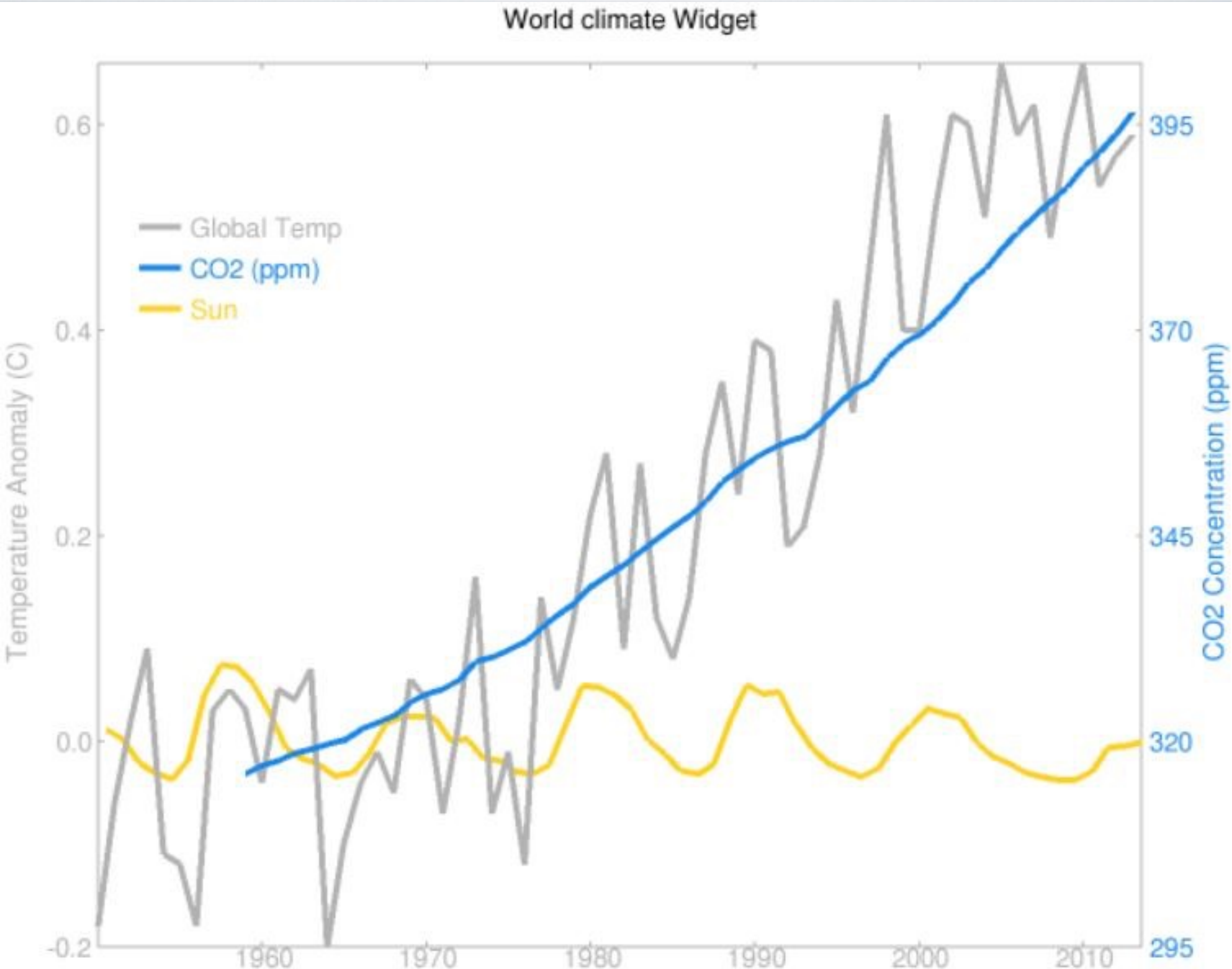
ATMOSPHERE ENERGY BALANCE

342 = 107 + 235

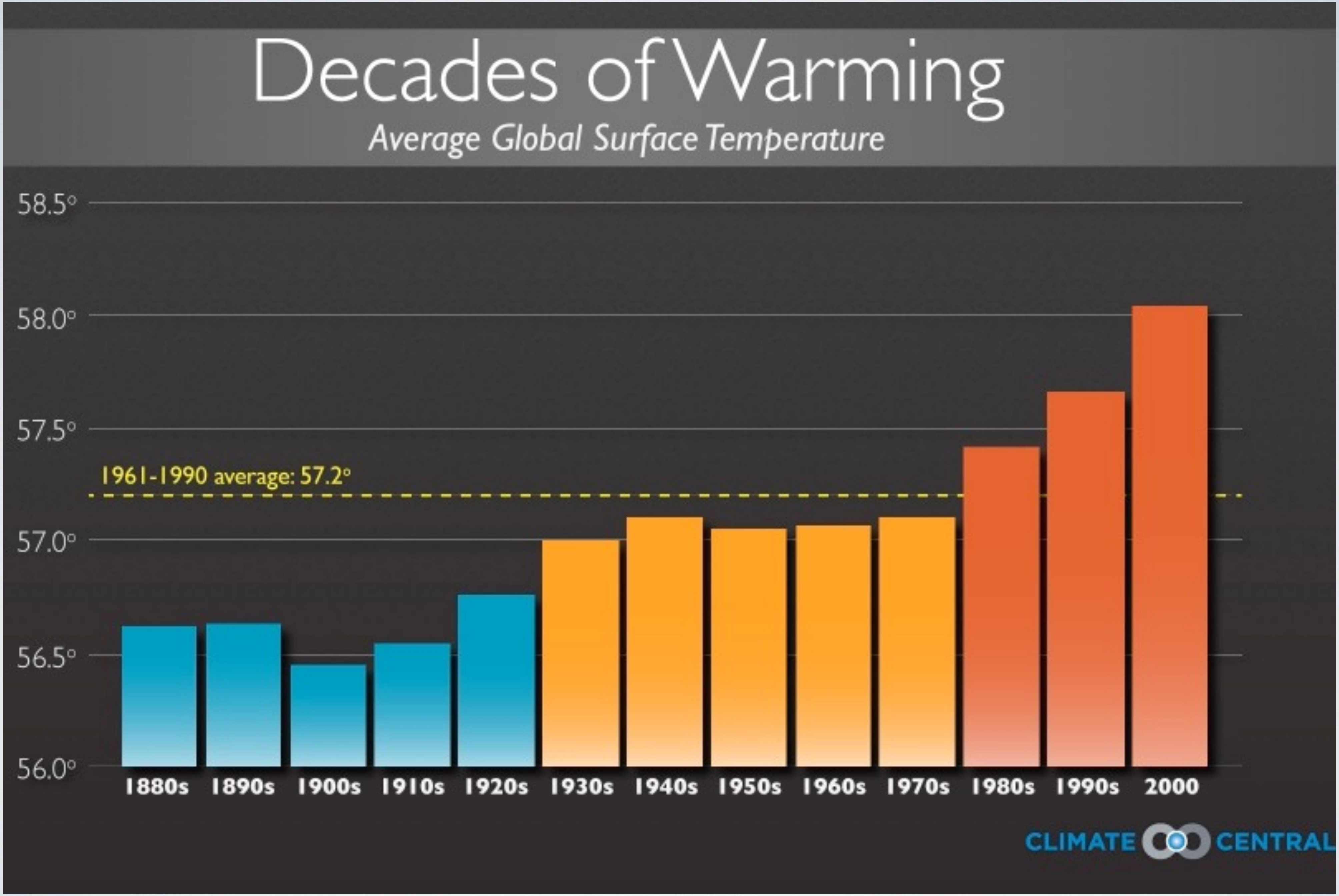


Modeling the Climate System





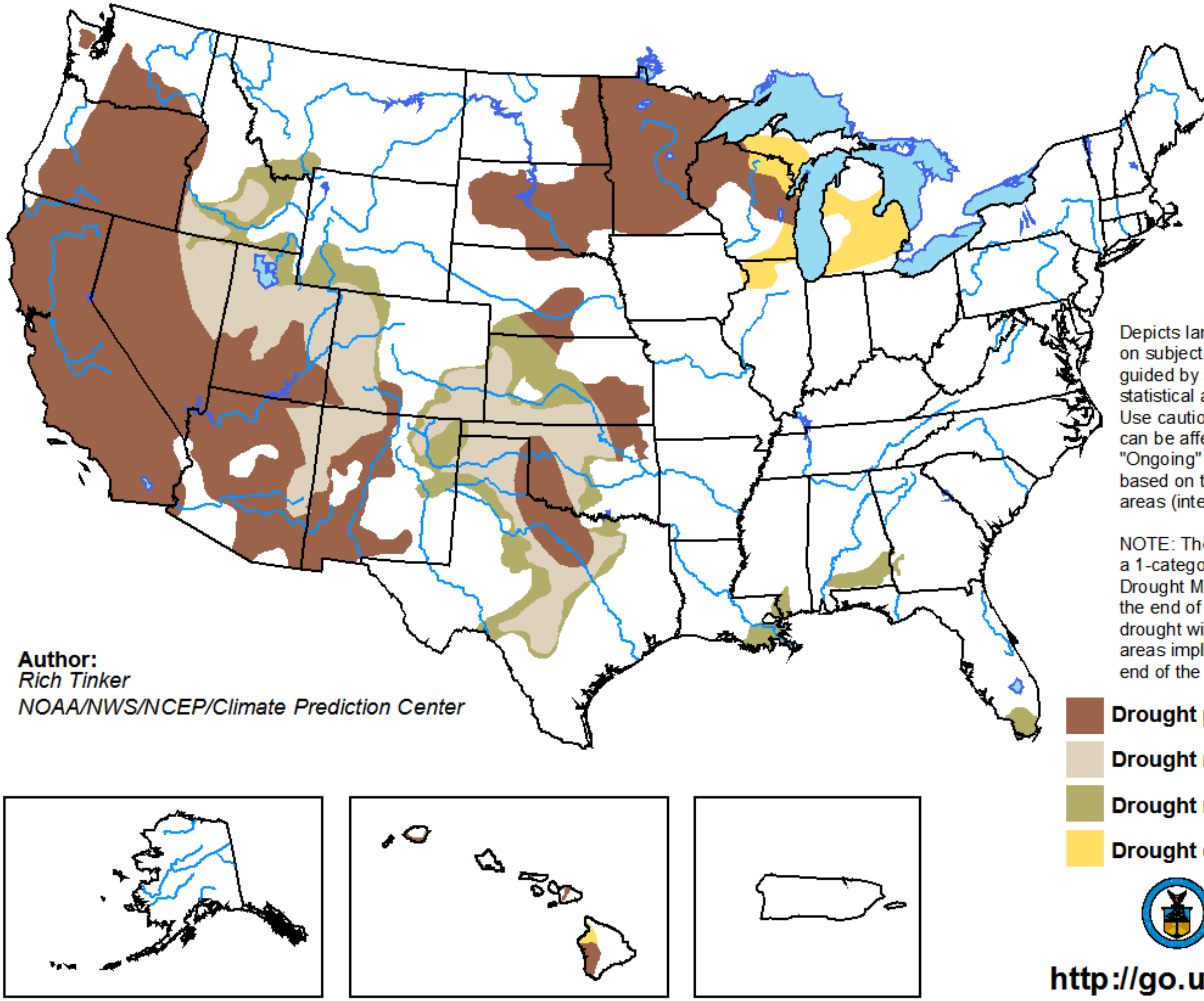
http://herdsoft.com/climate/widget/


Decades of Warming
Average Global Surface Temperature
58.5°
58.0°
57.5°
1961-1990 average: 57.2°
57.0°
56.5°
56.0°
1880s
1890s
1900s
1910s
1920s
1930s
1940s
1950s
1960s
1970s
1980s
1990s
2000
CLIMATE CENTRAL

U.S. Seasonal Drought Outlook

Drought Tendency During the Valid Period

Valid for April 16 - July 31, 2015
Released April 16, 2015



Depicts large-scale trends based on subjectively derived probabilities guided by short- and long-range statistical and dynamical forecasts. Use caution for applications that can be affected by short lived events. "Ongoing" drought areas are based on the U.S. Drought Monitor areas (intensities of D1 to D4).

NOTE: The tan areas imply at least a 1-category improvement in the Drought Monitor intensity levels by the end of the period, although drought will remain. The green areas imply drought removal by the end of the period (D0 or none).

Drought persists/intensifies

Drought remains but improve

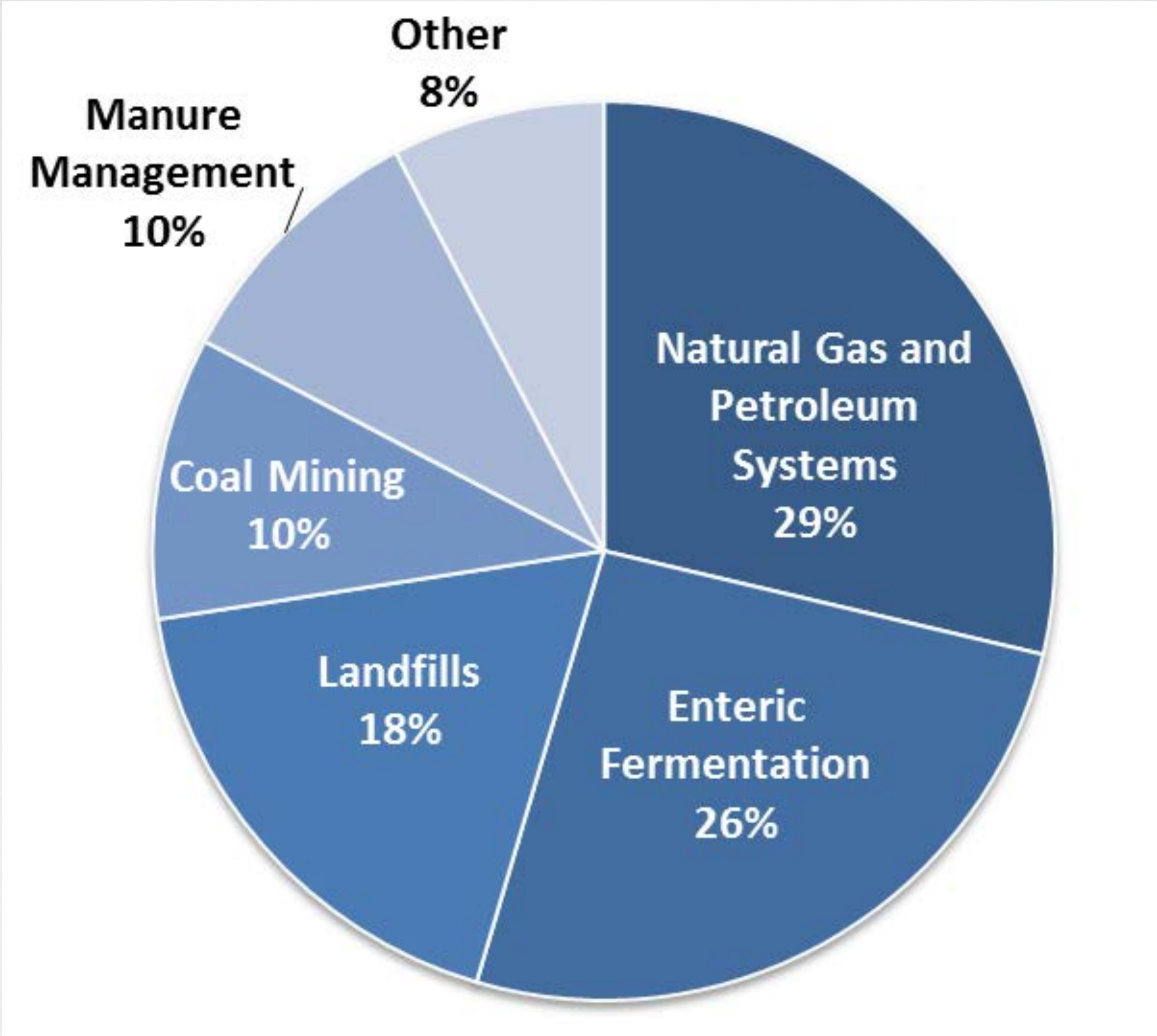
Drought removal likely

Drought development likely

Author:
Rich Tinker
NOAA/NWS/NCEP/Climate Prediction Center

http://go.usa.gov/hHTe

Methane has 25X impact of CO_2



http://epa.gov/climatechange/ghgemissions/gases/ch4.html

Methane has 25X impact of CO_2

http://www.dailymail.co.uk/sciencetech/article-2606956/Now-THATS-wind-power-Cows-wear-BACKPACKS-capture-emissions-miniature-power-stations.html

BIOFUELS

Fun Biofuel Facts

- Ethanol reduces greenhouse gas emissions up to 65 percent [source: Nebraska Ethanol Board].
- Perennial plants, such as switchgrass, provide an abundant source of power, generating five times as much energy as they take to grow [source: Biello].
- Biodiesel vehicles get 30 percent better fuel economy than gasoline-powered vehicles [source: Consumer Reports].

PLANT SEEDS AS BIOFUELS

- Company plans to have 250,000 acres of jatropha in Brazil, India and other countries
- Expected to eventually produce about 70 million gallons of fuel a year.
- Advances in molecular genetics and DNA sequencing technology led to domesticating jatropha in a few years, a process that once took decades

Start-Up Uses Plant Seeds for a Biofuel, By TODD WOODY, New York Times, December 24,

Biofuels now becoming economically viable

- Abengoa Bioenergy building a $500M plant to produce biofuels
- Plans to produce 25M gallons of biofuels / year
- Based on cellulosic ethanol from corn stalks and wheat straw

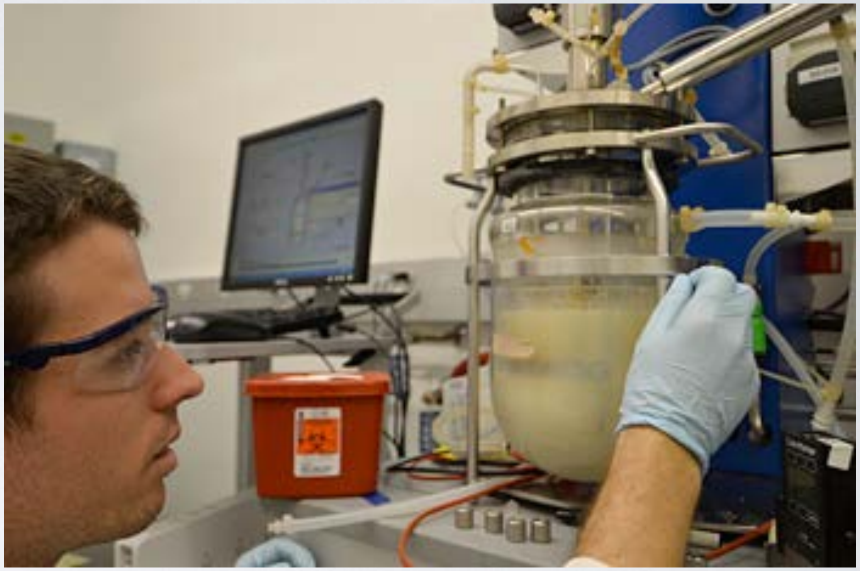
http://www.nytimes.com/2014/04/15/business/energy-environment/dual-turning-point-for-biofuels.html?_r=0

CHALLENGES STILL EXIST FOR BIOFUELS

- Design of plants that have more sugars with less lignin
- Need better processes for producing the sugars
- Many different types of fuels

SUGAR TO DIESEL

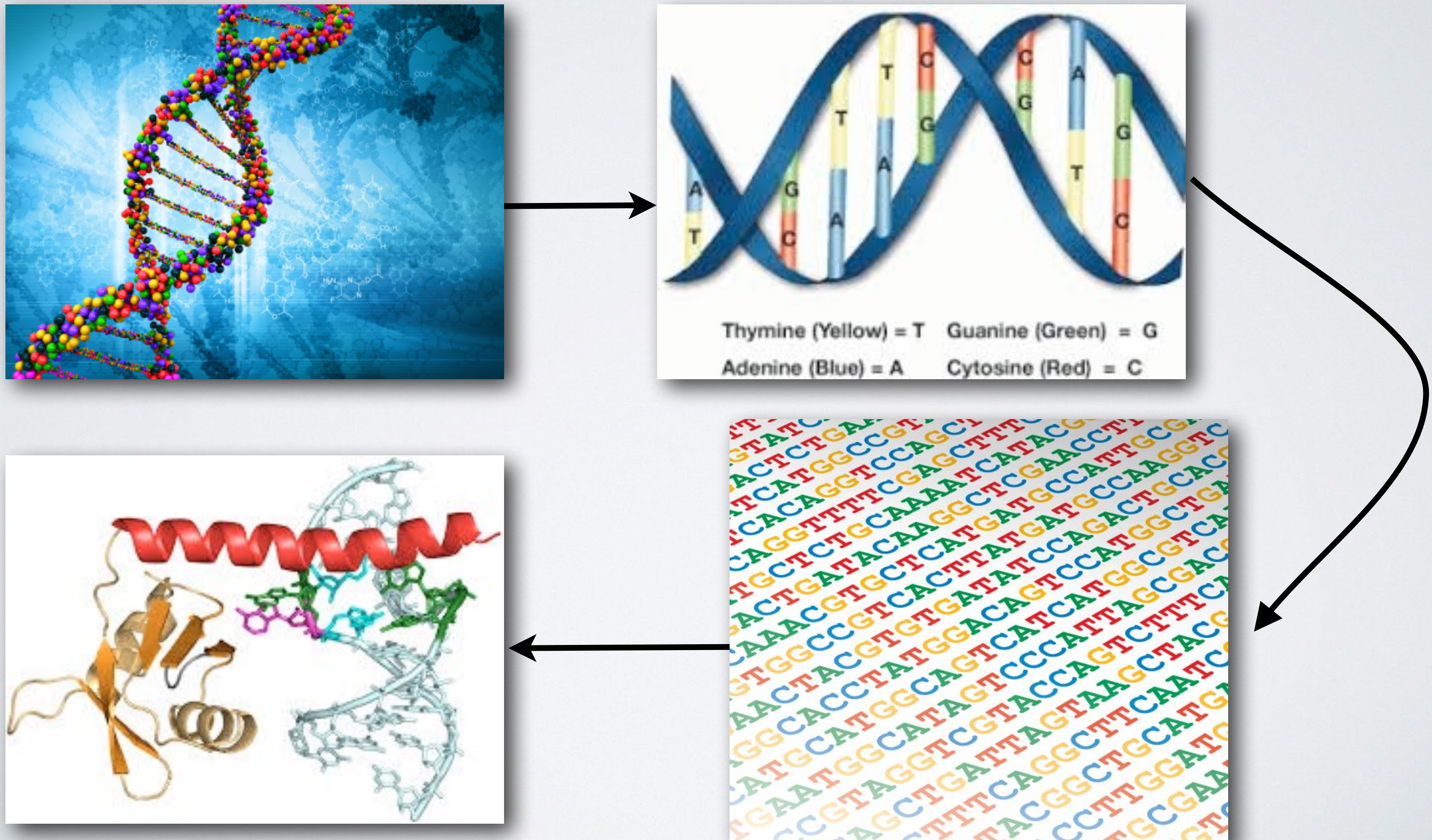
- UCB chemists and chemical engineers teamed up to produce diesel fuel from the products of a bacterial fermentation discovered nearly 100 years ago.
- The process produces a mix of products that contain more energy per gallon than ethanol
- Could be commercialized



Graduate student Zachary Baer *works with a fermentation chamber in the Energy Biosciences Building to separate acetone and butanol (clear top layer) from the yellowish Clostridium brew at the bottom. Robert Sanders photo.*

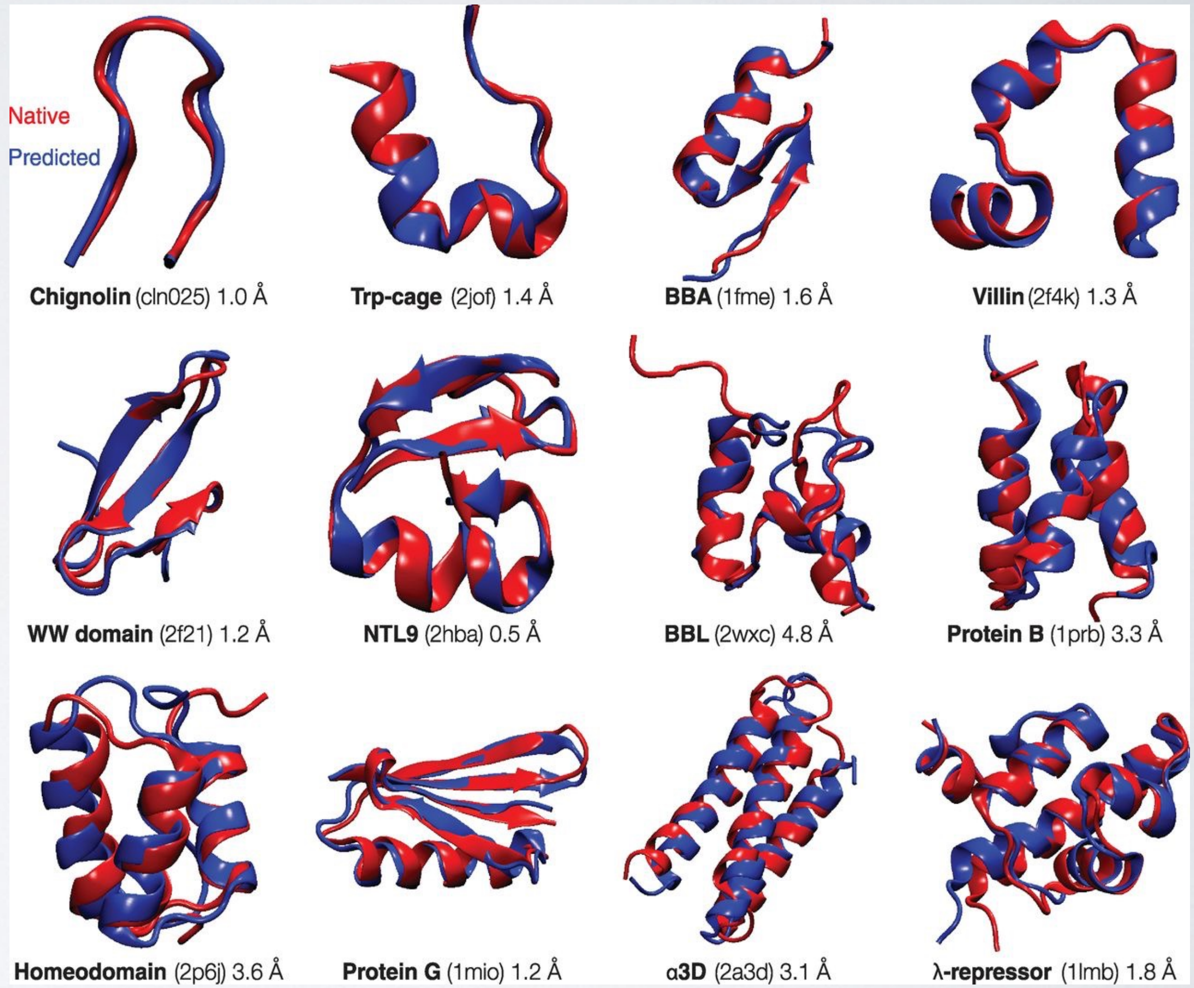
http://newscenter.berkeley.edu/2012/11/07/discovery-resurrects-process-to-convert-sugar-directly-to-diesel/
http://www.nature.com/nature/journal/v491/n7423/full/nature11594.html?WT.ec_id=NATURE-20121108

DNA to Proteins



PROTEIN FOLDING PROBLEM

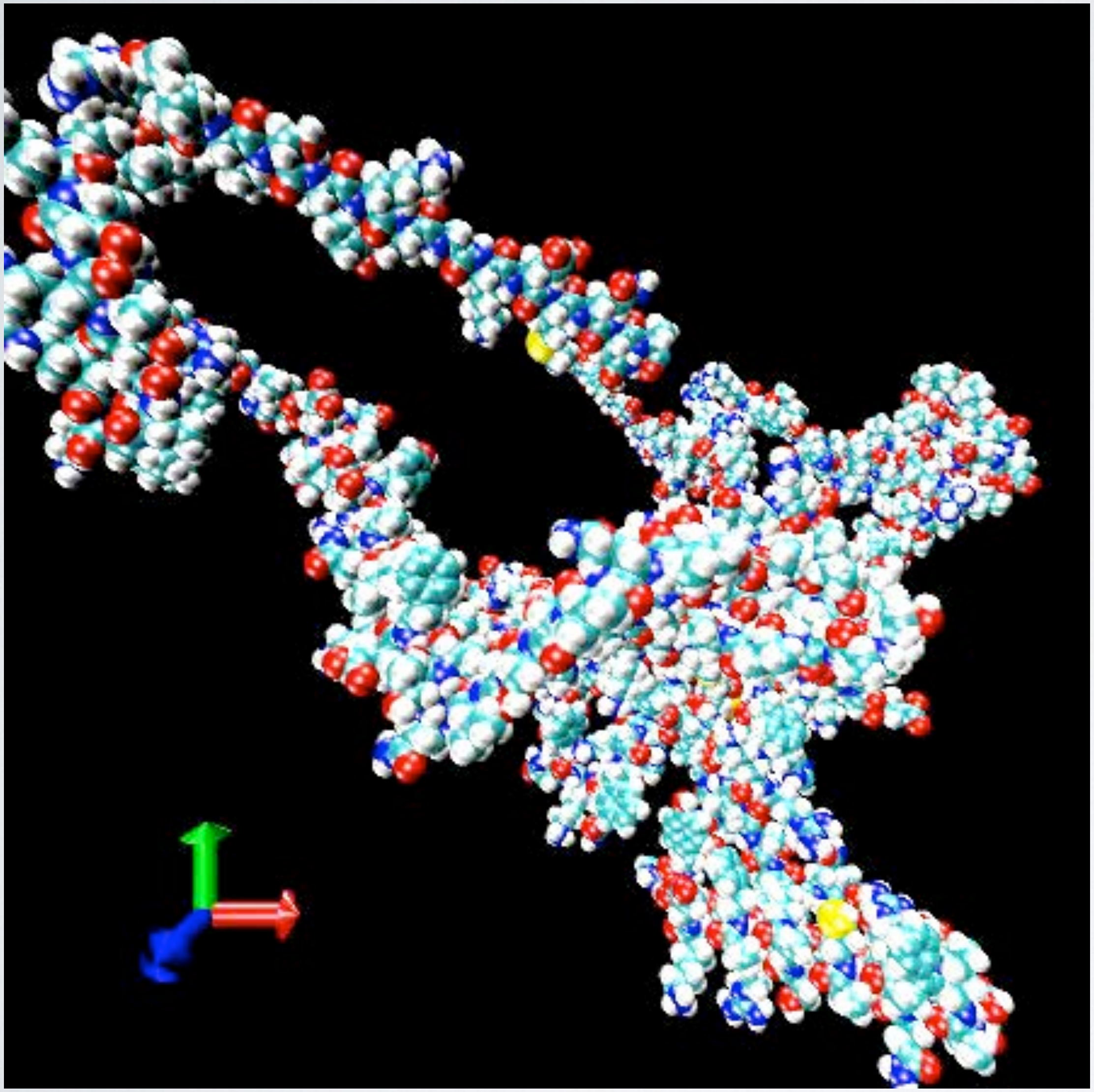
- Genome sequence is only the start
- The 3D shape of a protein determines its function
- One of the grand scientific challenges



K A Dill, and J L MacCallum Science 2012;338:1042-1046

Science AAAS

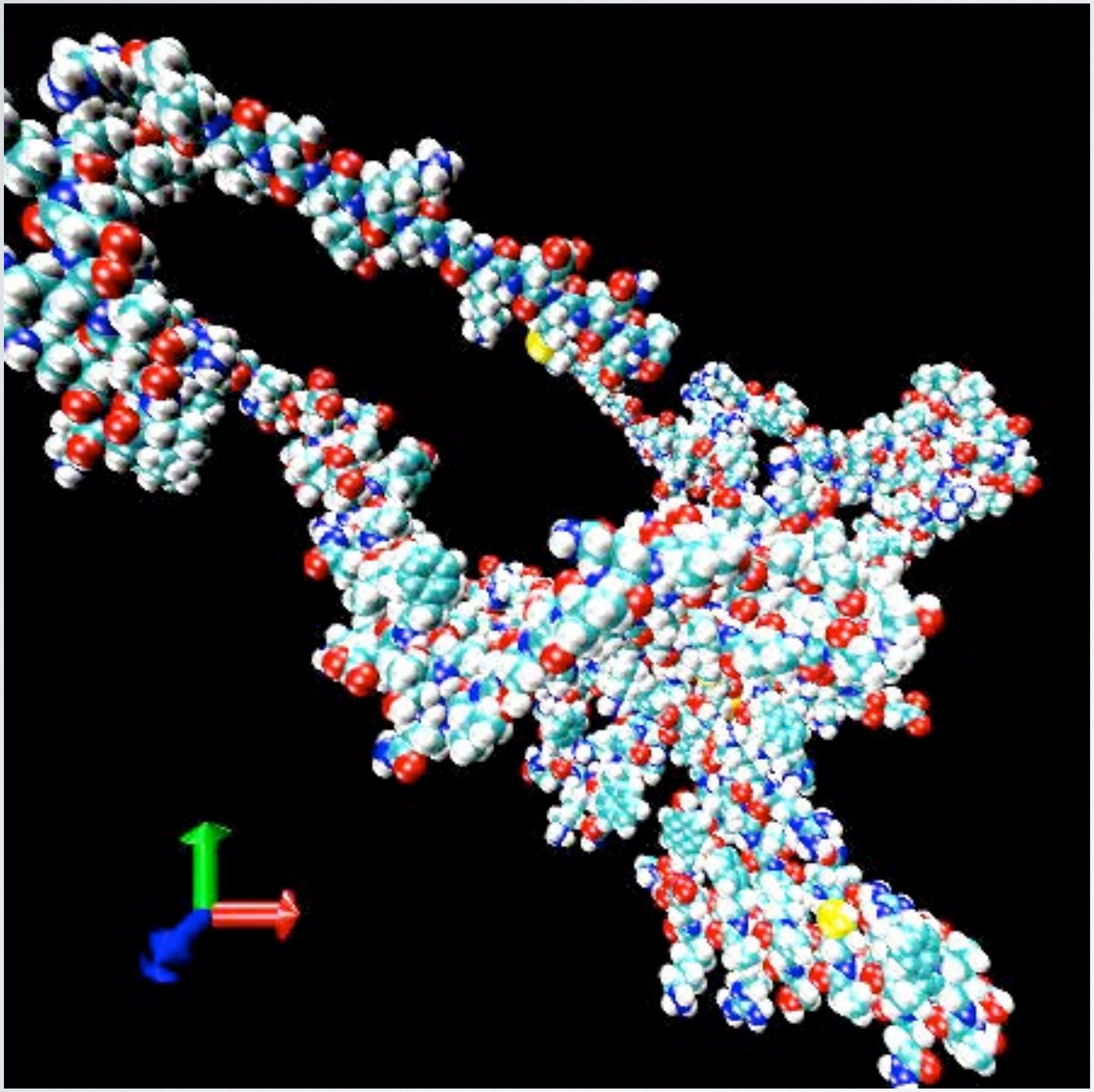
PROTEIN FOLDING



J.C. Meza et al. LBNL

- Computer (math) simulations can be used to predict 3D shapes of proteins
- Mathematical models can compute the energy of a molecule, which helps us understand their function
- Need new and better algorithms to analyze data

PROTEIN FOLDING



J.C. Meza et al. LBNL

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