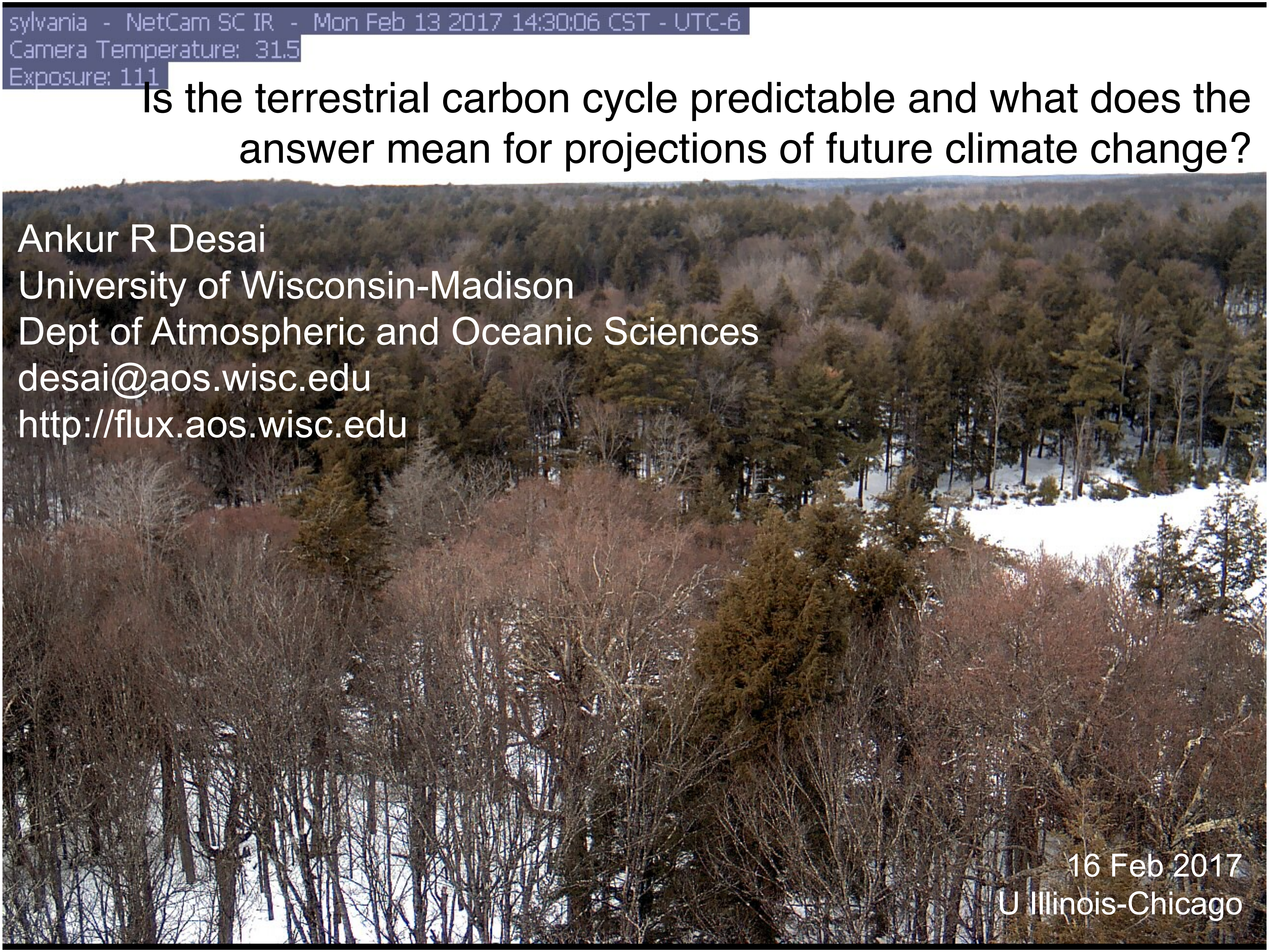
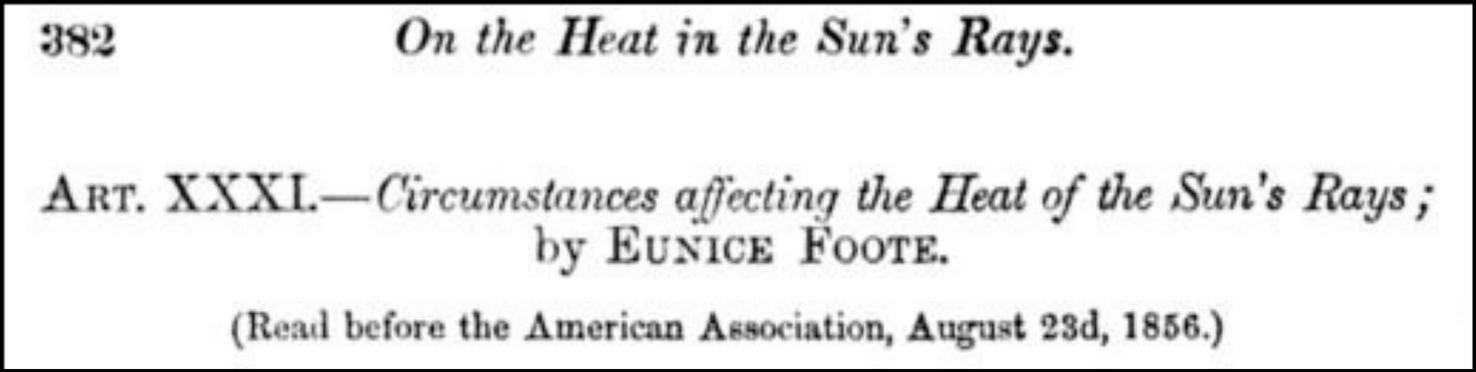


Is the terrestrial carbon cycle predictable and what does the answer mean for projections of future climate change?

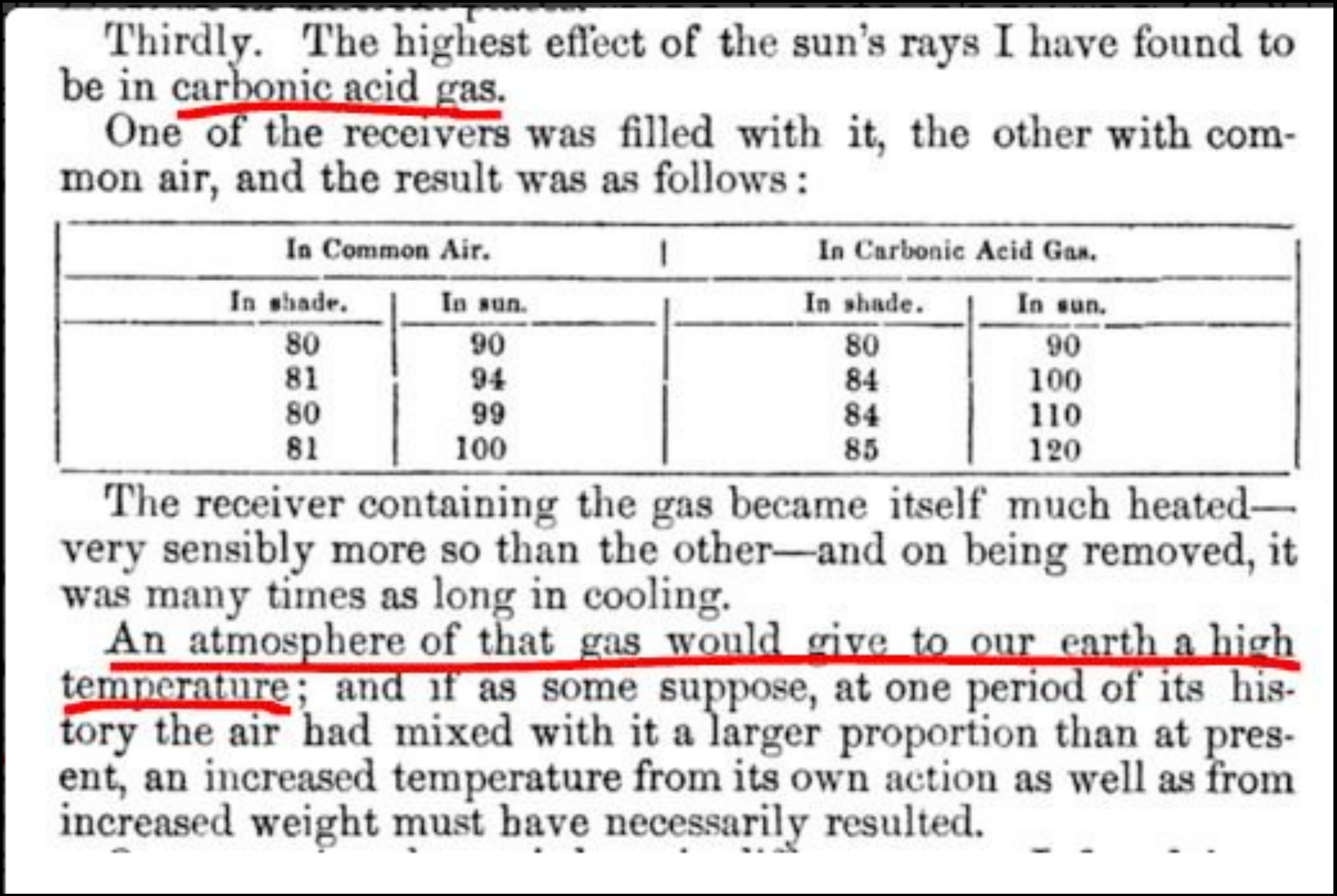
Ankur R Desai
University of Wisconsin-Madison
Dept of Atmospheric and Oceanic Sciences
desai@aos.wisc.edu
http://flux.aos.wisc.edu

16 Feb 2017
U Illinois-Chicago



ART. XXXI.—*Circumstances affecting the Heat of the Sun's Rays;*
by EUNICE FOOTE.

(Read before the American Association, August 23d, 1856.)



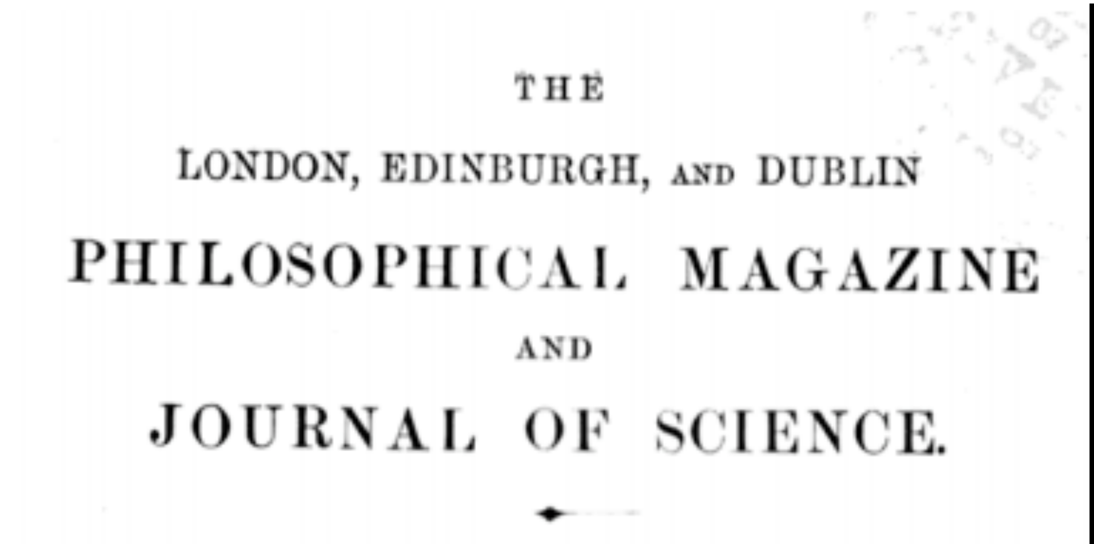
Thirdly. The highest effect of the sun's rays I have found to be in carbonic acid gas.

One of the receivers was filled with it, the other with common air, and the result was as follows:

In Common Air.		In Carbonic Acid Gas.	
In shade.	In sun.	In shade.	In sun.
80	90	80	90
81	94	84	100
80	99	84	110
81	100	85	120

The receiver containing the gas became itself much heated—very sensibly more so than the other—and on being removed, it was many times as long in cooling.

An atmosphere of that gas would give to our earth a high temperature; and if as some suppose, at one period of its history the air had mixed with it a larger proportion than at present, an increased temperature from its own action as well as from increased weight must have necessarily resulted.



THE

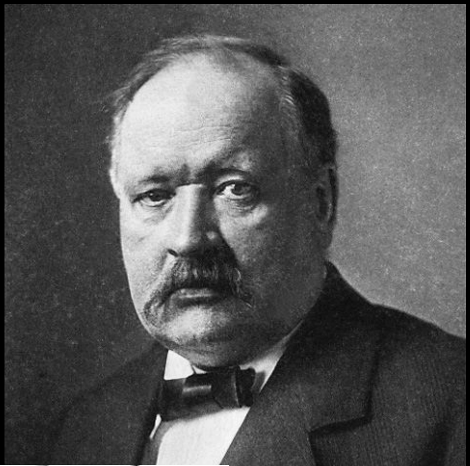
LONDON, EDINBURGH, AND DUBLIN

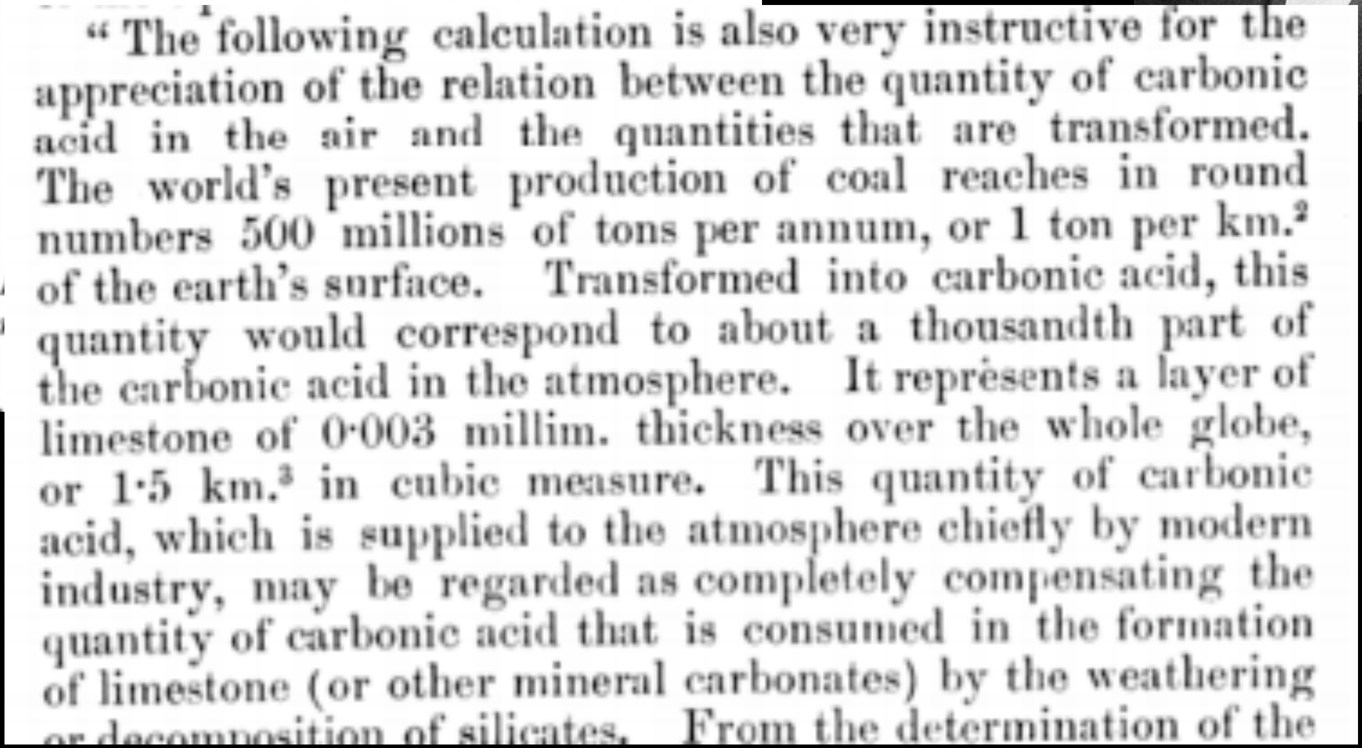
PHILOSOPHICAL MAGAZINE

AND

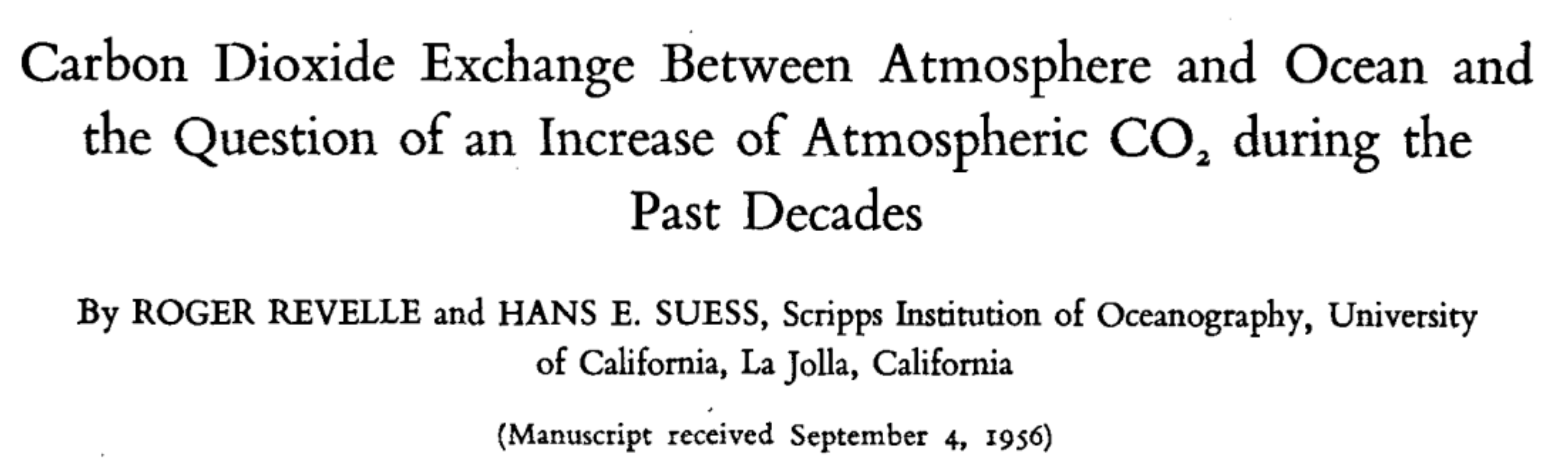
JOURNAL OF SCIENCE.

XXXI. *On the*
the Temperatu
ARRHENIUS *.





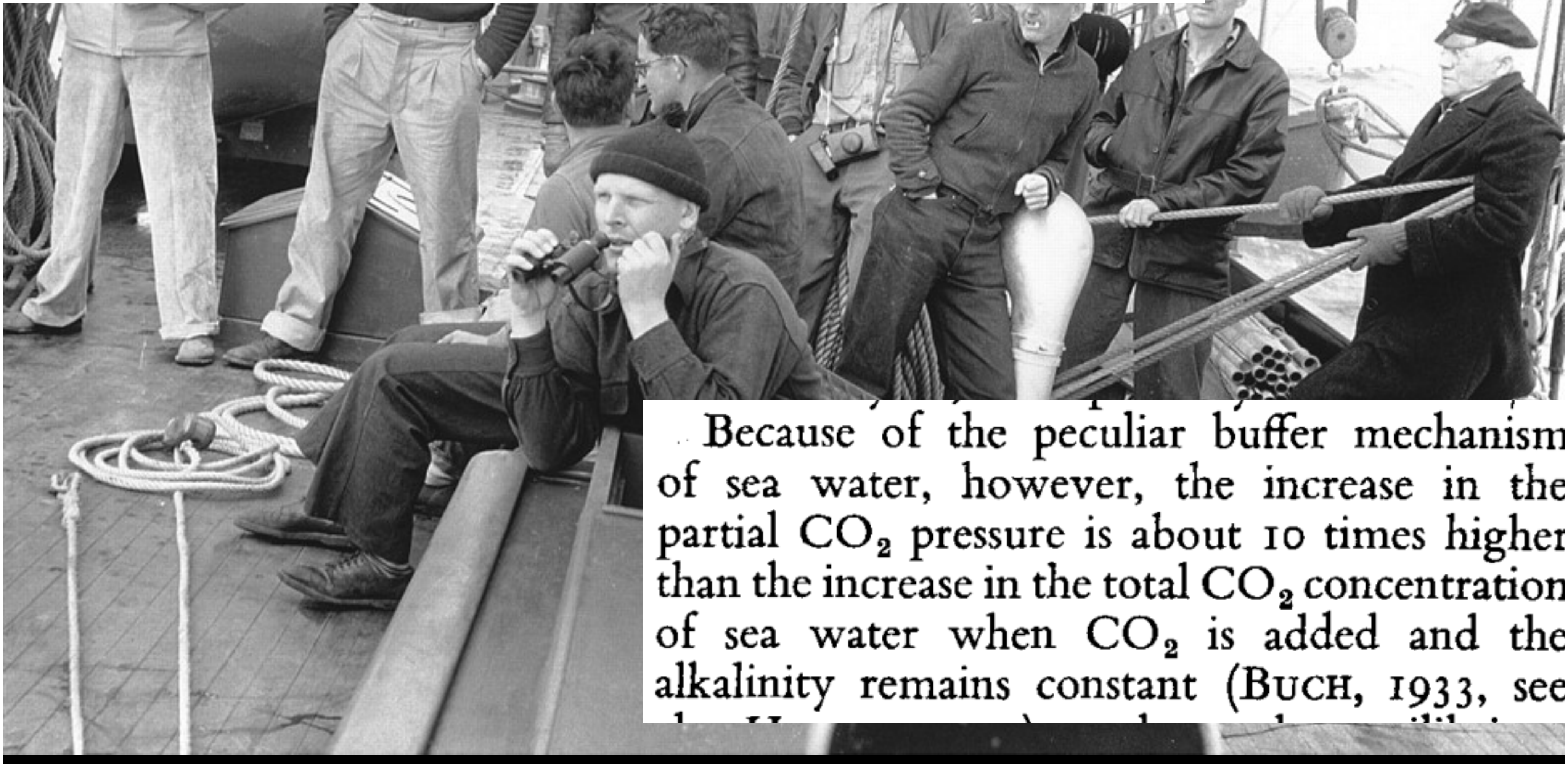
"The following calculation is also very instructive for the appreciation of the relation between the quantity of carbonic acid in the air and the quantities that are transformed. The world's present production of coal reaches in round numbers 500 millions of tons per annum, or 1 ton per km.^{2} of the earth's surface. Transformed into carbonic acid, this quantity would correspond to about a thousandth part of the carbonic acid in the atmosphere. It represents a layer of limestone of 0·003 millim. thickness over the whole globe, or 1·5 km.^{3} in cubic measure. This quantity of carbonic acid, which is supplied to the atmosphere chiefly by modern industry, may be regarded as completely compensating the quantity of carbonic acid that is consumed in the formation of limestone (or other mineral carbonates) by the weathering or decomposition of silicates. From the determination of the



Carbon Dioxide Exchange Between Atmosphere and Ocean and the Question of an Increase of Atmospheric CO_2 during the Past Decades

By ROGER REVELLE and HANS E. SUESS, Scripps Institution of Oceanography, University of California, La Jolla, California

(Manuscript received September 4, 1956)

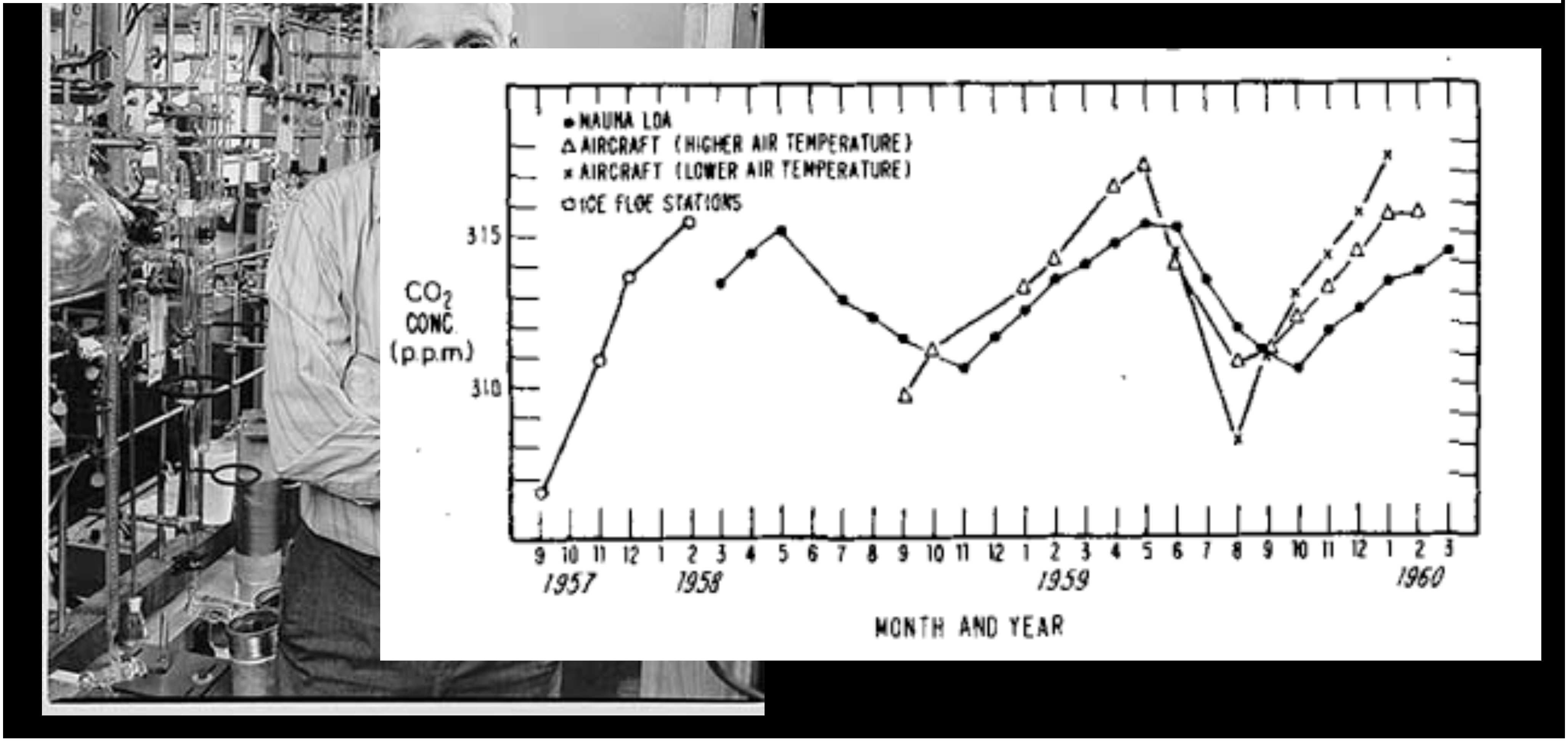


Because of the peculiar buffer mechanism of sea water, however, the increase in the partial CO_2 pressure is about 10 times higher than the increase in the total CO_2 concentration of sea water when CO_2 is added and the alkalinity remains constant (Buch, 1933, see

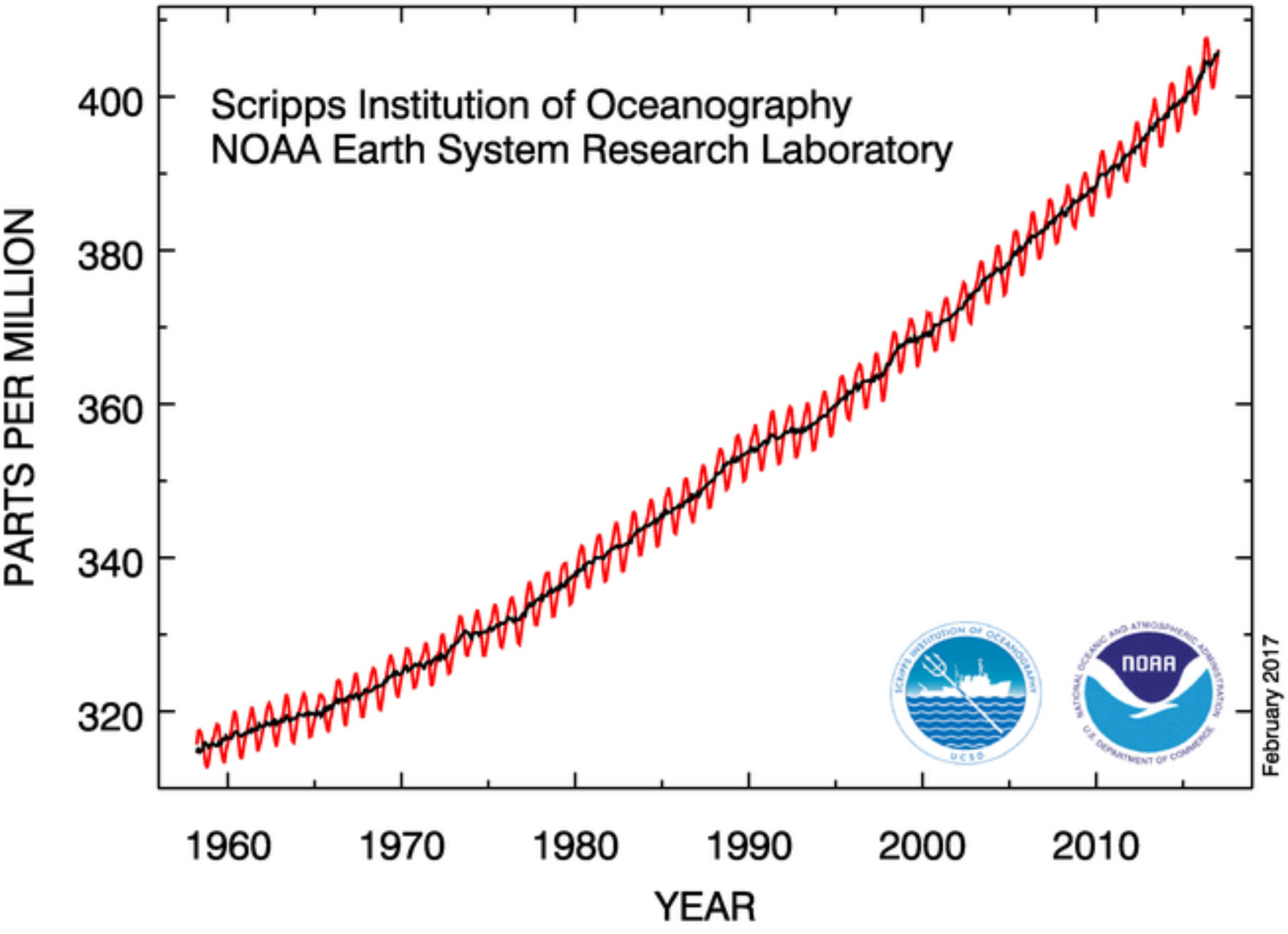
The Concentration and Isotopic Abundances of Carbon Dioxide in the Atmosphere

By CHARLES D. KEELING, Scripps Institution of Oceanography, University of California,
La Jolla, California

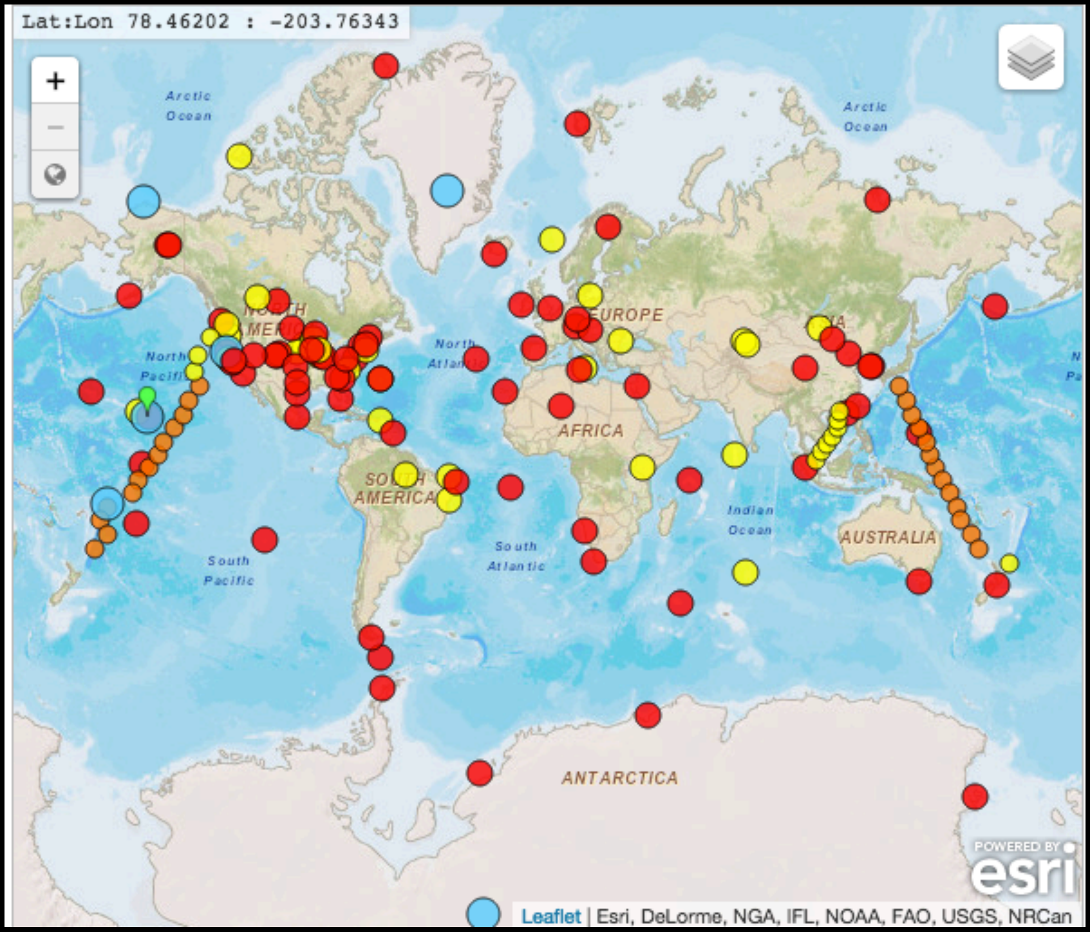
(Manuscript received March 25, 1960)

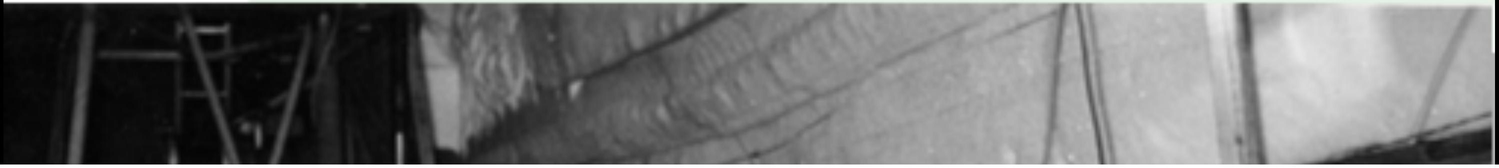


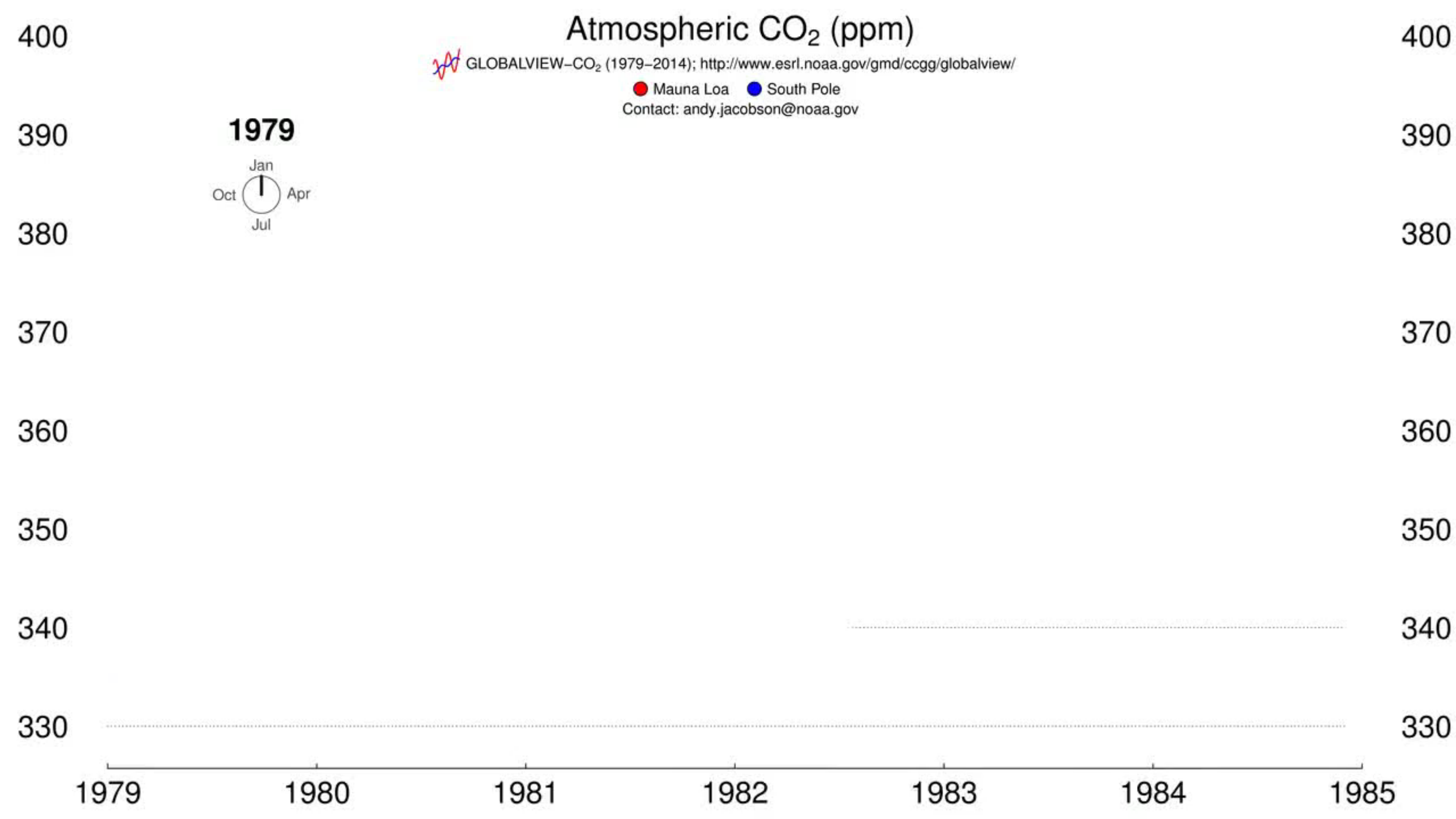
Atmospheric CO_2 at Mauna Loa Observatory



February 2017


Lat:Lon 78.46202 : -203.76343
+
–
Arctic Ocean
Arctic Ocean
NORTH AMERICA
North Pacific
North Atlantic
EUROPE
ASIA
North Pacific
AFRICA
SOUTH AMERICA
South Pacific
South Atlantic
Indian Ocean
AUSTRALIA
ANTARCTICA
POWERED BY esri
Leaflet | Esri, DeLorme, NGA, IFL, NOAA, FAO, USGS, NRCan



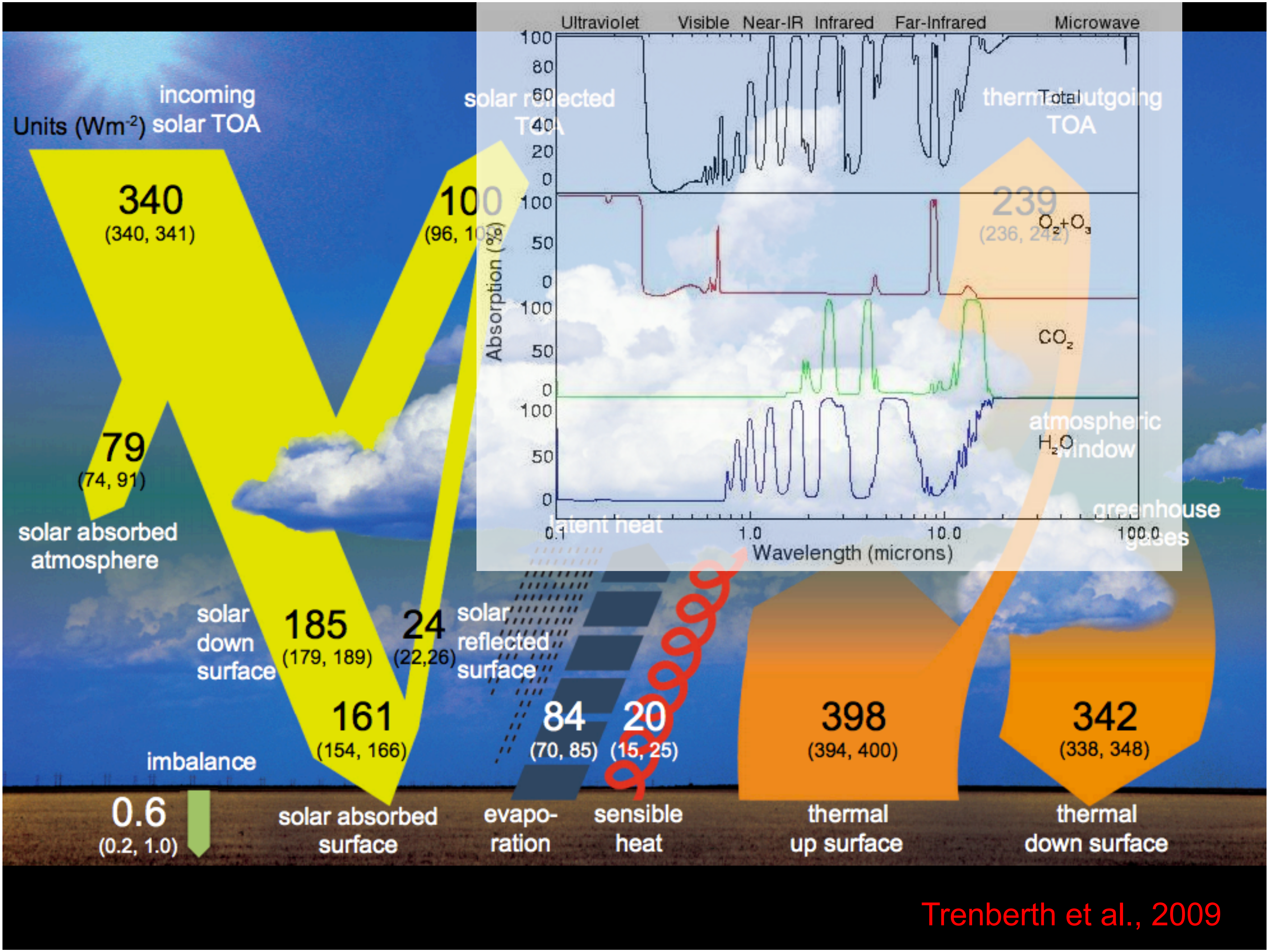


Atmospheric CO_2 (ppm)

GLOBALVIEW–CO_2 (1979–2014); http://www.esrl.noaa.gov/gmd/ccgg/globalview/

● Mauna Loa ● South Pole

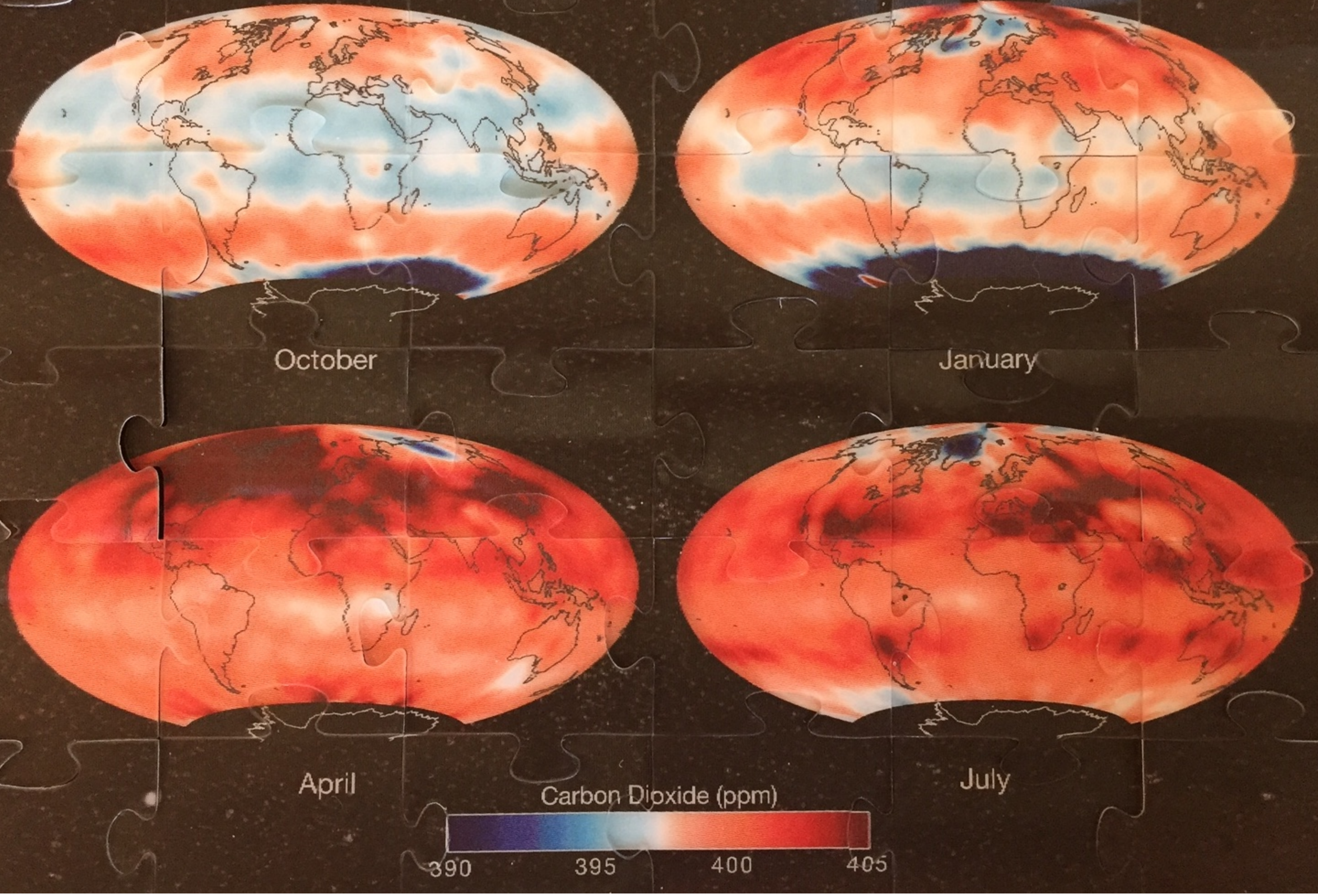
Contact: andy.jacobson@noaa.gov



Trenberth et al., 2009

SEASONAL CARBON DIOXIDE
2014 - 2015

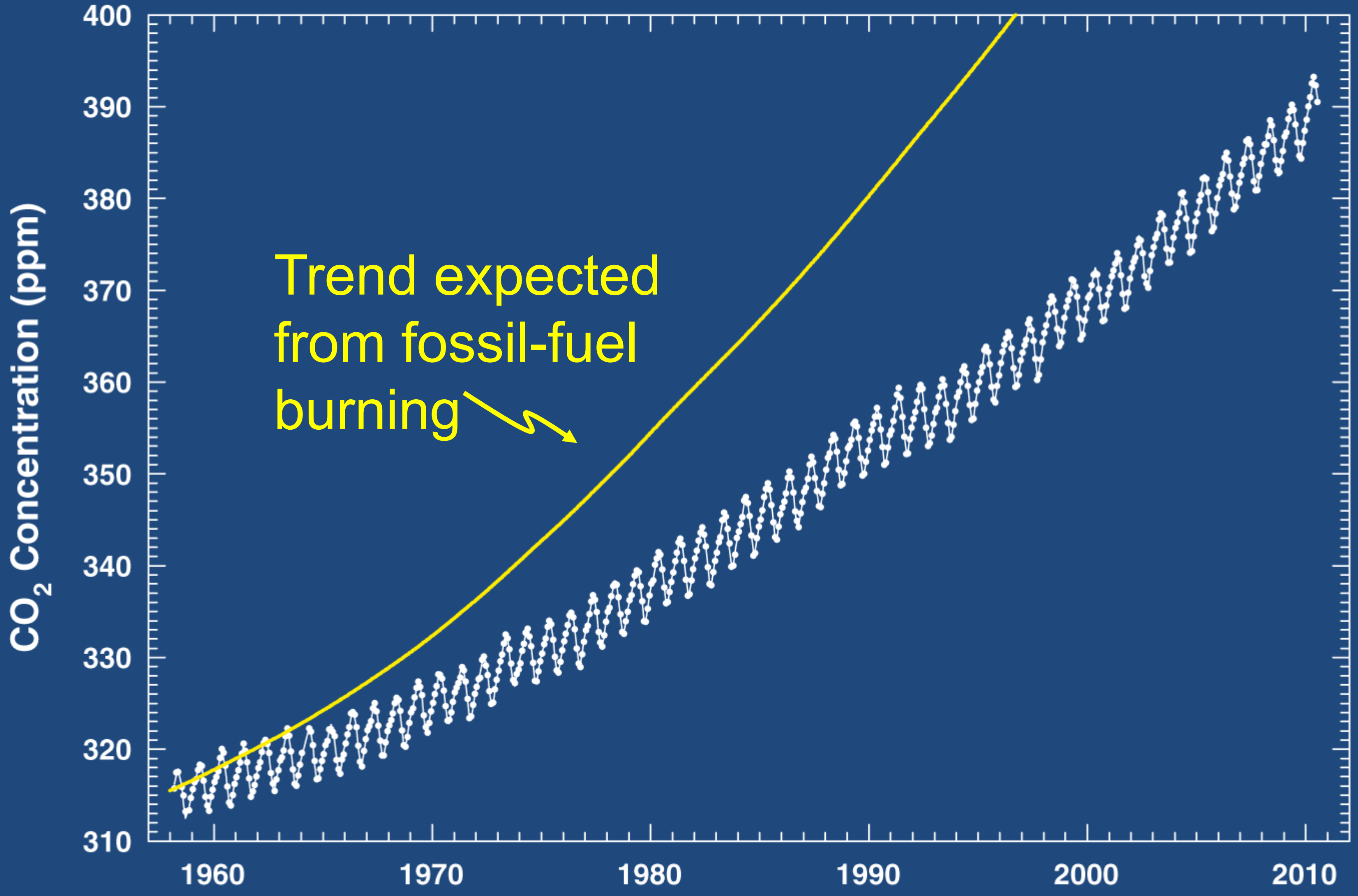
National Aeronautics and
Space Administration


October

January

April

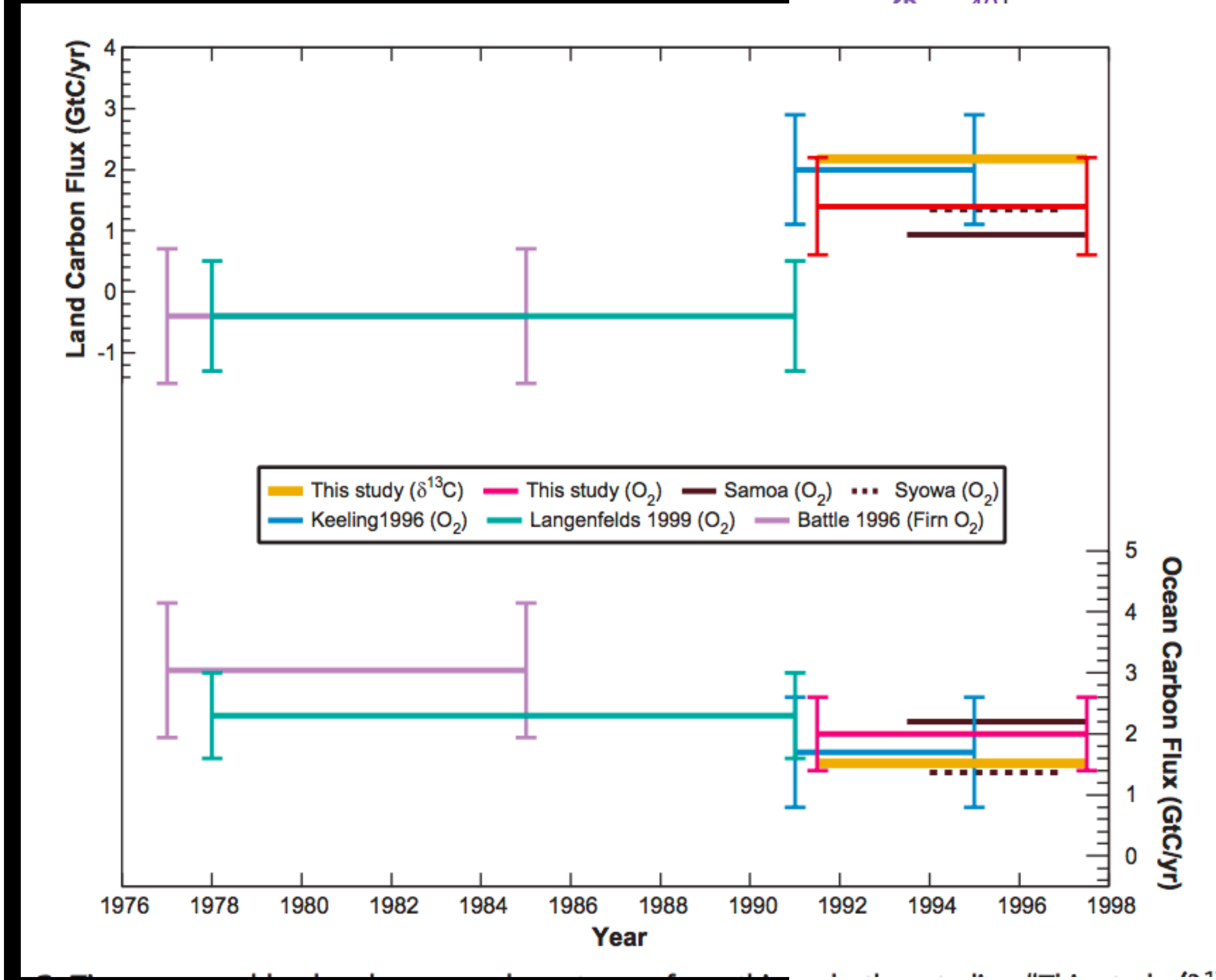
July

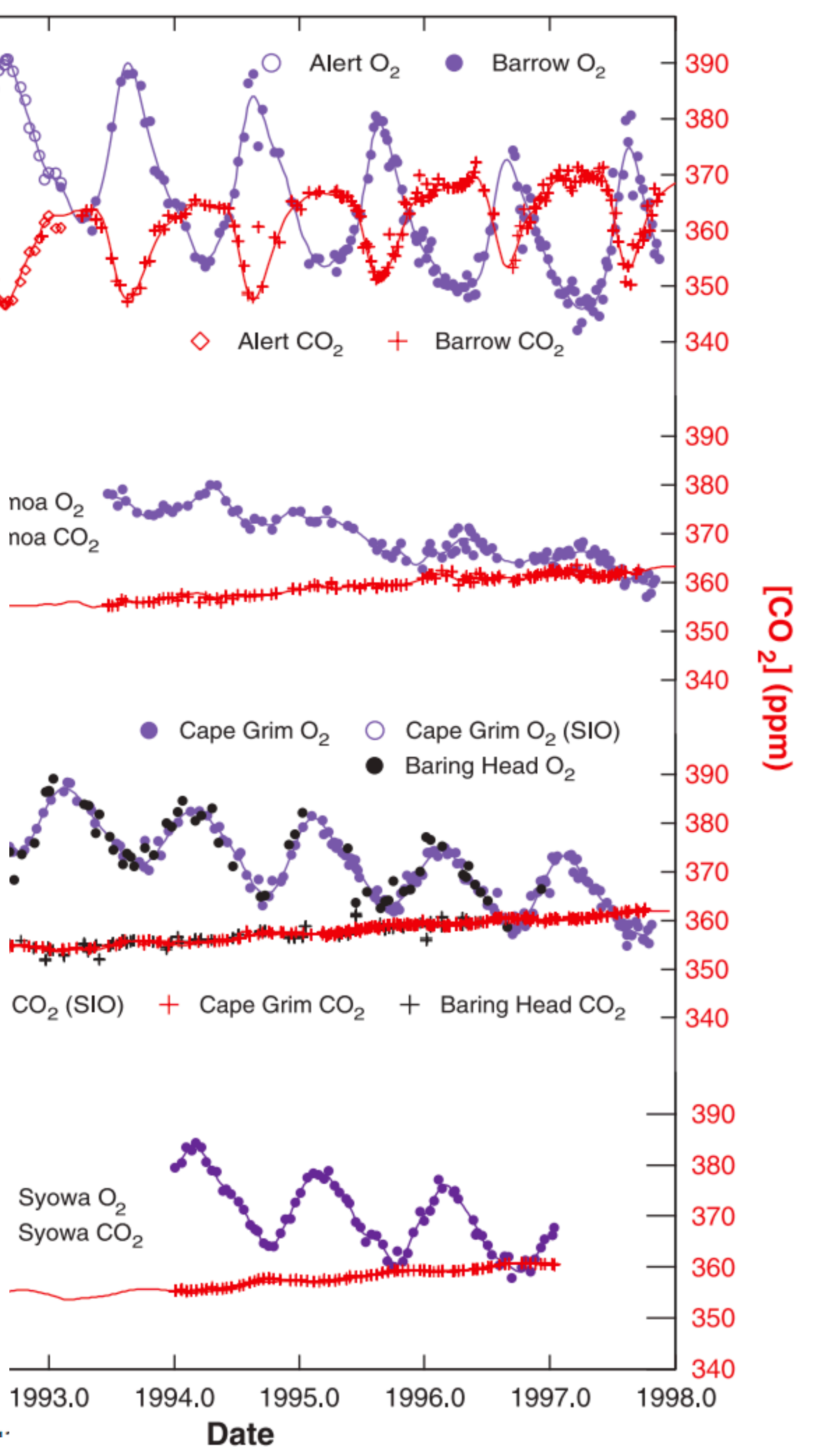


Trend expected from fossil-fuel burning
CO_2 Concentration (ppm)
400
390
380
370
360
350
340
330
320
310
1960
1970
1980
1990
2000
2010

Global Carbon Sinks a
Variability Inferre
Atmospheric O_2 an

M. Battle,[1]* M. L. Bender,[1] P. P. Tans,[2] J.
J. T. Ellis,[4] T. Conway,[2] R. J. Fra





Global carbon budget

The cumulative contributions to the global carbon budget from 1870

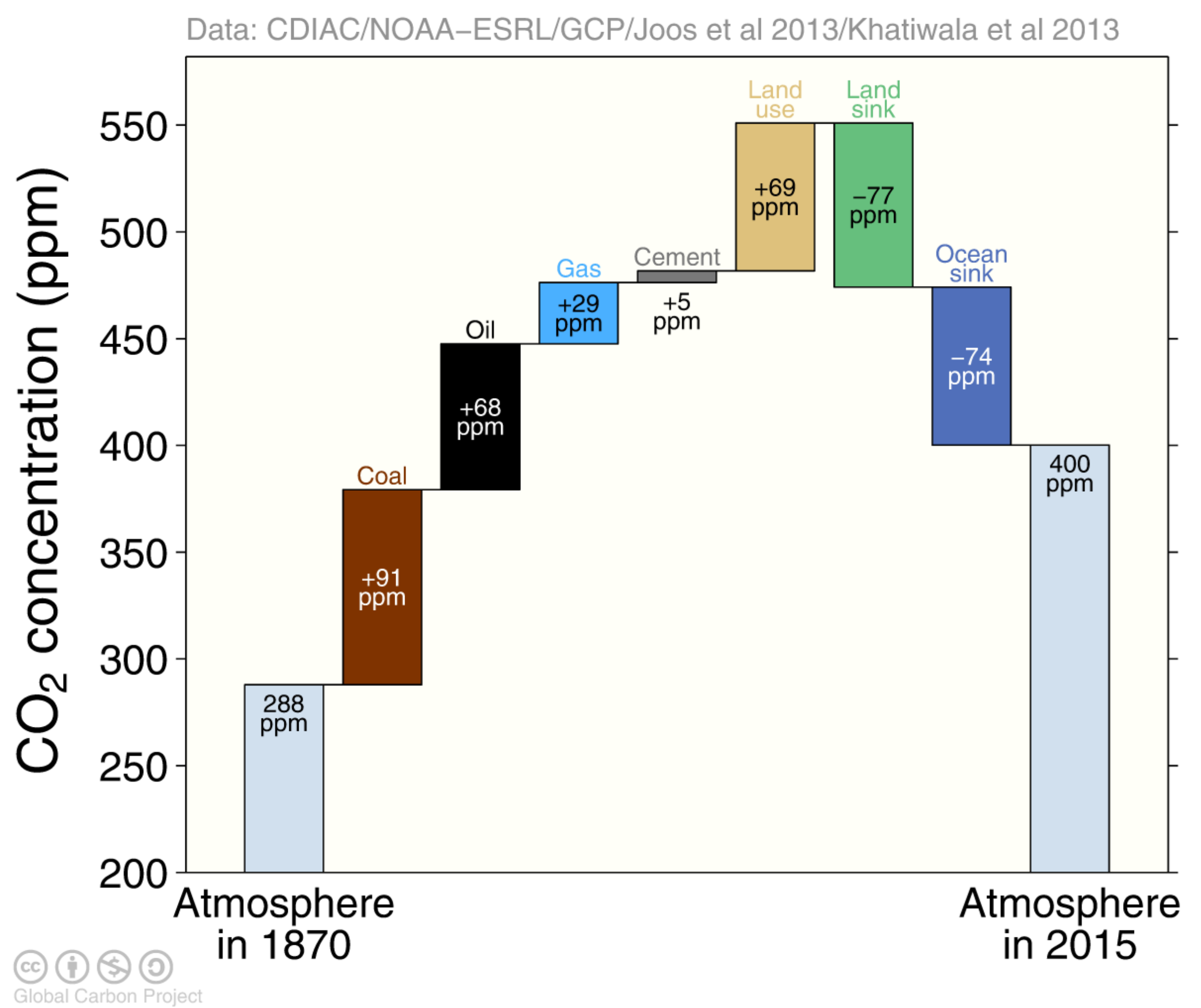
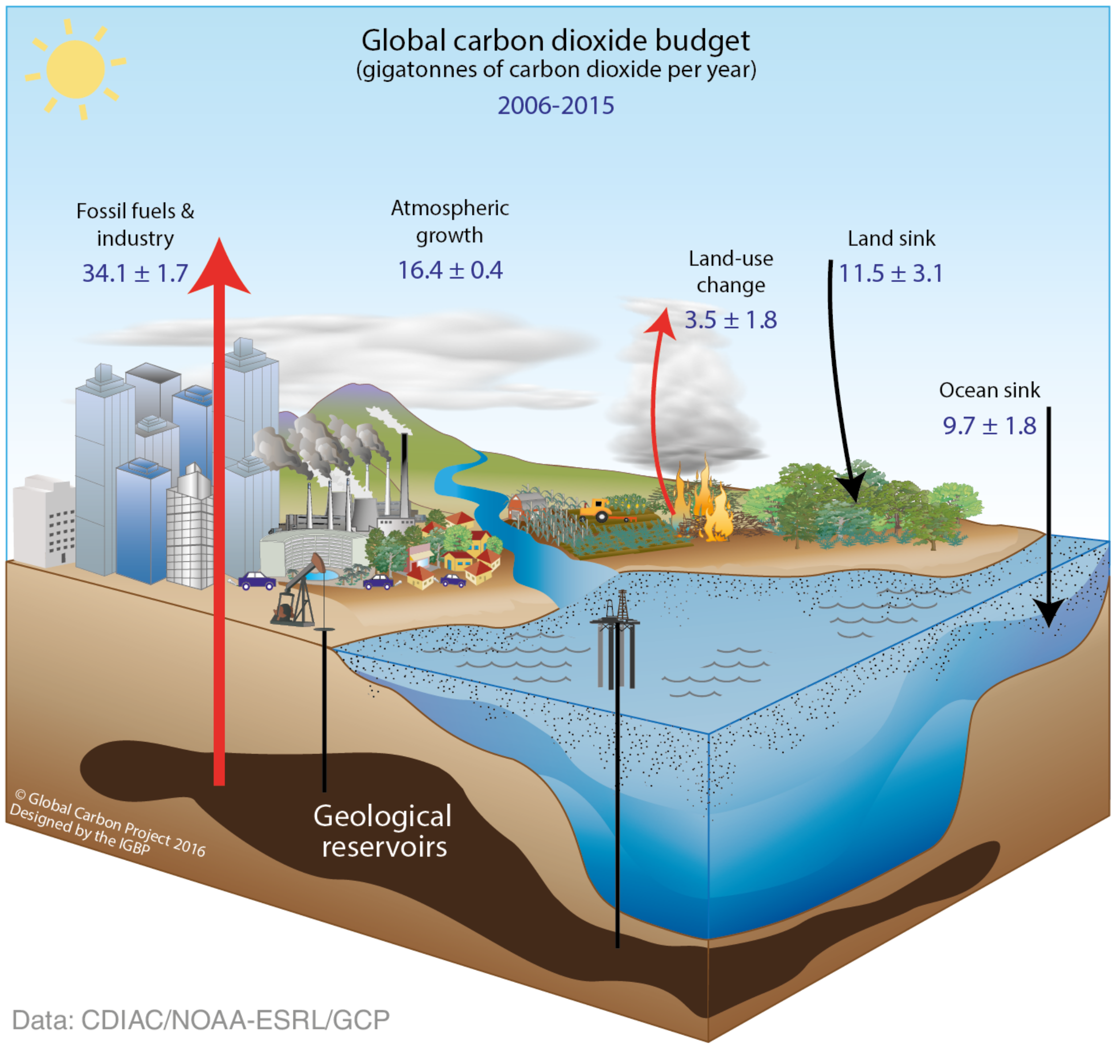


Figure concept from Shrink That Footprint

Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Joos et al 2013; Khatiwala et al 2013; Le Quéré et al 2016; Global Carbon Budget 2016

Anthropogenic perturbation of the global carbon cycle

Perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2006–2015 ($GtCO_2$/yr)



Data: CDIAC/NOAA-ESRL/GCP

Source: CDIAC; NOAA-ESRL; Le Quéré et al 2016; Global Carbon Budget 2016

Fate of anthropogenic CO_2 emissions (2006-2015)

34.1 $GtCO_2/yr$

91%

9%

3.5 $GtCO_2/yr$

Sources = Sinks

16.4 $GtCO_2/yr$

44%

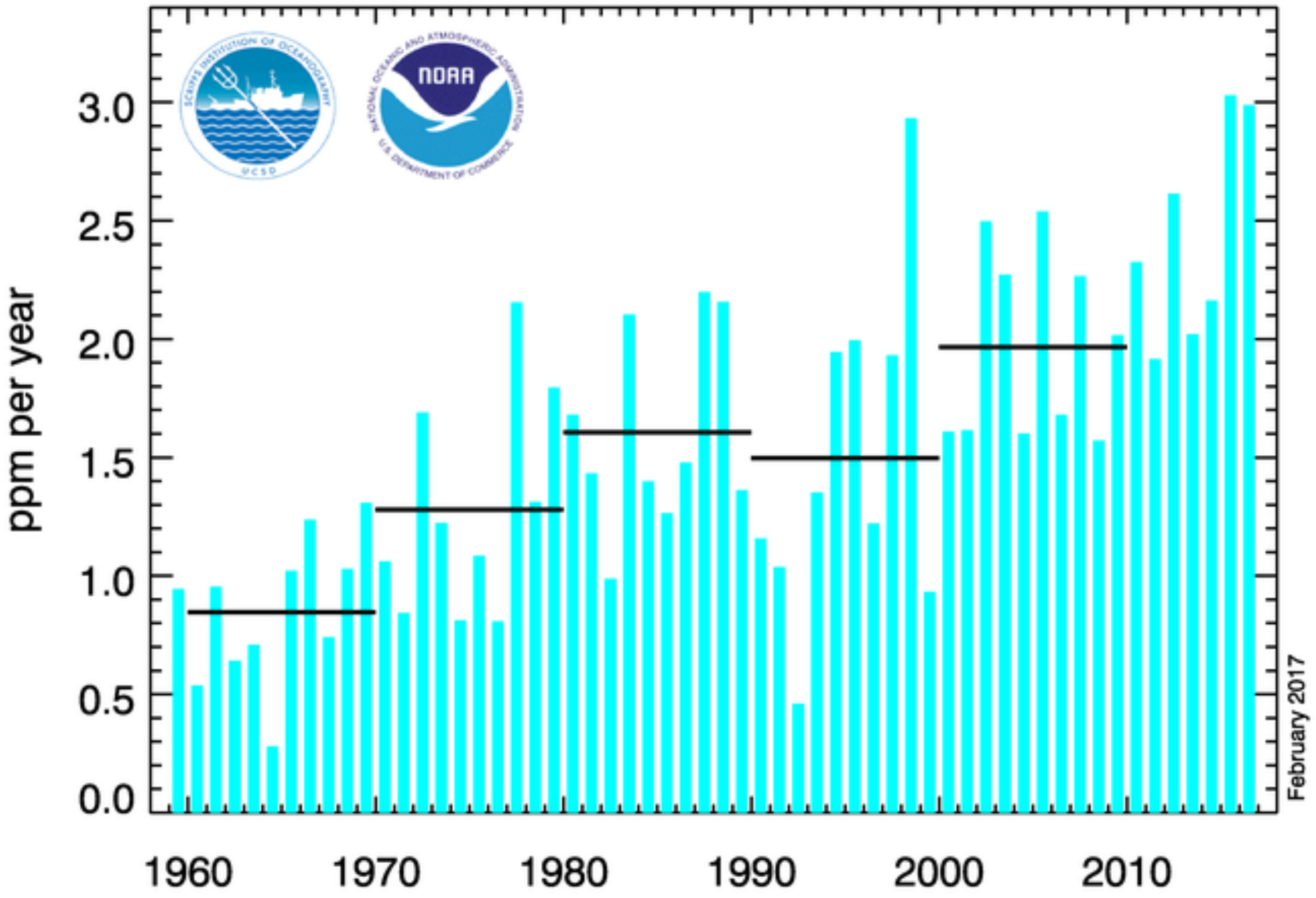
31%

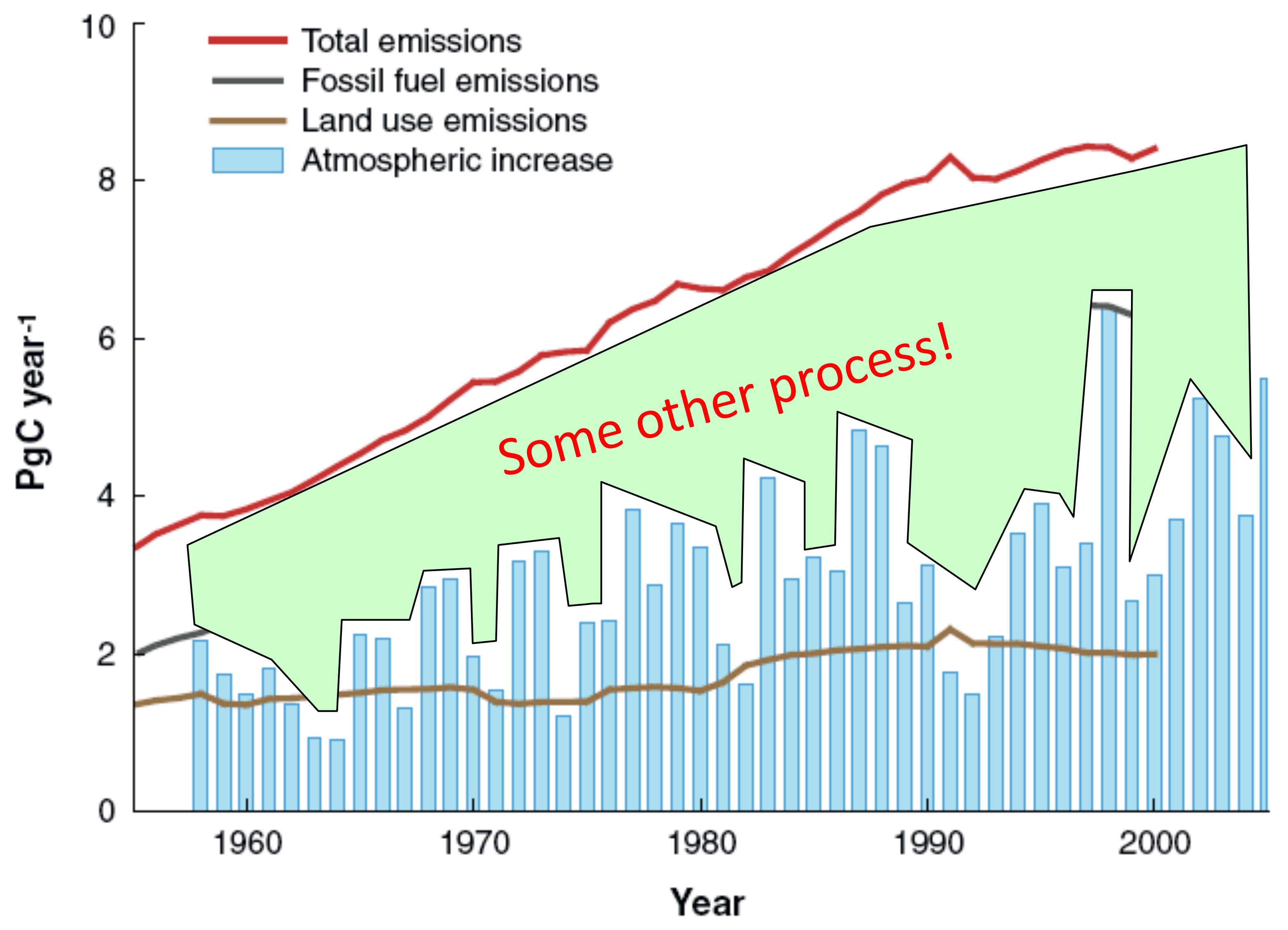
11.6 $GtCO_2/yr$

26%

9.7 $GtCO_2/yr$

Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Le Quéré et al 2016; Global Carbon Budget 2016 annual mean growth rate of CO_2 at Mauna Loa

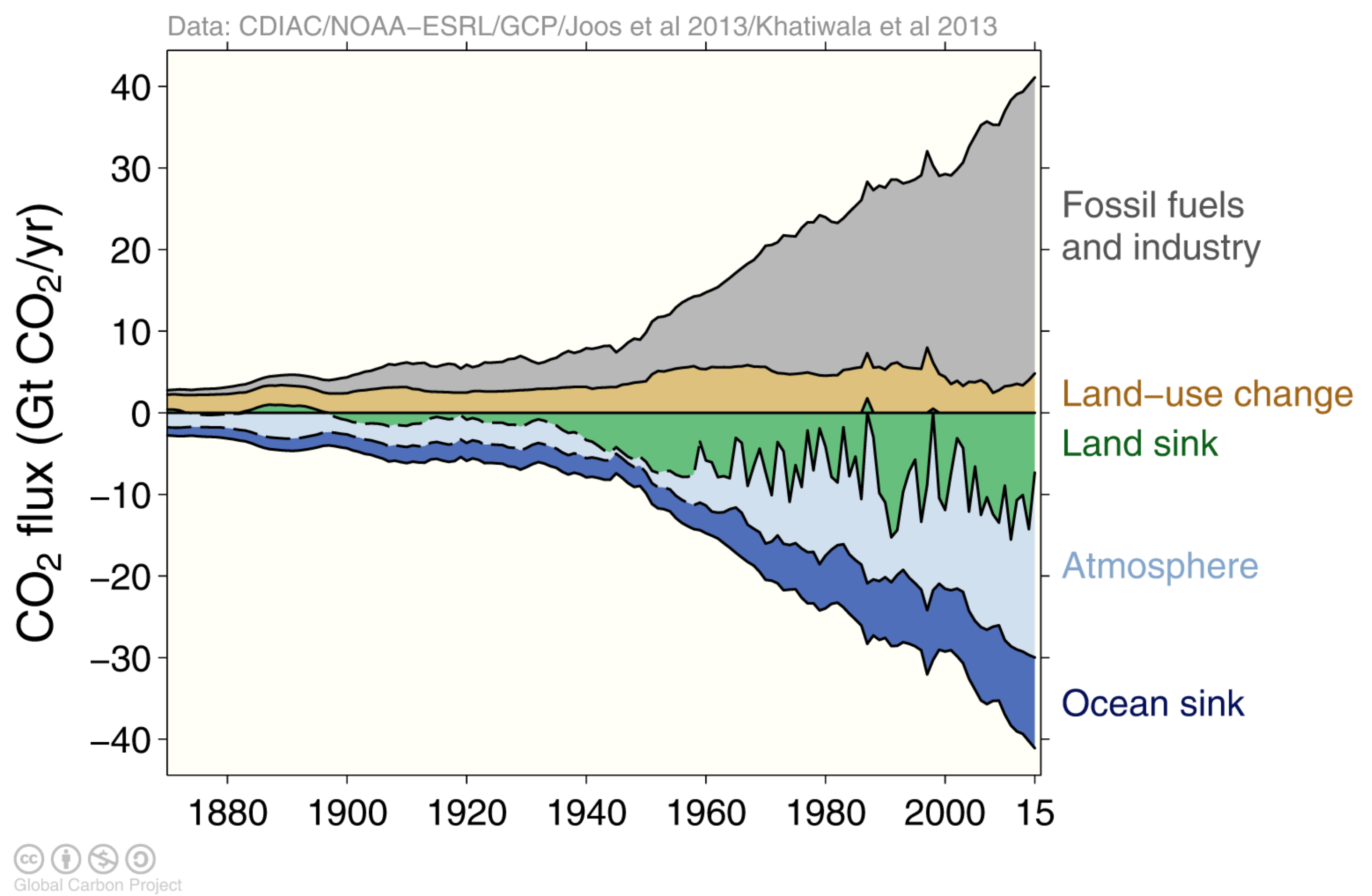




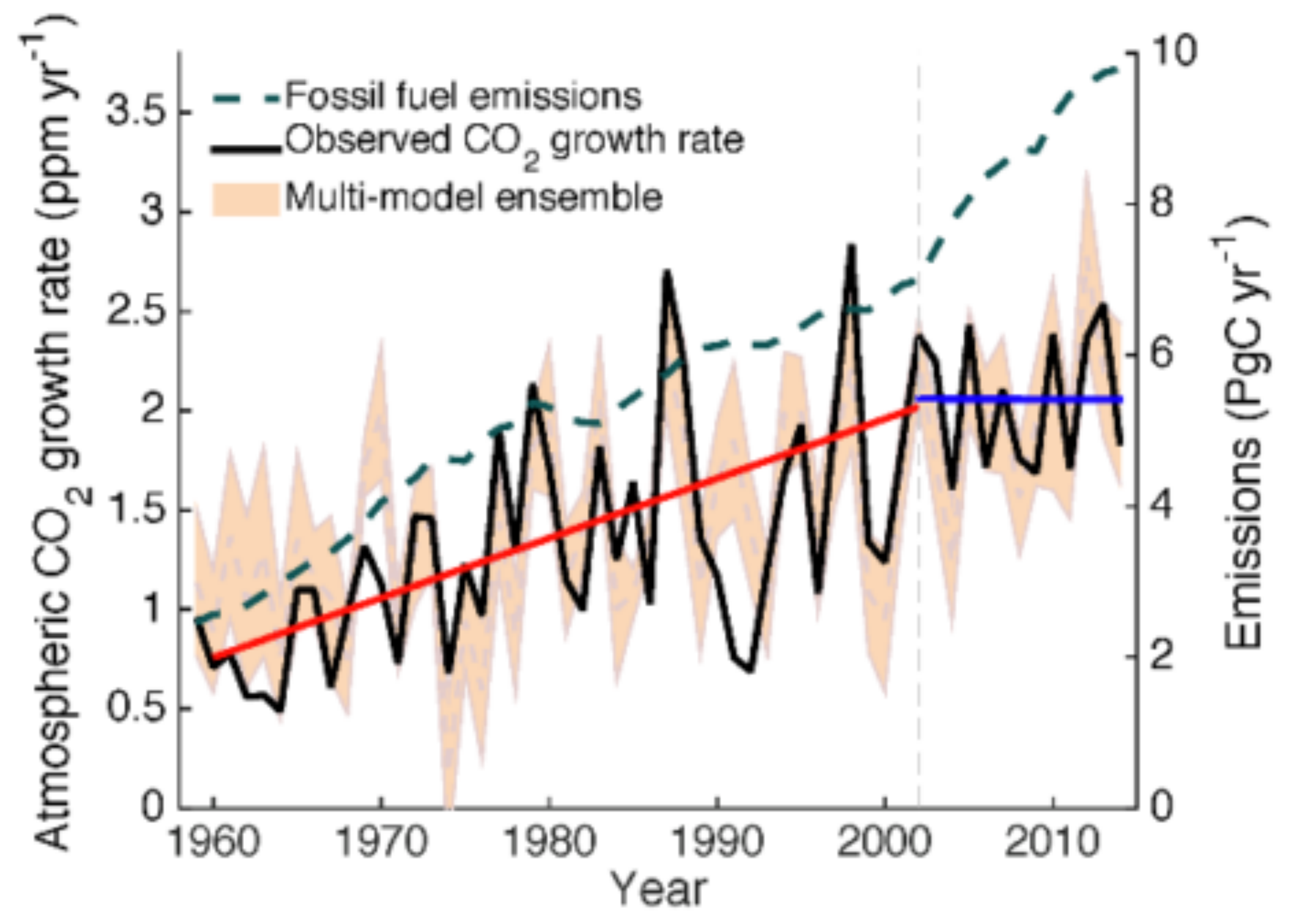
Houghton et al. (2007)

Global carbon budget

The carbon sources from fossil fuels, industry, and land use change emissions are balanced by the atmosphere and carbon sinks on land and in the ocean

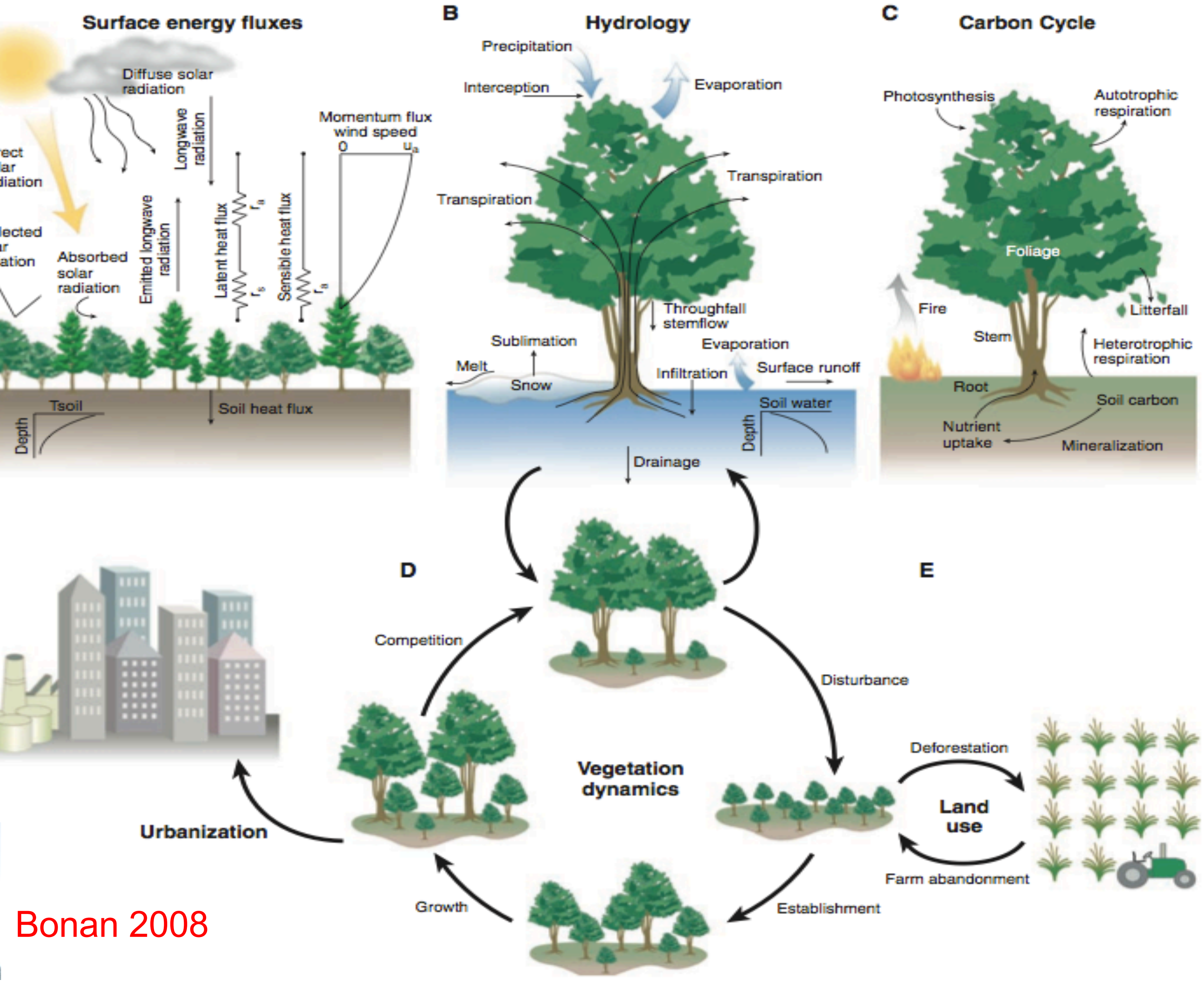


Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Joos et al 2013; Khatiwala et al 2013; Le Quéré et al 2016; Global Carbon Budget 2016

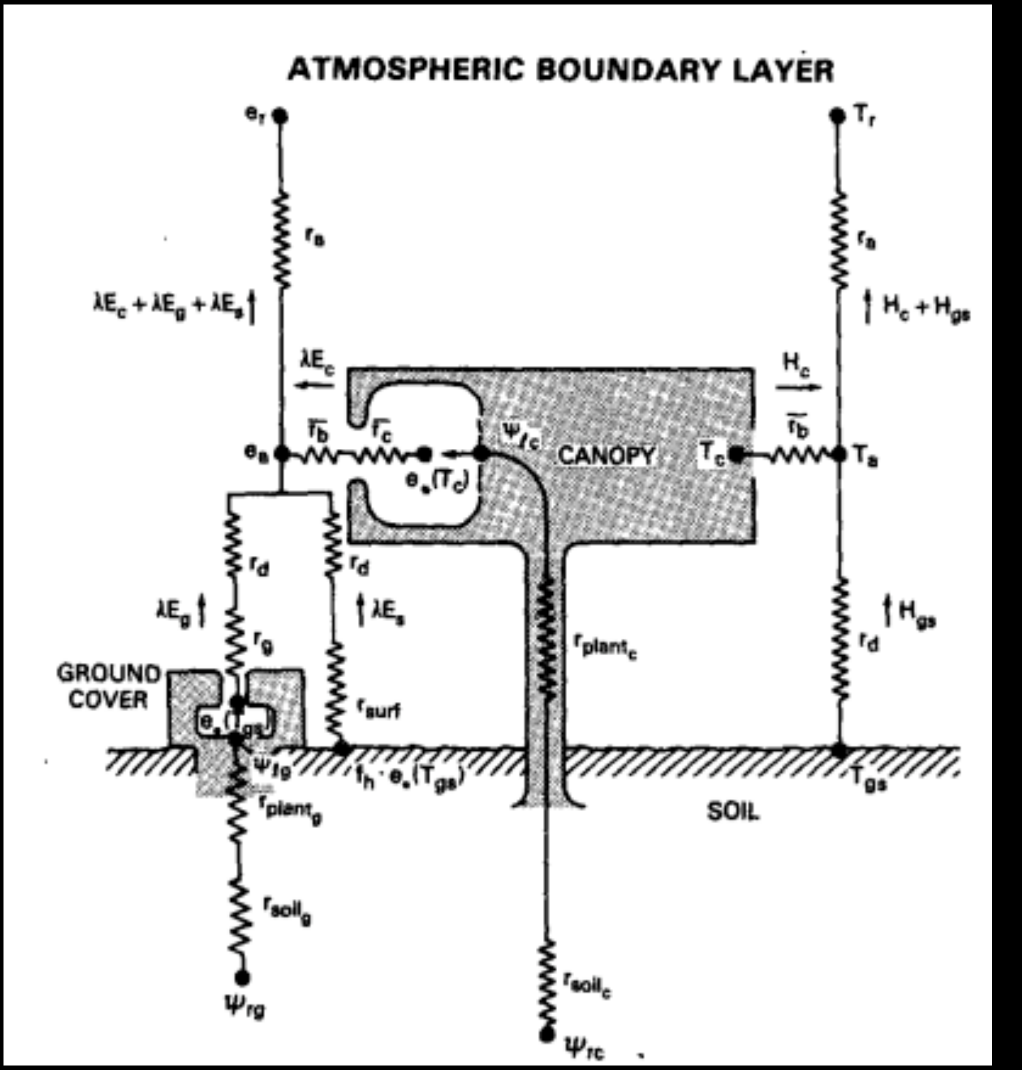


Keenan et al 2016

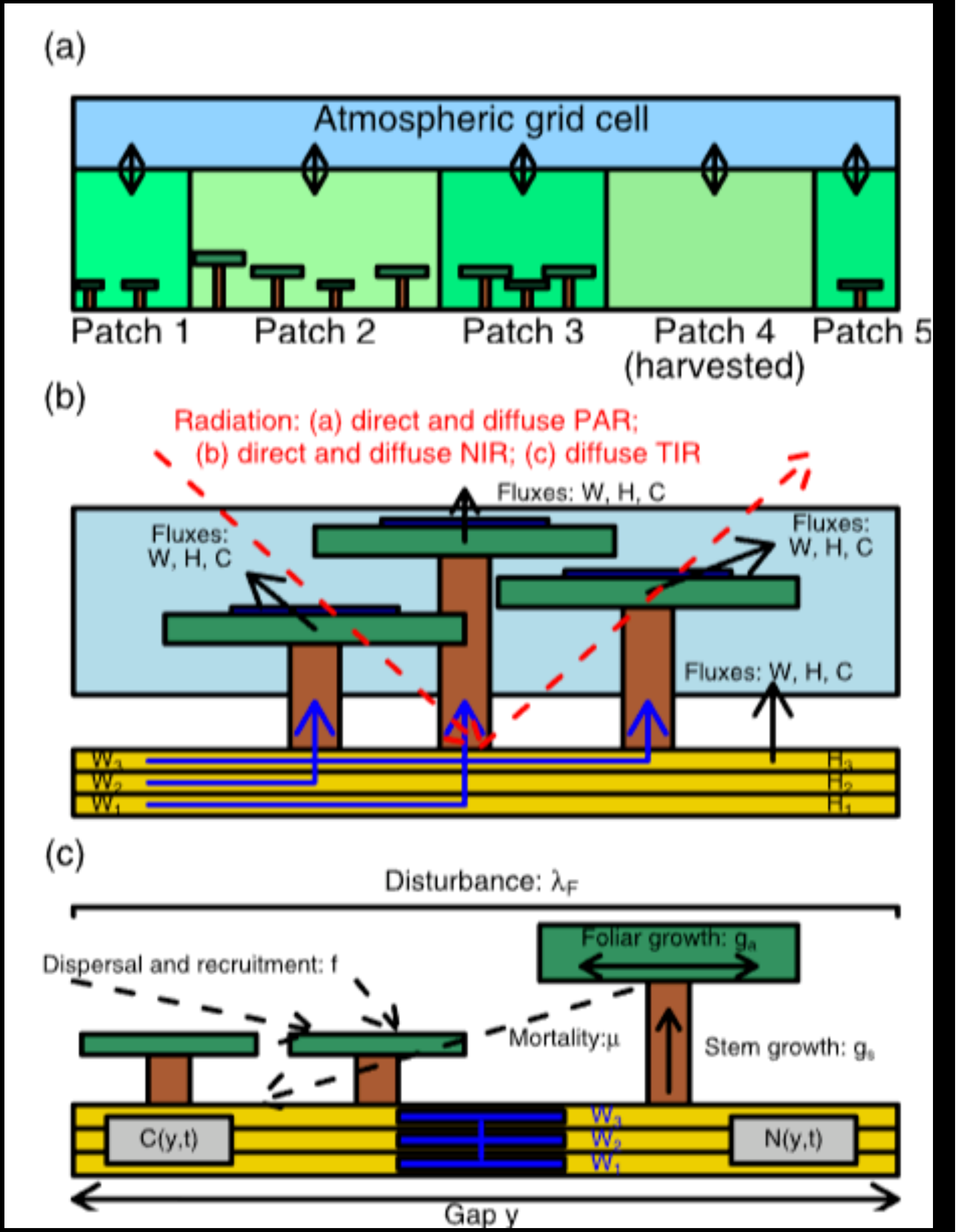
Forests in Flux



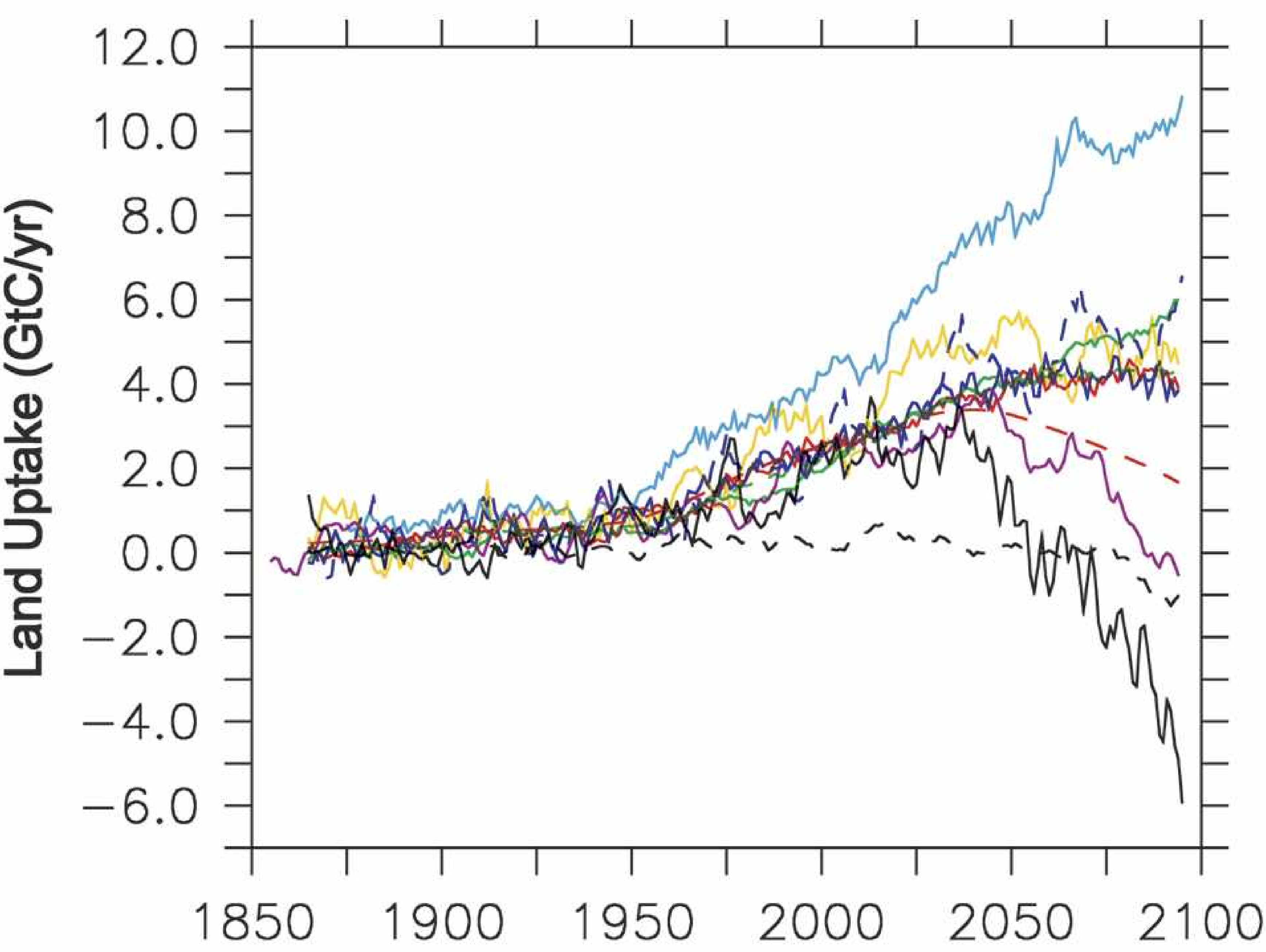
Bonan 2008



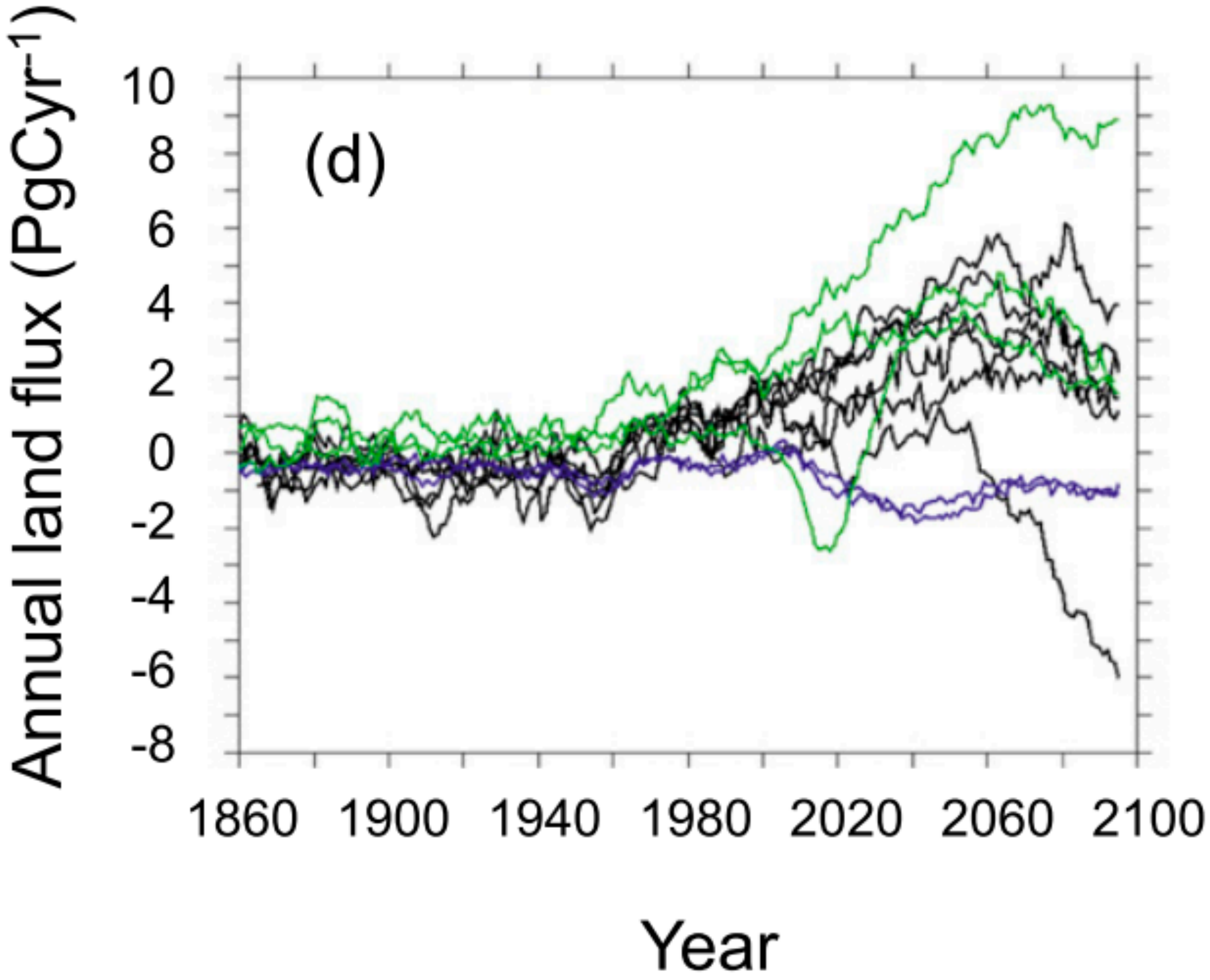
Sellers 1986



Medvigy 2009



Friedlingstein et al., 2006



Freidlingstein et al, 2014

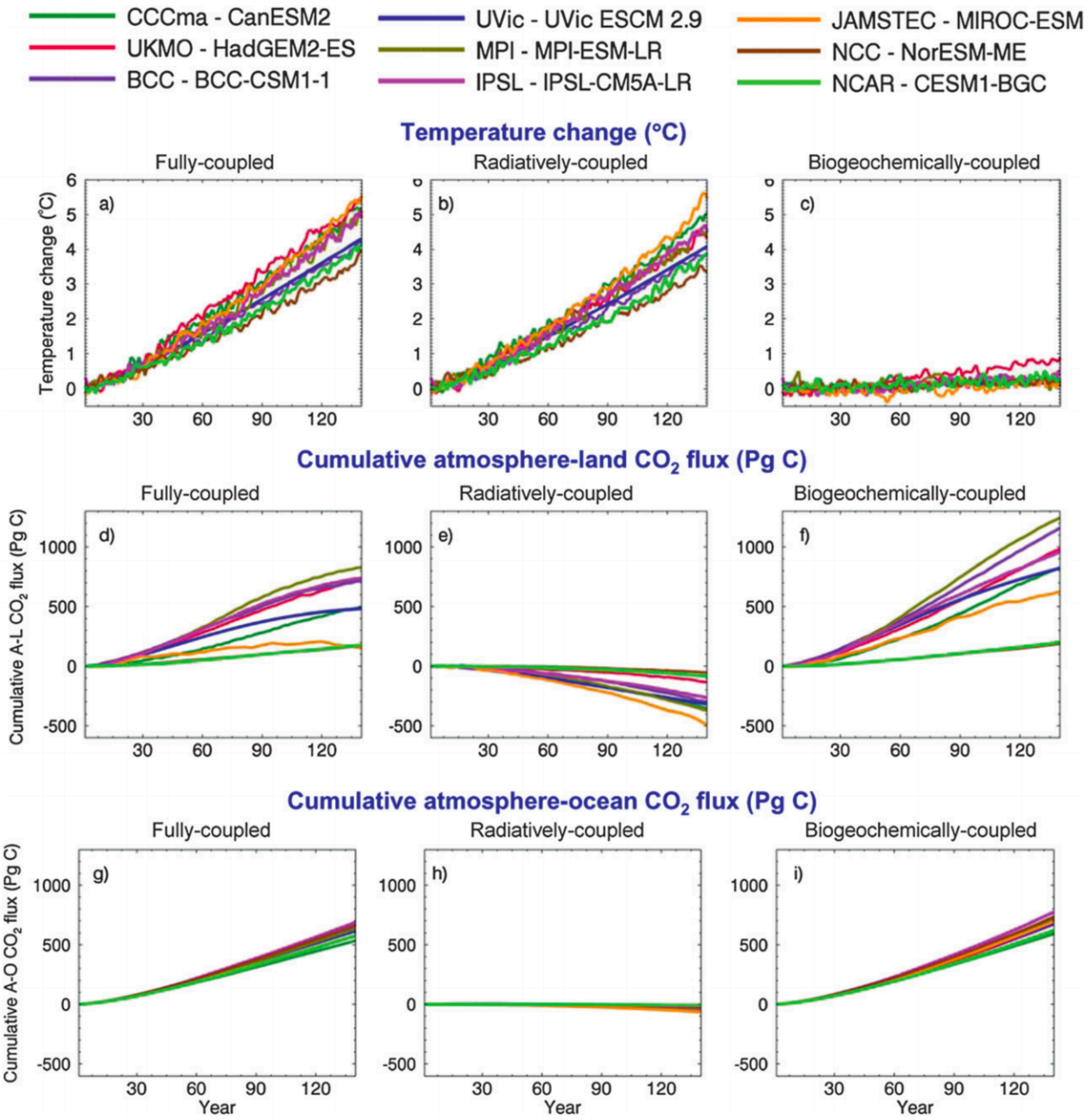
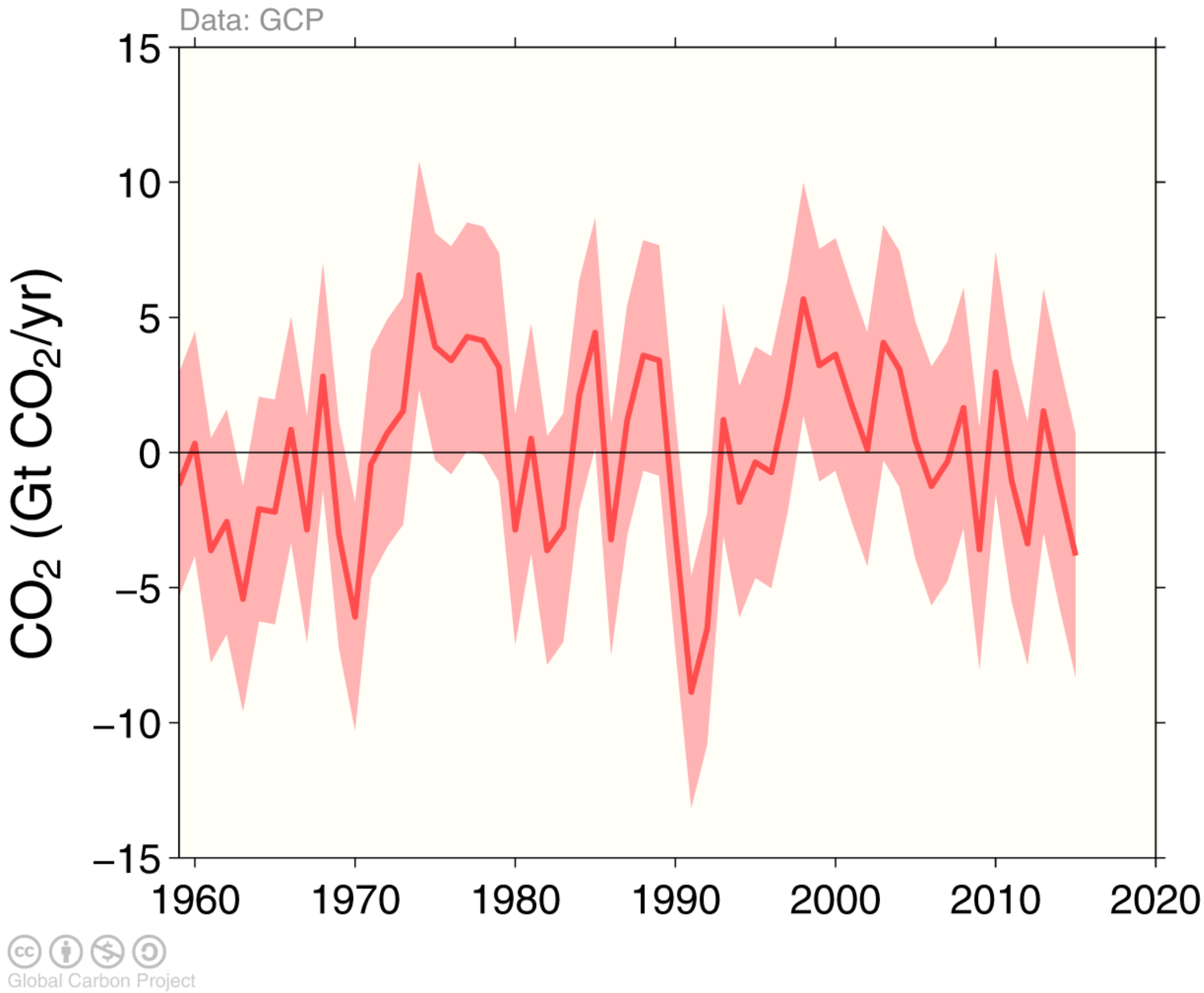


FIG. 2. (a)–(c) Simulated temperature change, (d)–(f) cumulative atmosphere–land CO_2 flux, and (g)–(i) cumulative atmosphere–ocean CO_2 flux from the fully, radiatively, and biogeochemically coupled 1% CO_2 increase simulations for the nine participating models. Note that in (d)–(f) the lines corresponding to the NorESM-ME and CESM1-BGC models essentially overlay each other.

Remaining uncertainty in the global carbon balance

Large uncertainties in the global carbon balance remain
and hinder independent verification of reported CO_2 emissions

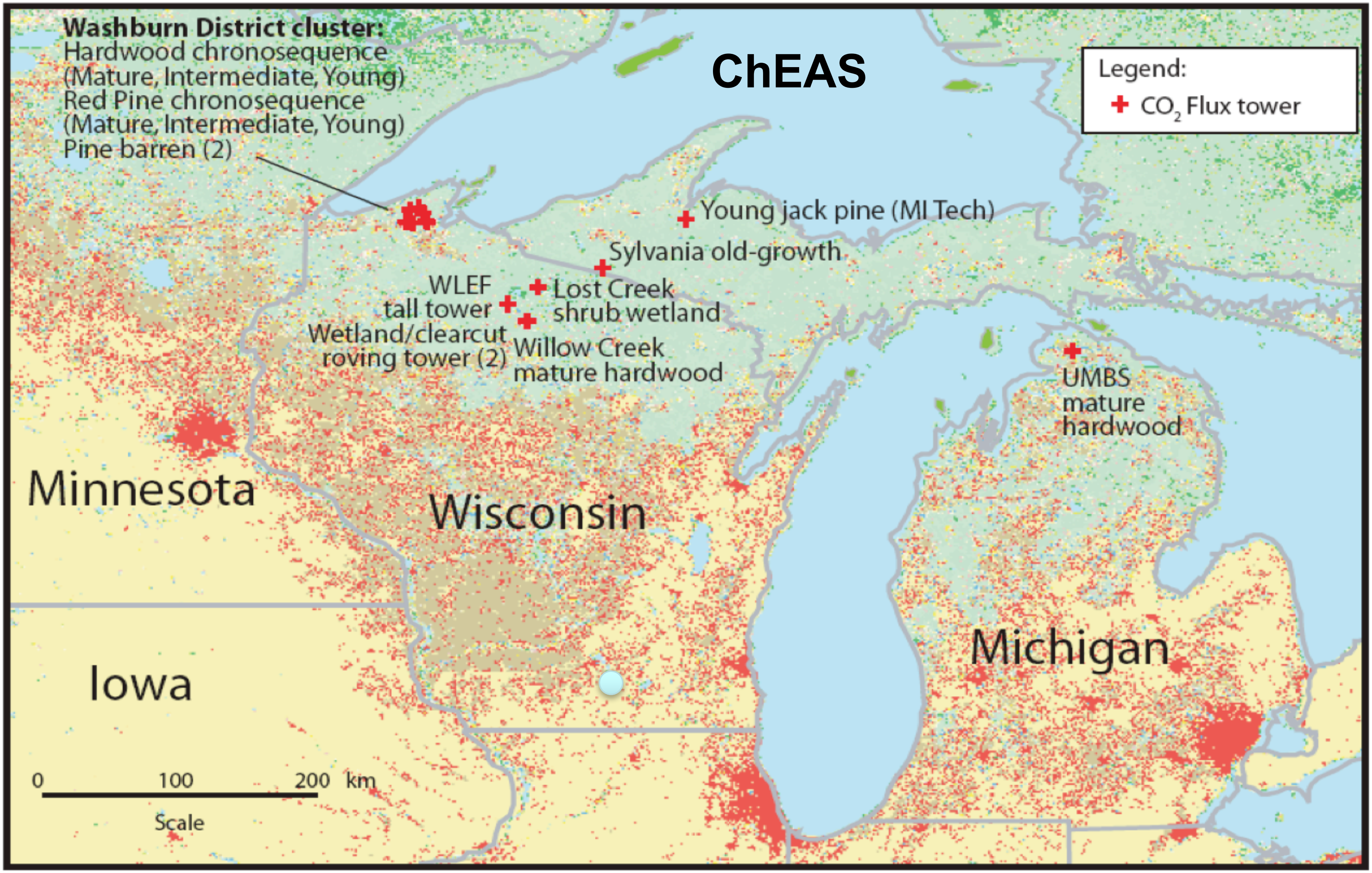


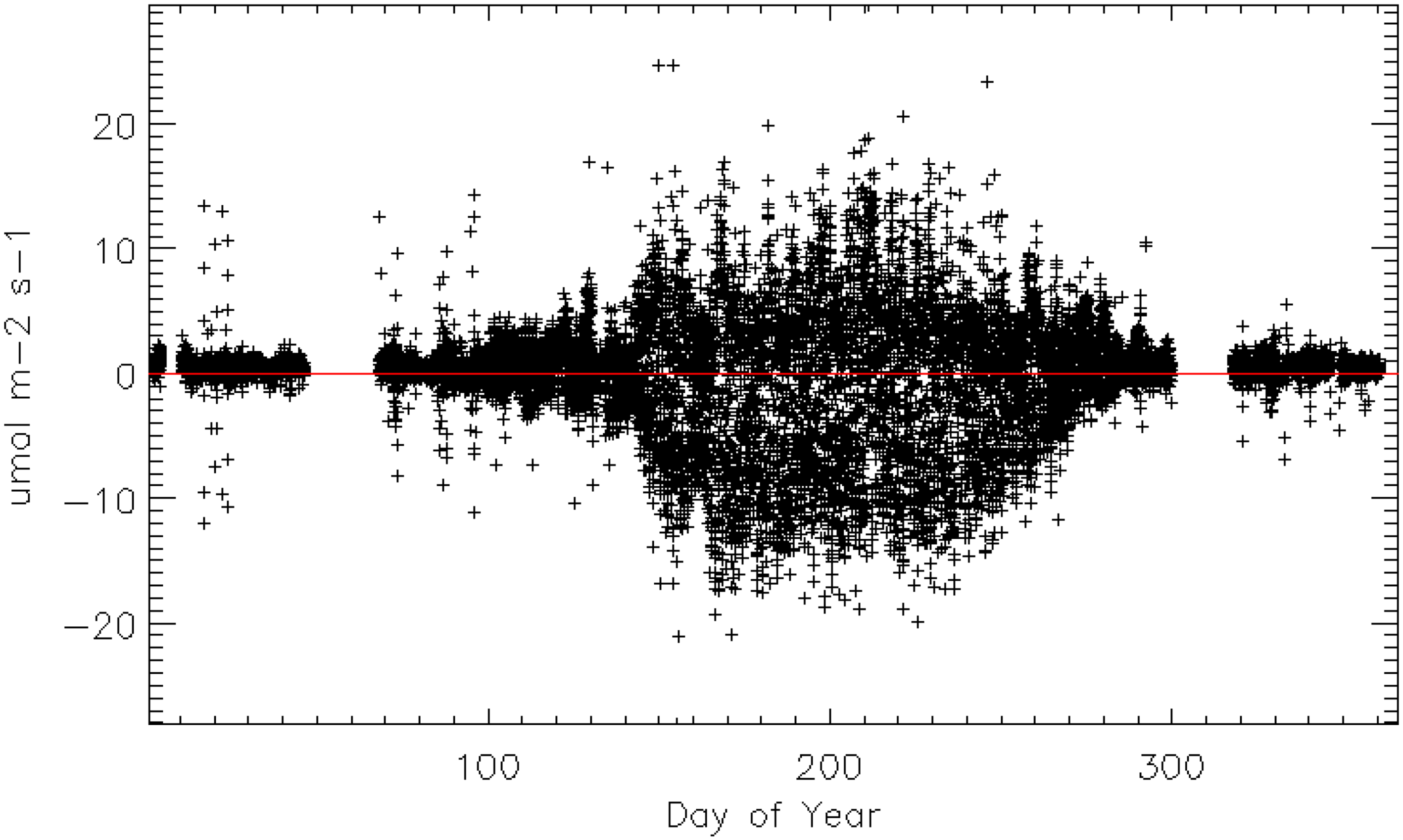
The remaining uncertainty is the carbon left after adding independent estimates for total emissions, the atmospheric growth rate, and model-based estimates for the land and ocean carbon sinks
Source: Le Quéré et al 2016; Global Carbon Budget 2016

30 hours

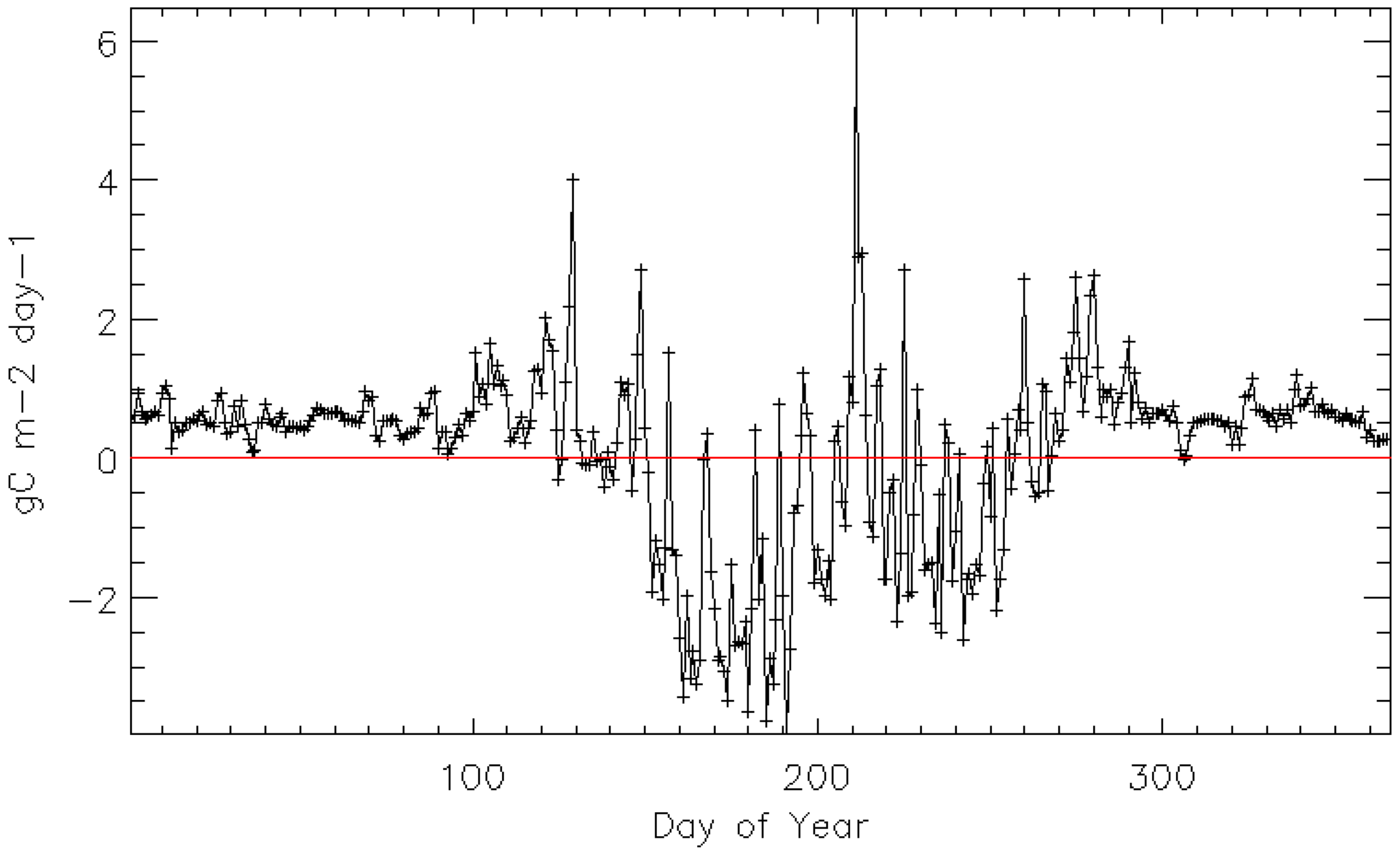
1980s 1990s 1995s 2000s 2010s

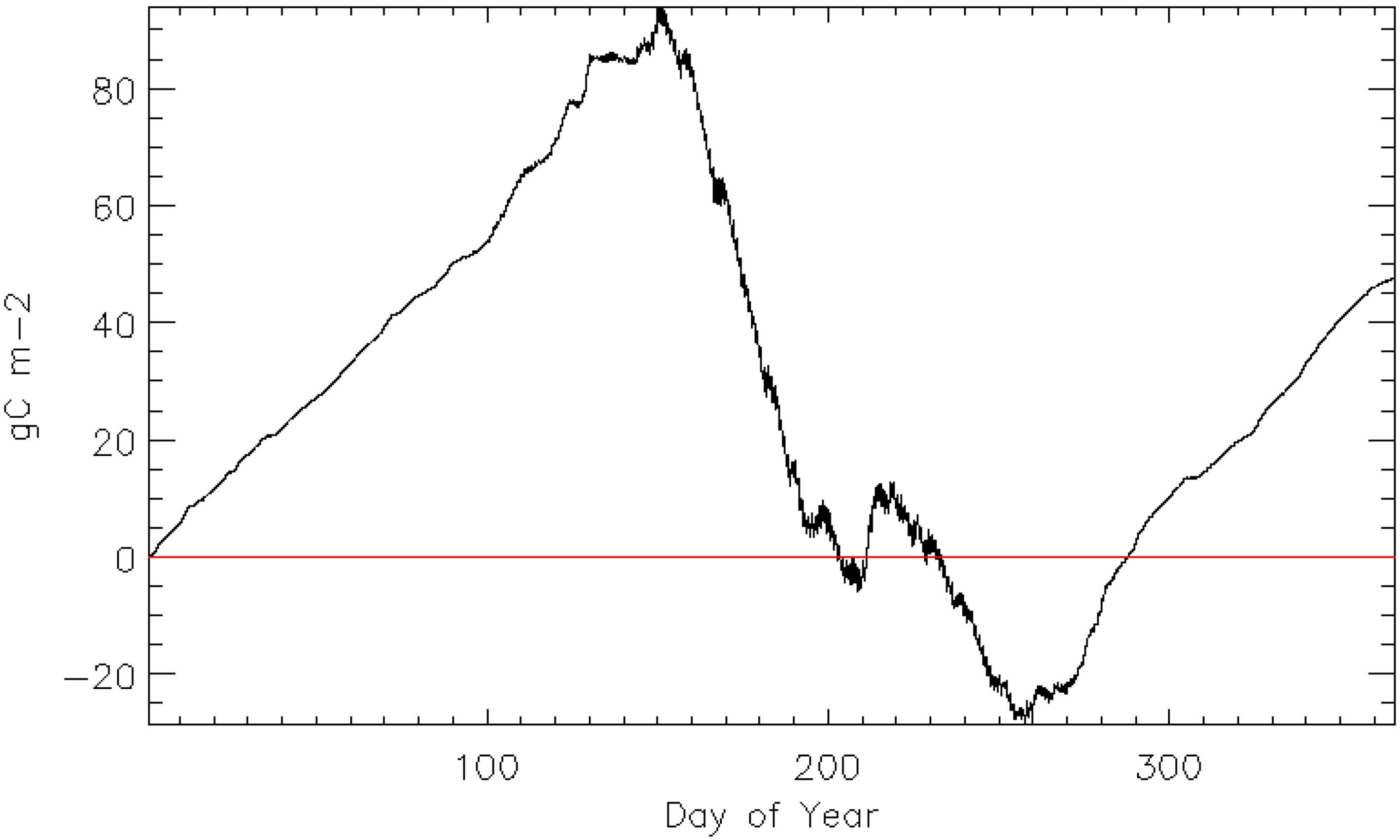
ChEAS

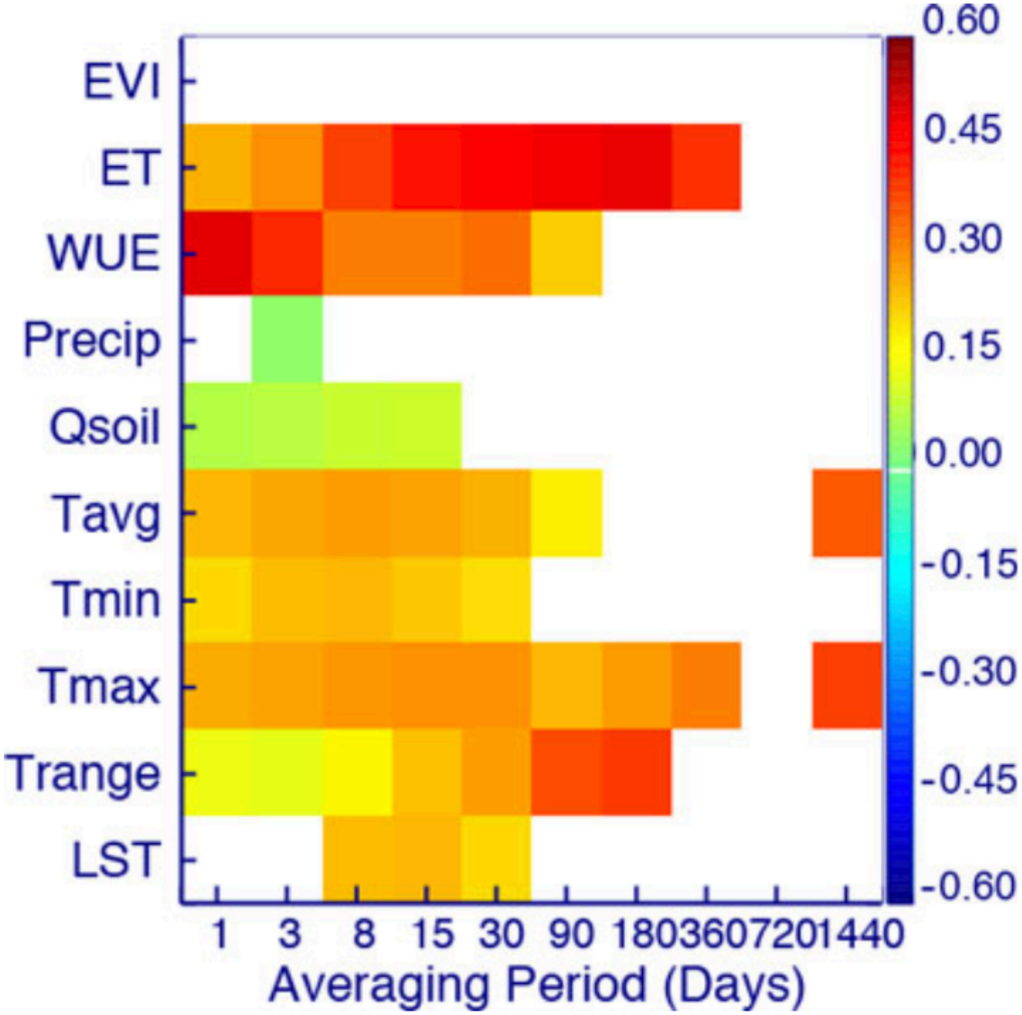

Washburn District cluster:
Hardwood chronosequence
(Mature, Intermediate, Young)
Red Pine chronosequence
(Mature, Intermediate, Young)
Pine barren (2)
Legend:
✚ CO_2 Flux tower
Young jack pine (MI Tech)
Sylvania old-growth
WLEF
tall tower
Lost Creek
shrub wetland
Wetland/clearcut
roving tower (2)
Willow Creek
mature hardwood
UMBS
mature
hardwood
Minnesota
Wisconsin
Michigan
Iowa
0
100
200
km
Scale

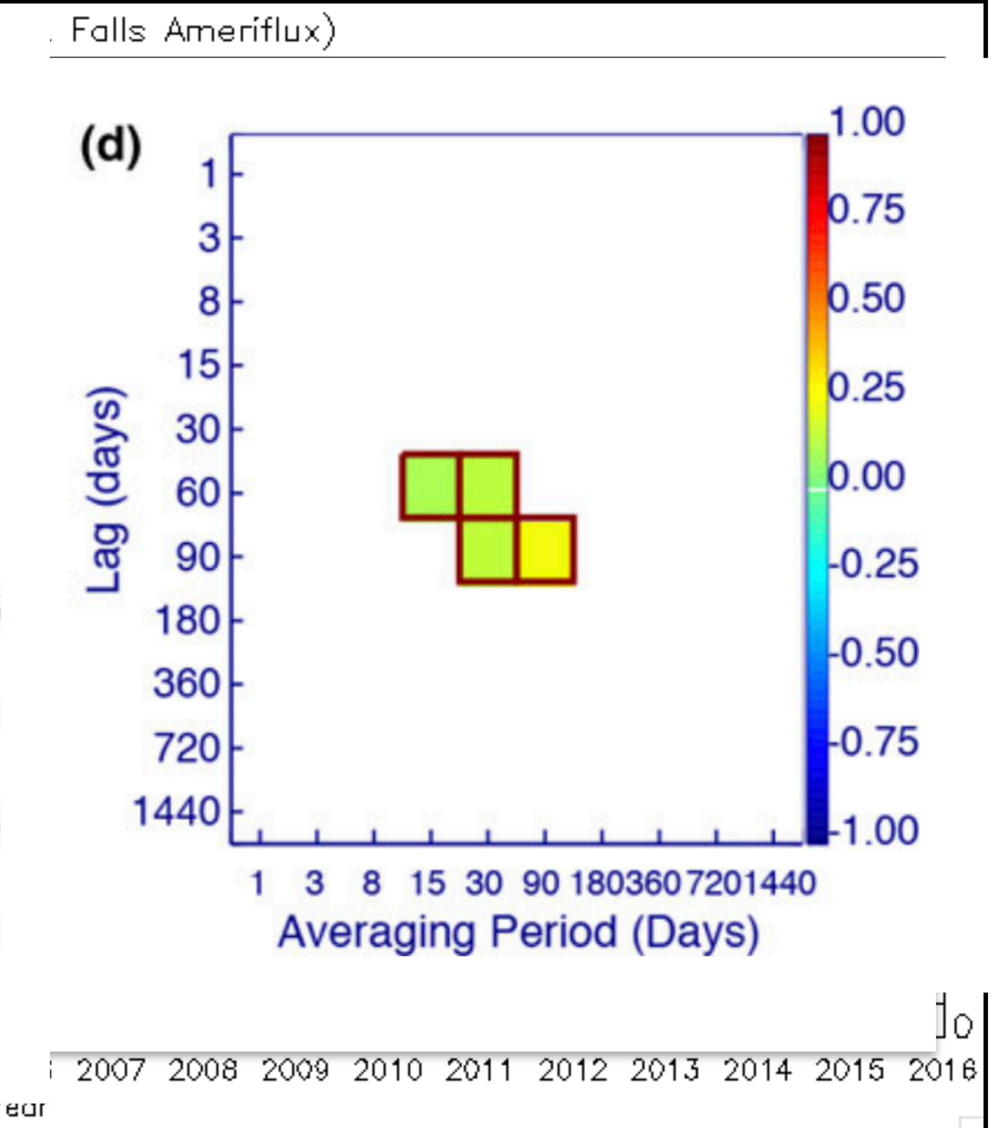


20
10
0
−10
−20
umol m−2 s−1
100
200
300
Day of Year

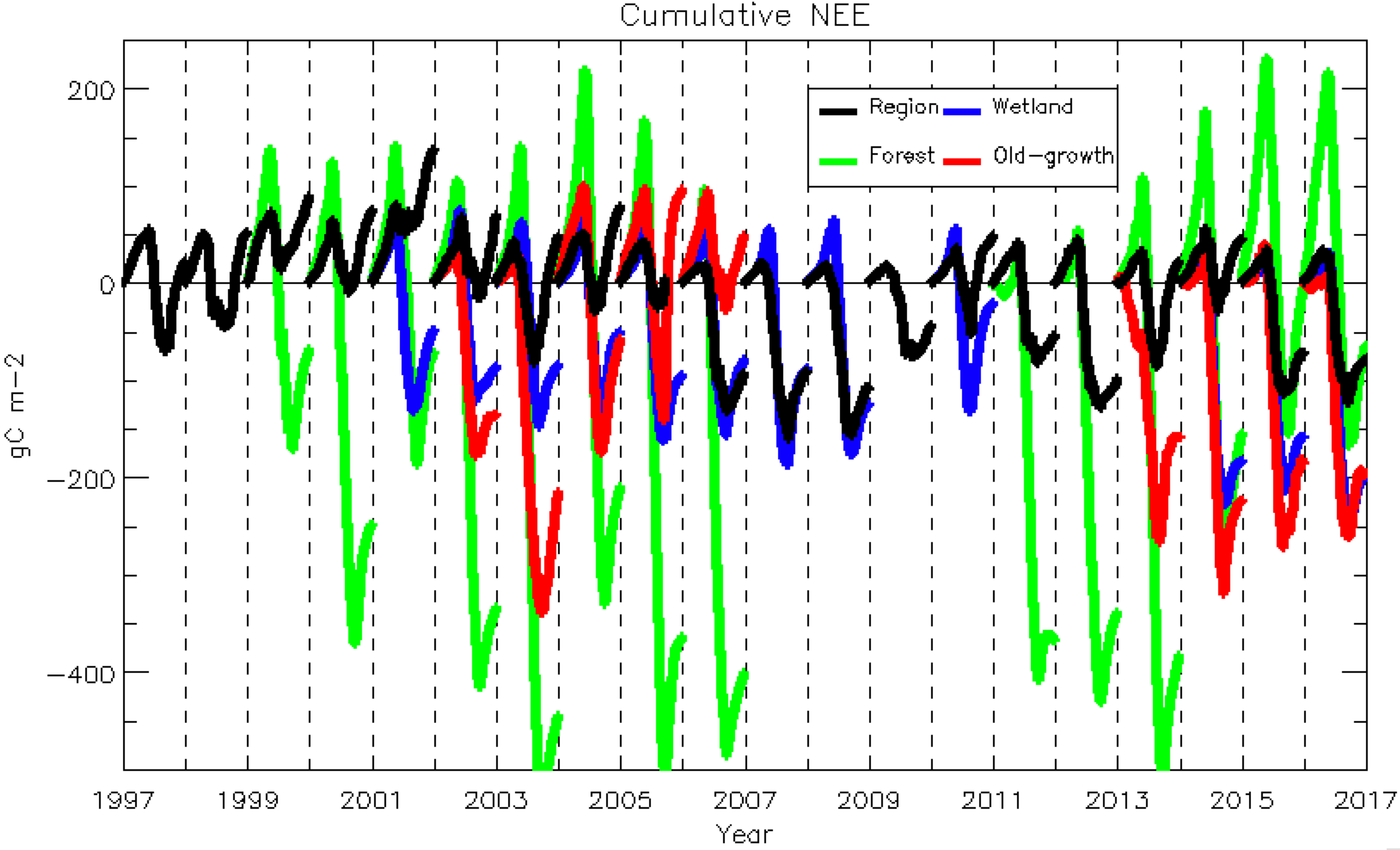

gC m−2 day−1
6
4
2
0
−2
100
200
300
Day of Year

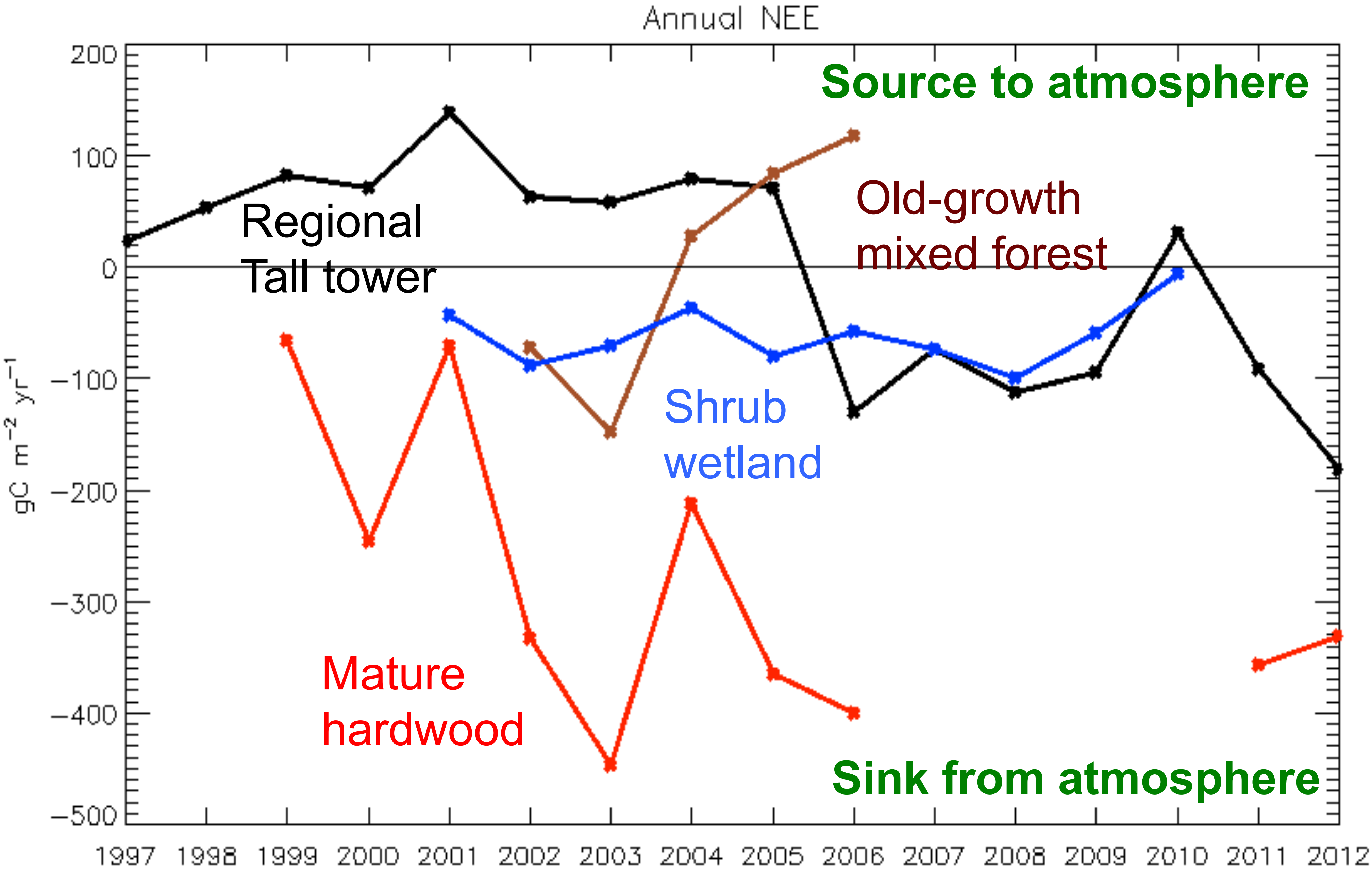

gC m−2
80
60
40
20
0
−20
100
200
300
Day of Year





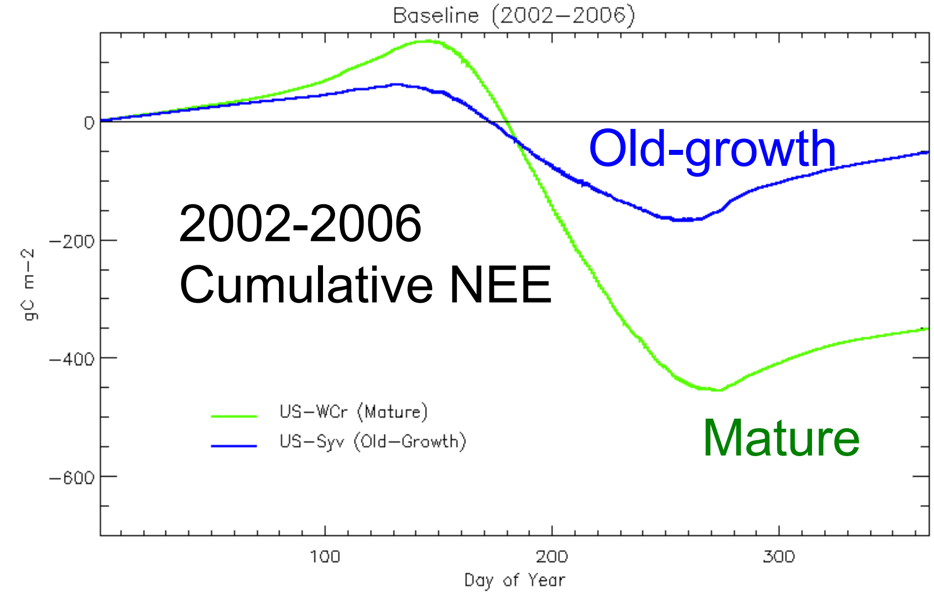
Desai, Photosynthesis Research, 2014

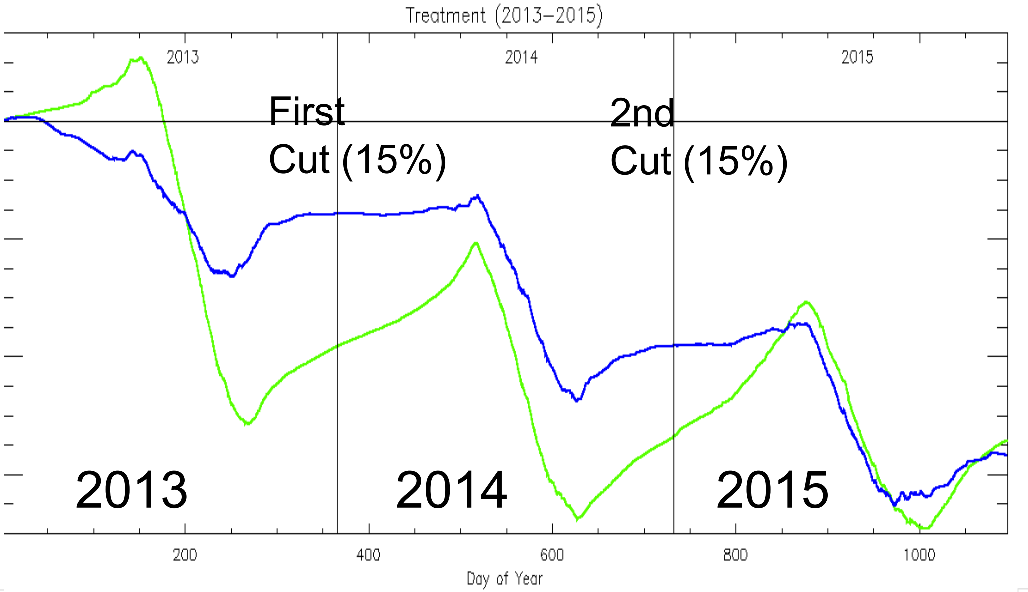

Cumulative NEE
Region
Wetland
Forest
Old−growth
200
0
−200
−400
gC m−2
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
Year

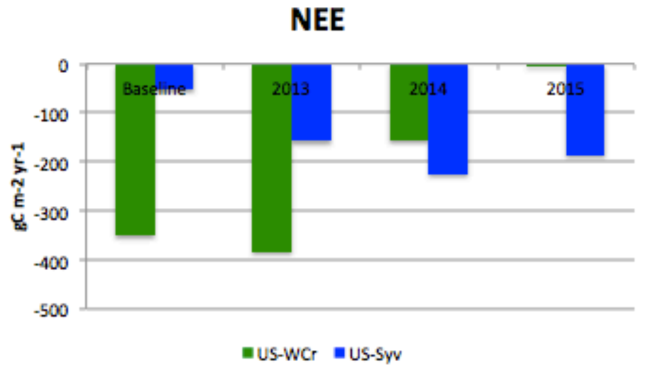

Annual NEE
200
100
0
−100
−200
−300
−400
−500
gC m^{-2} yr^{-1}
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Source to atmosphere
Regional Tall tower
Old-growth mixed forest
Shrub wetland
Mature hardwood
Sink from atmosphere

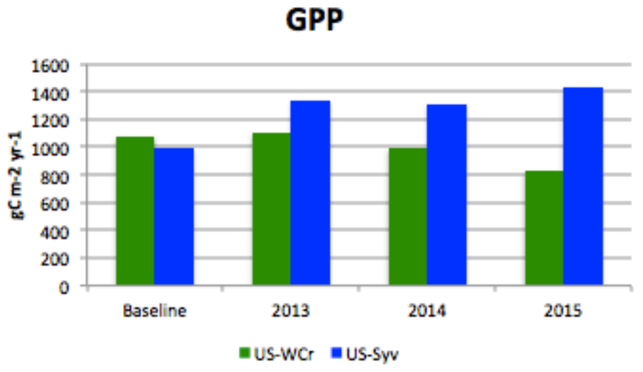
MANAGEMENT > CLIMATE => Models need to focus on harvest beyond clear-cutting

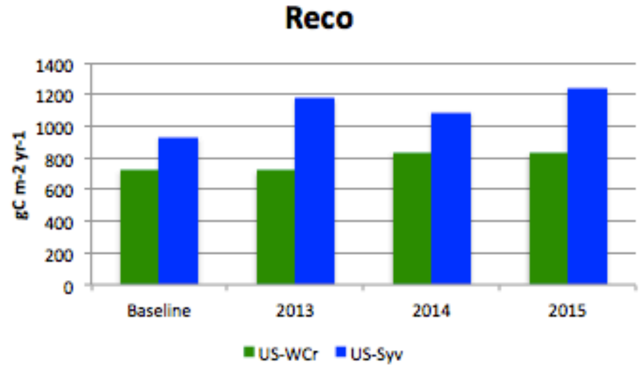
A 30% thinning leads to 15% GPP drop and 15% R_{eco} rise at a Midwestern forest (US-WCr), making productive hardwoods act more like old-growth (US-Syv), for first two years

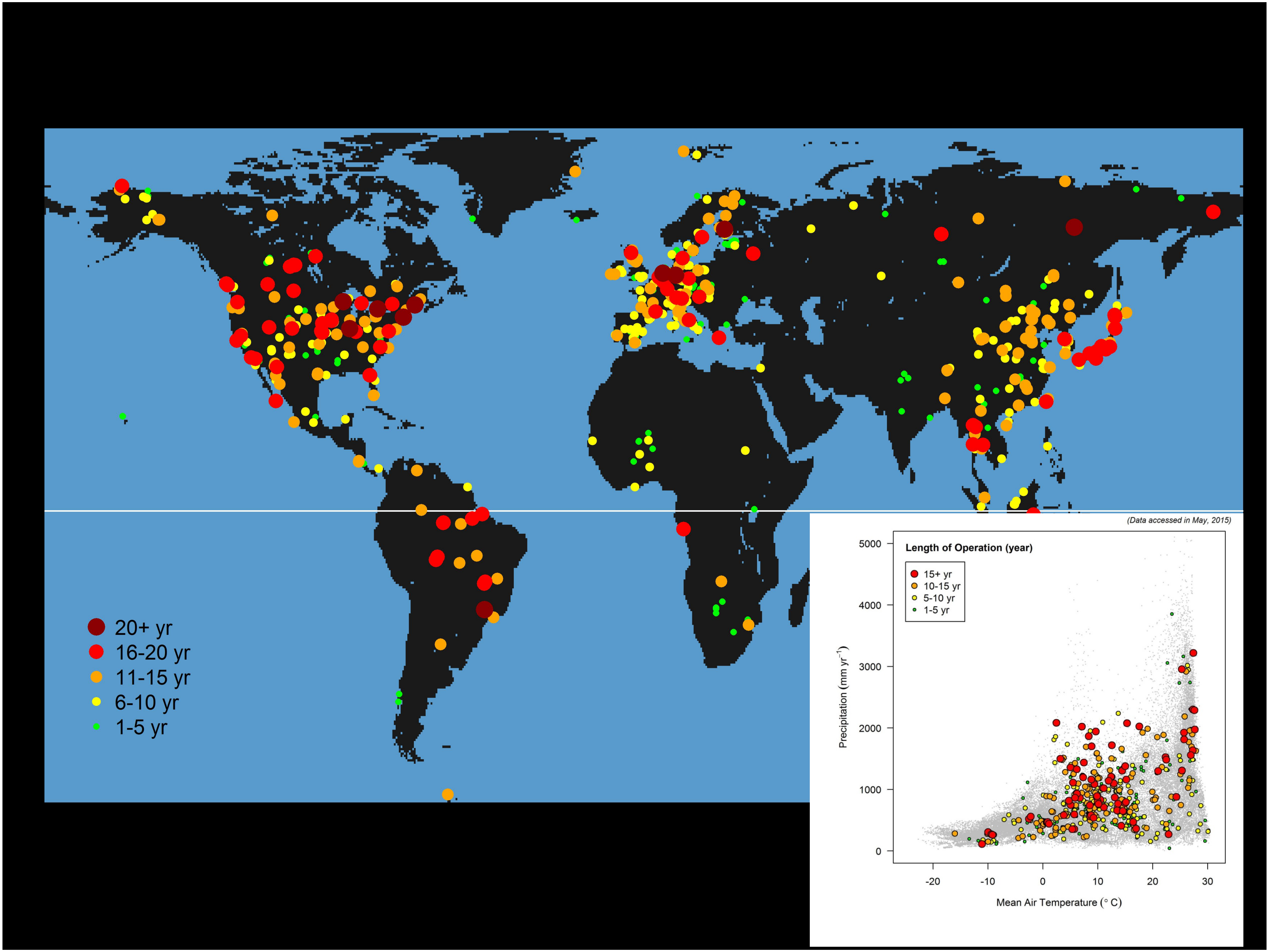






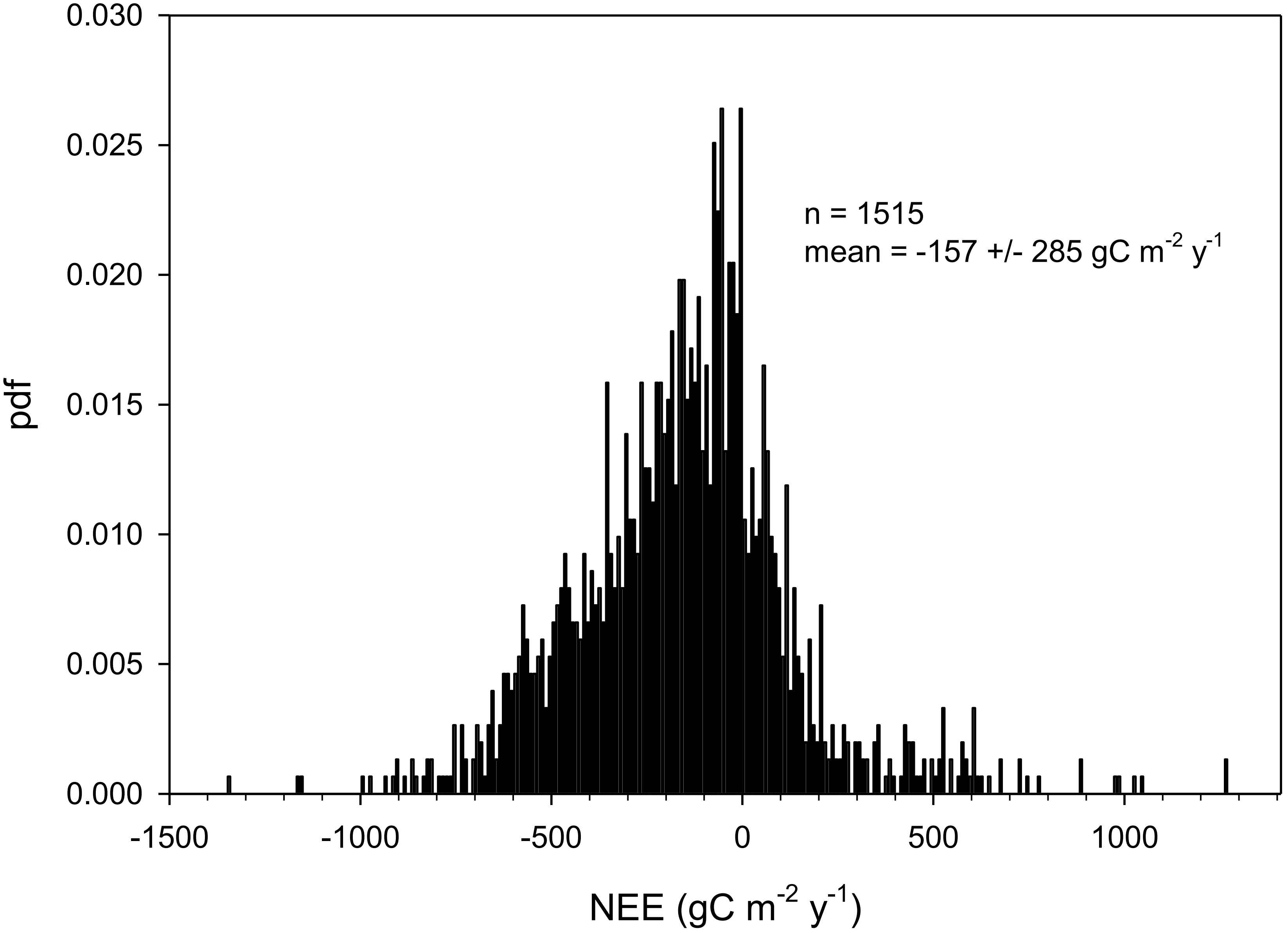






(Data accessed in May, 2015)

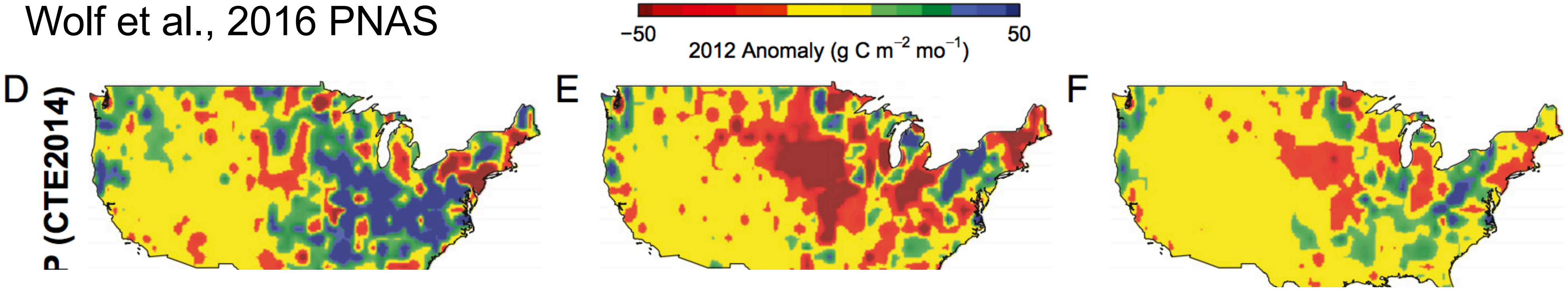
Published Data, March, 2015

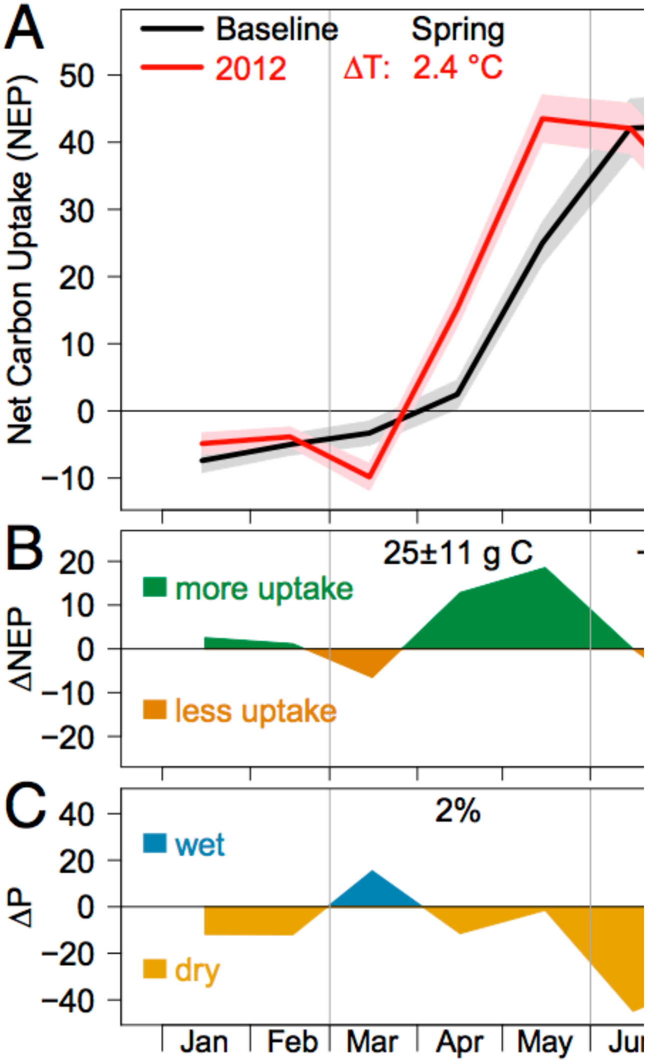


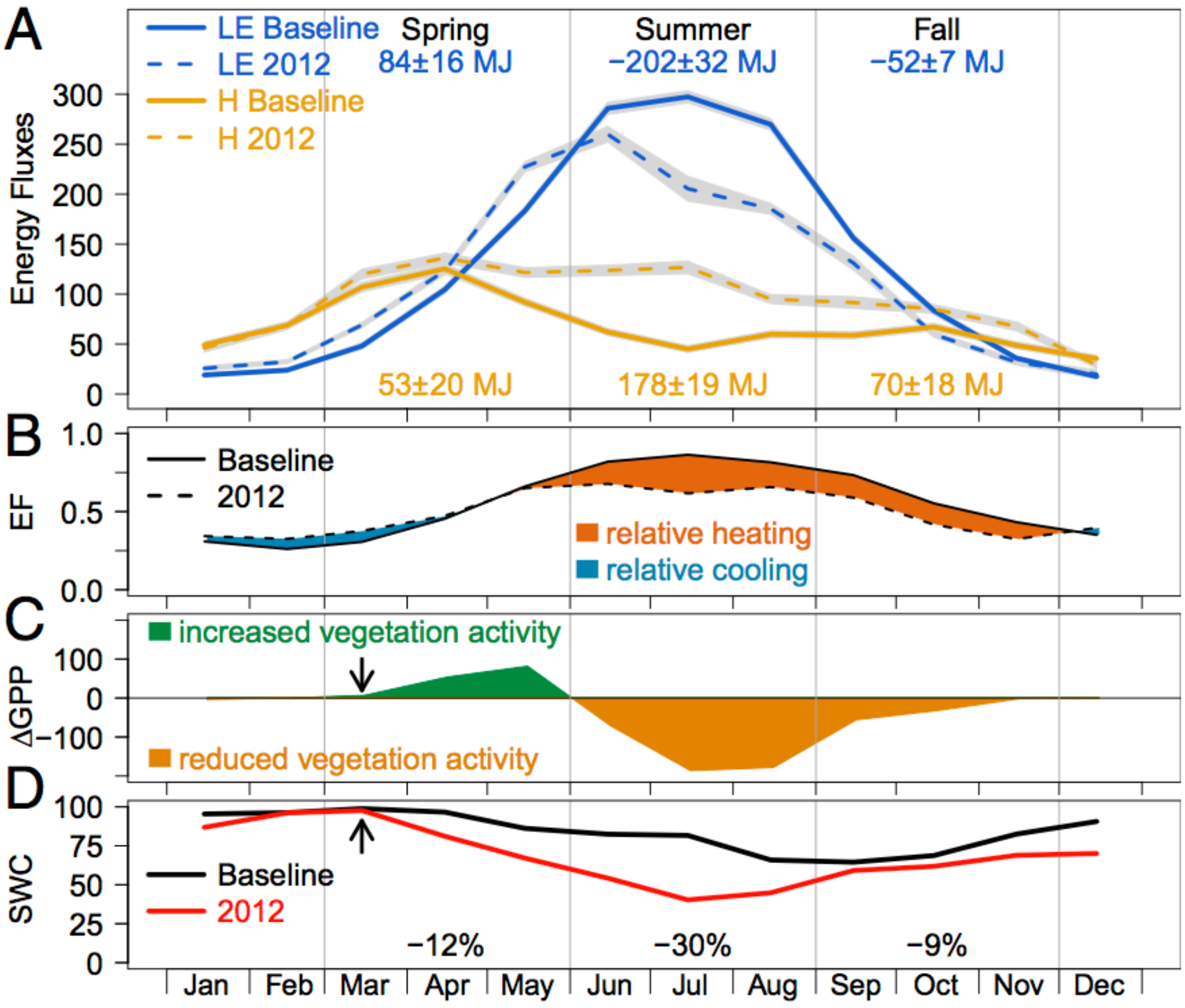
n = 1515

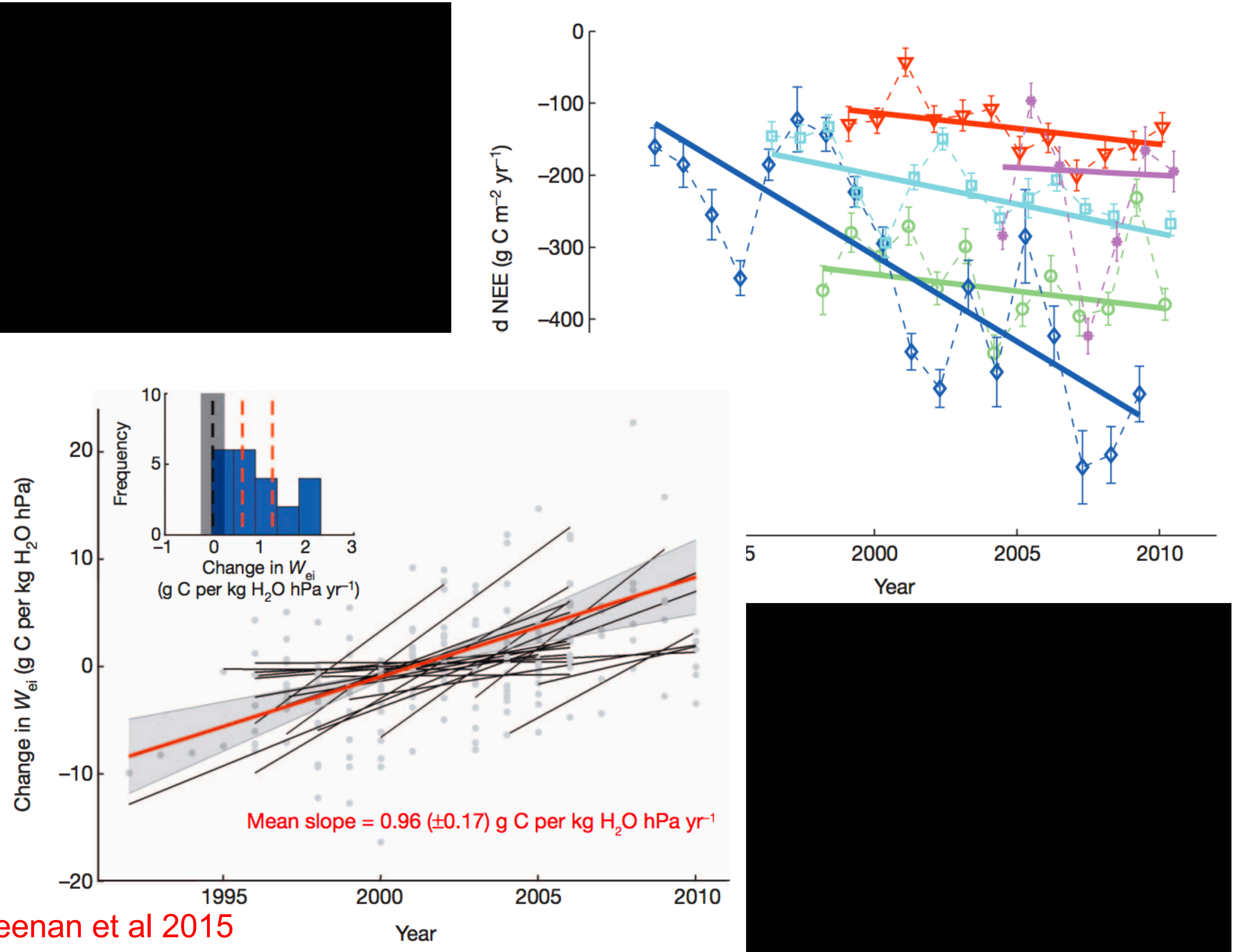
mean = -157 +/- 285 gC m^{-2} y^{-1}

Wolf et al., 2016 PNAS



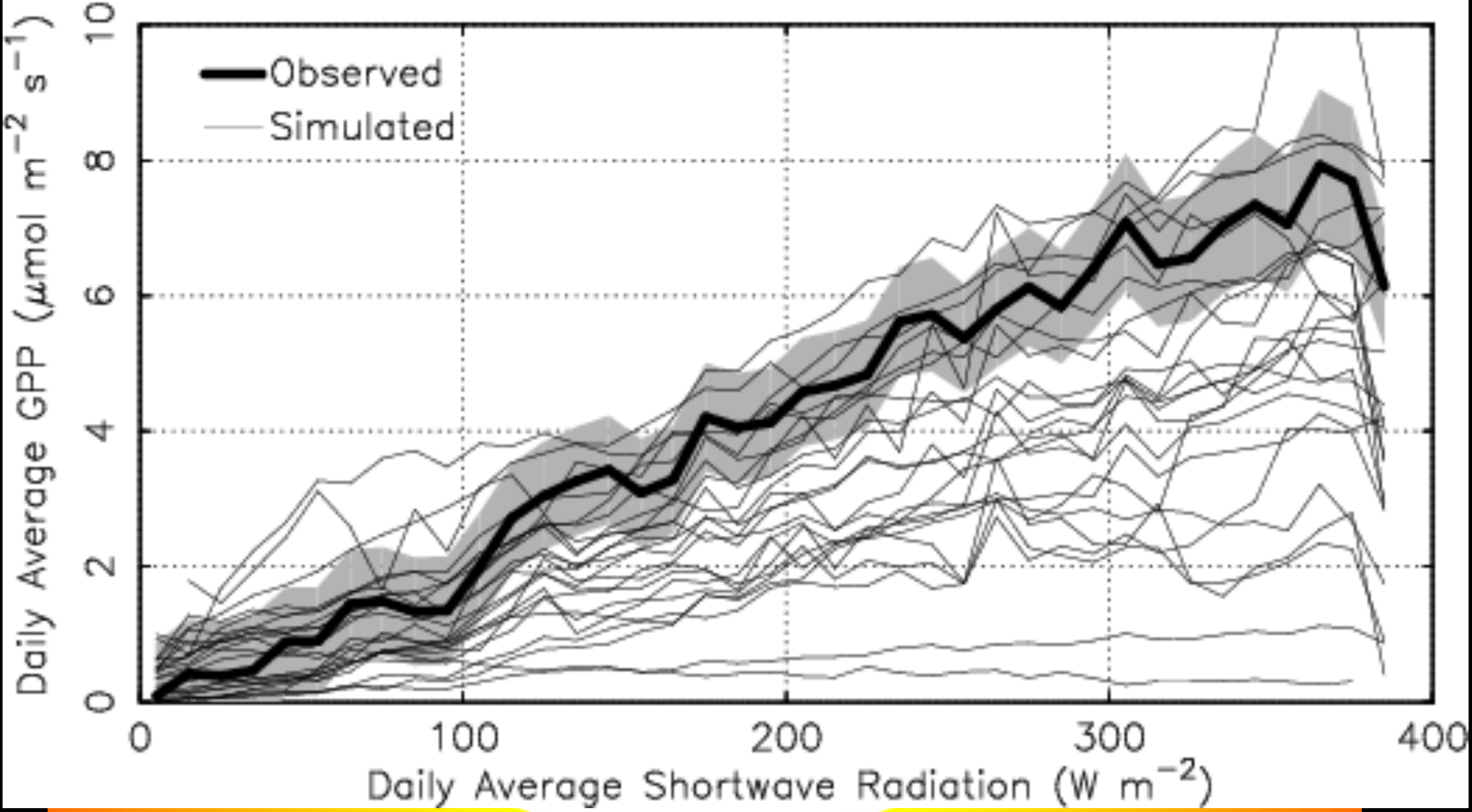






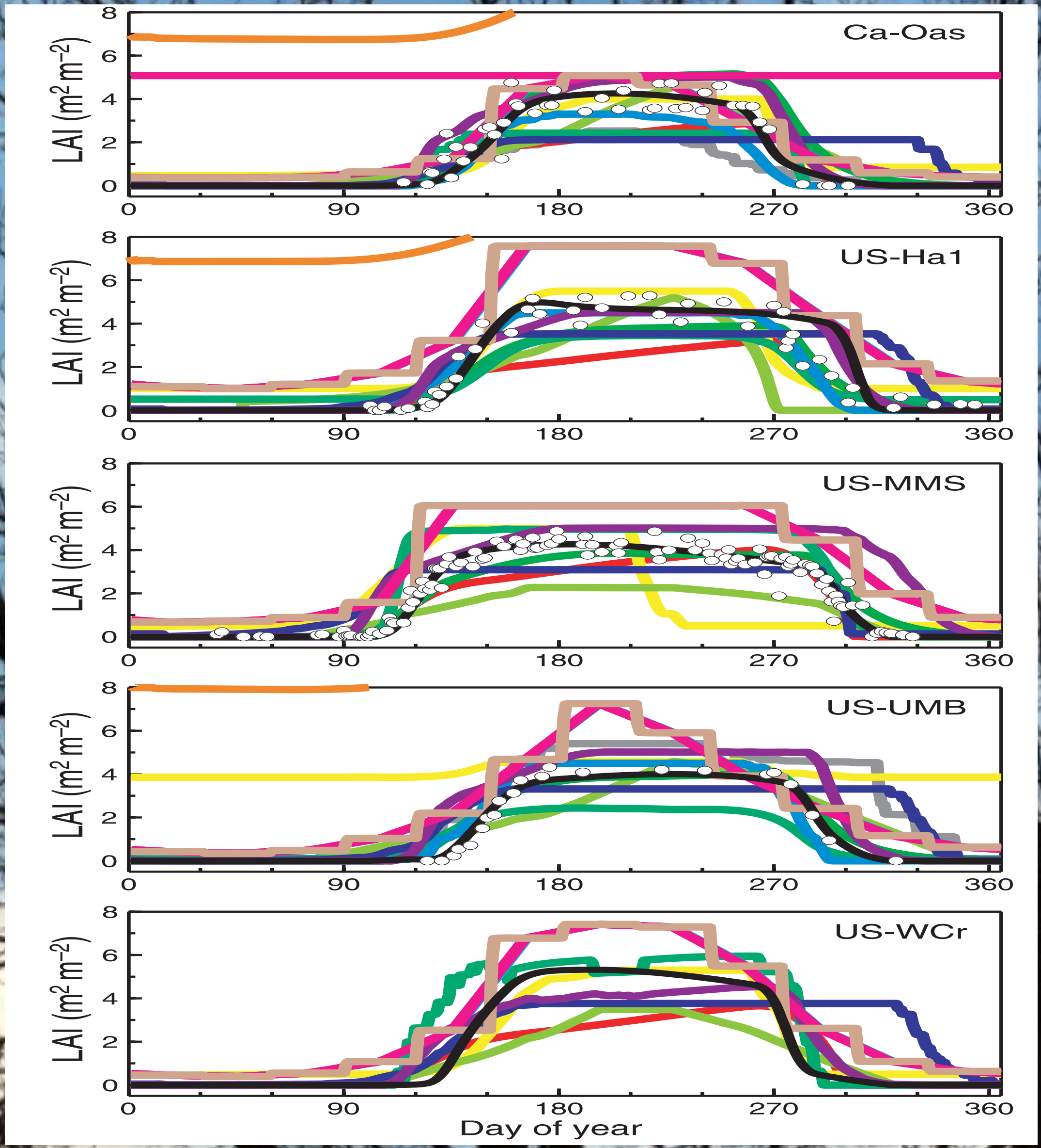
Keenan et al 2015

Light

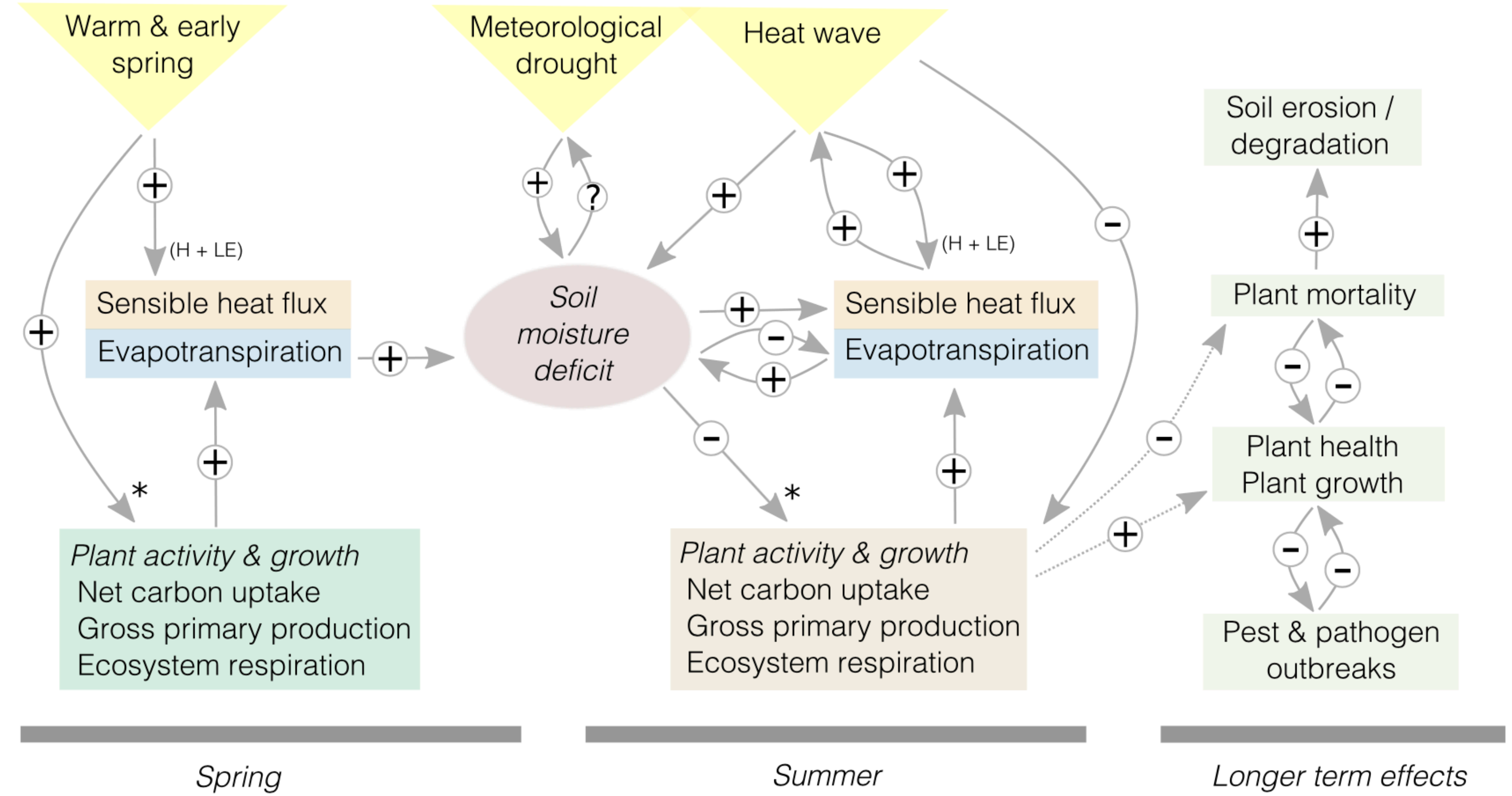


Schaefer et al., 2012

Phenology



Richardson et al., 2012



Warm & early spring

Meteorological drought

Heat wave

(H + LE)

Sensible heat flux

Evapotranspiration

Soil moisture deficit

?

(H + LE)

Sensible heat flux

Evapotranspiration

Soil erosion / degradation

Plant mortality

Plant health
Plant growth

Pest & pathogen outbreaks

Plant activity & growth
Net carbon uptake
Gross primary production
Ecosystem respiration

*

Plant activity & growth
Net carbon uptake
Gross primary production
Ecosystem respiration

*

Spring

Summer

Longer term effects

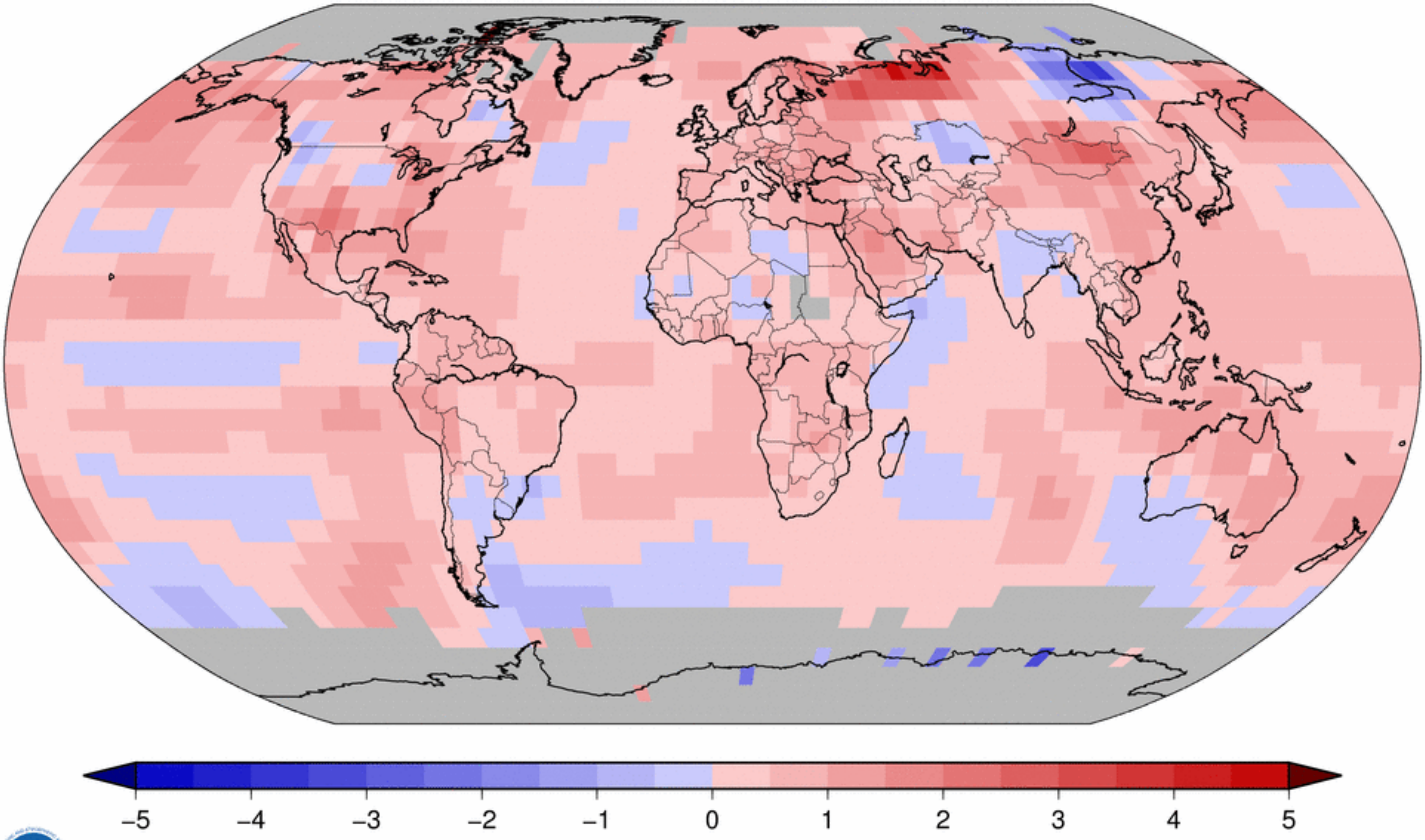
* Climate effects on ecosystem carbon fluxes are shown only in qualitative terms. Individual fluxes might be affected differently by climate extremes (see text).

Sippel et al., 2016

Land & Ocean Temperature Departure from Average Jul 2016

(with respect to a 1981–2010 base period)

Data Source: GHCN–M version 3.3.0 & ERSST version 4.0.0

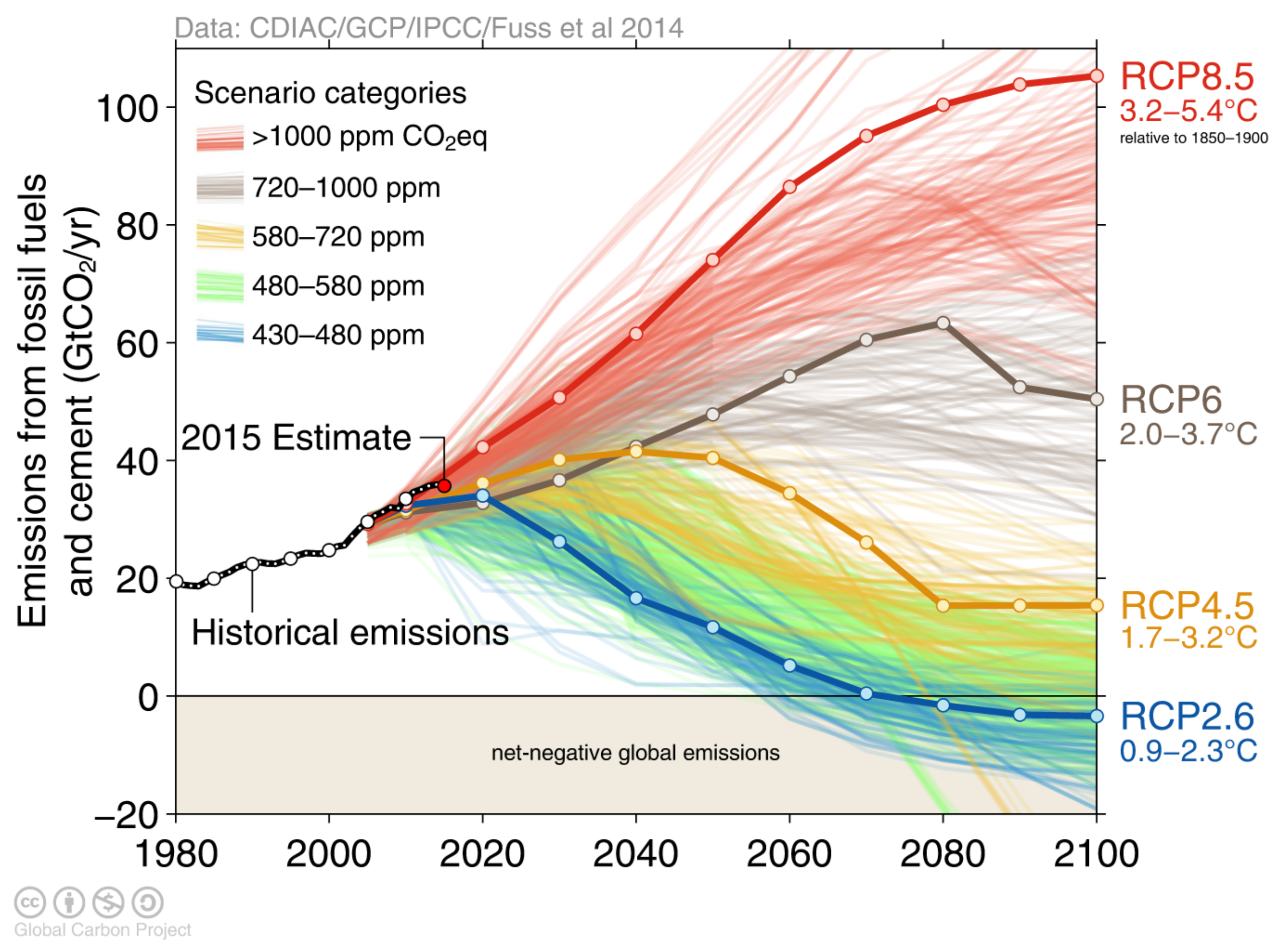


National Centers for Environmental Information
Mon Aug 15 07:11:22 EDT 2016

Please Note: Gray areas represent missing data
Map Projection: Robinson

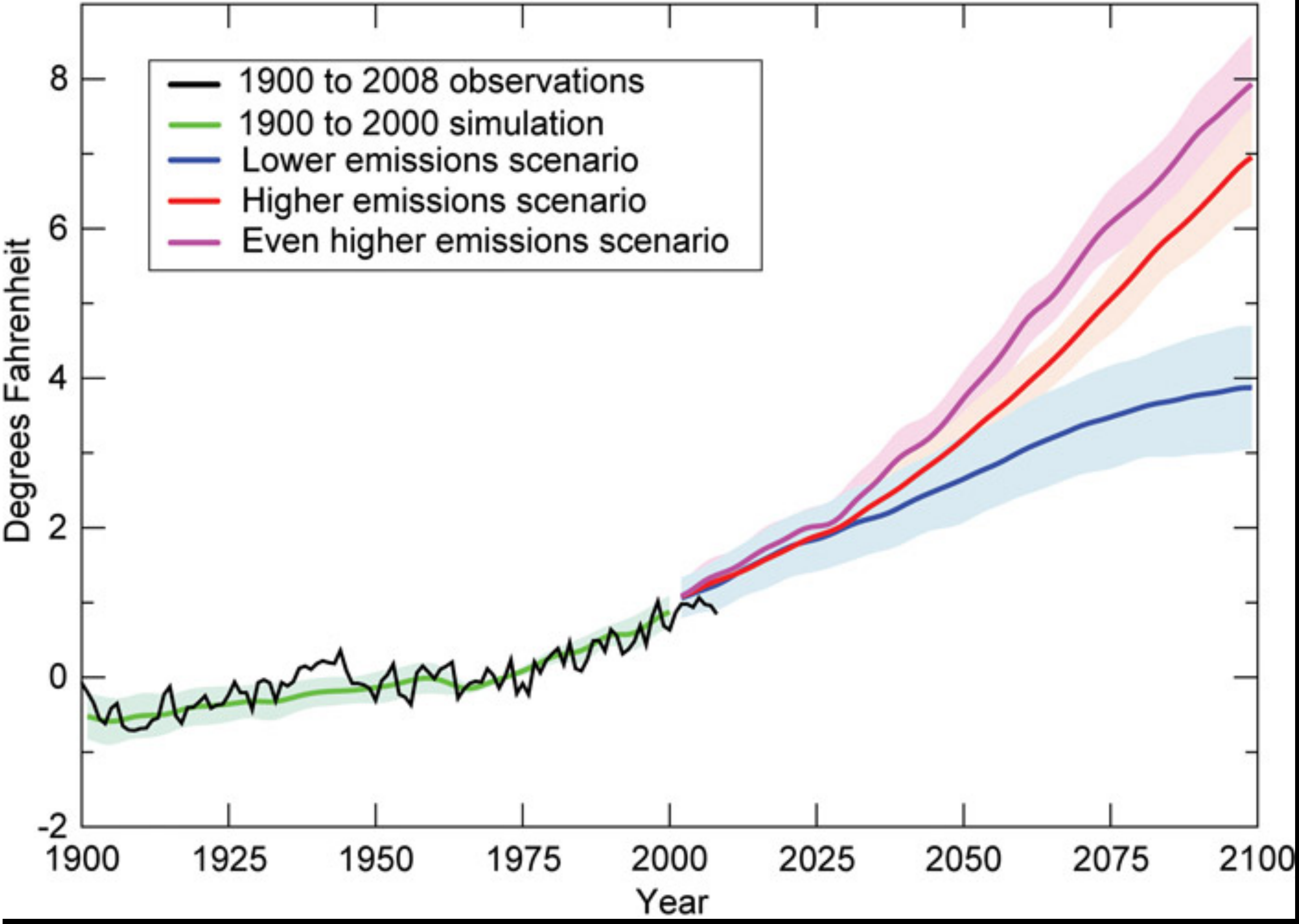
Observed emissions and emissions scenarios

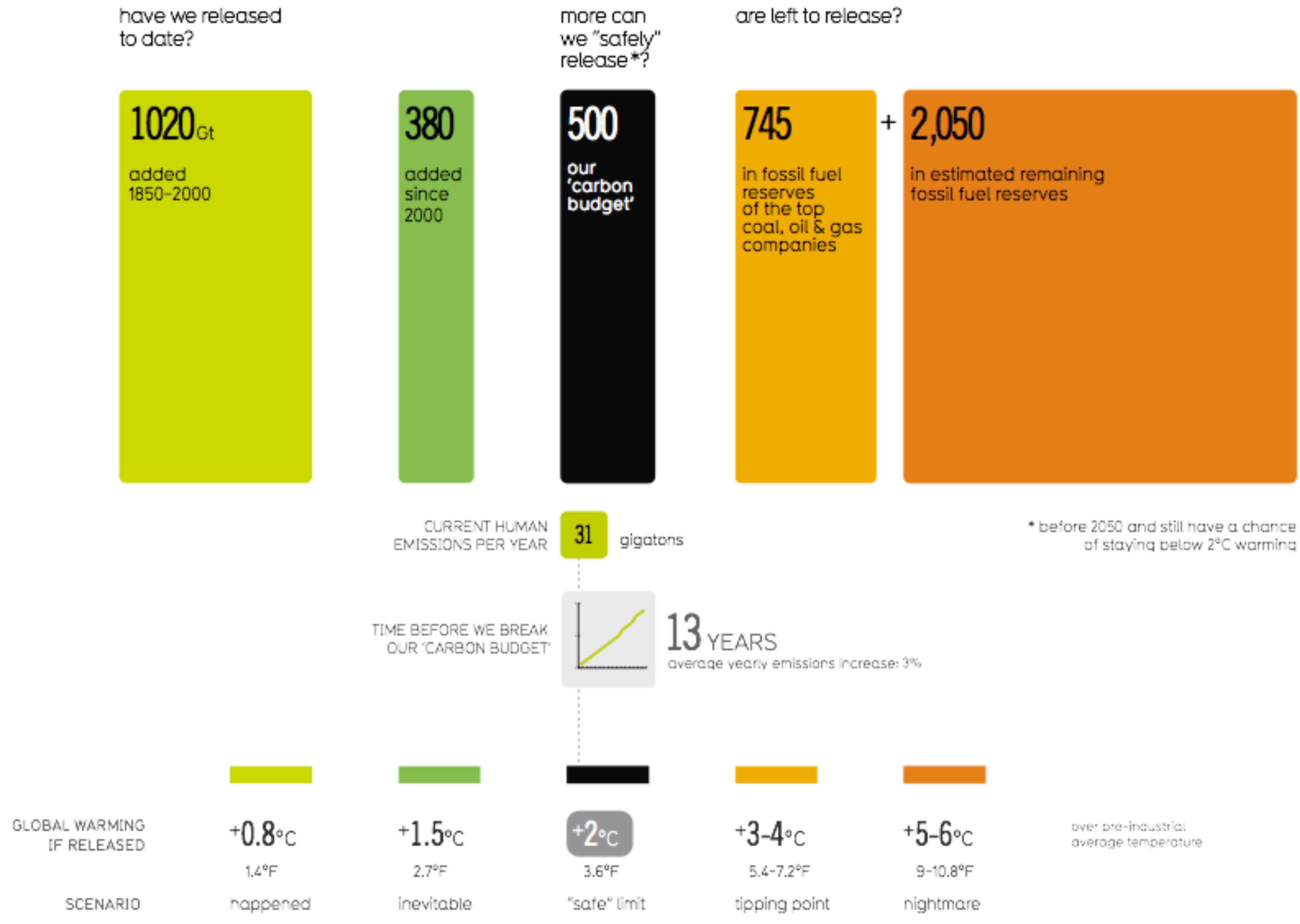
The emission pledges submitted to the Paris climate summit avoid the worst effects of climate change (red), most studies suggest a likely temperature increase of about 3° C (brown)



Over 1000 scenarios from the IPCC Fifth Assessment Report are shown

Source: Fuss et al 2014; CDIAC; Global Carbon Budget 2015


1900 to 2008 observations
1900 to 2000 simulation
Lower emissions scenario
Higher emissions scenario
Even higher emissions scenario
Degrees Fahrenheit
8
6
4
2
0
-2
1900
1925
1950
1975
2000
2025
2050
2075
2100
Year



have we released to date?

more can we "safely" release*?

are left to release?

1020 Gt added 1850-2000

380 added since 2000

500 our 'carbon budget'

745 in fossil fuel reserves of the top coal, oil & gas companies

\+ **2,050** in estimated remaining fossil fuel reserves

CURRENT HUMAN EMISSIONS PER YEAR **31** gigatons

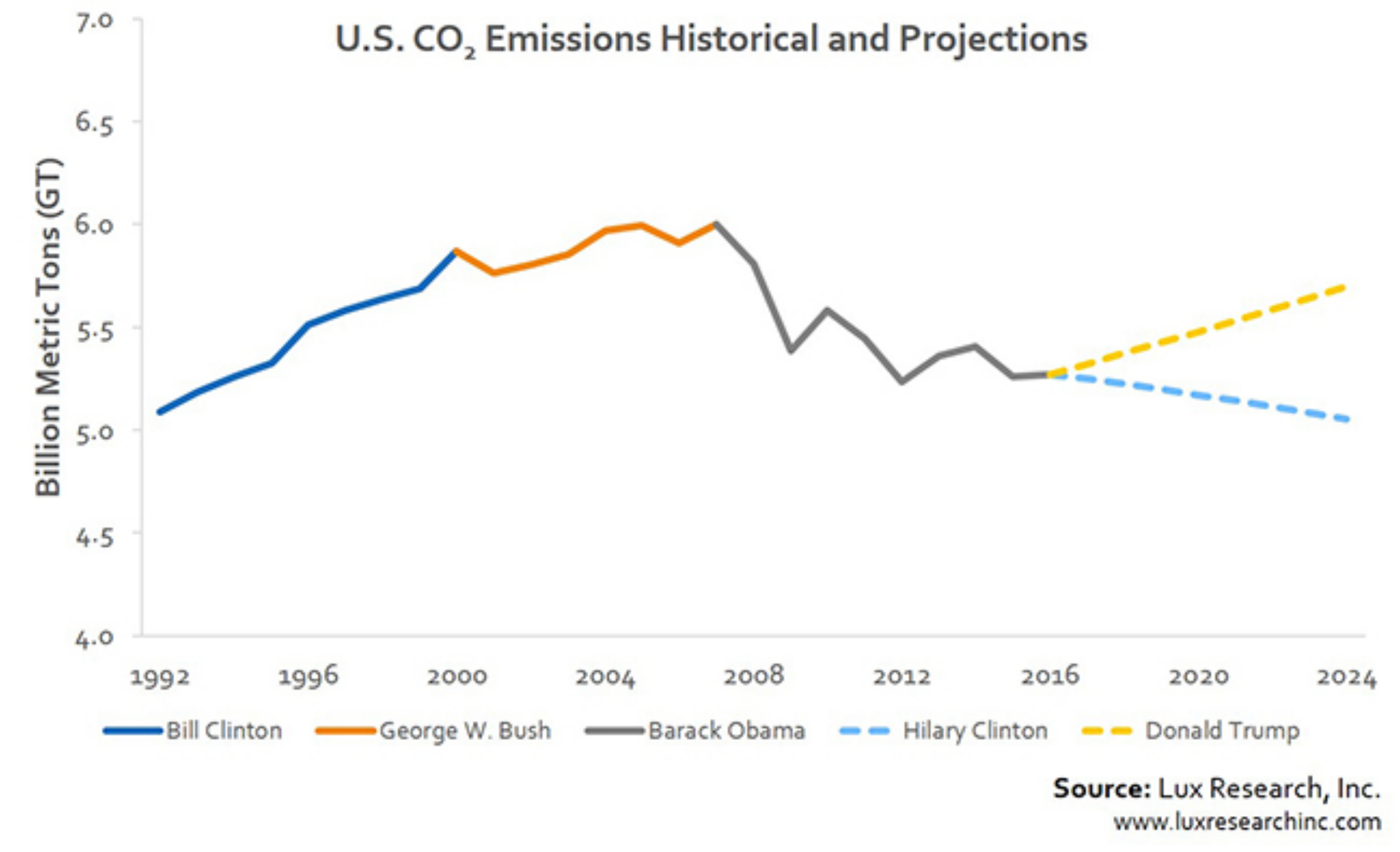
* before 2050 and still have a chance of staying below 2°C warming

TIME BEFORE WE BREAK OUR 'CARBON BUDGET' **13** YEARS

average yearly emissions increase: 3%

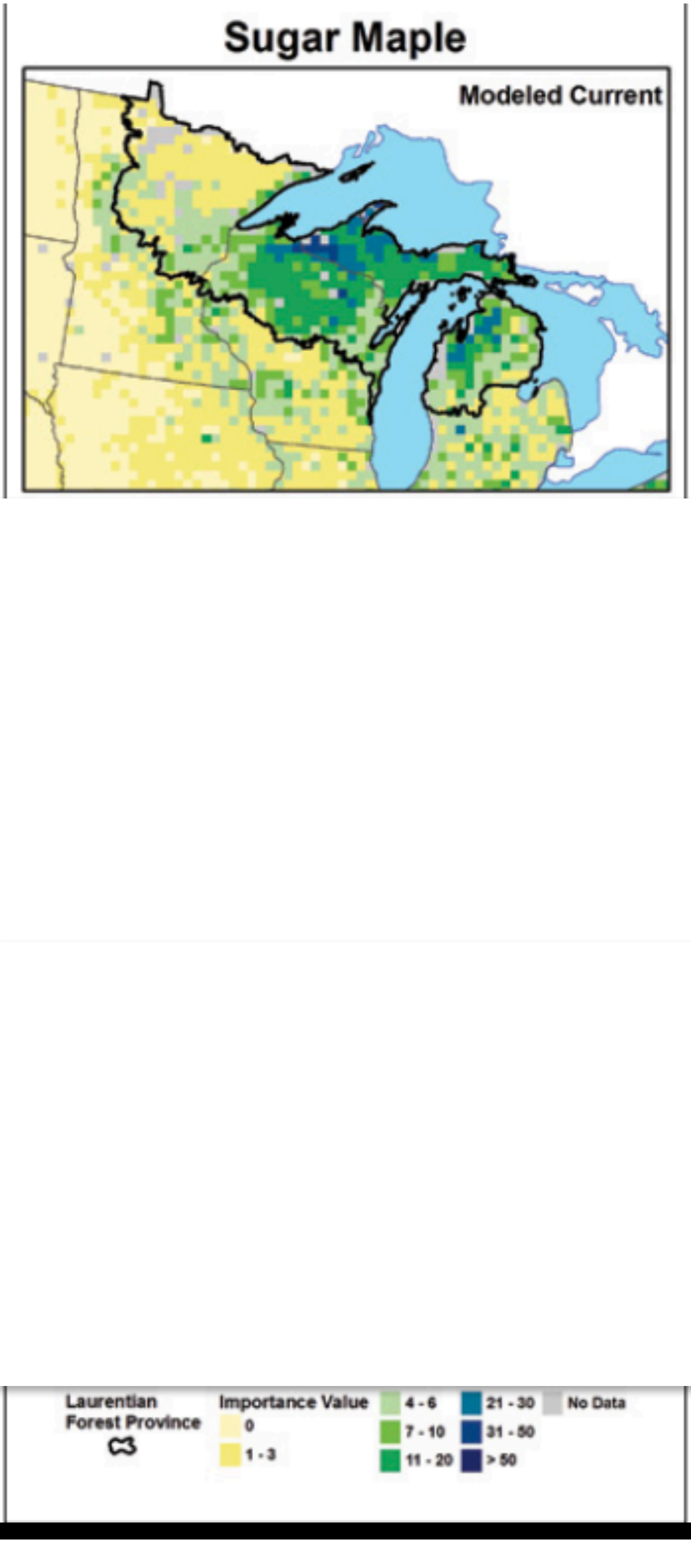
GLOBAL WARMING IF RELEASED	+0.8°C	+1.5°C	+2°C	+3-4°C	+5-6°C	over pre-industrial average temperature
	1.4°F	2.7°F	3.6°F	5.4-7.2°F	9-10.8°F	
SCENARIO	happened	inevitable	"safe" limit	tipping point	nightmare	

http://www.informationisbeautiful.net/2012/how-many-gigatons-of-co2/

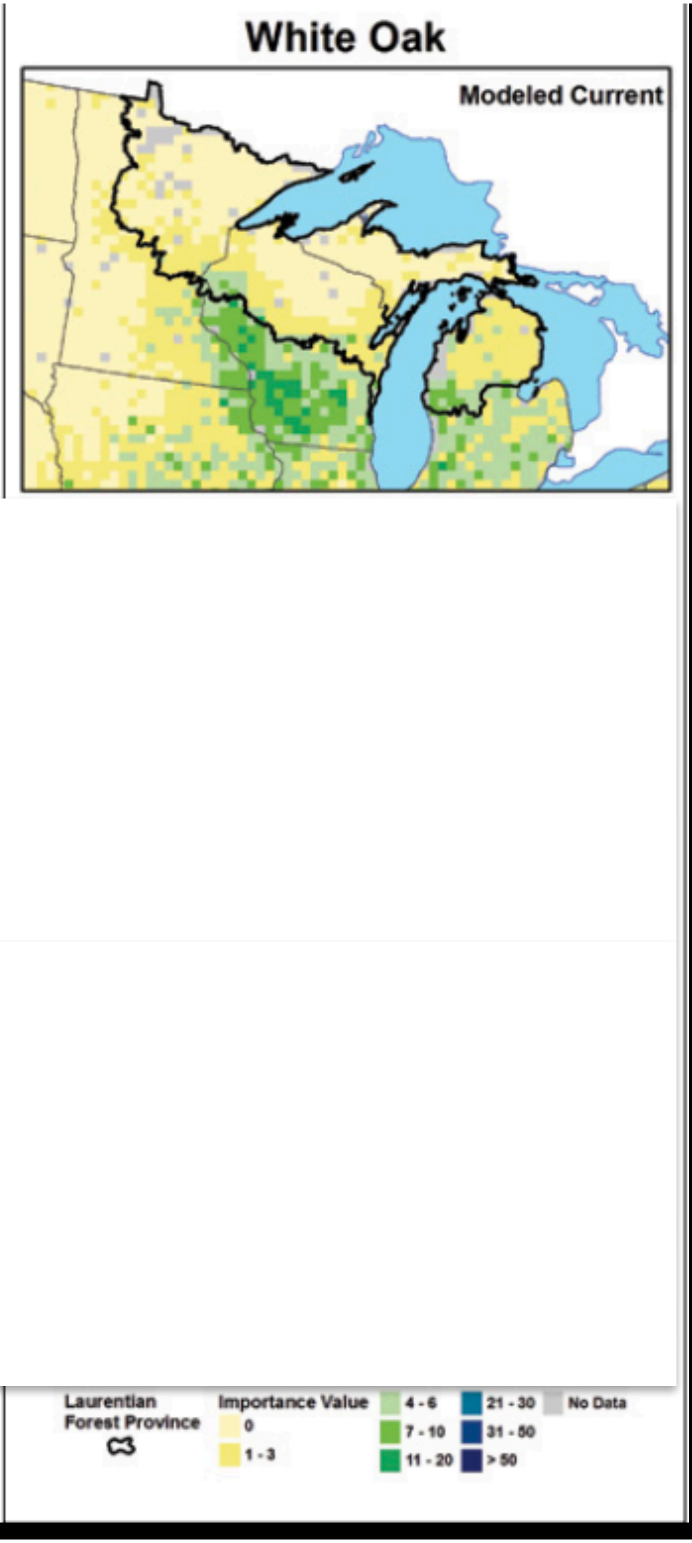


Source: Lux Research, Inc.
www.luxresearchinc.com

http://www.vox.com/2016/11/9/13571318/donald-trump-disaster-climate

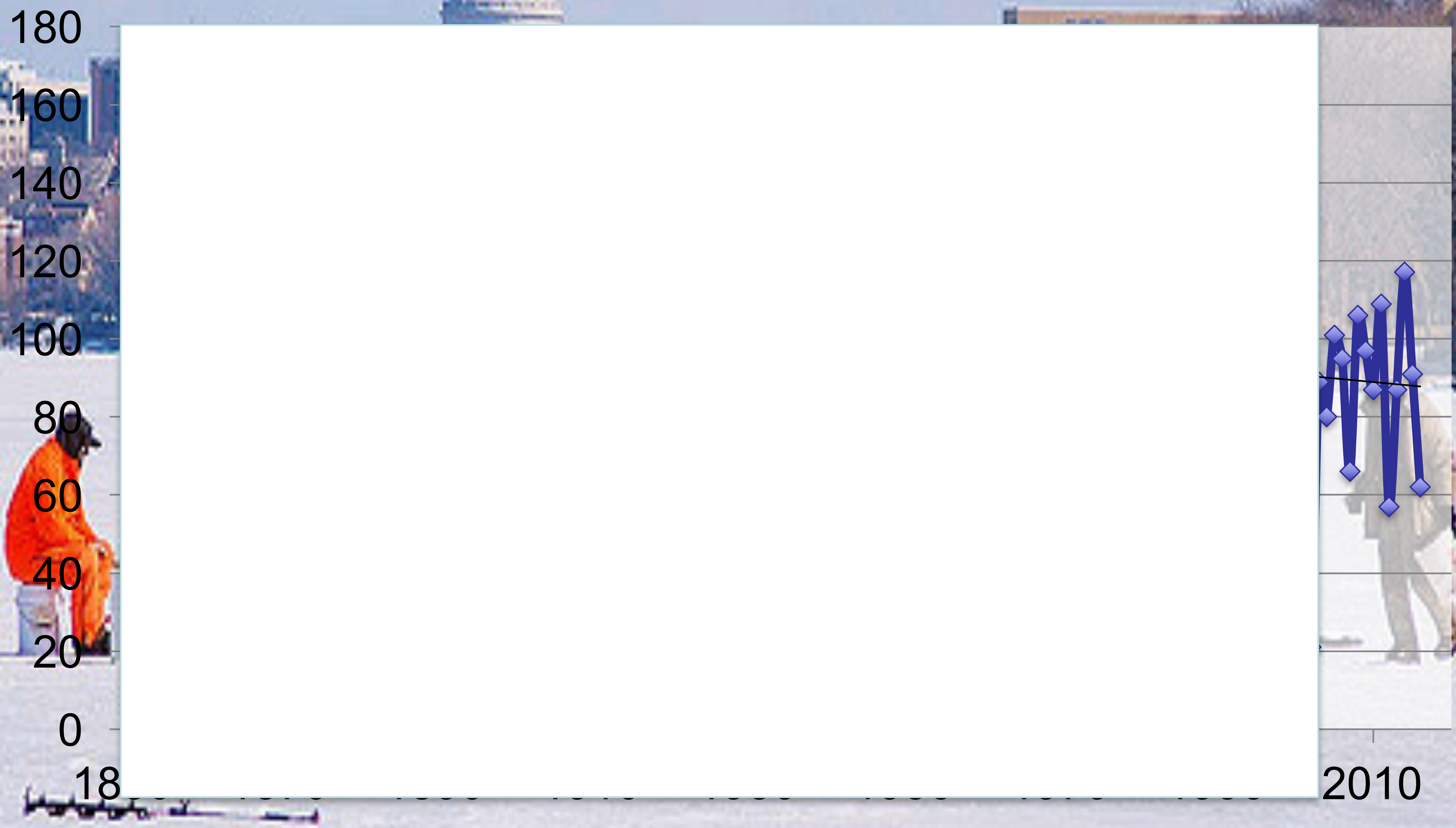


Sugar Maple



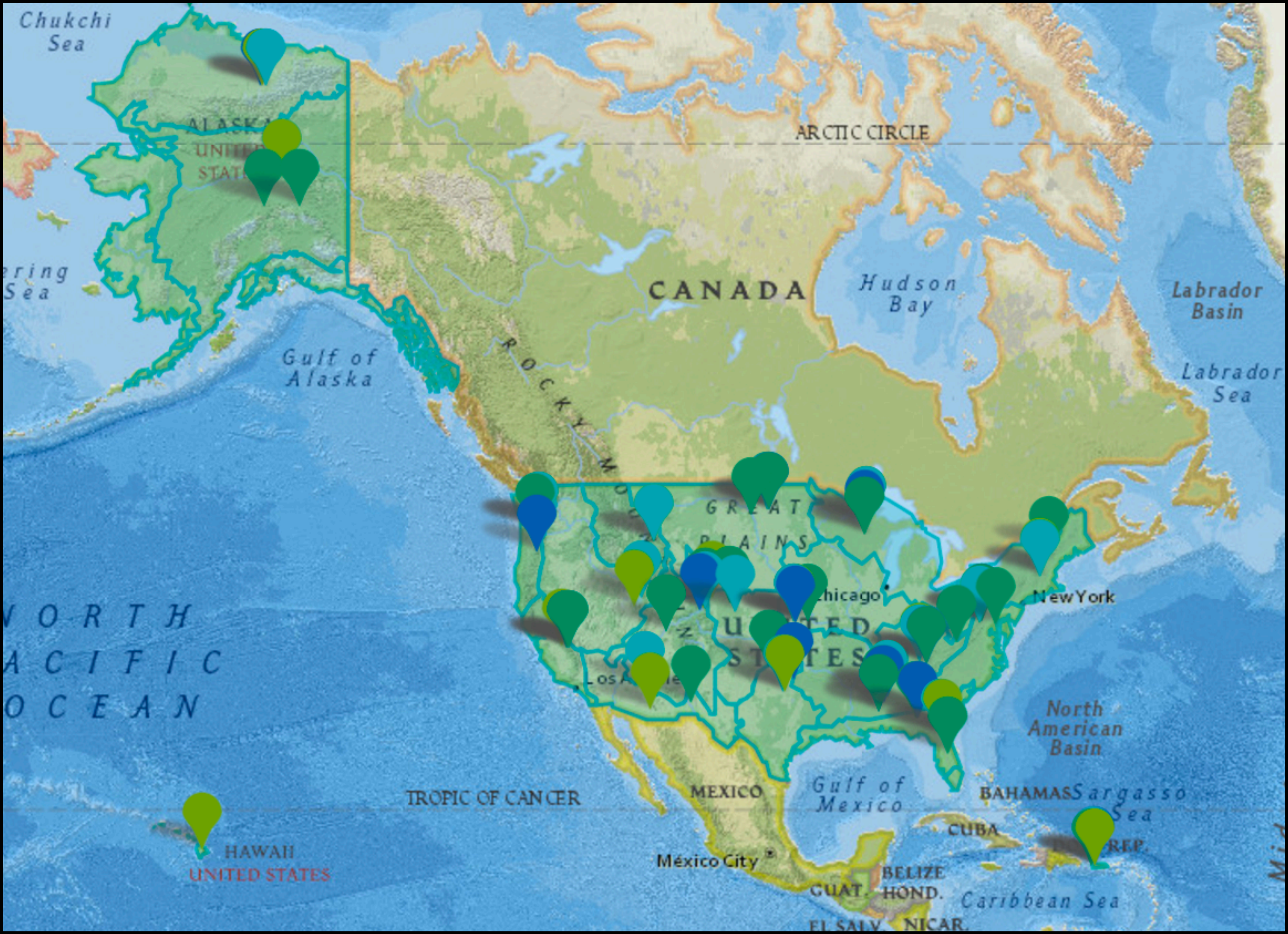
White Oak

The Invisible Present



neon®

National Ecological Observatory Network



ELEMENTS

SPACE, CLIMATE CHANGE, AND THE REAL MEANING OF THEORY

By Piers Sellers, AUGUST 17, 2016

Climate science is based on theory.

In the end, science always, always wins in arguments like these. Google Leonardo da Vinci or Johannes Kepler to check on this. You can fool yourself, you can fool other people for a while, but you can't fool Mother Nature. We humans have historically displayed resourcefulness and ingenuity when presented with a serious challenge. We now have the tools to observe, understand, and predict climate change, and we have the resources of an entire global civilization to deal with its consequences and reduce the chances of catastrophic warming. I remain optimistic because of my faith in the spirit and energy of the people I saw in the lighted cities of the world from my perch in space. But I cannot help observing that the years are slipping by, each warmer than the last, with slow progress being made. We need to get on with the necessary fixes—

Ankur Desai, desai@aos.wisc.edu, 608-520-0305, http://flux.aos.wisc.edu
http://ameriflux.lbl.gov/ http://fluxnet.fluxdata.org/