Examining Effects of Black Carbon on Climate and How to Mitigate Them Through Different Transportation Options

Mark Z. Jacobson
Atmosphere/Energy Program
Dept. of Civil & Environmental Engineering
Stanford University

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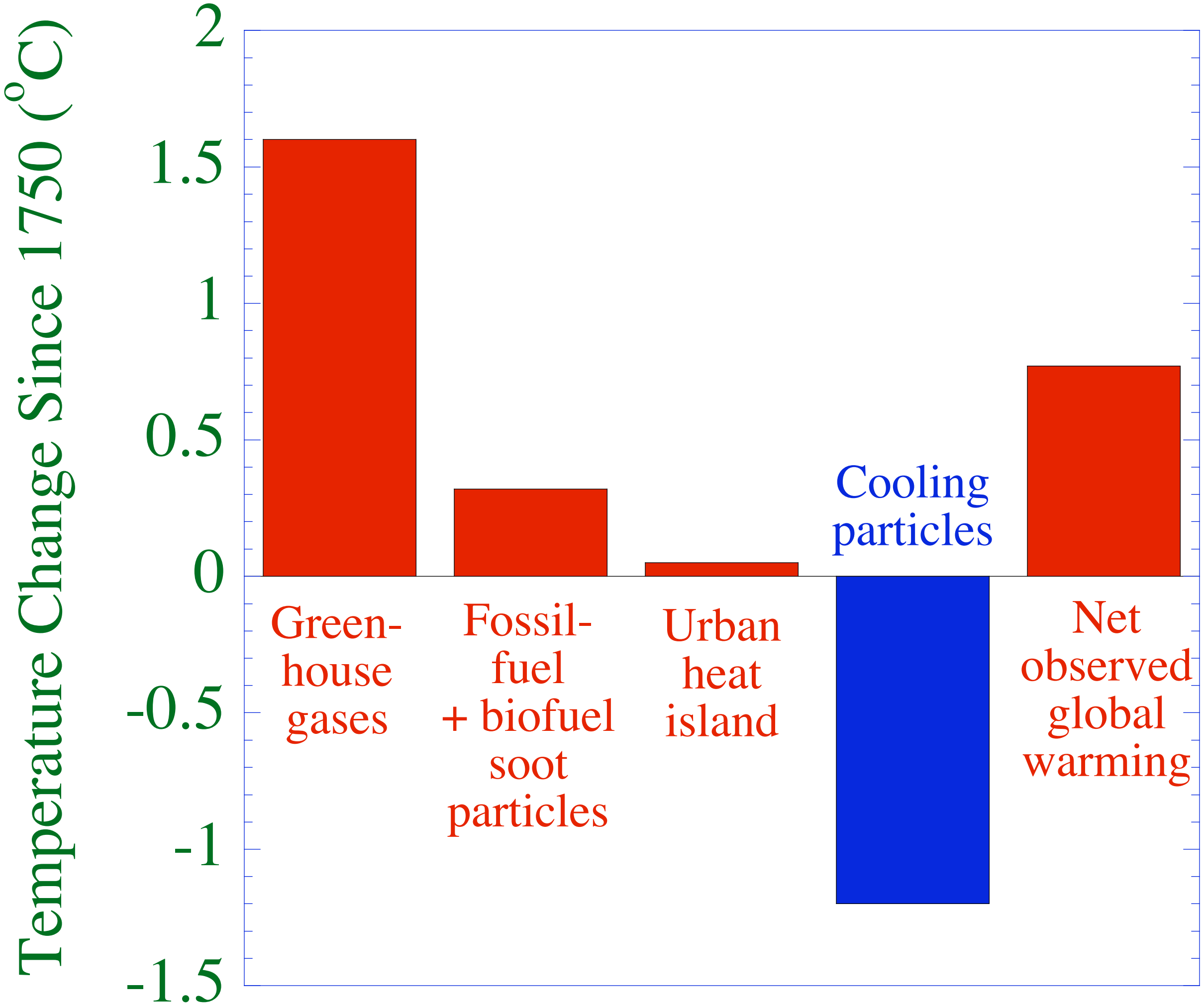
Causes of Global Warming



M.Z. Jacobson

GATOR-GCMOM Model

Gas processes
- Emissions
- Photochemistry
- Gas-to-particle conversion
- Cloud removal

Aerosol processes
- Emissions
- Nucleation/condensation
- Gas dissolution
- Aqueous chemistry
- Crystallization
- Aerosol-aerosol coagulation
- Aerosol-cloud coagulation
- Dry deposition
- Sedimentation
- Rainout/washout

Meteorological processes
- Pressure, winds, temp., TKE

Cloud processes
- Subgrid clouds, size-resolved physics
- Liquid/ice growth on aerosol particles
- Liquid drop freezing/breakup
- Hydrometeor-hydrometeor coagulation
- Hydrometeor-aerosol coagulation
- Precipitation, aer./gas rainout/washout
- Below-cloud evaporation/melting
- Lightning from collision bounceoffs

Radiative transfer
- UV/visible/near-IR/thermal-IR
- Gas/aerosol/cloud scat./absorption
- Predicted snow, ice, water albedos

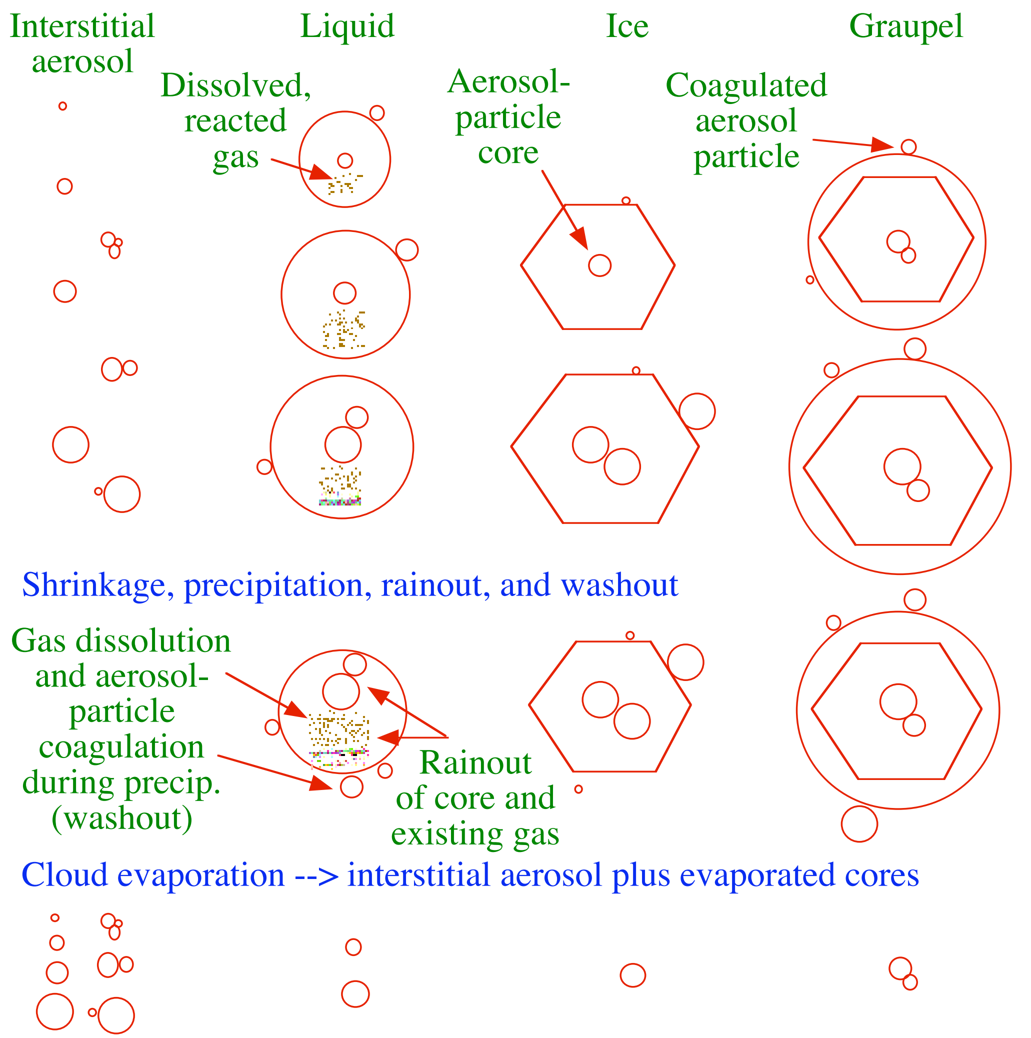
Surface processes
- Soil, water, snow, sea ice, vegetation, road, roof temperatures/moisture
- Ocean 2-D dynam., 3-D diffus/chem.
- Ocean-atmosphere exchange

Cloud Microphysical and Chemical Processes

Condensation/deposition of water vapor onto aerosol particles

Coagulation: Aerosol-aerosol, Aerosol-liquid, Aerosol-ice, Aerosol-graupel, Liquid-liquid, Liquid-ice, Liquid-graupel, Ice-ice, Ice-graupel, Graupel-graupel

Gas dissolution. aqueous chemistry, hom.-het. freezing, contact freezing



Size Distributions Treated

FF Soot	Intern.-mix	Liq.	Ice	Graupel
Number	Number	Number	Number	Number
BC	BC	BC	BC	BC
POM	POM	POM	POM	POM
SOM	SOM	SOM	SOM	SOM
H_2O-h	H_2O-h	H_2O-h	H_2O-h	H_2O-h
H^+	H^+	H^+	H^+	H^+
H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4
HSO_4-	HSO_4-	HSO_4-	HSO_4-	HSO_4-
NH_4^+	NH_4^+	NH_4^+	NH_4^+	NH_4^+
NO_3-	NO_3-	NO_3-	NO_3-	NO_3-
Cl-	Cl-	Cl-	Cl-	Cl-
NH_4NO_3	NH_4NO_3	NH_4NO_3	NH_4NO_3	NH_4NO_3
$(NH_4)_2SO_4$	$(NH_4)_2SO_4$	$(NH_4)_2SO_4$	$(NH_4)_2SO_4$	$(NH_4)_2SO_4$
	Na^+	Na^+	Na^+	Na^+
	Soildust	Soildust	Soildust	Soildust
	Pollen/spore	Pollen/spore	Pollen/spore	Pollen/spore
		H_2O(l)	H_2O(ice)	H_2O(ice)

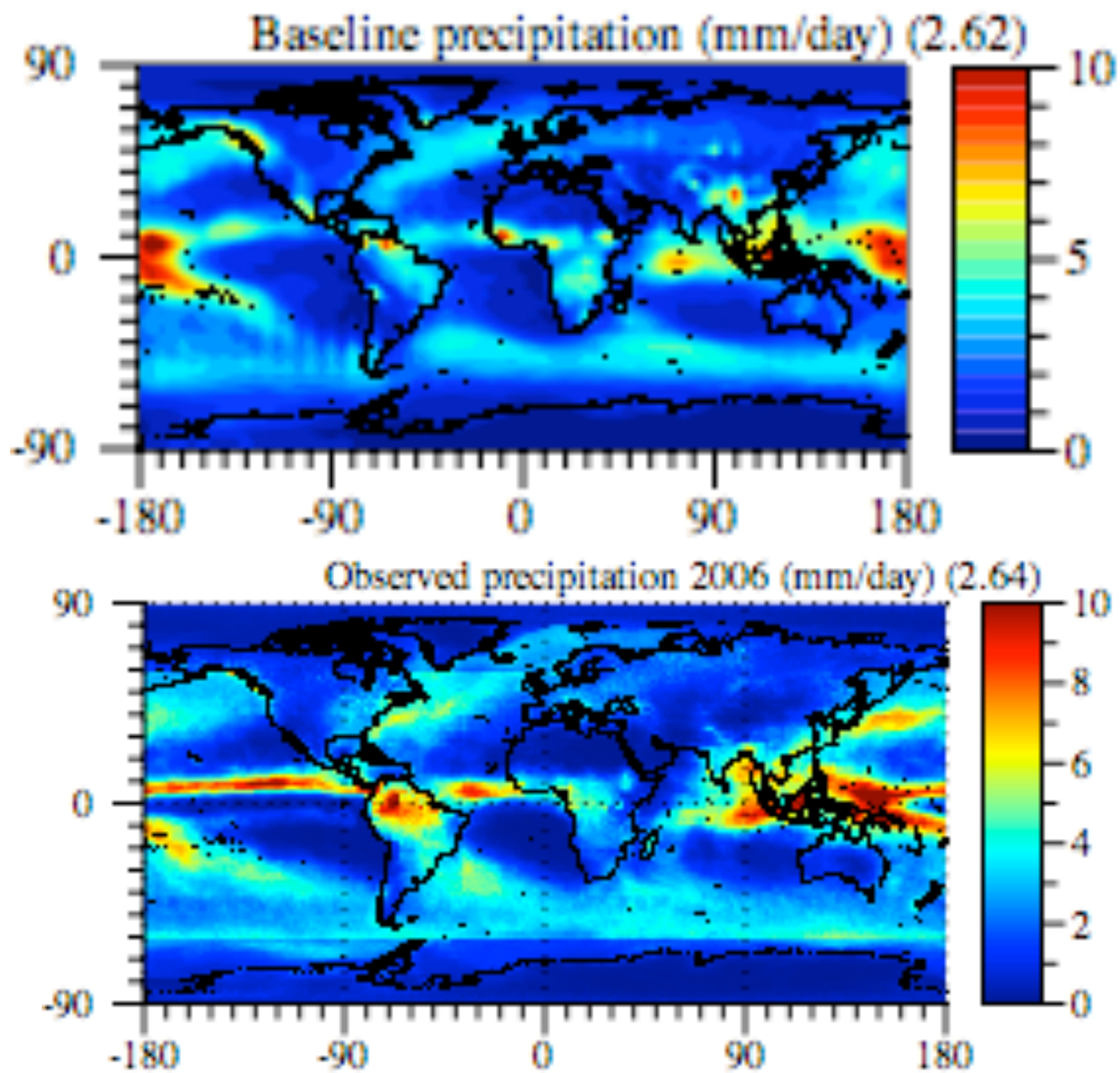
Fossil- and Bio-fuel Emissions (Tg/yr)

	Fossil-Fuel	Biofuel
BC	3.2	1.6
POC	2.4	6.5
S(VI)	0.03	0.3
Na^+		0.023
K^+ as Na^+		0.14
Ca^{2+} as Na^+		0.18
Mg^{2+} as Na^+		0.08
NH_4^+		0.018
NO_3-		0.16
Cl-		0.30
H_2O-hydrated	calculated	calculated
H+	calculated	calculated

+ 43 gases

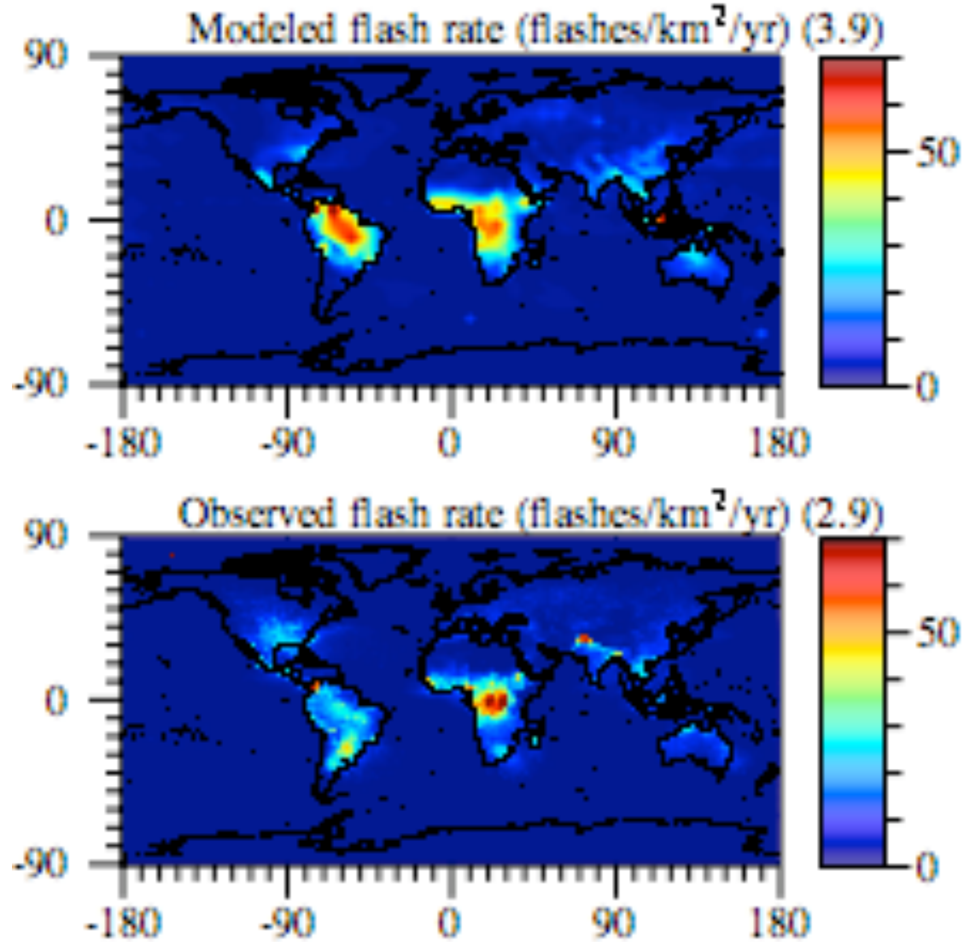
BC/POC from Bond et al. (2004); other emis factors Andreae, Ferek

Modeled vs. Measured Annual Precipitation



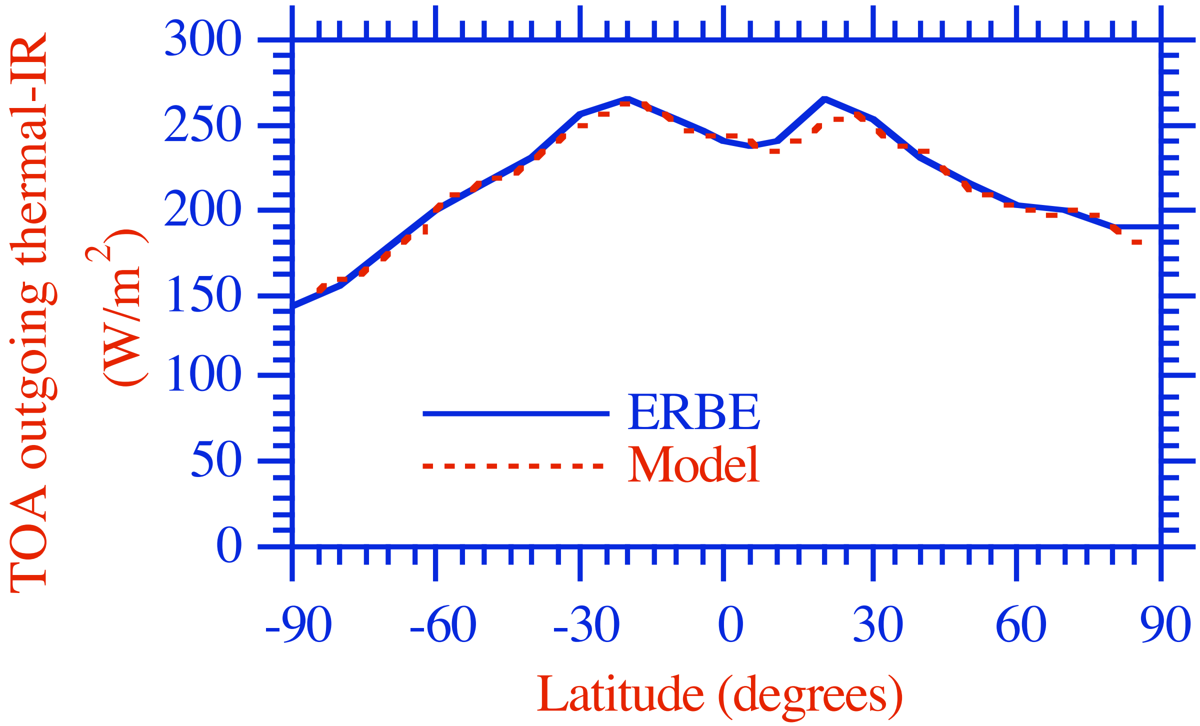
Data from
Huffman et al.

Modeled vs. Measured Annual Lightning Flash Rate



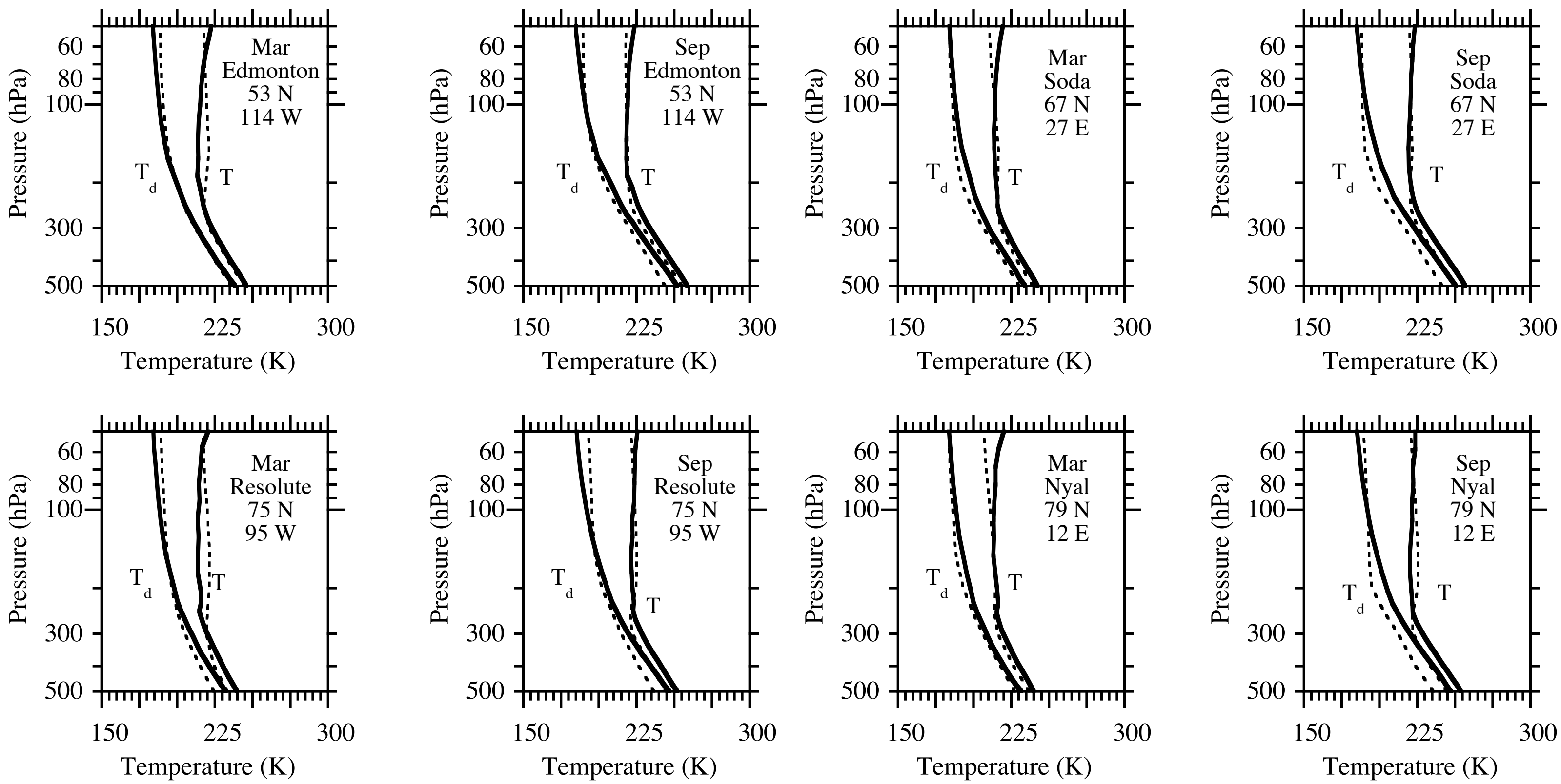
Data from NASA LIS/OTD Science Team

Modeled vs. Measured Thermal-IR



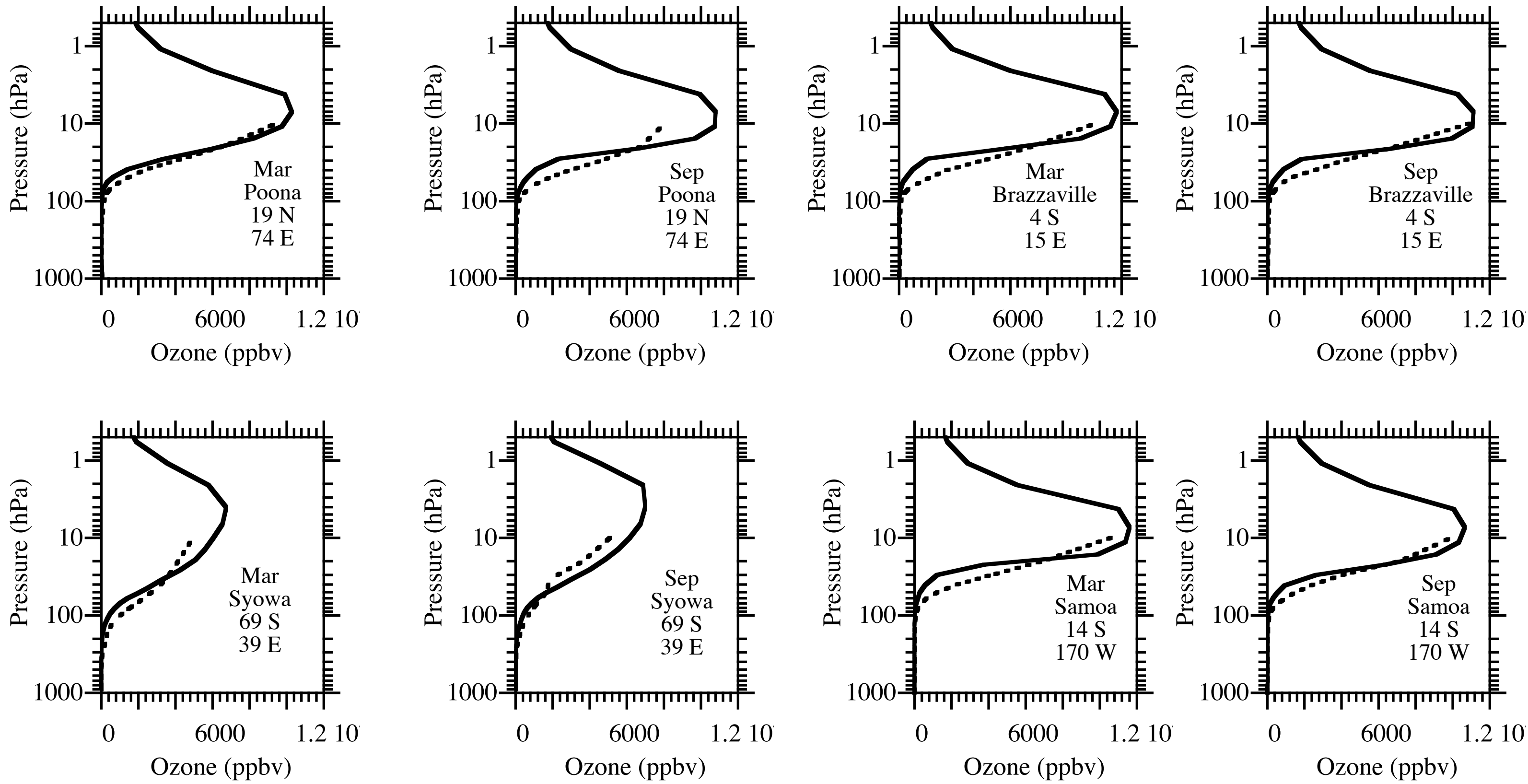
Data from Kiehl et al., 1998

Modeled vs. Measured Paired in Space Monthly T and T_d



Data from FSL (2008)

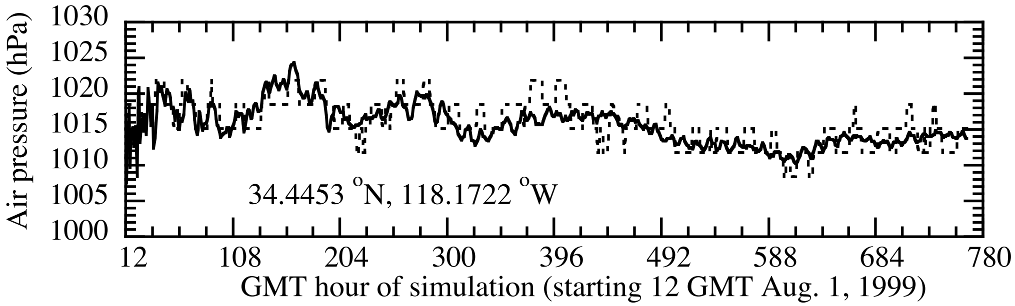
Modeled vs. Measured Paired in Space Monthly Climatological Ozone



Data from Logan et al. (1999)

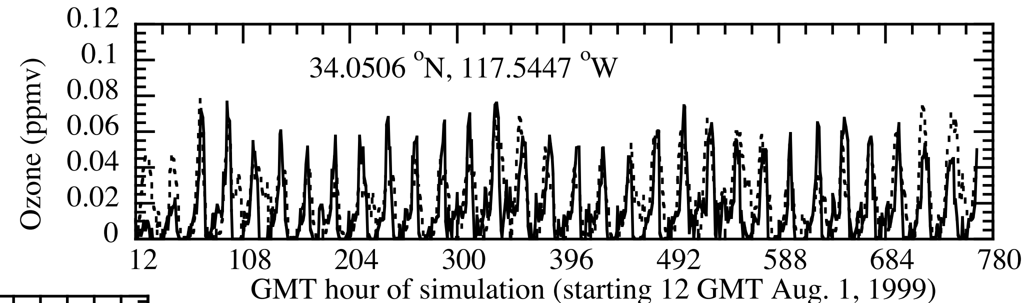
30-Day Weather Predictions vs. Data

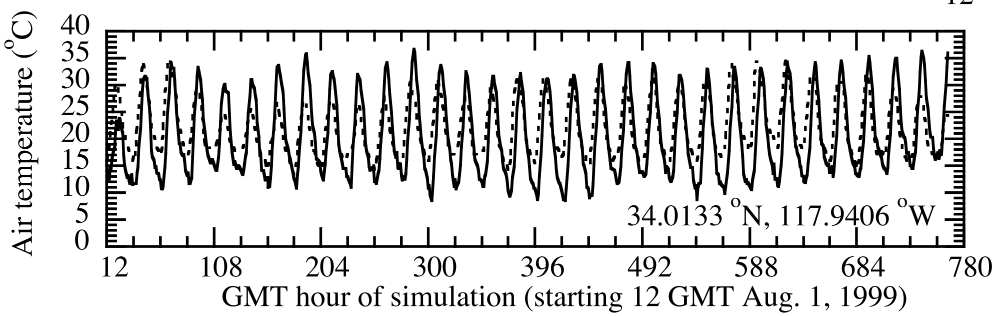
Results with no model spinup or data assimilation



Pressure

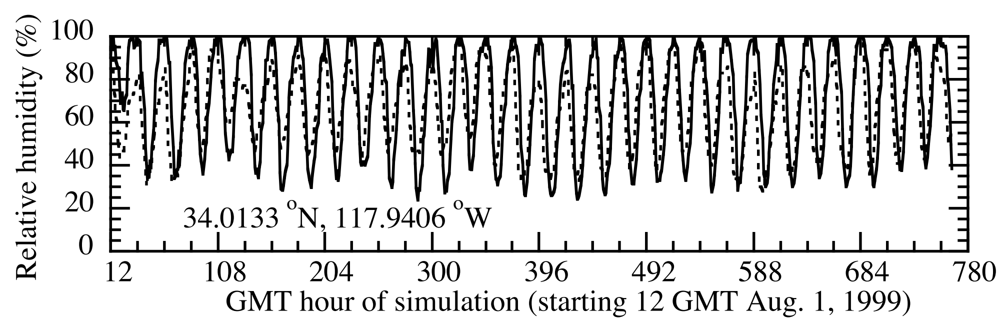
Ozone





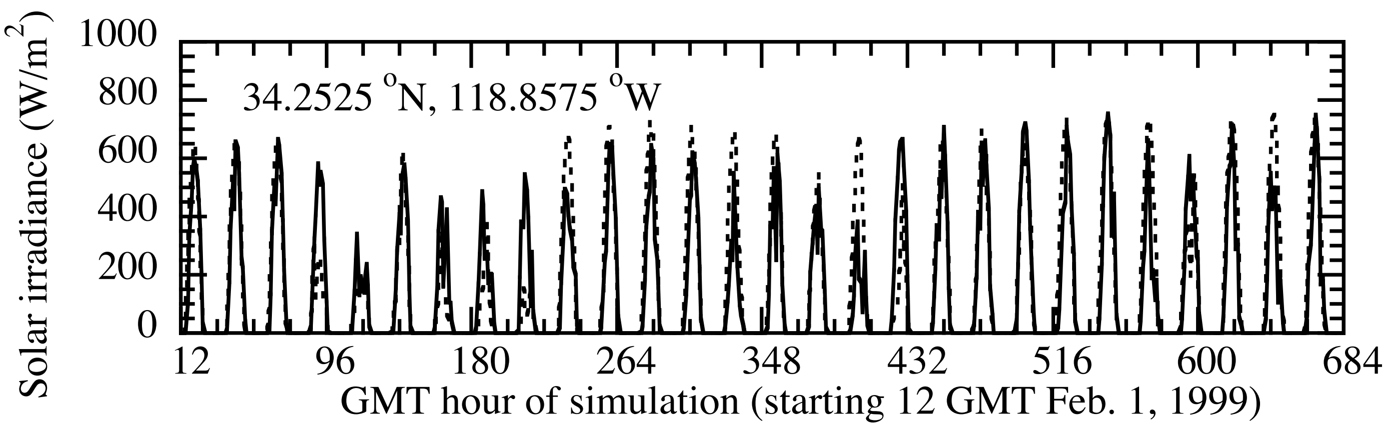
Temperature

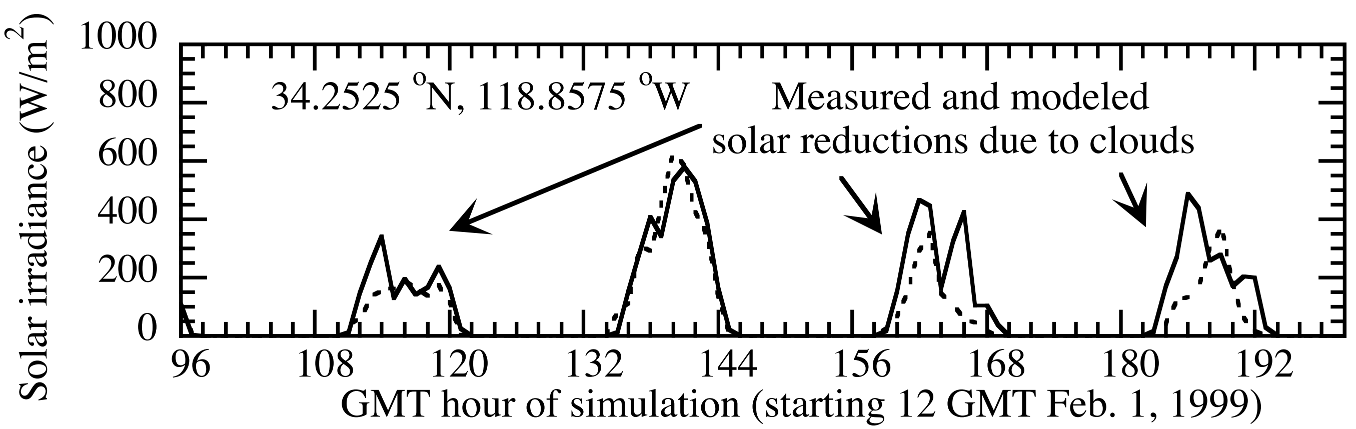
RH



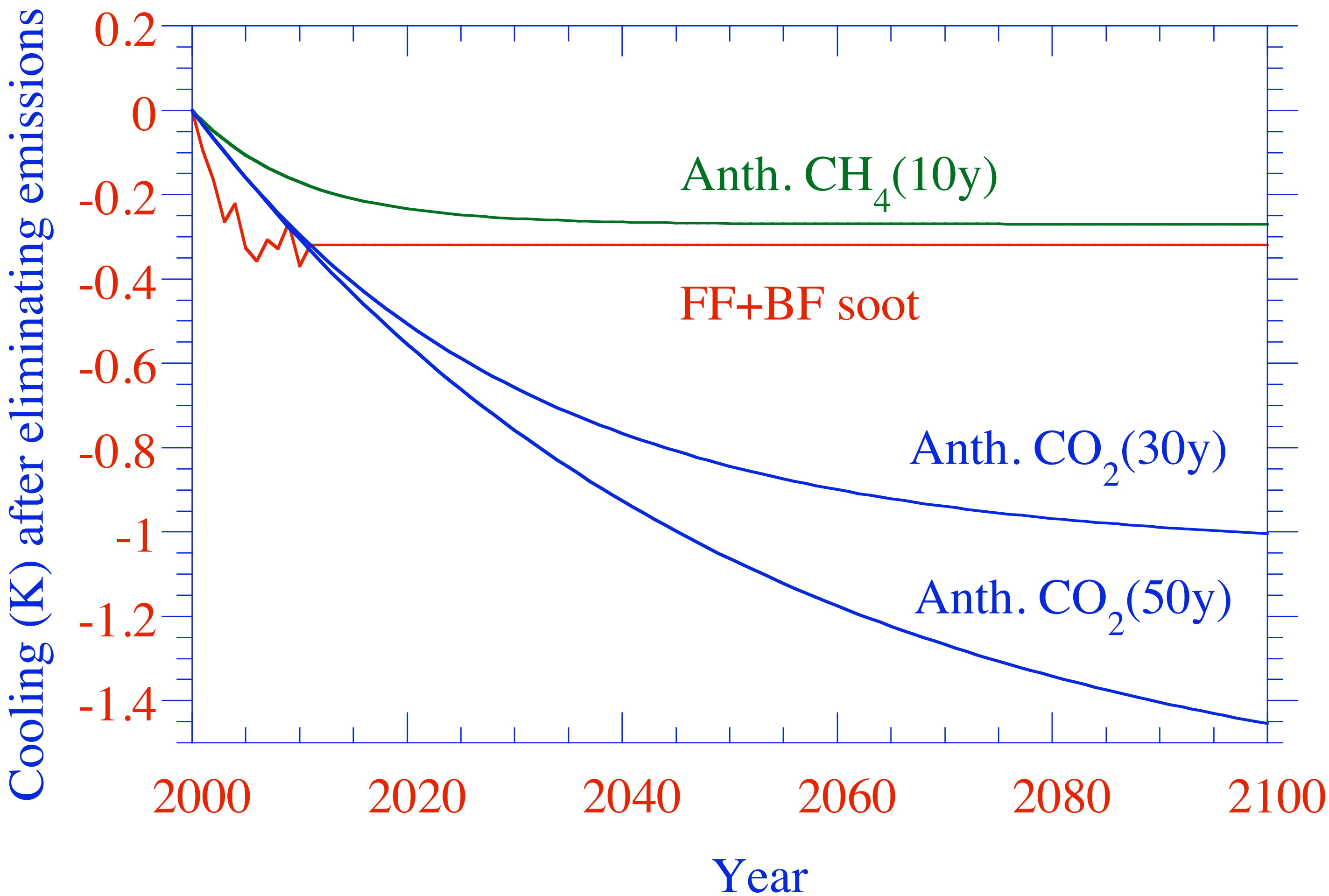
Model vs. Measured Solar Radiation

Model predicted the location and magnitude of cloud reduction of sunlight for four days in a row





Global Cooling Due to Eliminating Anthropogenic CO_2, CH_4, FF+BF Soot Emissions



FF Soot, BC Global Warming Potential

20- and 100-yr warming due to FF soot (ΔT-FF soot):	0.24 K
Global FF soot emissions) (ΔE-FF soot):	5.68 Tg
20-yr warming due to anthropogenic CO_2 (ΔT-CO_2):	0.5 K
100-yr warming due to anthropogenic CO_2 (ΔT-CO_2):	1-1.45 K
Global CO_2 emissions (fossil+perm. deforest.) (ΔE-CO_2)	29,700 Tg

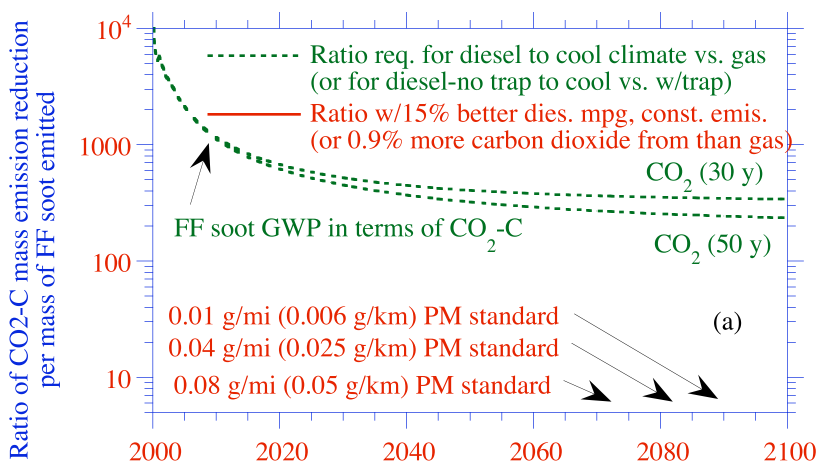
GWP = (ΔT-X/ΔE-X) / (ΔT-CO_2/ΔE-CO_2)

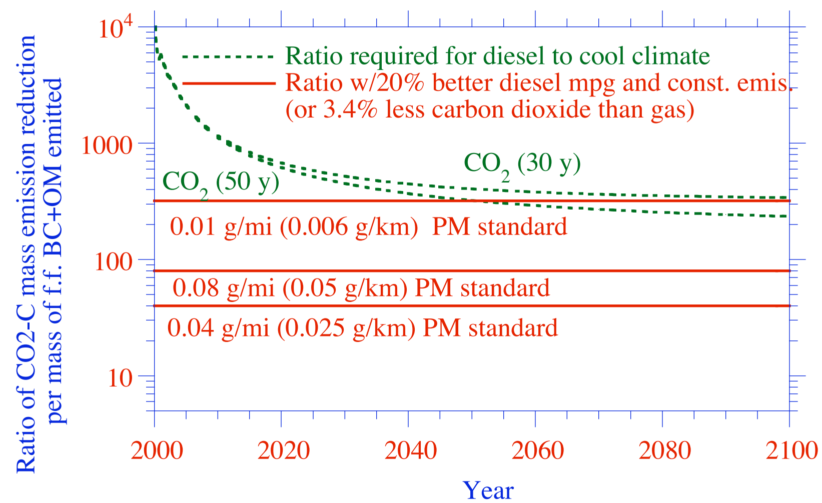
X	20-year GWP	100-year GWP
FF soot*	2510	865 - 1255
BC in FF soot	4480	1545 – 2240

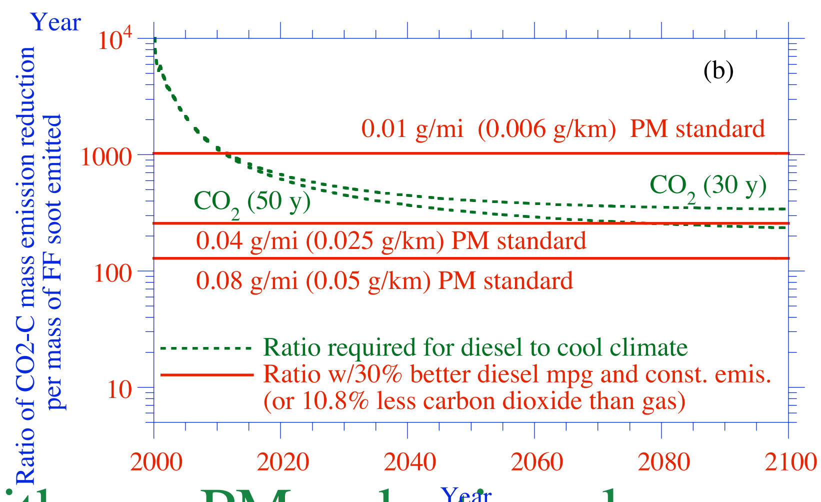
*(56% BC+43% POC+1% sulfate)

Multiply by 12/44 for GWP relative to CO_2-C

Diesel with vs. w/o Trap; Diesel v. Gas



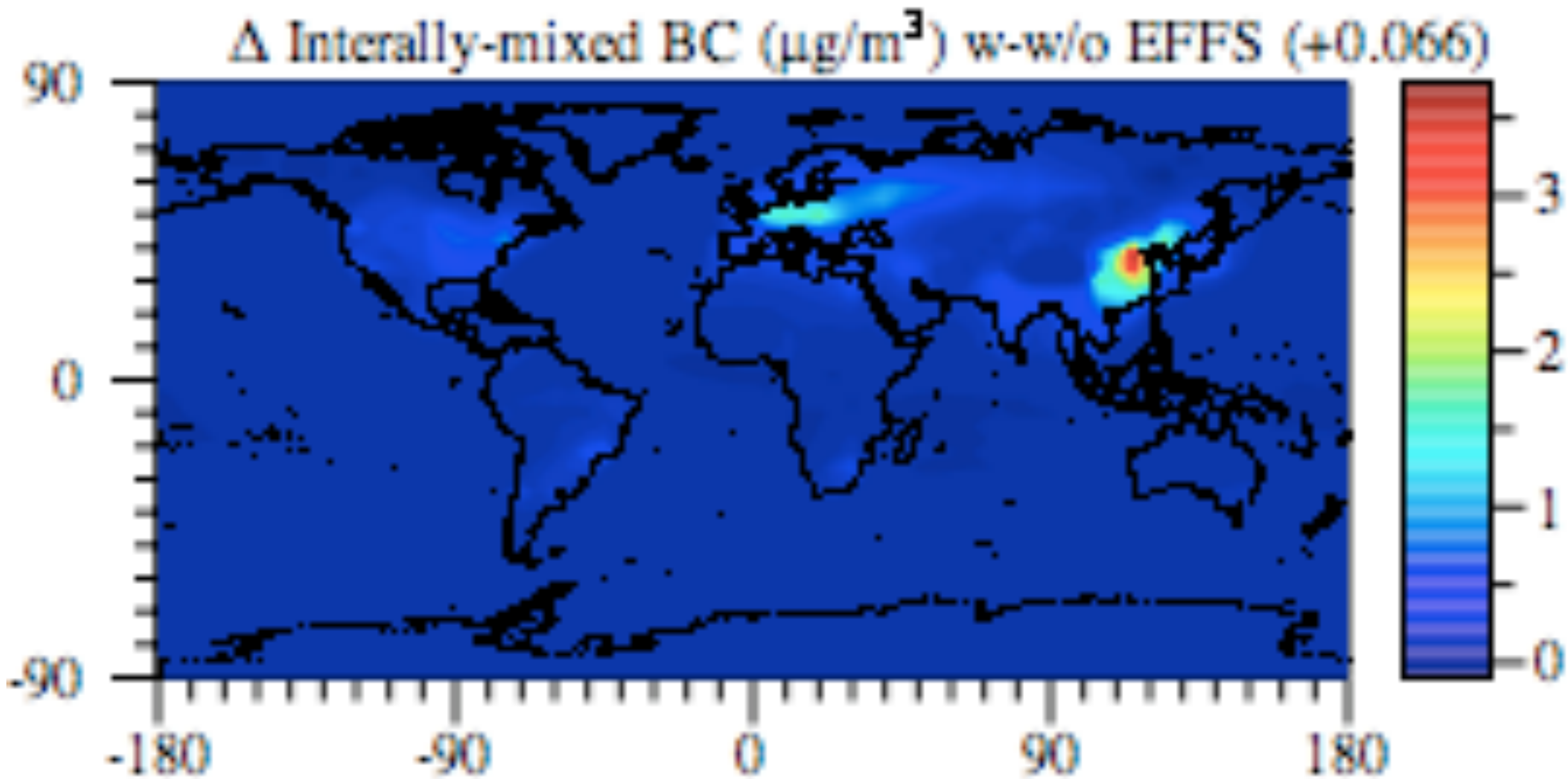




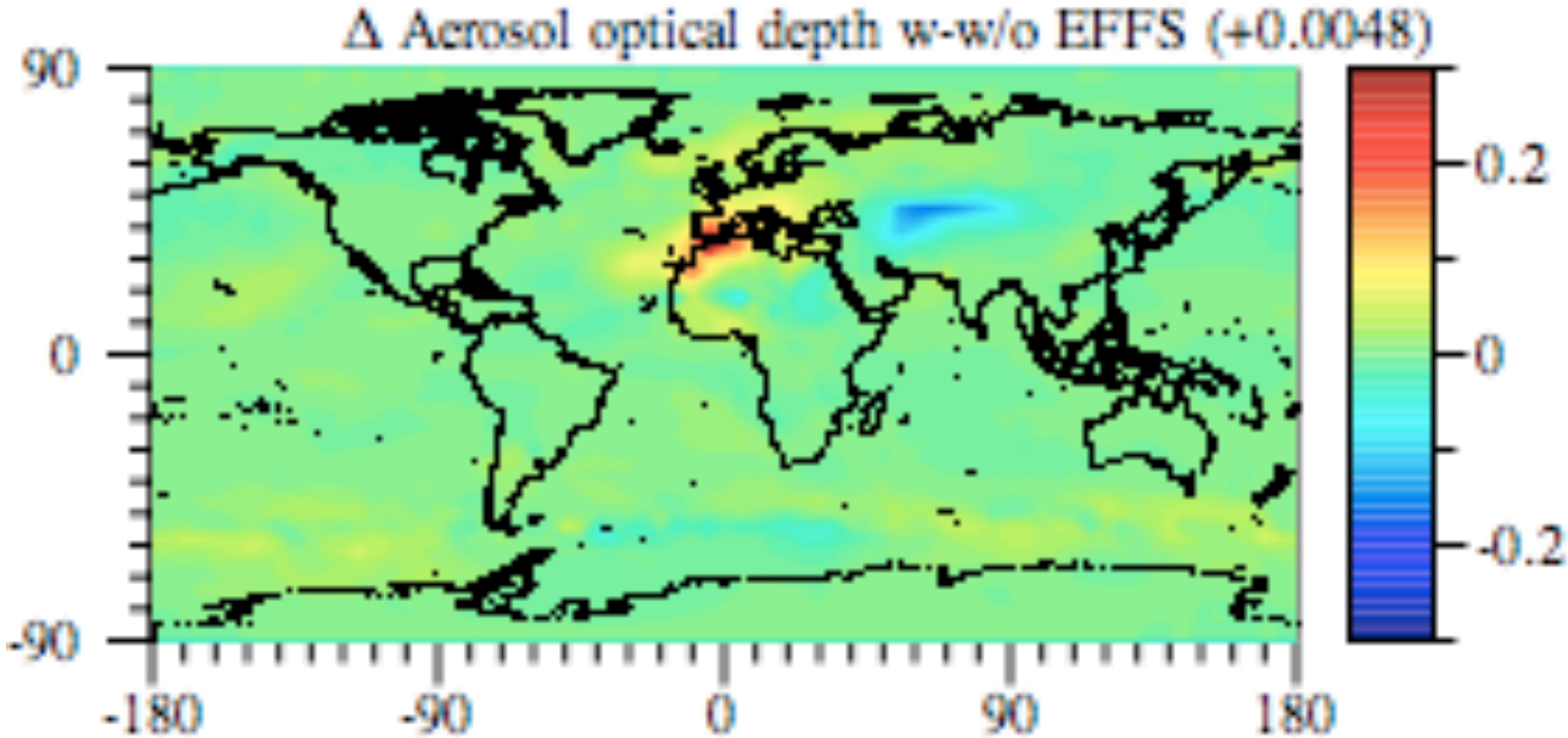
Adding a trap with any PM reduction always reduces warming over 100 years regardless if CO_2 at any fuel penalty < 30%

Gasoline vehicles reduce warming over diesel with a trap over 100 years when diesel has 18% or less mpg advantage over gas.

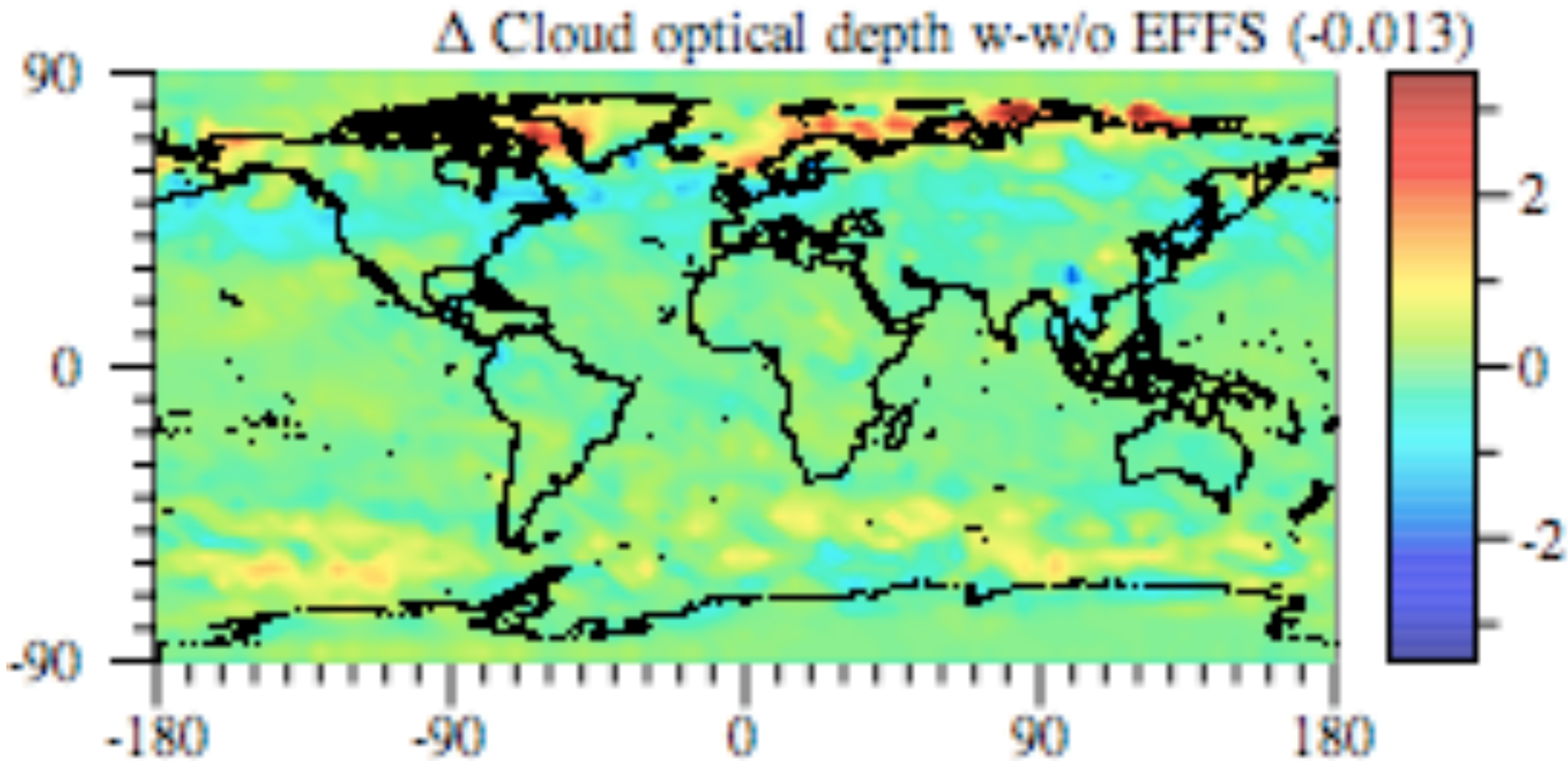
BC Changes Due to FF Soot after 6 years



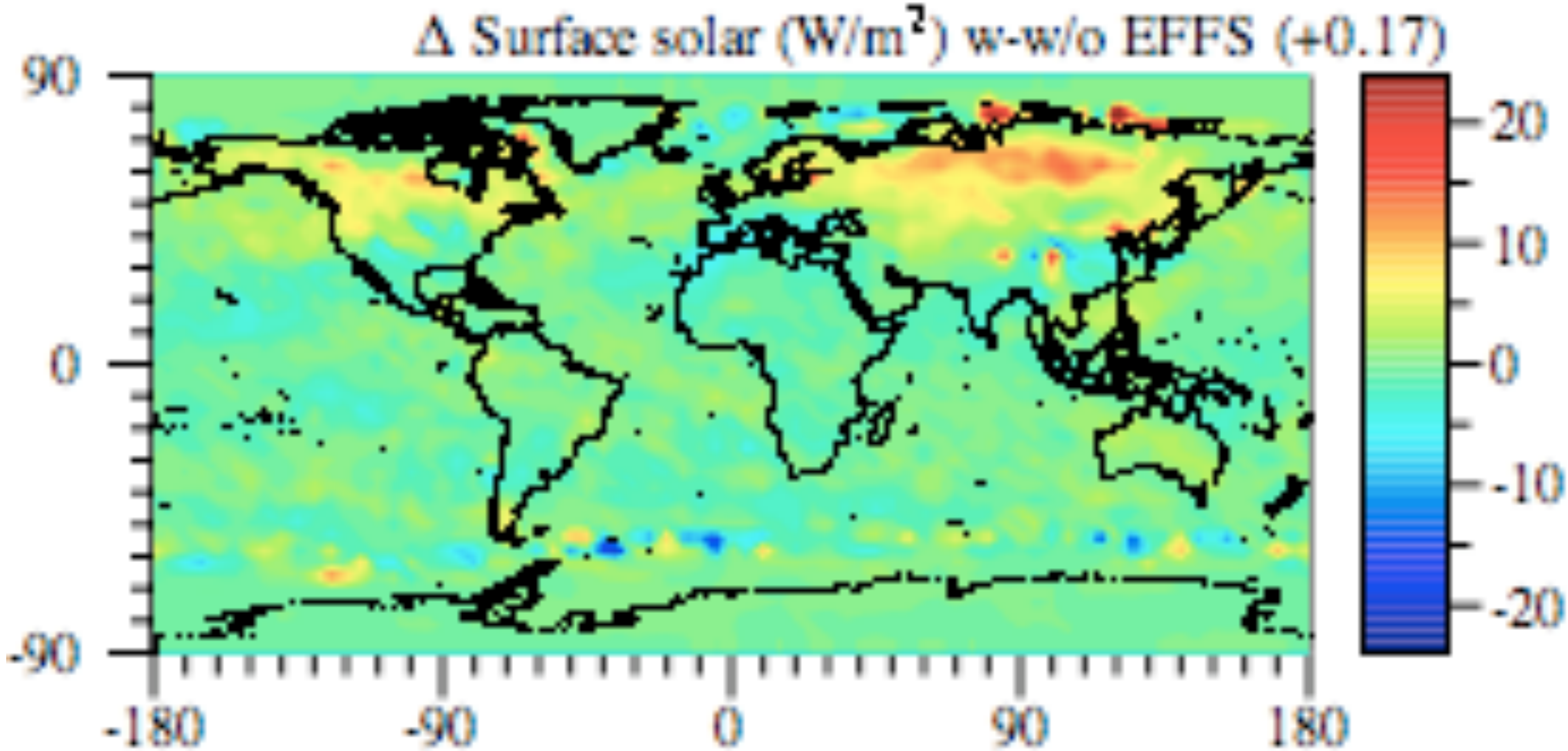
AOD Changes Due to FF Soot after 6 years



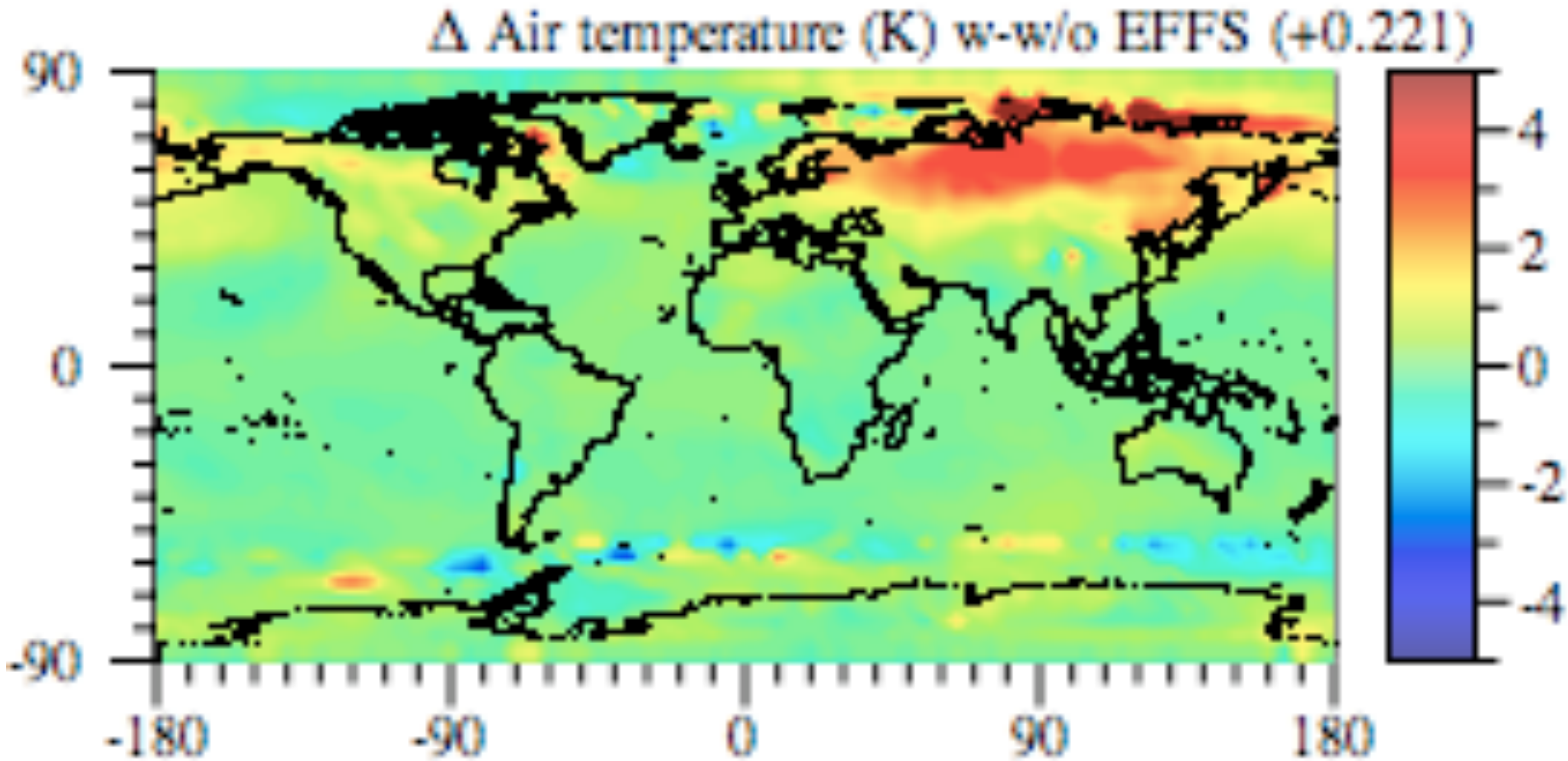
Cloud OD Changes Due to FF Soot



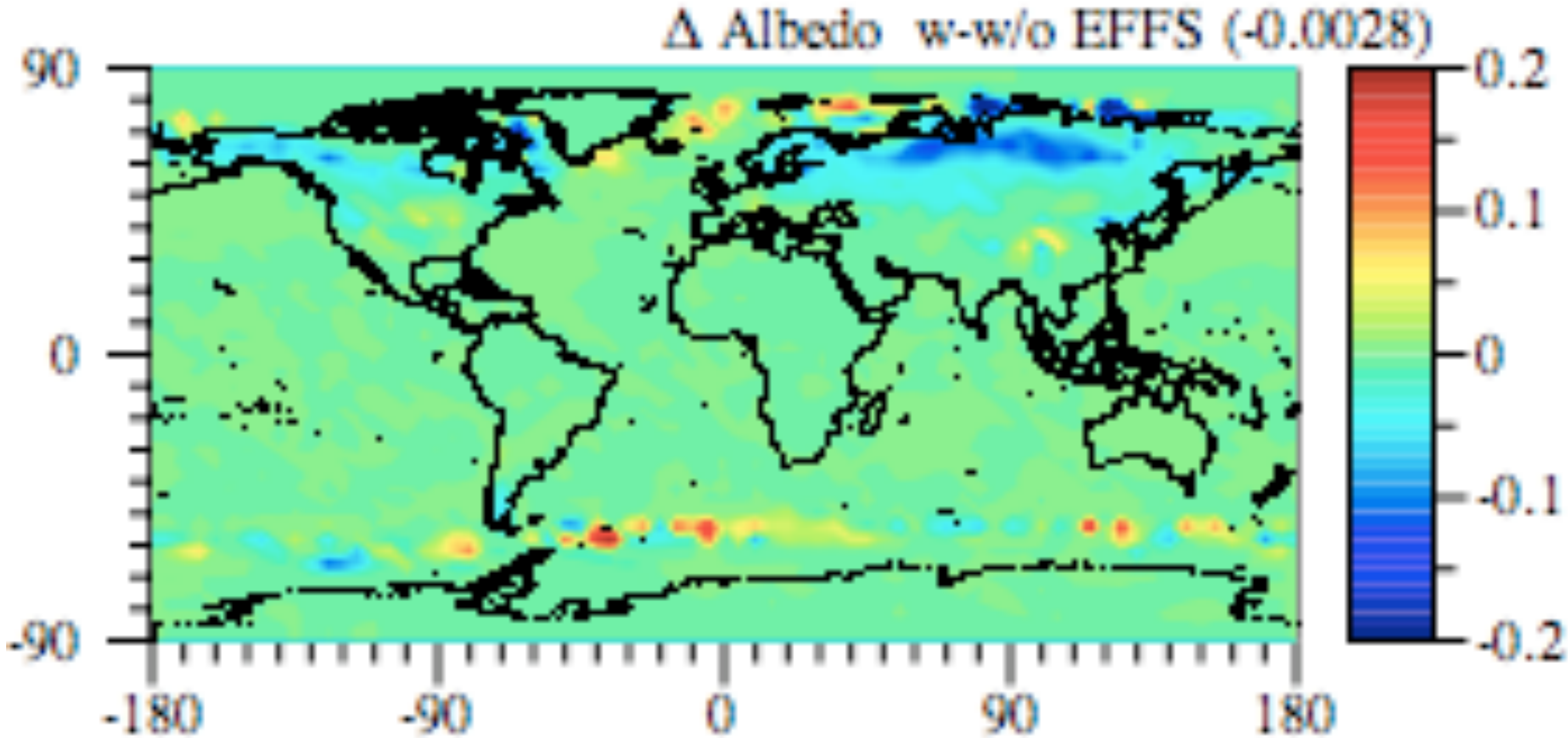
Surface Solar Changes Due to FF Soot



Temperature Changes Due to FF Soot (6 yr)



Surface Albedo Changes Due to FF Soot



Comparison of Energy Solutions to Global Warming

Electricity Sources

Wind turbines

Solar photovoltaics (PV)

Geothermal power plants

Tidal turbines

Wave devices

Concentrated solar power (CSP)

Hydroelectric power plants

Nuclear power plants

Coal with carbon capture and sequestration (CCS)

Liquid Fuel Sources

Corn ethanol (E85)

Cellulosic ethanol (E85)

Vehicle Technologies

Battery-electric vehicles (BEVs)

Hydrogen fuel cell vehicles (HFCVs)

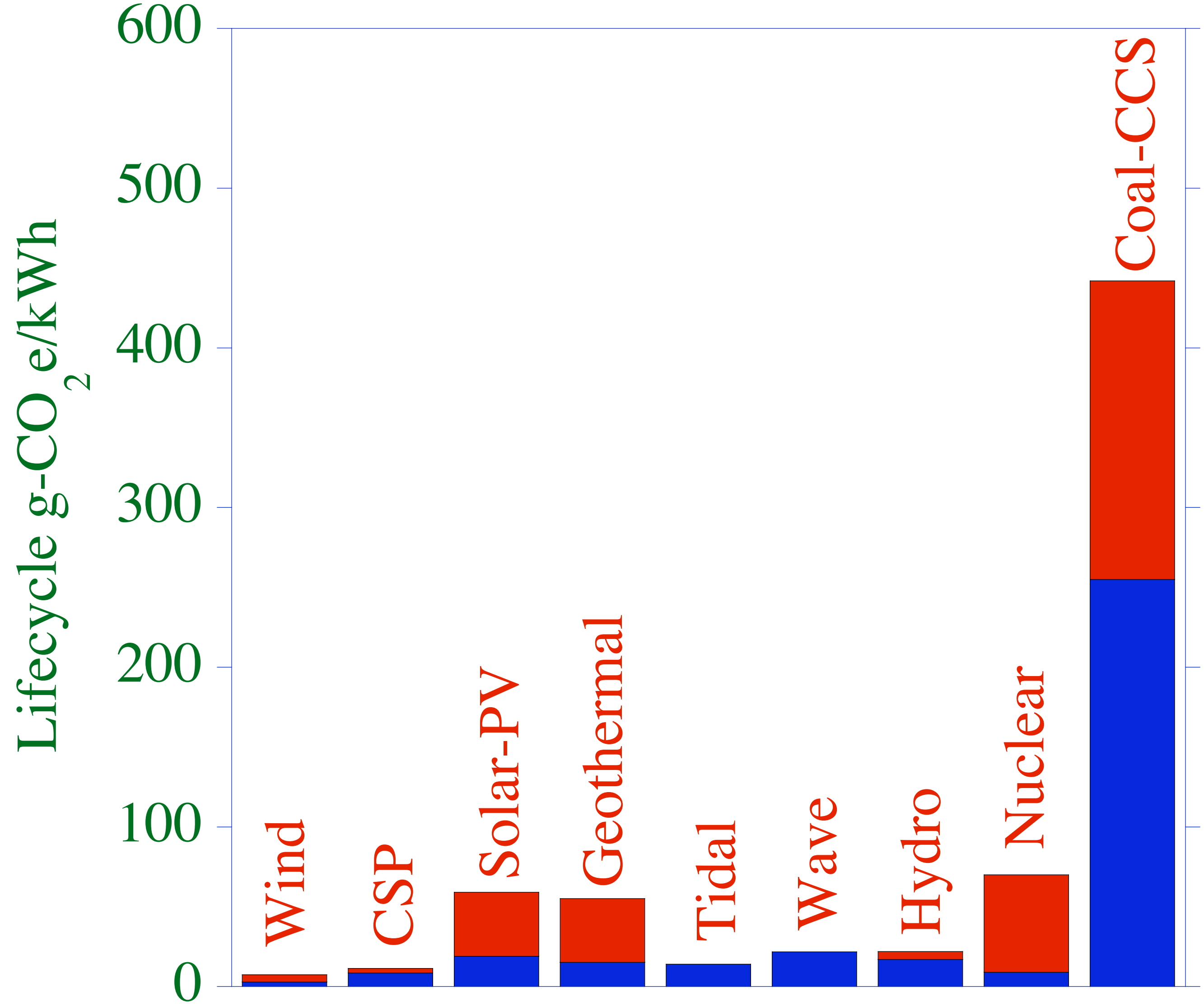
Flex-fuel vehicles (FFVs)

Effects Examined

Resource abundance
Carbon-dioxide equivalent emissions
- Lifecycle
- Opportunity cost emissions from planning-to-operation delays
- Leakage from carbon sequestration
- Nuclear war / terrorism emission risk from nuclear-energy

Air pollution mortality
Water consumption
Footprint on the ground
Spacing required
Effects on wildlife
Thermal pollution
Water chemical pollution / radioactive waste
Energy supply disruption
Normal operating reliability

Lifecycle CO_2e of Electricity Sources



Time Between Planning & Operation

Nuclear: 10-19 y (lifetime 40 y)

Site permit (NRC): 3.5 y minimum with new regs. – 6 y

Construction permit approval and issue 2.5-4 y

Construction time 4-9 years (Low value Europe/Japan)

Hydroelectric: 8-16 y (lifetime 80 y)

Coal-CCS: 6-11 y (lifetime 35 y)

Geothermal: 3-6 y (lifetime 35 y)

Ethanol: 2-5 y (lifetime 40 y)

CSP: 2-5 y (lifetime 30 y)

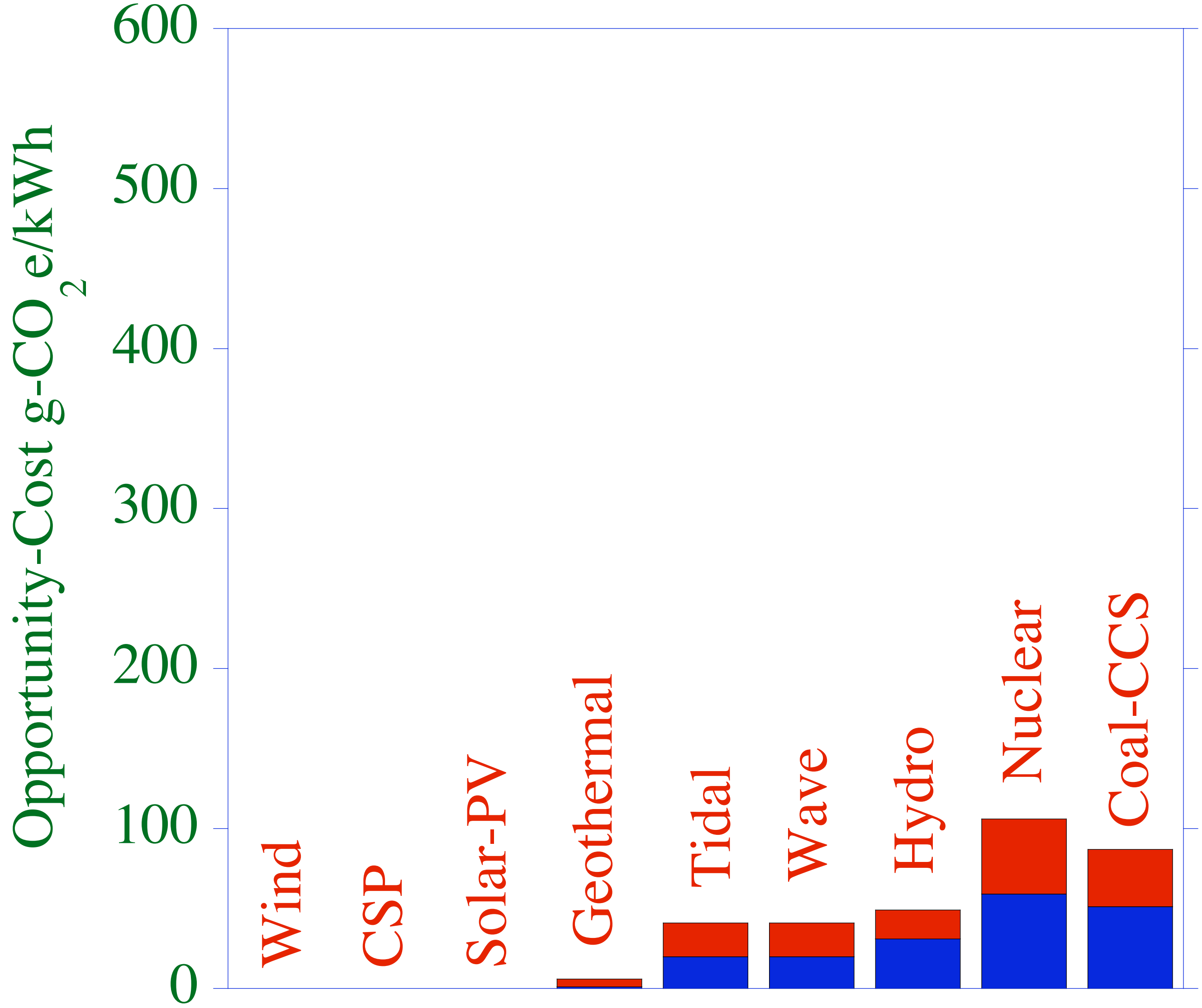
Solar-PV: 2-5 y (lifetime 30 y)

Wave: 2-5 y (lifetime 15 y)

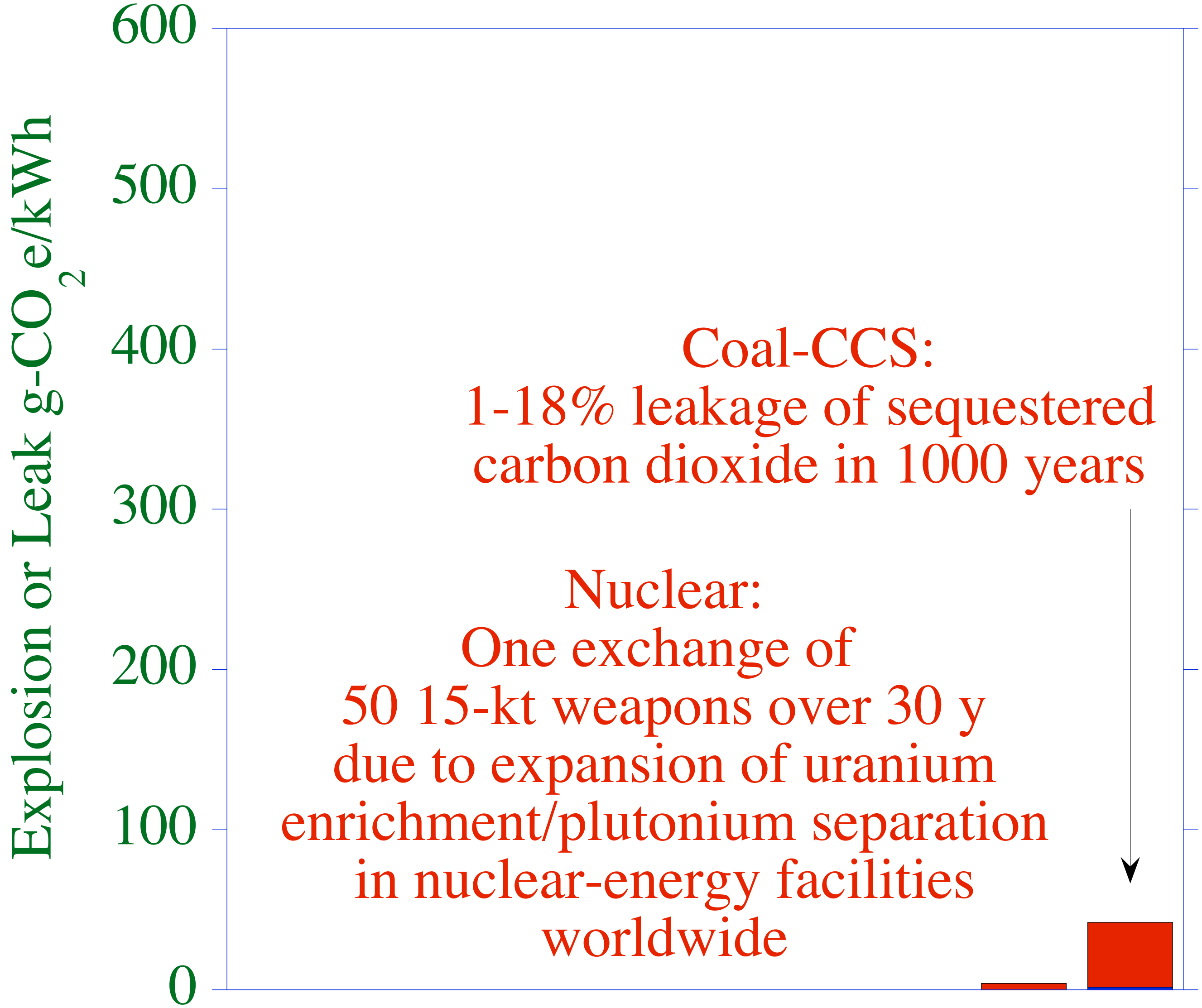
Tidal: 2-5 y (lifetime 15 y)

Wind: 2-5 y (lifetime 30 y)

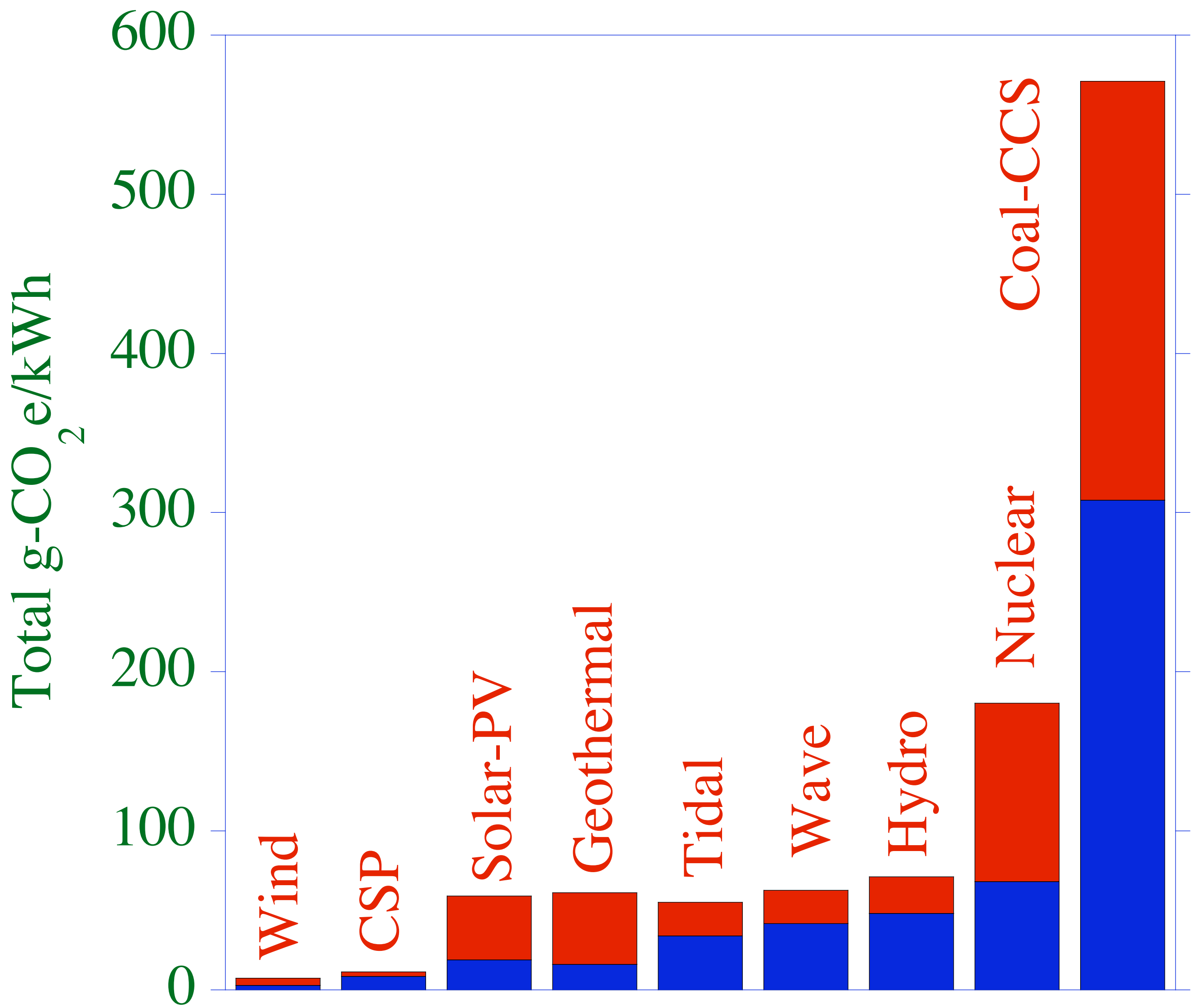
Opportunity-Cost CO_2e of Electricity Sources



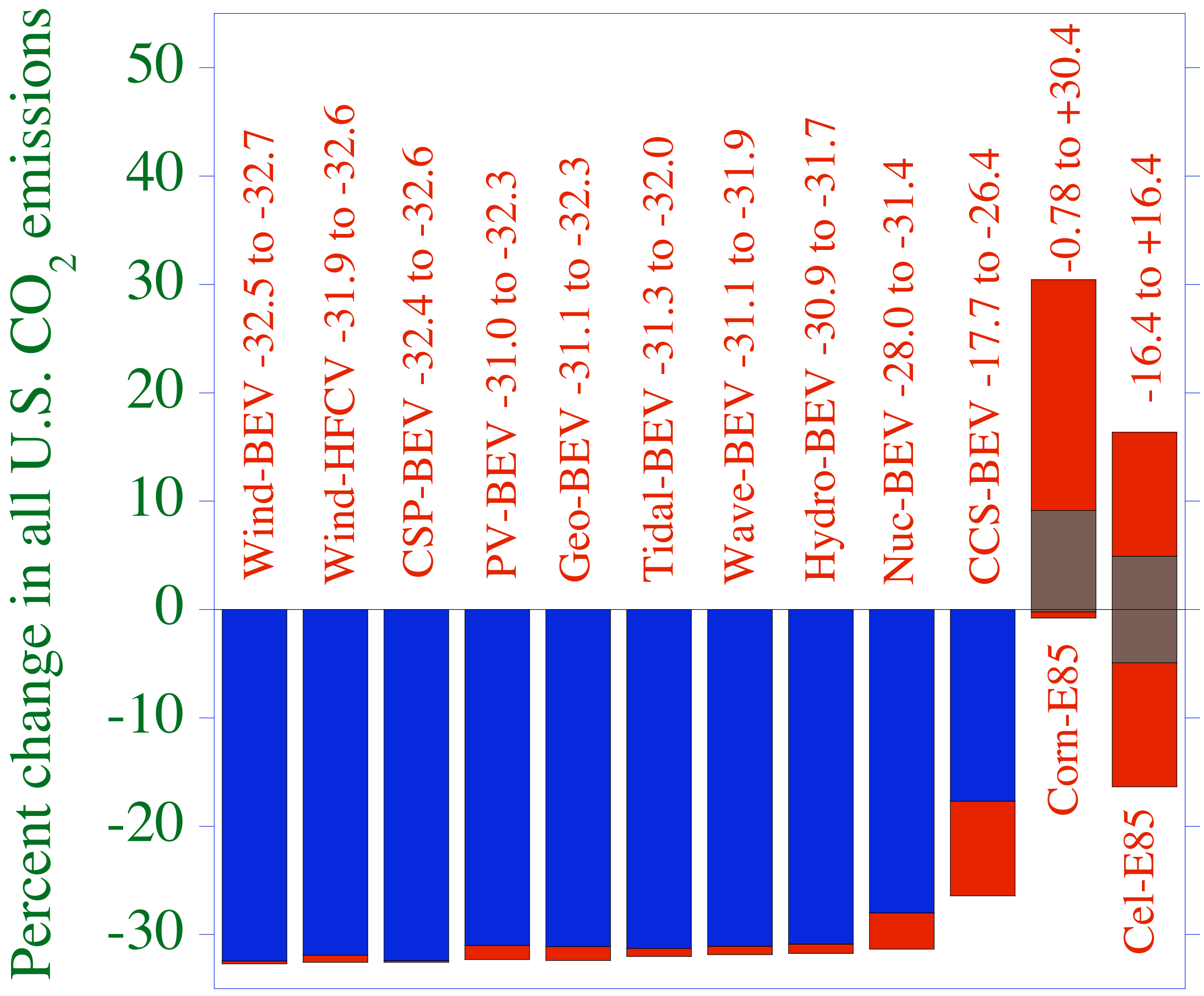
War/Leakage CO_2e of Nuclear, Coal



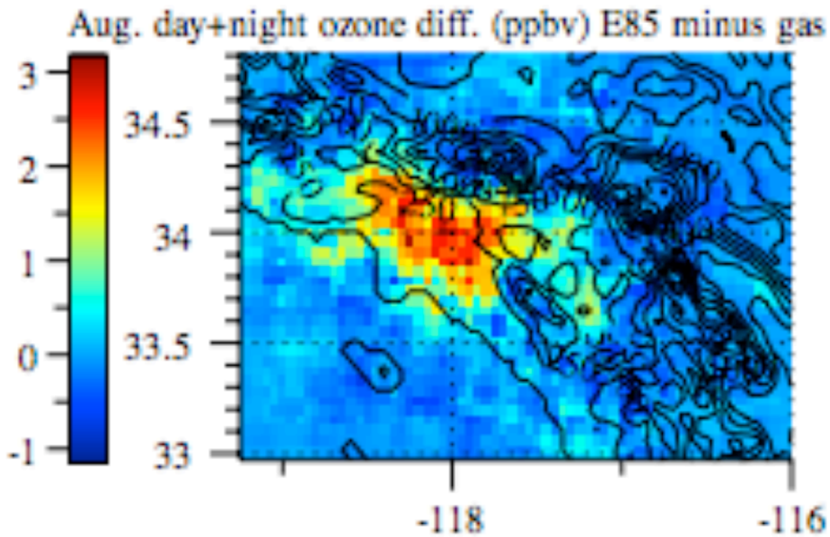
Total CO_2e of Electricity Sources

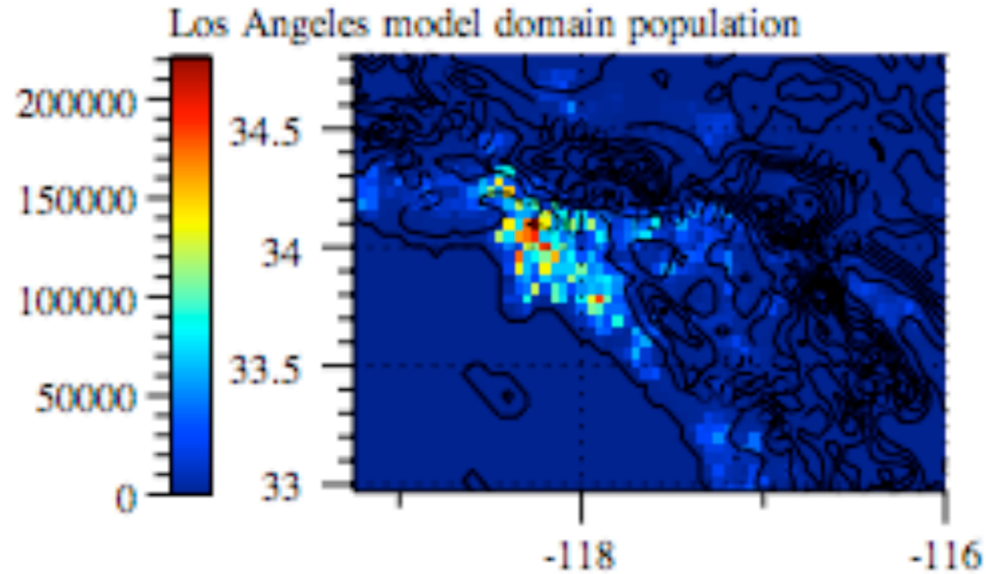


Percent Change in U.S. CO_2 From Converting to BEVs, HFCVs, or E85



Effect in 2020 of E85 vs. Gasoline on Ozone and Health in Los Angeles

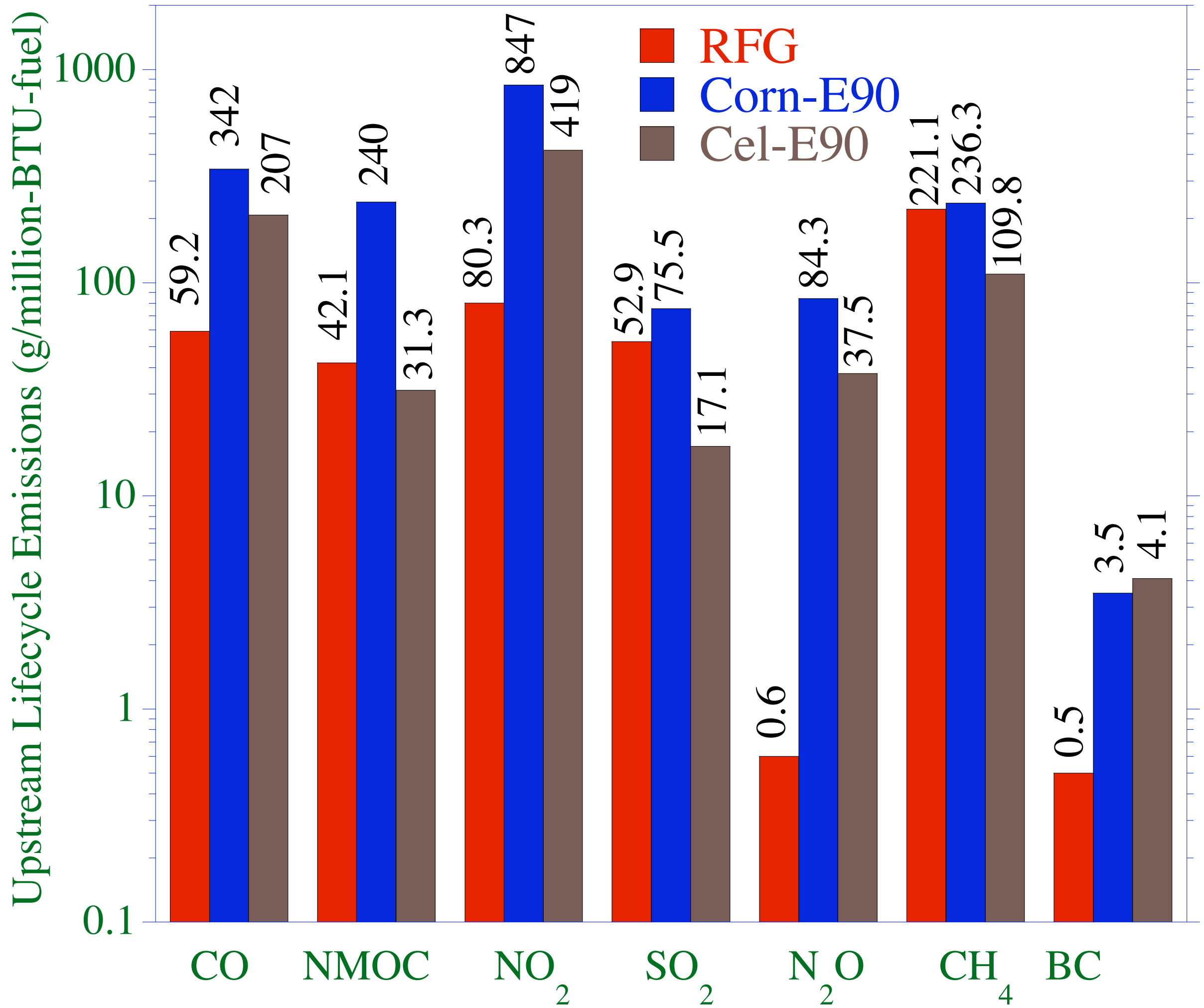




Change in ozone deaths/yr due to E85: +120 (+9%) (47-140)

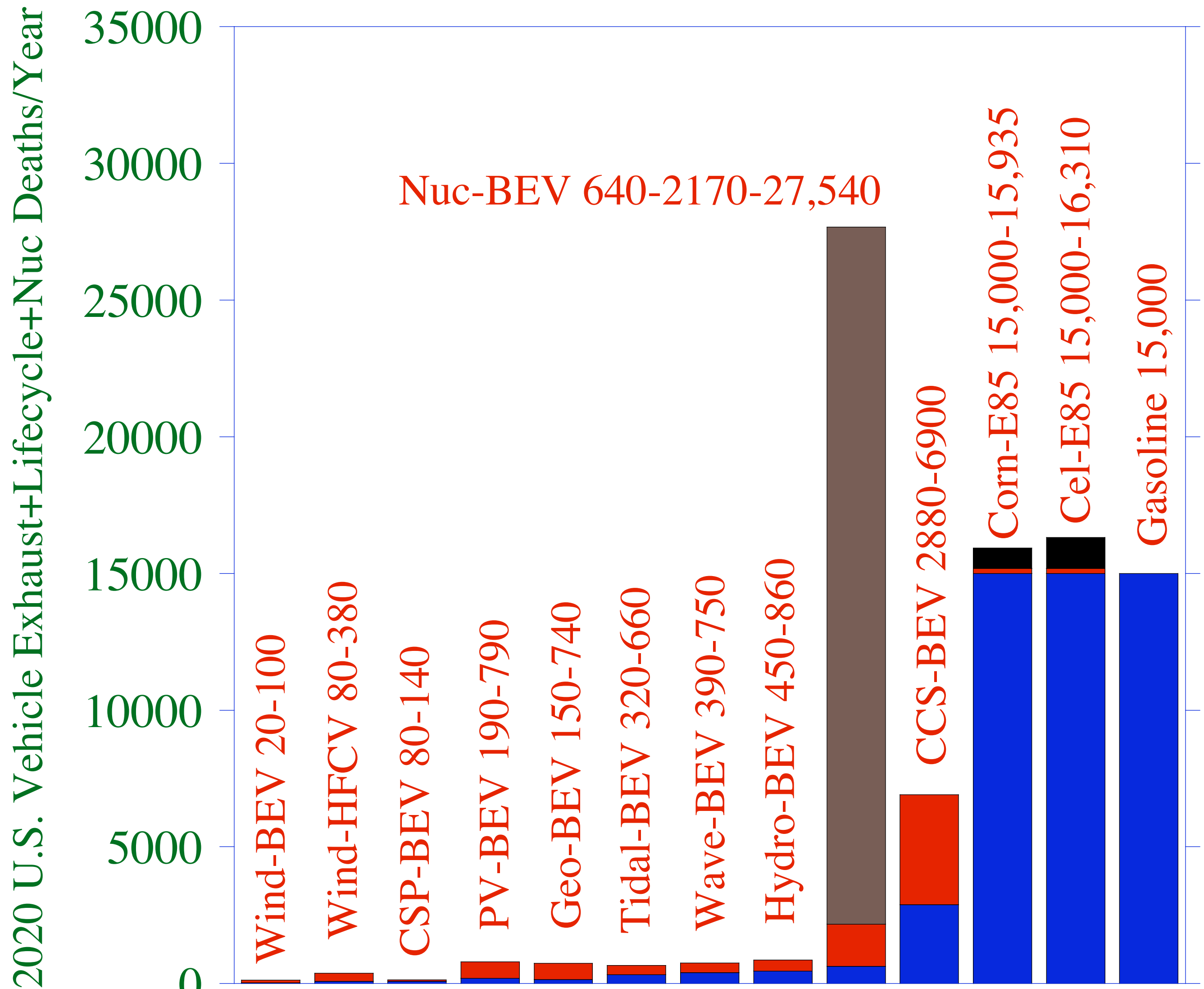
Changes in cancer/yr due to E85: -3.5 to +0.3

Upstream Lifecycle Emissions Gasoline, Corn-E90, Cellulosic-E90



DeLucchi, 2006

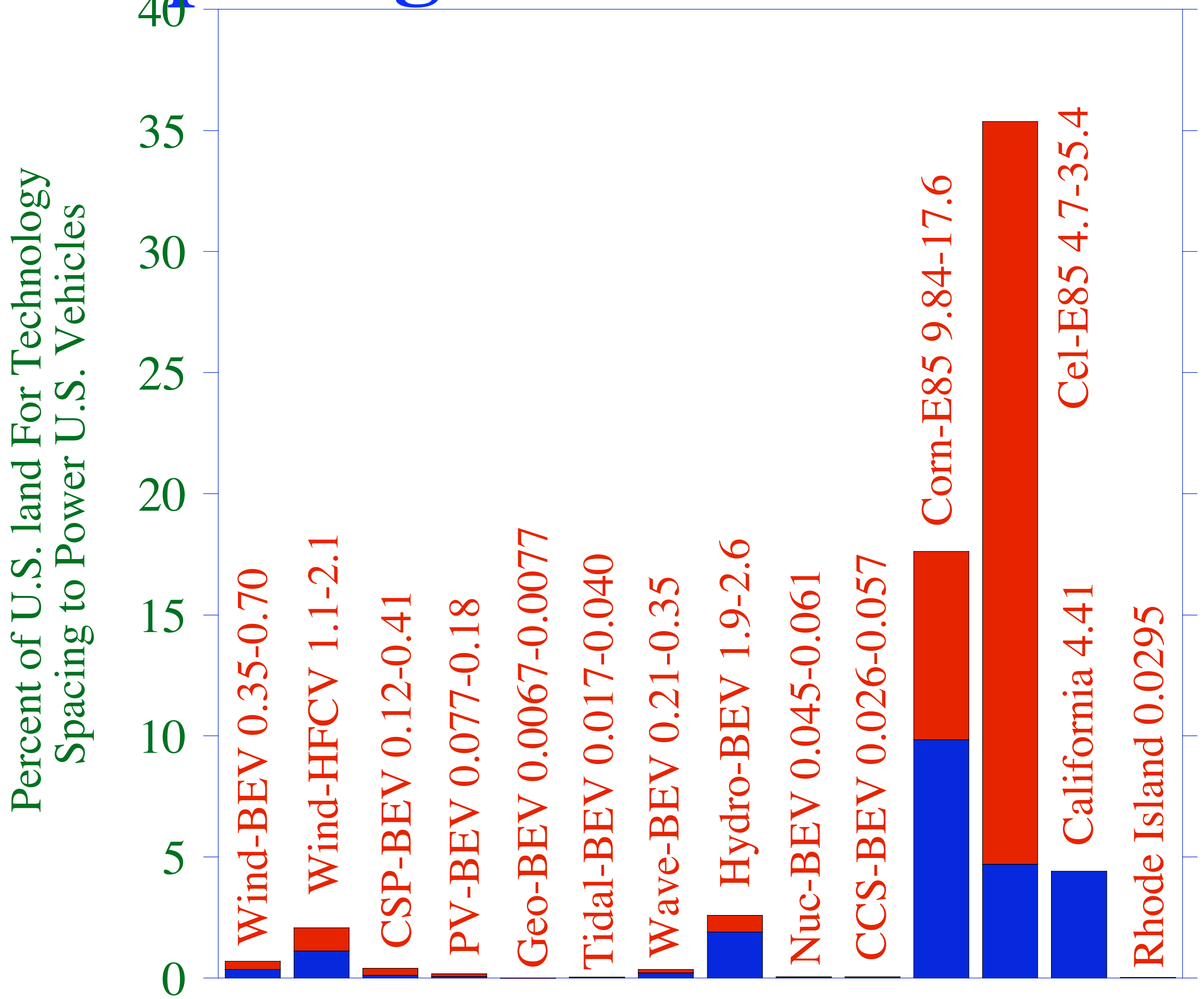
Low/High U.S. Air Pollution Deaths For 2020 BEVs, HFCVs, E85, Gasoline



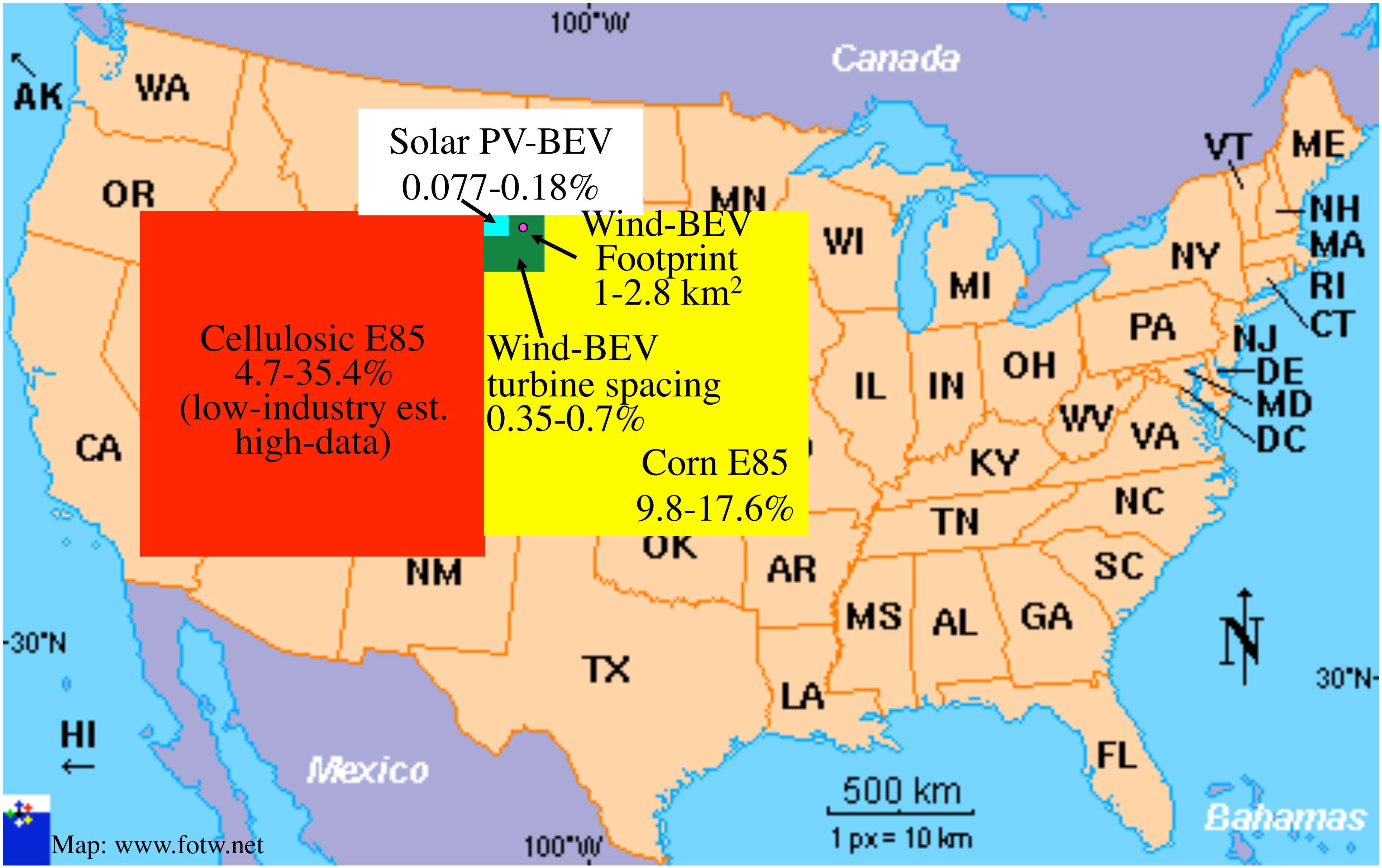
Ratio of Footprint Area of Technology to Wind-BEVs to Run All U.S. Vehicles

Wind-BEV	1:1 (1-3 square kilometers)
Wind-HFCV	3-3.1:1
Tidal-BEV	100-130:1
Wave-BEV	240-440:1
Geothermal-BEV	250-570:1
Nuclear-BEV	770-1100:1
Rhode Island	960-3000:1
Coal-CCS-BEV	1900-2600:1
PV-BEV	5800-6600:1
CSP-BEV	12,200-13,200:1
Hydro-BEV	84,000-190,000:1
California	143,000-441,000:1
Corn-E85	570,000-940,000:1
CSP-BEV	470,000-1,150,000:1

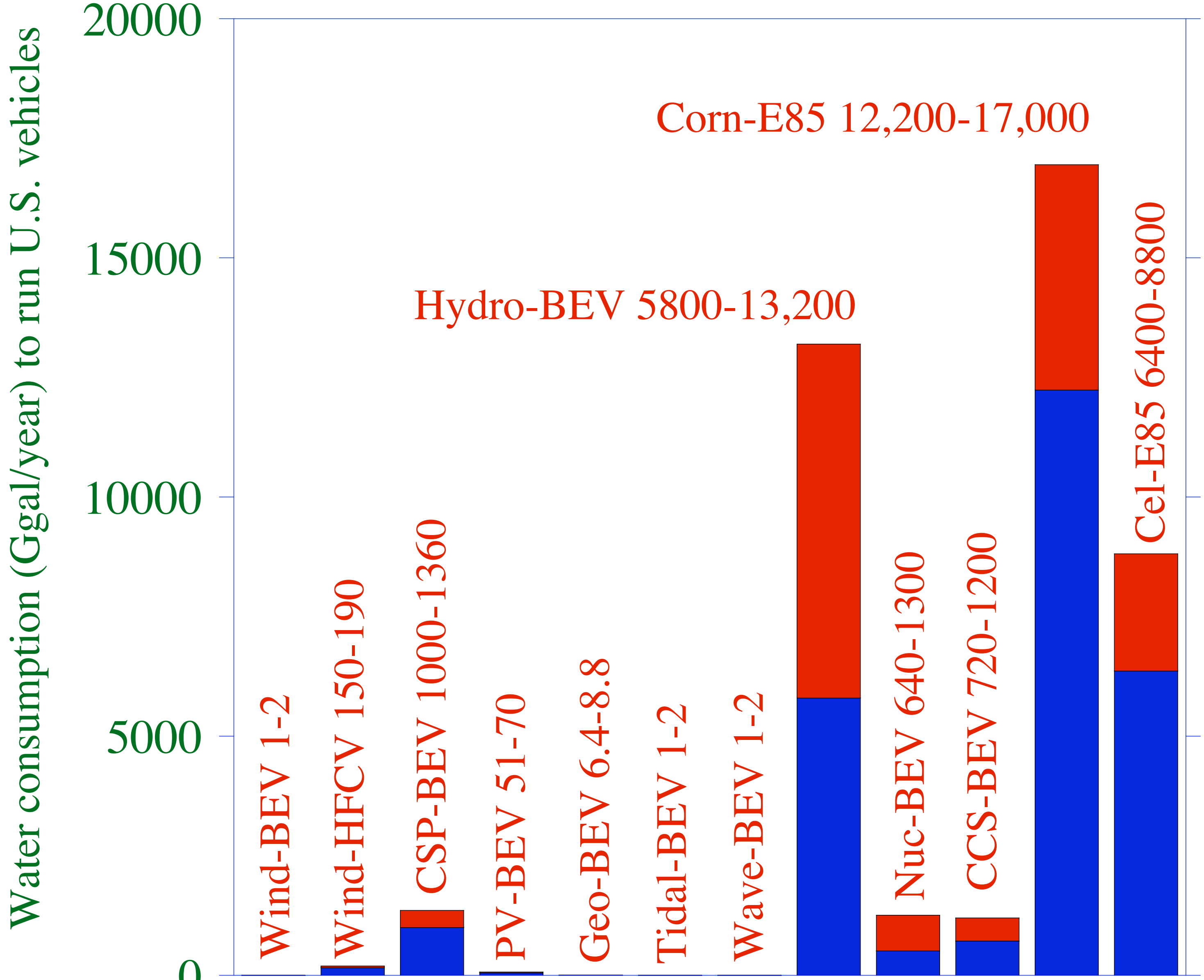
Percent of U.S. (50 states) for Footprint + Spacing to Run U.S. Vehicles



Area to Power 100% of U.S. Onroad Vehicles



Water Consumed to Run U.S. Vehicles



U.S. water demand = 150,000 Ggal/yr

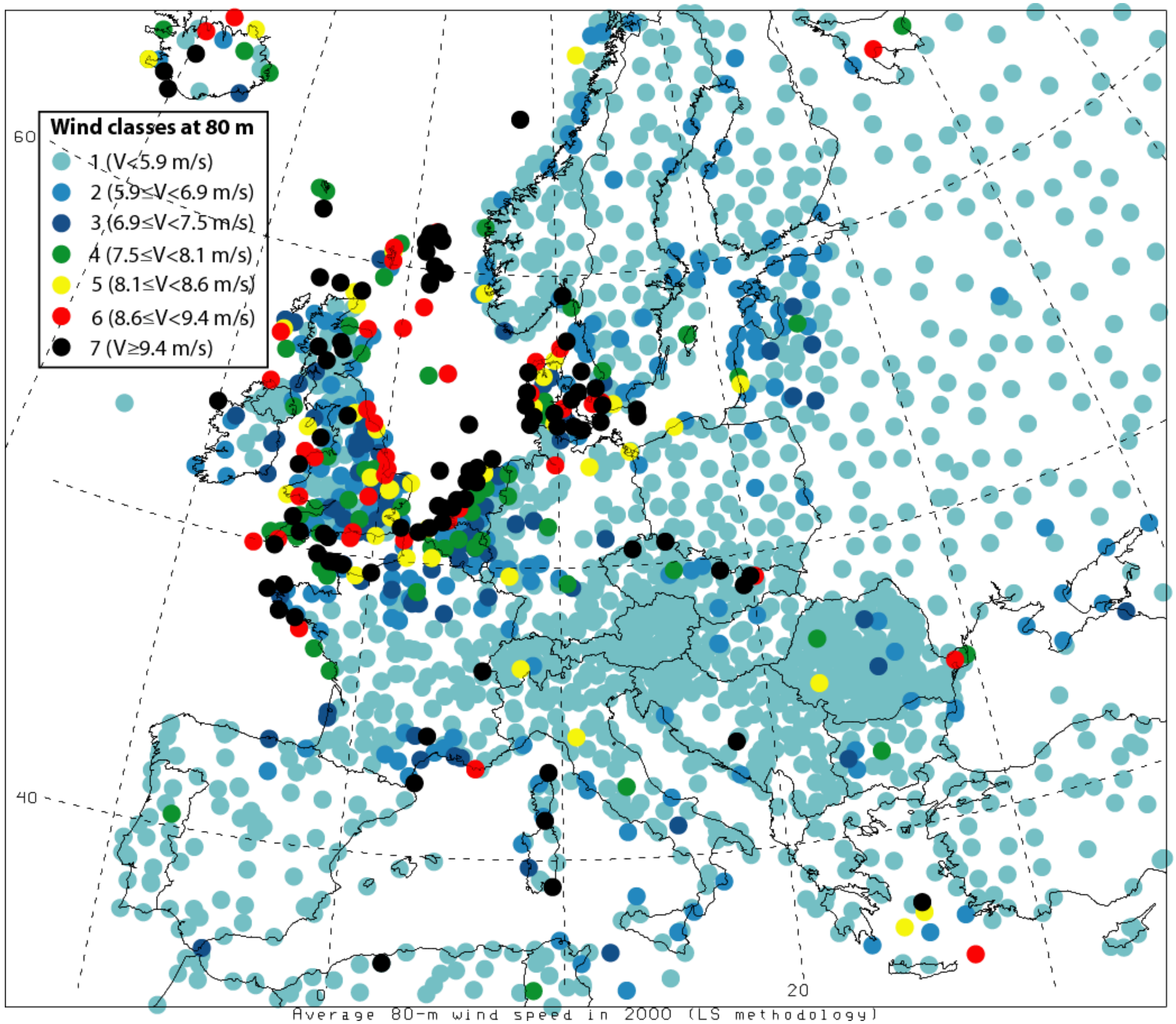
Global Wind, Solar Availability

	Max	Potential	Current
Wind over land > 6.9 m/s (TW)	72	47	0.02
Solar over land (TW)	1700	340	0.001

Global electric power demand (TW)	1.6-1.8
Global overall power demand (TW)	9.4-13.6

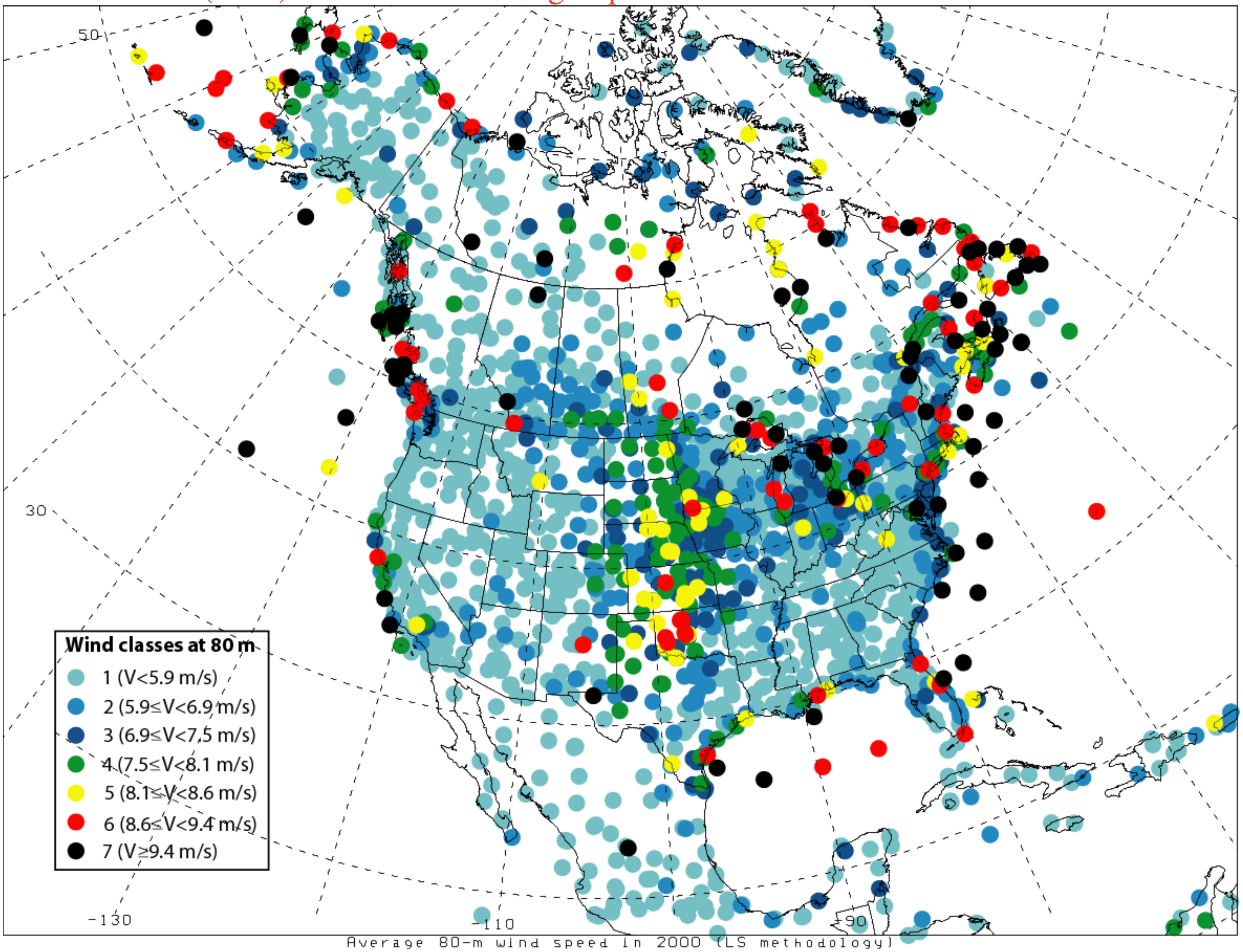
Mean 80-m Wind Speed in Europe

Archer and Jacobson (2005) www.stanford.edu/group/efmh/winds/



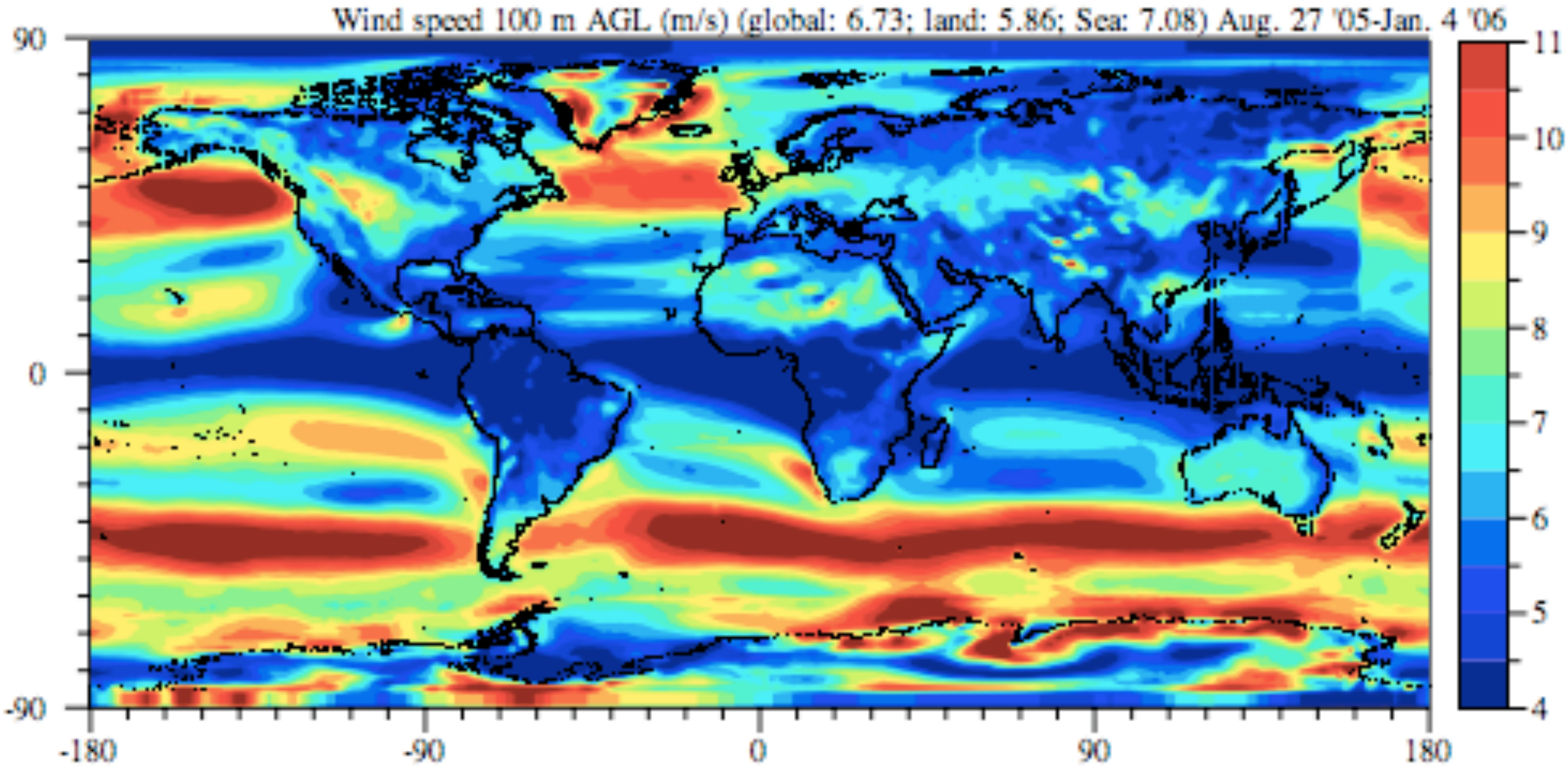
Mean 80-m Wind Speed in North America

Archer and Jacobson (2005) www.stanford.edu/group/efmh/winds/

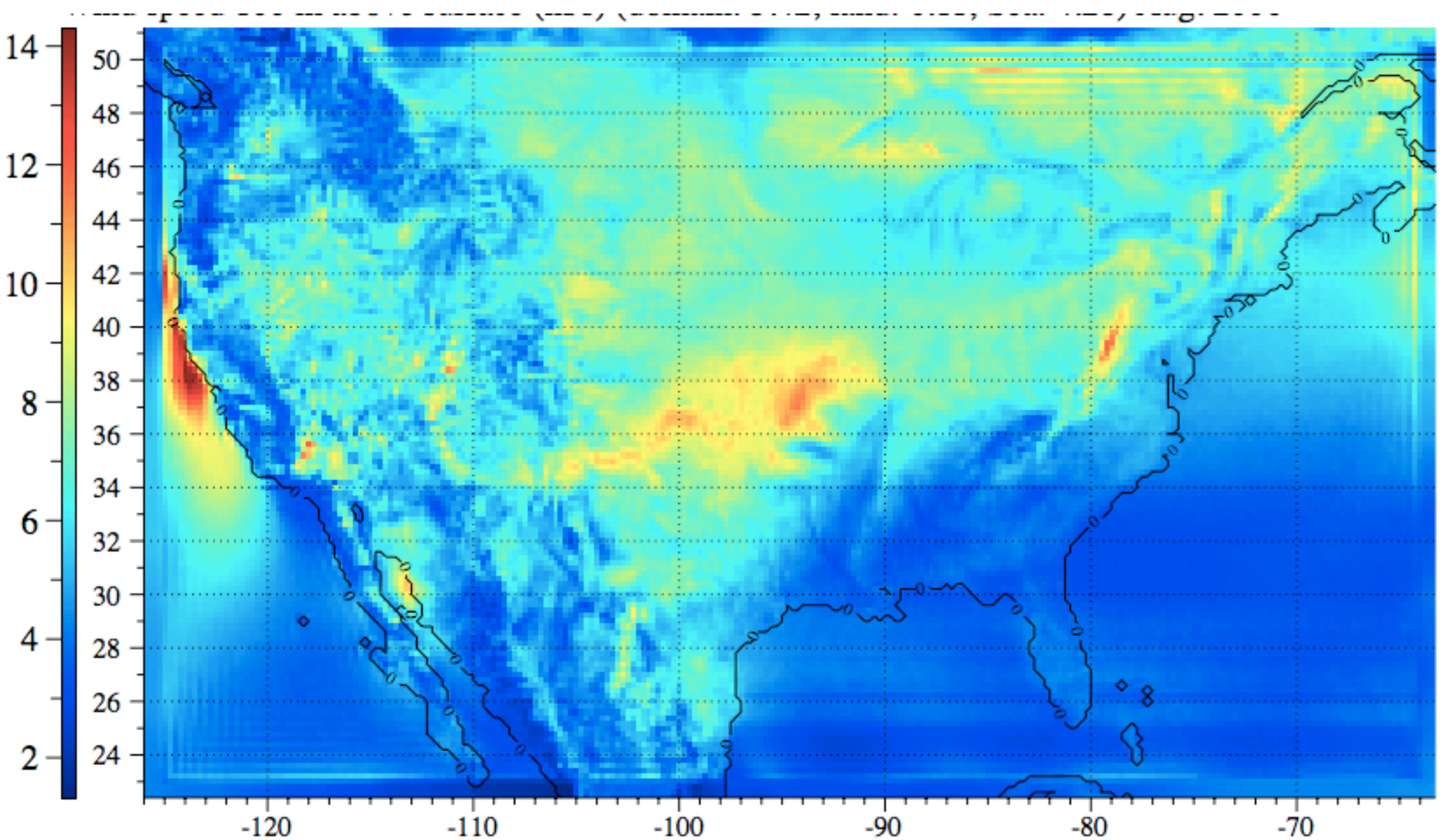


Modeled World Wind Speeds at 100 m

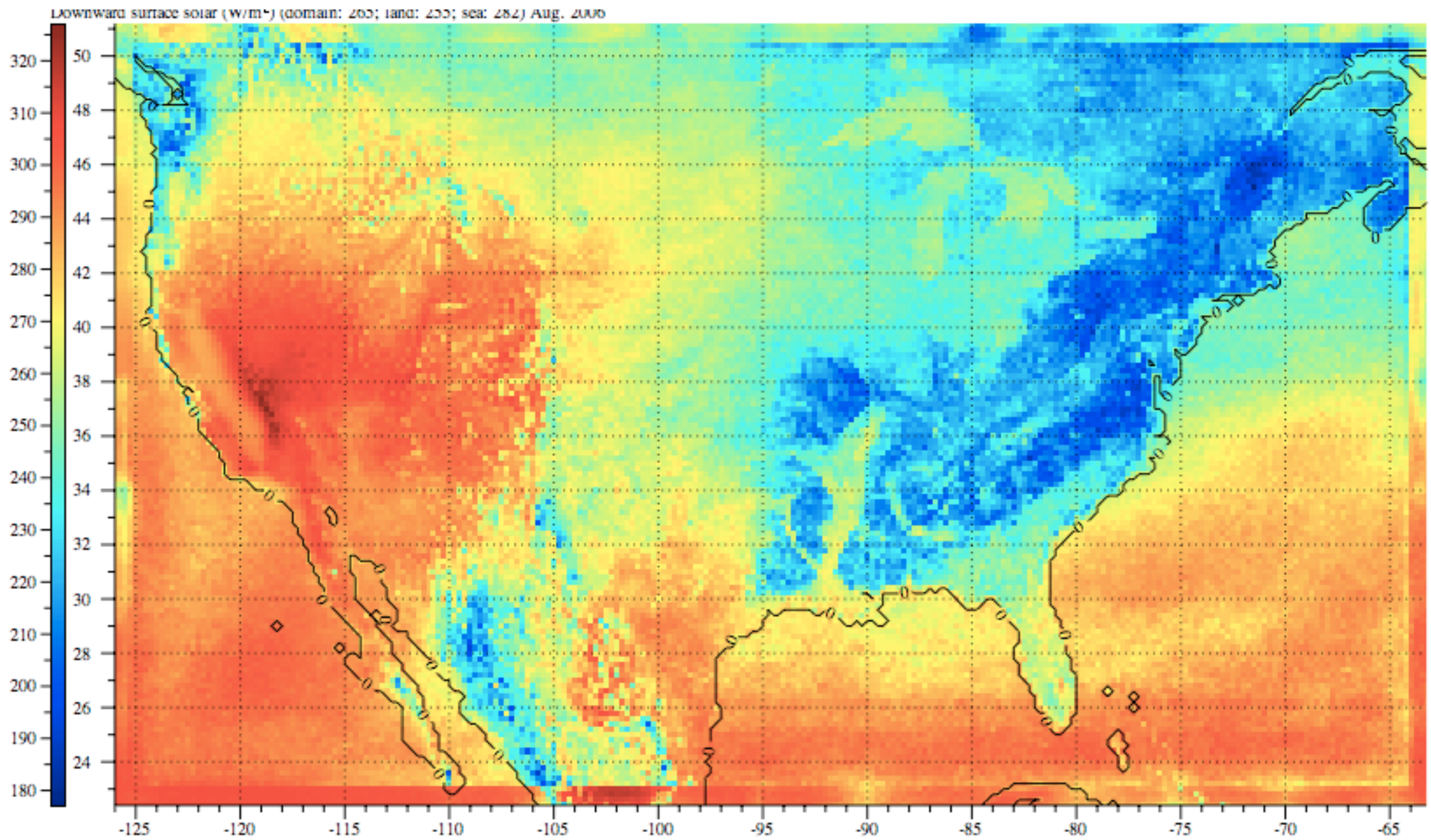
Average wind power over land outside Antarctica where wind speed > 6.9 m/s ~ 100 TW



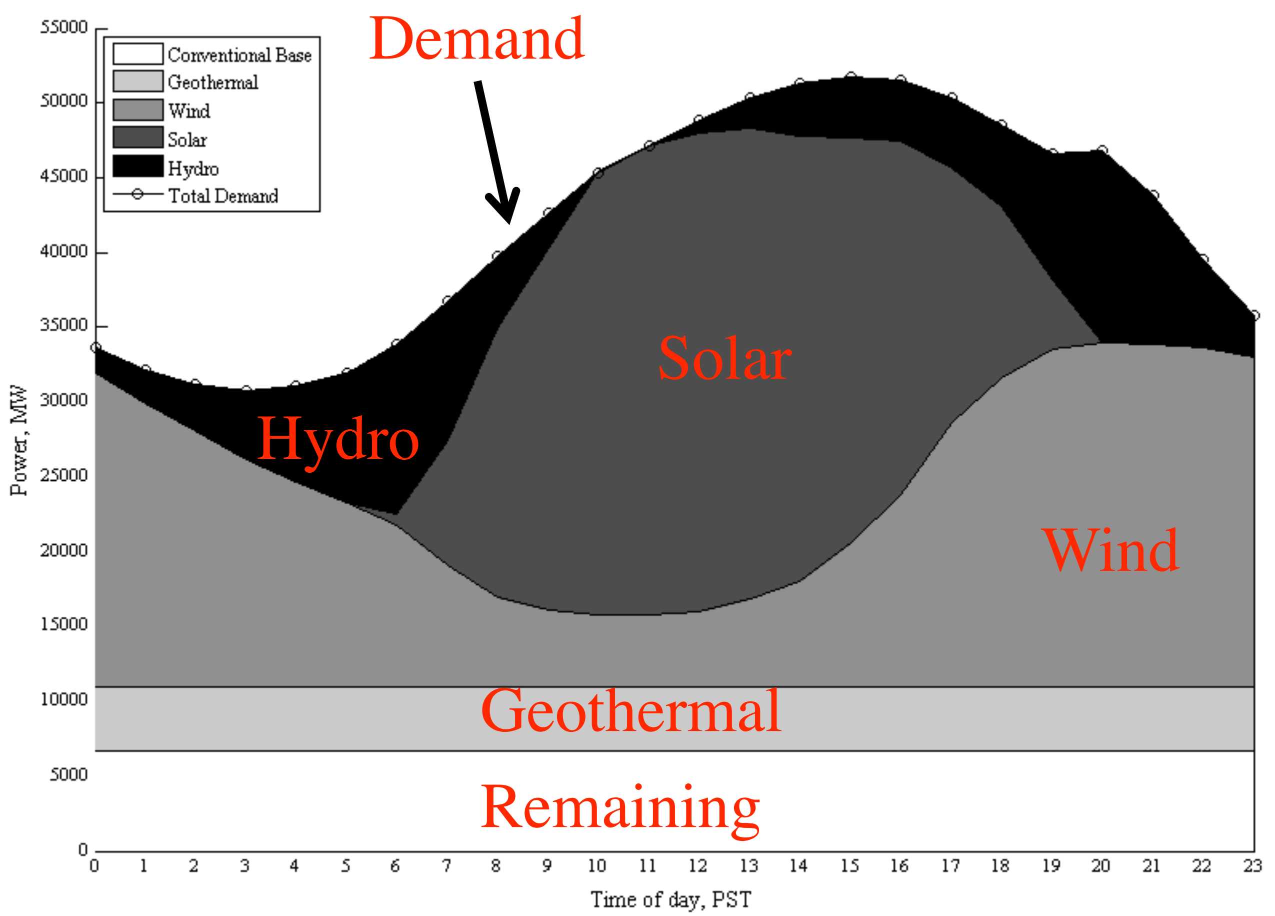
Modeled Aug. U.S. Wind Speeds at 100 m



Modeled Aug. U.S. Downward Surf. Solar

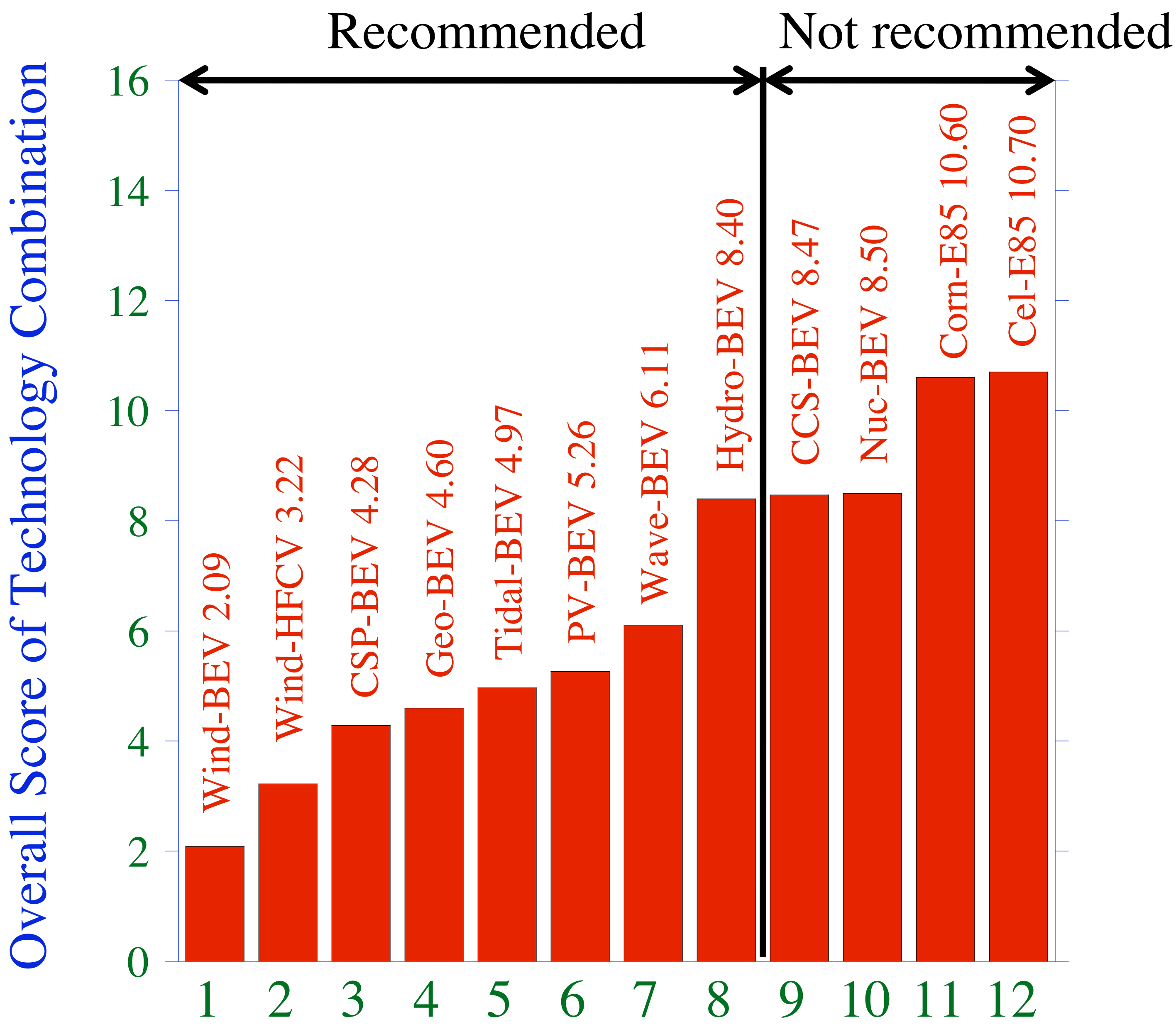


Matching Hourly Electricity Demand in Summer 2020 With 80% Renewables with no change in current hydro



Hoste et al. (2008)

Overall Scores/Rankings (Lowest is Best)



Summary

The GWP of fossil-fuel soot, based on repeated results over multiple simulations with a model evaluated against data for numerous parameters on several scales is estimated to be ~860-1260 over 100 years and ~2500 over 20 years.

Adding a particle trap to a diesel vehicle is always expected to reduce global warming, even in the case of a large fuel penalty for the trap, due to the strong warming effect of black carbon.

Regardless of improvements due to a trap, the conversion of combustion vehicles to battery electric or hydrogen fuel cell vehicles powered by clean electricity provide significantly better benefits than a diesel with a trap.

Summary

The use of wind CSP, geothermal, tidal, PV, wave, and hydro to provide electricity for battery-electric and hydrogen fuel cell vehicles and, by extension, electricity for the residential, industrial, and commercial sectors, will result in the most global warming, air pollution, and other externality benefits among the energy options considered here. The combination of these technologies should be advanced as a solution to global warming, air pollution, and energy security.

Coal-CCS and nuclear offer less benefit thus represent a climate and health opportunity cost loss and should not be advanced over these other options.

Corn and cellulosic ethanol provide no provable benefit and the greatest negative impacts thus their advancement over other options will severely damage efforts to solve global warming and air pollution problems.

More at
www.stanford.edu/group/efmh/jacobson/revsolglobwarmairpol.htm
Energy Environ. Sci. (2008) doi:10.1039/b809990C