

# Causes of and Solutions to Global Warming

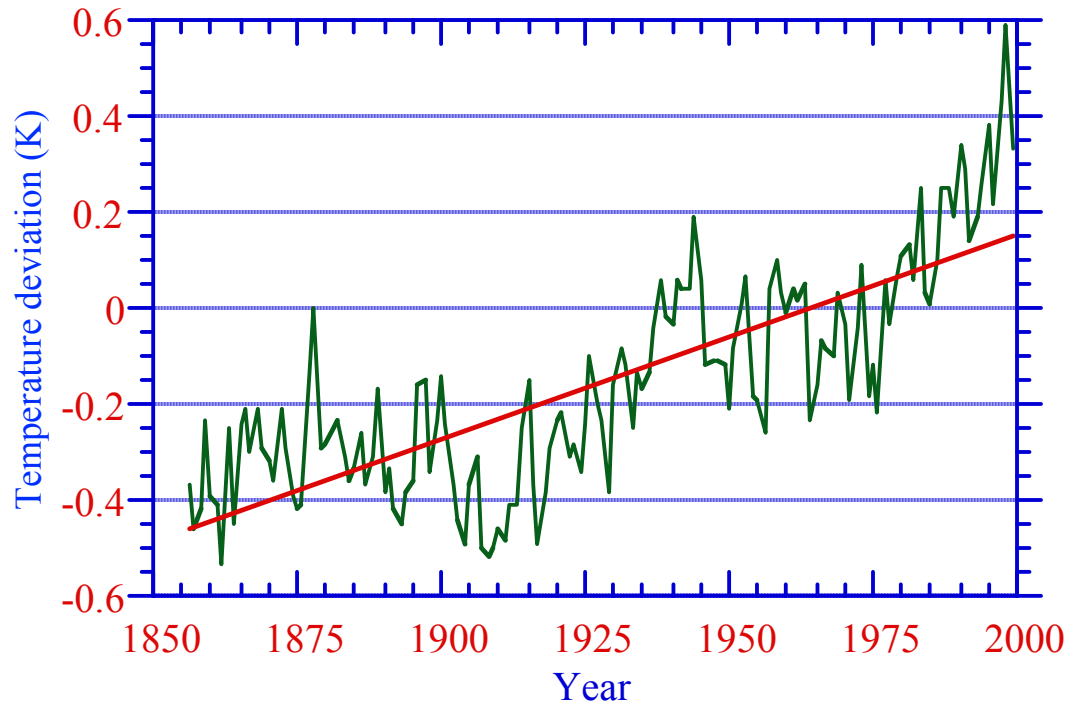
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# Temperature Changes From 1856-1999 Relative to 1961-1990 Mean (From Surface Measurements)



Jones et al. (2000)

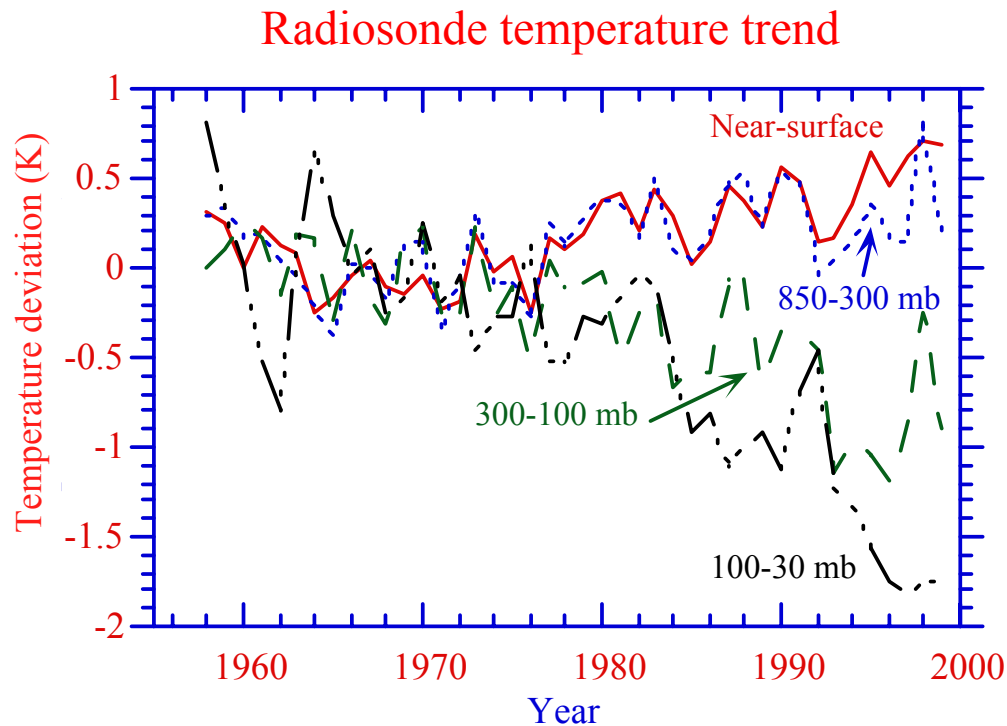
# Historic Rates of Temperature Change

The current rate of temperature increase is unprecedented for an interglacial period

Period	Years ago	Temperature Change (K) Per 100 Years
From 1958 to 1998 (radiosonde records)	42-2	+1.4
From 1958 to 1998 (land- and ship measurements)	42-2	+1.1
From 1856 to 1998 (land- and ship measurements)	144-2	+0.43
During the last 1000 years (Vostok core)	1000-0	+0.052
Deglaciation after Younger-Dryas (Vostok core)	12,632-11,191	+0.3
Last years of deglaciation after Younger-Dryas (Vostok core)	11,237-11,191	+2.2
Deglaciation leading to last interglacial period (Vostok core)	138,000-128,000	+0.13

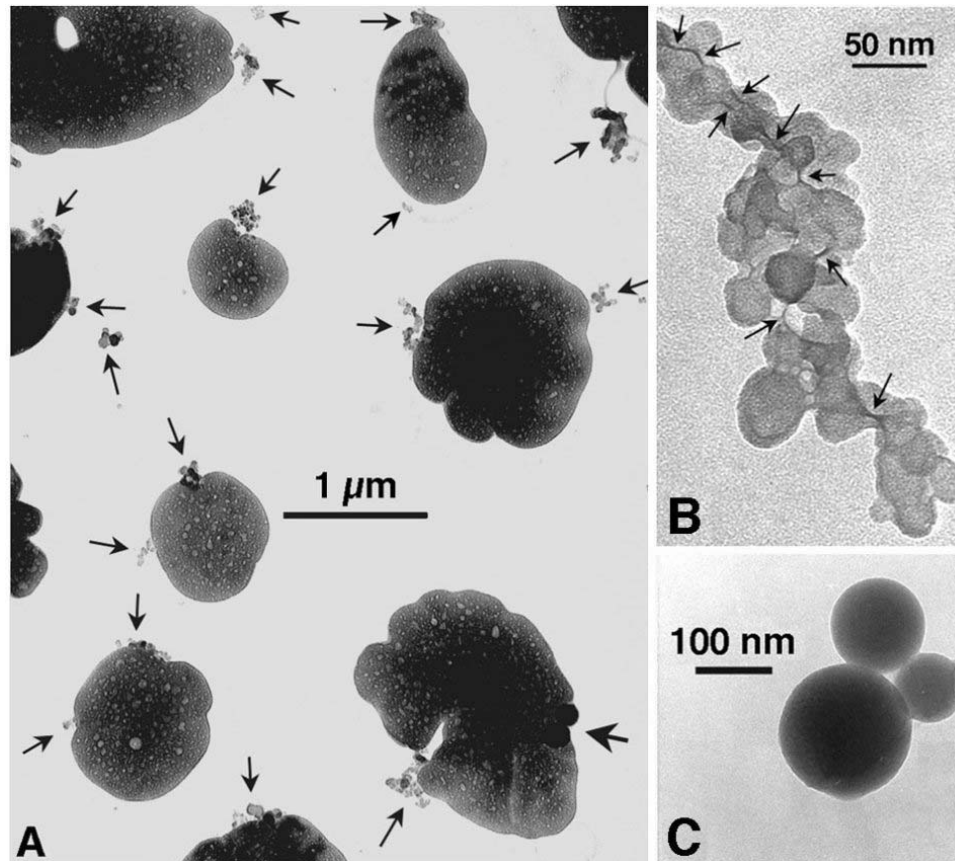
# Evidence of Near-Surface Global Warming: Stratospheric Cooling

Absorption of upward infrared radiation by greenhouse gases in the troposphere prevents absorption of some of this radiation by background ozone and carbon dioxide in the stratosphere, cooling the stratosphere.



Angell et al. (1999)

# Soot particles (arrows) coated by ammonium sulfate



Pósfai et al. (1999)

# Estimated Global Direct Forcing (W/m<sup>2</sup>)

## Anthropogenic Greenhouse Gases (IPCC, 2001)

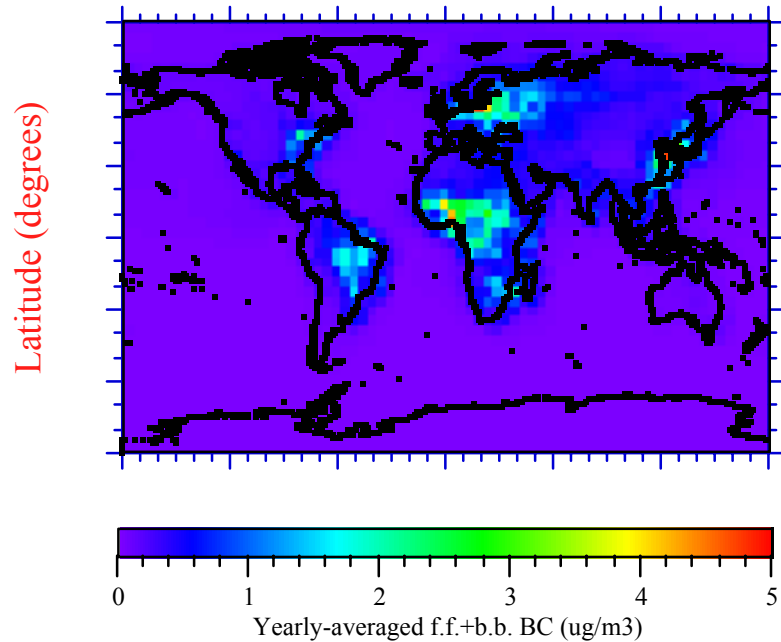
- Carbon Dioxide +1.46
- Methane +0.48
- Nitrous oxide +0.15

## Fossil-fuel+Biomass-Burning Black Carbon (*Nature* 409, 695-697, 2001)

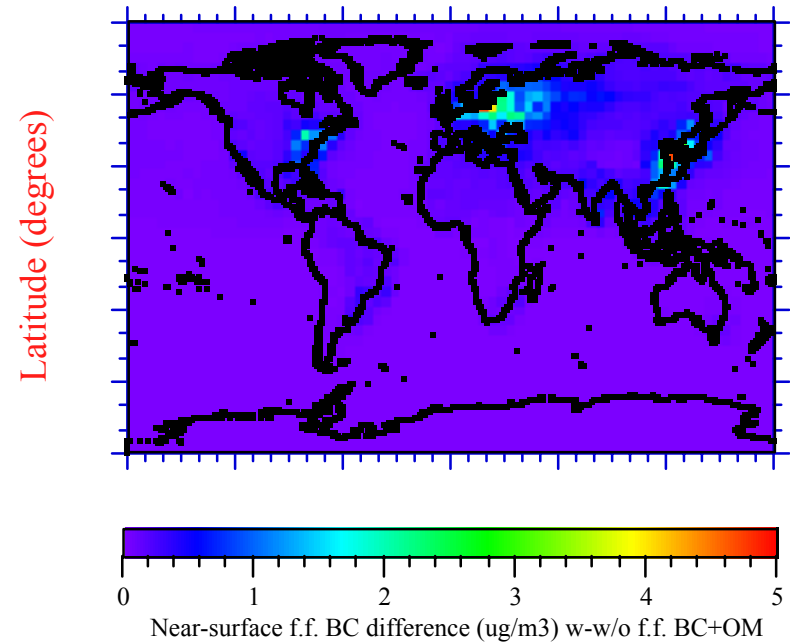
- Between externally and internally mixed +0.55

# Annually-Averaged BC Concentration

From all sources



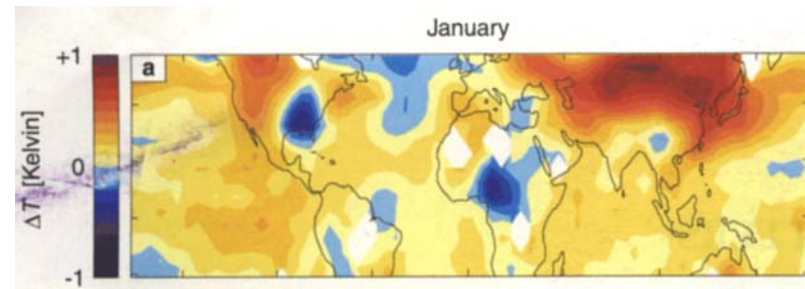
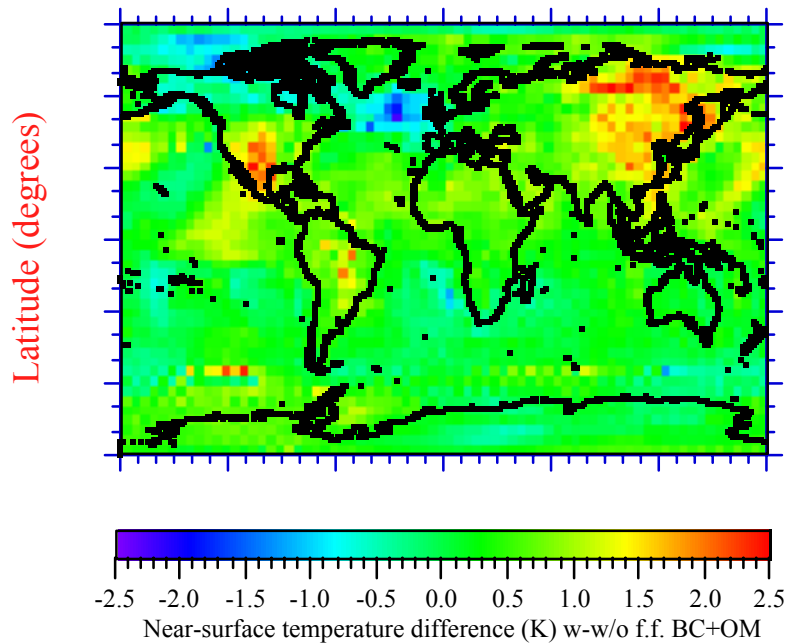
From fossil-fuel sources



# Near-Surface Temperature Difference Due to Fossil-Fuel Soot and Observed Temperature Trend

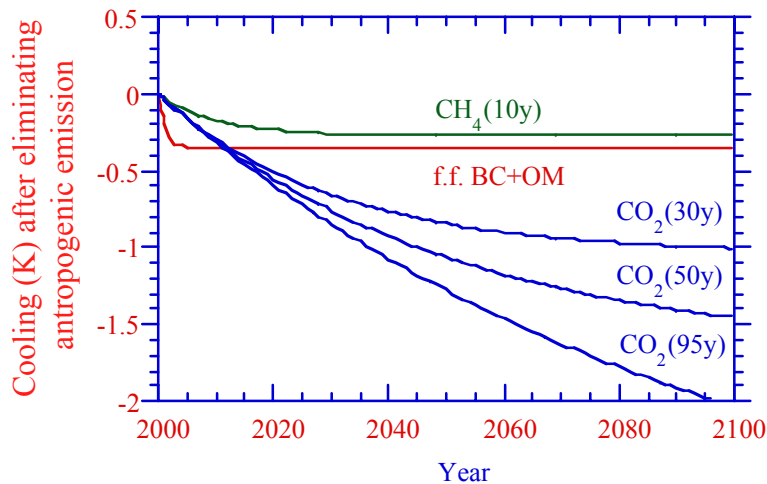
Model

Observed

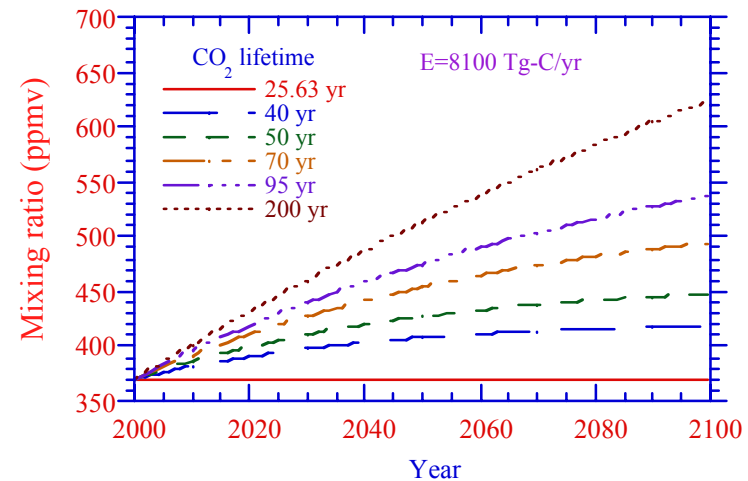


Schneider and Held (2001)

# Temperature Changes Due to Eliminating Emissions of Anthropogenic CO<sub>2</sub>, CH<sub>4</sub>, and f.f. BC+OM



Temperature changes (K) due to Eliminating constant emission of anthropogenic CO<sub>2</sub>, CH<sub>4</sub>, and f.f. BC+OM



Increase in anthropogenic CO<sub>2</sub> mixing ratio ( $\chi$ ) over next 100 years at constant emission rate ( $E$ ) for different CO<sub>2</sub>

lifetimes ( $\tau$ )

$$\frac{d\chi(t)}{dt} = E - \frac{\chi(t)}{\tau}$$

$$\chi(t) = \chi(0)e^{-t/\tau} + \tau E(1 - e^{-t/\tau})$$

# Turbines off the Coast of Gotland, Sweden



Copyright © 2000 NEG Micon

# Turbines Near Horns Reef, Denmark



Copyright © 2000 Peter Christiansen Elsamprojekt A/S, Denmark

# Direct Cost of Energy From Large Turbine

$$E = P \times 8760 \times CF$$

E = Energy (kWh/yr)

P = Rated power (kW)

CF = Capacity Factor ( $0.087 \times V_{avg} - P/D^2$ )

$V_{avg}$  = Mean-annual Rayleigh-distributed wind speed (m/s)

D = Blade diameter (m)

1500 kW turbine, 77-m diameter blade, 7-7.5 m/s annual winds

Energy (E) =  $4.7\text{-}5.2 \times 10^6$  kWh/yr

Cost of turbine (80%)+installation+land  
+financing+roads+local transmission

= \$1000/kW

Amortize over 20 years @6-8%

= \$131,000-153,000/yr

Annual O&M @ 1.5-2.5% of turbine

= \$18,000-\$30,000/yr

Total Cost

= \$149,000-\$183,000/yr

Cost/Unit Energy

= 2.9-3.9 cents/kWh

## Direct and Externality Costs of Three Energy Sources

	Direct cost (¢/kWh)	Global warming cost (¢/kWh)	Particle health (¢/kWh)	Other health/ environmental cost (¢/kWh)	Total cost (¢/kWh)
New coal plant	3.5-4.0 <sup>a</sup>	0.4-1.0 <sup>c</sup>	4-10 <sup>e</sup>	1.6-3.3 <sup>f</sup>	9.5-18
New natural gas plant	3.3-3.6 <sup>a</sup>	0.7-1.1 <sup>c</sup>	0.4-2 <sup>e</sup>	0.5-1.1 <sup>f</sup>	4.9-7.8
Large wind turbine	2.9-3.9 <sup>b</sup>	<0.1 <sup>d</sup>	<0.1 <sup>d</sup>	<0.1 <sup>d</sup>	2.9-4.2

<sup>a</sup>DOE Office of Fossil Energy (2001)

<sup>c</sup>Derived From UNEP (2001)

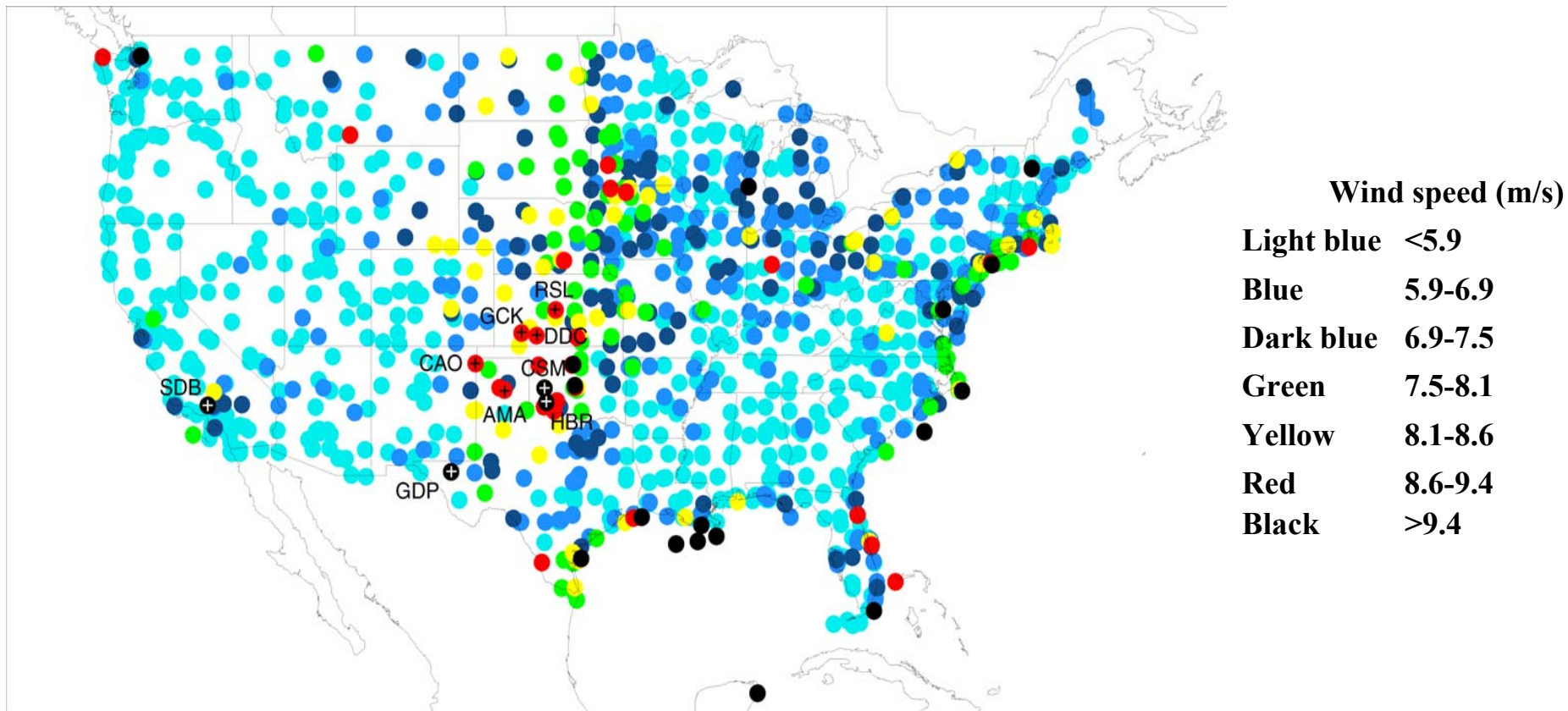
<sup>e</sup>*Atmos. Environ.* 35, 4763 (2001)

<sup>b</sup>*Science* 293, 1438 (2001)

<sup>d</sup>Cost from turbine manufacturing

<sup>f</sup>European Commission (1995)

# Map of Yearly-Average Wind Speed at 80 m Above Ground for the Year 2000



Archer and Jacobson (2003)

<http://www.stanford.edu/group/efmh/winds/>

# Number of Turbines Required for the U.S. to Satisfy the Kyoto Protocol as of 1999

Electric energy from coal in the U.S. (1999) = 1.89 trillion kWh

Energy reduction required to reduce CO<sub>2</sub> emission  
to satisfy Kyoto Protocol = 1.1 trillion kWh

Number of 1.5 MW, 77-m turbines required  
with  $V=7-7.5$  m/s = 214,000-236,000

Area required for 1 turbine:  $A = 4D \times 7D$  = 0.16 km<sup>2</sup> (6 turbines/km<sup>2</sup>)

Area required for all turbines = 194 km x 194 km

# Economic Benefits of Air Pollution Regulation

- Thomas Midgley (1925): “Tetraethyl lead is the only material available which can bring about these (antiknock) results, which are of vital importance to the continued economic use by the general public of all automotive equipment, and unless a grave and inescapable hazard exists in the manufacture of tetraethyl lead, its abandonment cannot be justified”

Vehicle lead was regulated in 1976. Today, no new U.S. vehicles use lead and no vehicles knock.

- 1970 Clean Air Act Amendments required 90% reductions in CO, HCs, and NO<sub>x</sub>. The catalytic converter was subsequently invented. Between 1970-2000, the U.S. population increased by one-third but the number of vehicles sold doubled and the GDP doubled.
- 2003 OMB study: Health and social benefits of enforcing tough new clean-air regulations during the past decade were 5-7 times greater in economic terms than were the costs of compliance.

# Summary

- The rate of near-surface temperature increase today is unprecedented for an interglacial period. Evidence of global warming includes stratospheric cooling.
- CO<sub>2</sub> is the main cause of global warming, and due to its long lifetime, must be controlled immediately. Control of fossil-fuel soot (BC+OM) may be the fastest method of slowing global warming for a specific period. Such control will reduce health problems associated with soot.
- The direct cost of energy from new, large wind turbines in the presence of mean-annual winds >6.9 m/s is now similar to that from new natural gas and coal power plants. Almost one-quarter of the U.S. experiences mean-annual winds >6.9 m/s. A previously uncharted resource of wind is along the southeastern and southern coasts.
- The U.S. could satisfy the Kyoto Protocol as of 1999 by replacing 60% of coal energy with that from 225,000 1.5 MW turbines placed over a 194 km x 194 km area.

# Interpretation of Science in Politics

- “Reductions in black carbon plus organic matter emissions from fossil-fuel sources will not only slow global warming, but also improve health”

Paper requested by White House  
May 18, 2001

- "The Kyoto Protocol was fatally flawed...

“Kyoto also failed to address two major pollutants that have an impact on warming, black soot and tropospheric ozone.”

“Reducing both would not only address climate change, but also dramatically improve people’s health.”

President George W. Bush  
June 12, 2001