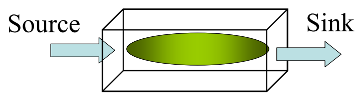
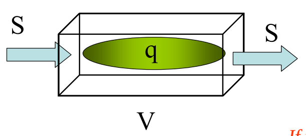
Steady State Box Model

A defined volume of air (the box) receives pollution from a source, while pollution is removed at the same time by a sink process



In a "*steady state*" the concentration (and the total amount) of the pollutant inside the box does not change (is constant)

Box Model Formula



$$q = \frac{S \times \tau}{V}$$

If we know the source rate of a pollutant and its residence time in the atmosphere, we can calculate its concentration in a given volume.

V = Volume of box
S = Source rate
= Sink rate
τ = residence time (τ: tau)
q = steady state concentration of pollutant in box

Sources and Sinks

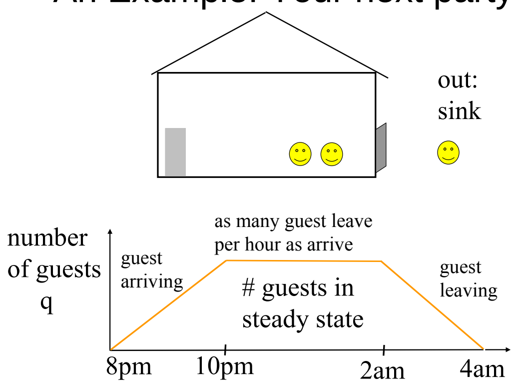
Sources:
Everything that introduces pollutants into the air in the box

- direct emissions (cars, industry,…)
- transport by wind
- chemical formation

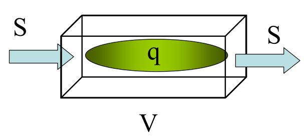
Sinks:
Processes that remove or convert pollutants

- wind blows pollutants away (ventilation)
- chemical conversion
- pollutants are deposited on the ground (rainfall)

An Example: Your next party



Box Model Formula



$$q = \frac{S \times \tau}{V}$$

V = Volume of box
S = Source rate
= Sink rate
τ = residence time (τ: tau)
q = steady state concentration
of pollutant in box

Source/Sink Rates

$$S = \frac{\text{Amount of substance emitted/lost in time interval t}}{\text{time interval t}}$$

in a steady state the source and the sink rates are equal

Party:

Source rate: People arriving per hour
Sink rate: People leaving per hour
Let's say S = 5 guests/hour

Residence time

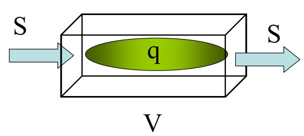
τ = average period of time that a molecule of a pollutant is in the box before it is removed

Party:

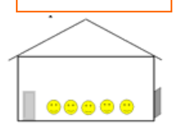
How long does a guest **<u>on average</u>** stay in your home.

Let's say τ *= 2 hours*

Box Model Formula

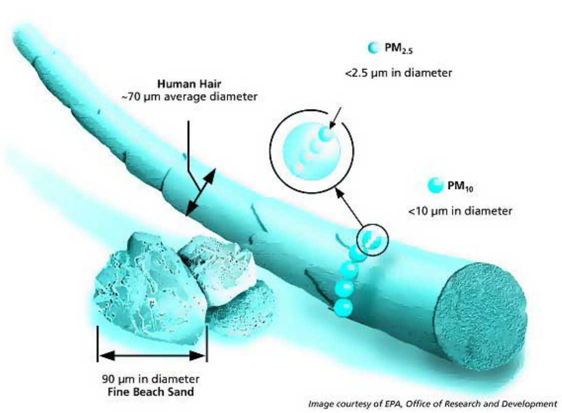


$$q = \frac{S \times \tau}{V}$$



Your party at steady-state:
S = 5 guests/hour
τ= 2 hours
V = 1

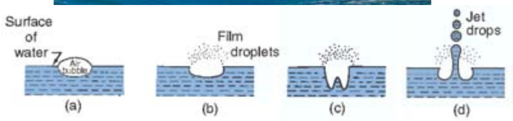
Average number of guests in your house?
q=S x τ = *5 guests/hour x 2 hours = 10 guests*



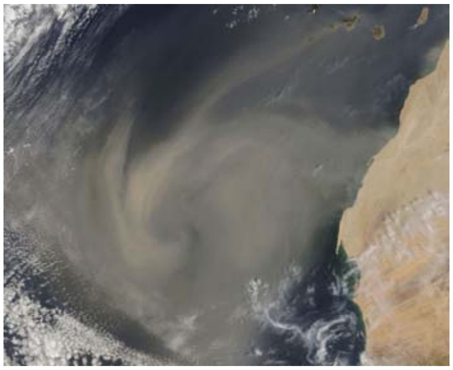
Sources of aerosols

- Biological: seeds, pollen, spores (1-250 μm); bacteria, algae, fungi, viruses (<1 μm)
- Solid Earth: dust, volcanoes
- Oceans: sea-salt
- Anthropogenic (~20% mass): fires (soot and ash); dust from roads; wind erosion of tilled land; fuel combustion; industrial processes
- Chemical formation: gas (SO_2, HNO_3, hydrocarbons,) condensing onto existing particles, or forming new particles.

SEA SPRAY



Dust Storm off West Africa (sept. 2005)



http://visibleearth.nasa.gov/view_rec.php?id=20238

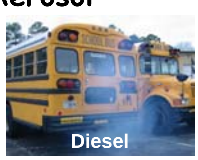
Mount St. Helens (Fall, 1982)

Peter Frenzen, available from Mount Saint Helens National Volcanic Monument Photo Gallery

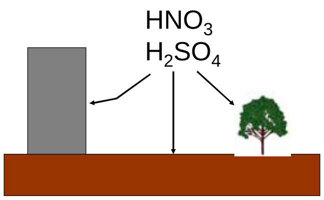
Prescribed Burn in Big Horn National Forest, Wyoming (1981)

Fig. 5.7. U.S. Forest Service, available from National Renewable Energy Lab.

Urban Aerosol



Dry Deposition



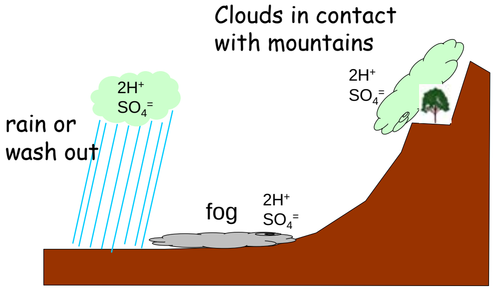
Aerosols are taken up by surfaces, i.e. ground, buildings, plants

Factors that govern dry deposition rates:

- Level of atmospheric turbulence
- Chemical properties of depositing species
- Nature of surface itself

Wet Deposition

Aerosols are taken up into water droplets, which are then deposited



Particle concentrations in the atmosphere

Polluted environments PM$_{10}$~ 100 μg/m^3

Take a volume of 1 m^3 of air (bathtub size)
→Mass of 100 μg of particles = 0.0001 grams
(10 billion or more particles)

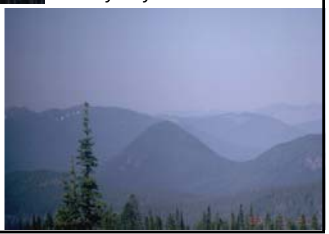
Marine background ~ 10 μg/m^3
Arctic ~ 1 μg/m^3

Clear day: VR=240km

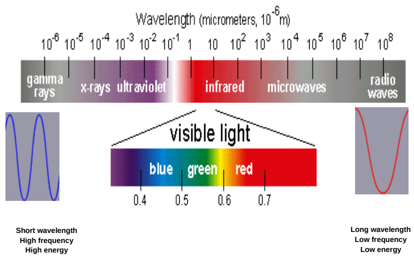
VR = visibility range

Hazy day: VR=80km

Visibility impairment in Mt. Rainier National Park



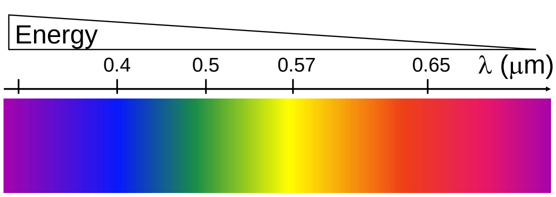
Wavelengths vary over many orders of magnitude



http://www.nrao.edu/whatisra/mechanisms.shtml

Wavelengths

Visible light (0.4 - 0.7 μm)



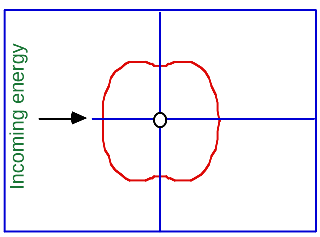
blue green yellow red

Ultraviolet
0.1 - 0.4 μm

Infrared (heat)
0.7 - 100μm

Gas (Rayleigh) Scattering

Redirection of radiation by a gas molecule without a net transfer of energy to the molecule

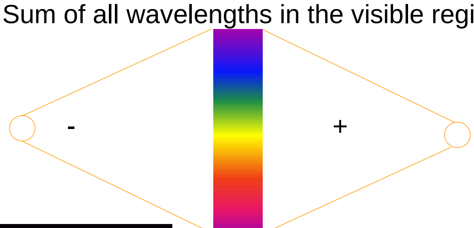


Probability distribution of where a gas molecule scatters incoming light

Figure 7.4

What is white light?

Sum of all wavelengths in the visible region.



Radiation Scattering by a Sphere

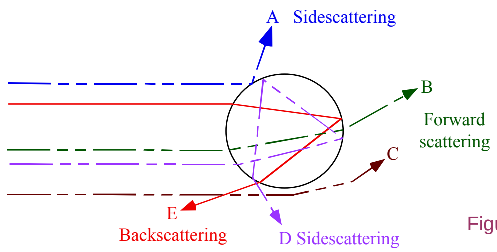


Figure 7.15

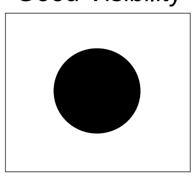
Visibility

Visibility is defined as the ability to distinguish a perfectly black surface from a white background

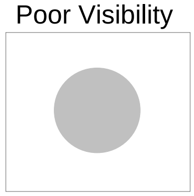
Expressed as visibility length

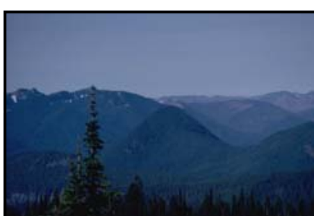
Particles decrease visibility!

Good Visibility



Poor Visibility

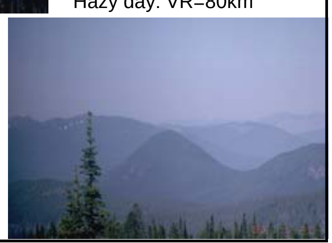




Clear day: VR=240km

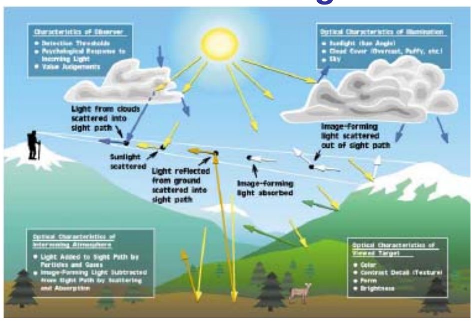
VR = visibility range

Hazy day: VR=80km



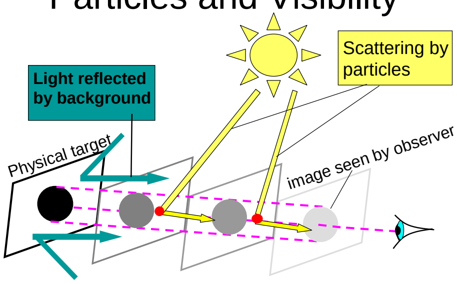
Visibility impairment in Mt. Rainier National Park

Processes Affecting Visibility



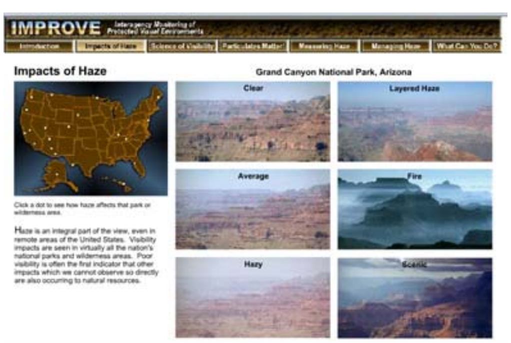
from "*Introduction to Visibility*" by William C. Malm

Particles and Visibility



Visibility at National Parks

http://vista.cira.colostate.edu/improve/Education/VisConcepts.swf

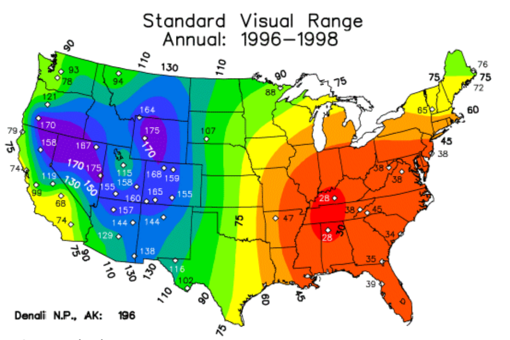


Visibility in the US

Typical visual ranges

- Western U.S.: 90-180 km (50-100 miles), ~ one-half of what it would be without human-made air pollution.
- Eastern U.S.: 30-60 km (15-40miles), or about one-third of the visual range under natural conditions.

Visibility in the US



IMPROVE web site:
http://vista.cira.colostate.edu/views/Web/GraphicViewer/seasonal.htm

Visibility in the US

Fig. 7.2 Geographical distribution of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic carbon (VOC) gas emissions.

from "*Introduction to Visibility*" by William C. Malm

Air Quality Standards for Particulate Matter (PM)

PM_{10}: (particles smaller than 10 μm)
24 hour average 150μg / m^3

$PM_{2.5}$: (particles smaller than 2.5 μm)
24 hour average: 35μg / m^3
annual average: 15μg / m^3

PM = Particulate Matter = particles = aerosols

Air Quality Guide for Particle Pollution

Air Quality	Air Quality Index (AQI)	Health Advisory
Good	0 – 50	None.
Moderate	51 – 100	Unusually sensitive people should consider reducing prolonged or heavy exertion.
Unhealthy for sensitive groups	101 – 150	People with heart or lung disease, older adults, and children should reduce prolonged or heavy exertion.
Unhealthy	151 – 200	People with heart or lung disease, older adults, and children should avoid prolonged or heavy exertion. Everyone else should reduce prolonged or heavy exertion.
Very unhealthy (Alert)	201 - 300	People with heart or lung disease, older adults, and children should avoid all physical activity outdoors. Everyone else should avoid prolonged or heavy exertion.

An AQI of 100 for particles up to 2.5 micrometers in diameter corresponds to a level of 40 micrograms per cubic meter (averaged over 24 hours). An AQI of 100 for particles up to 10 micrometers in diameter corresponds to a level of 150 micrograms per cubic meter (averaged over 24 hours).

Health effects of aerosol particles

"Our bodies natural defenses help us to cough or sneeze larger particles out of our bodies. But those defenses don't keep out smaller particles, those that are smaller than 10 microns, or micrometers, in diameter, or about one-seventh of the diameter of a single human hair. These smaller particles get trapped in the lungs, while the smallest are so minute they can pass through the lungs into the blood stream, just like essential oxygen."

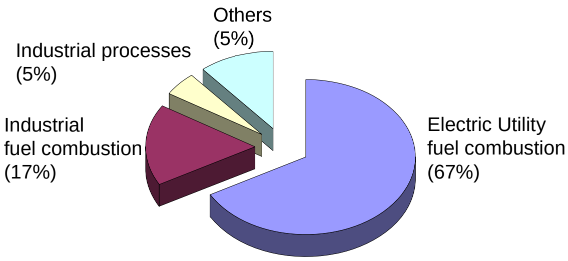
Quote from the American Lung Association:

http://lungaction.org.reports/sota05_heffects.html

UW MESA Air Pollution Study

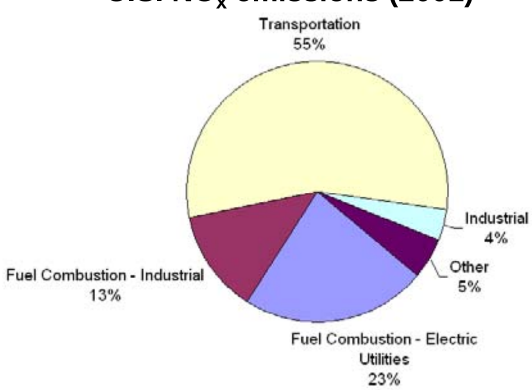
http://depts.washington.edu/mesaair/

U.S. SO_2 emissions (1996)

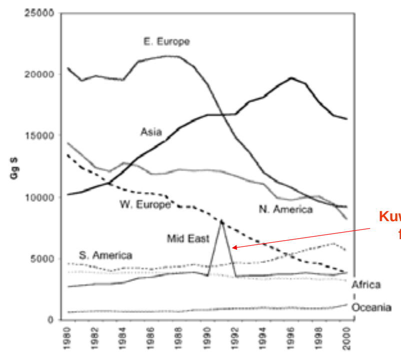


Sulfur content: Coal 1 - 6% S
Oil 1 - 2% S
Gas ~ 0.5% S

U.S. NO_x emissions (2001)



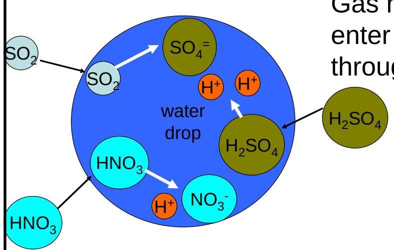
Recent Trends in Sulfur Emissions (1980-2000)



Stern, Chemosphere 58 (2005)

Uptake of gases in water

Gas molecules can enter a water droplet through the surface



pH Scale

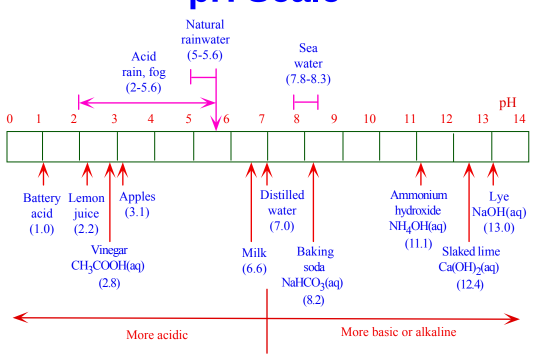
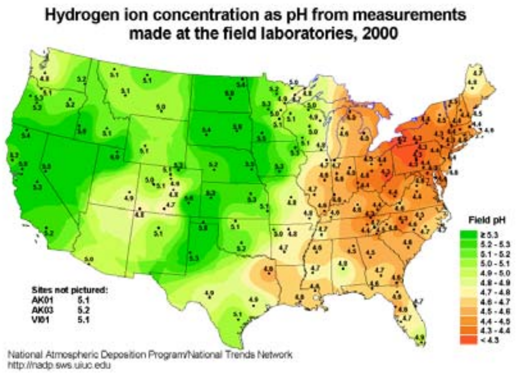
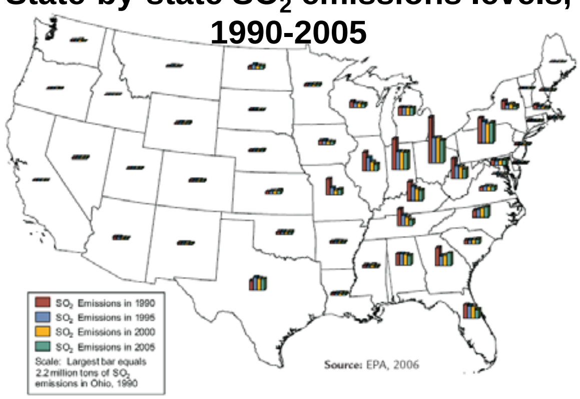


Figure 10.3

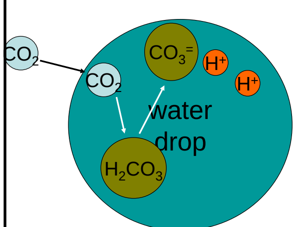
Acidity of acid rain



State-by-state SO_2 emissions levels, 1990-2005



Natural pH of rain



Uptake of CO_2 in water leads to Carbonic Acid H_2CO_3

→ at ~360 ppmv CO_2 natural rain is acidi

pH (natural rain) ~ 5.6

acid (+ H_2SO_4) rain pH ~ 5 - 4
acid fog minimum reported pH ~ 1.7

Liming of a Lake in Sweden

Tero Niemi / Naturbild

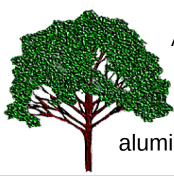
Influence on Ecosystems

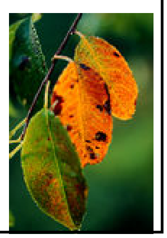
Forests

Damages leafs

Effects depend on the “buffering capacity” of soil

Acid rain weakens trees





aluminum (toxic)

removal of nutrients

nutrients: Ca, Mg, K

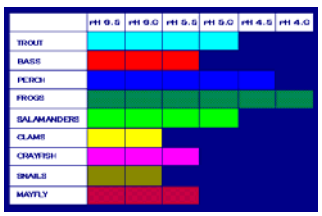
Acidified Forest, Oberwiesenthal, Germany (1991)

Stefan Rosengren/Naturbild

Acidified forest near Most, Czechoslovakia (1987)

Owen Bricker, United States Geological Survey

Effects on Aquatic Ecosystems

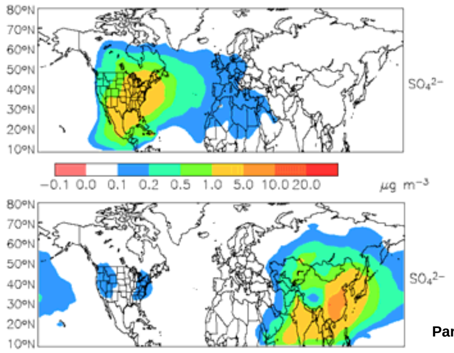


http://www.epa.gov/airmarkets/acidrain/effects/surfacewater.html#fish

Sandstone Figure in 1908 and 1968, Westphalia, Germany

Herr Schmidt-Thomsen

Export of sulfate aerosols from the U.S. & Asia



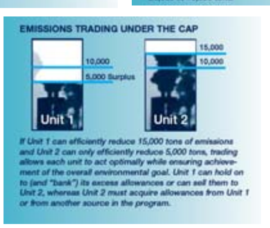
Park et al. [2003]

Transpacific transport of pollution from Asia accounts for 30% of background sulfate aerosols over US

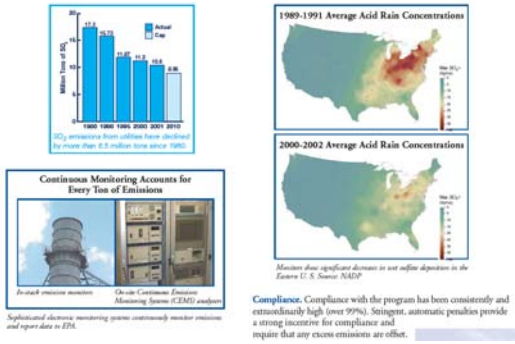
Acid Rain Program in the US

- Created under 1990 Clean Air Act Amendments
- Goal: reduce SO_2 emissions from power plants by 50% by 2010 from 1980 levels (10 million tons). Uses market-based *cap and trade*. Program started 1995. + also NOx reductions
- Over 10 year period (1995-2005): SO_2 emissions from power plants down by 7 million tons (41% reduction compared to 1980 levels).
- Reduction in acid deposition (~30% reduction in NE US 1990-2005).

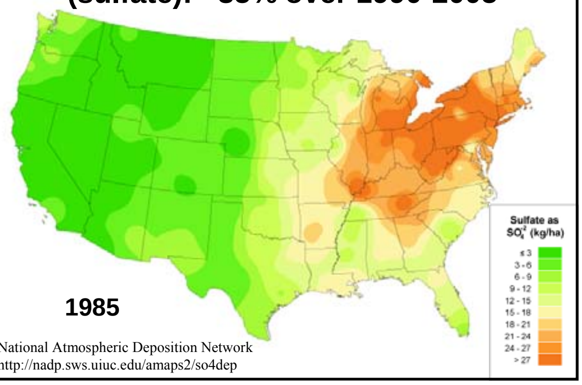
Cap and Trade – SO_2



Cap and Trade Effectiveness



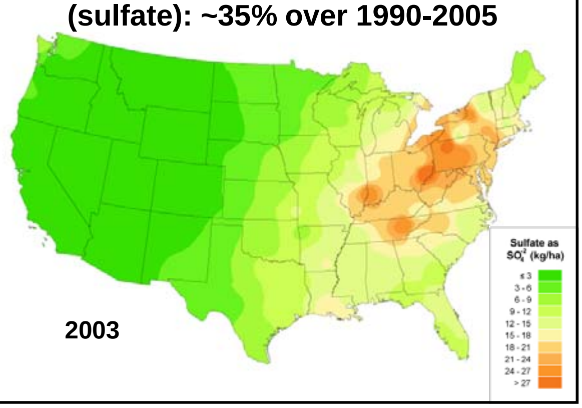
Reduction in acid rain deposition (sulfate): ~35% over 1990-2005



1985

National Atmospheric Deposition Network
http://nadp.sws.uiuc.edu/amaps2/so4dep

Reduction in acid rain deposition (sulfate): ~35% over 1990-2005

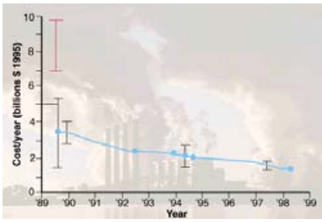


2003

Costs of 1990 Clean air act amendment

- Initially estimated to be ~$10 billion /year
- Actual costs ~$1-2 billion/year

→ cap and trade is more economical than strict regulations. Scrubbers turned out to be cheaper than expected and unexpected gains from switching to low sulfur coal



Kerr, Science, 1998.

Cost-effectiveness of Acid Rain Program

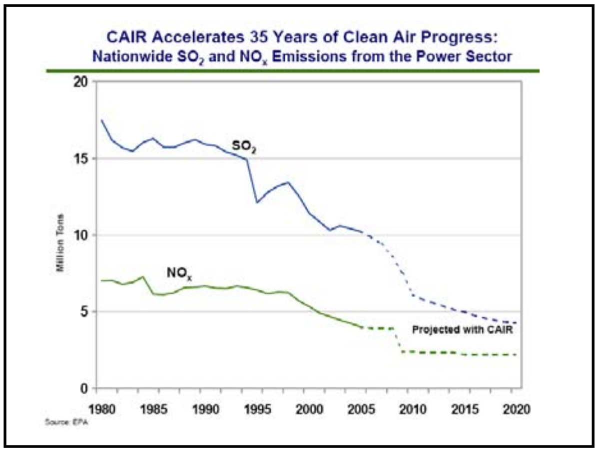
- Costs = $3 billion/year.
- Benefits = $122 billion/year [PM→ human health; visibility; ecosystems]
- 40-to-1 benefit/cost ratio!

Now: SO_2 and NO_x emissions from power plants were planned (2005) to be regulated as part of the ***Clean Air Insterstate Rule (CAIR).*** (Also a clean air mercury rule) 3.7 million ton SO_2 cap (2010). 1.5 million ton NO_x cap (2010). Was supposed to go into effect January 1, 2009, but…

→ went to DC circuit court and eliminated July 11, 2008, due to a fundamental argument about the cap and trade approach (among other arguments)

Clean Air Interstate Rule

The Clean Air Interstate Rule would have covered 28 eastern states and the District of Columbia. Air emissions in these states contribute to unhealthy levels of ground-level ozone, fine particles or both in downwind states. The rule uses a cap and trade system to reduce the target pollutants—sulfur dioxide (SO_2) and nitrogen oxides (NO_x)—by 70 percent.



Problems with CAIR

North Carolina and some electric-power producers opposed aspects of the regulation. The major objection to CAIR was the inability of the EPA to guarantee each state would reduce its emissions sufficiently to prevent interference with air quality downwind. The emissions trading systems set up by CAIR was to reduce emissions overall, and prevent transport of pollution generally, but the EPA couldn't promise that each state would reduce emissions sufficiently.

- July 11, 2008

North Carolina vs. EPA

Court found "more than several fatal flaws in the rule" and vacated the rule in its entirety

- December 23, 2008

Court granted rehearing. The EPA needs to replace it with a new rule that fits the court's view of the agency's powers under the Clean Air Act.

EPA proposes transport rule

July 6, 2010

- Will replace CAIR when final
- Addresses problems with CAIR by largely eliminating interstate trading.
- Will improve air quality in the eastern U.S. by reducing power plant emissions from 31 states and D.C.
- By 2014, would reduce power plant SO_2 emissions by 71%, and NO_x emissions by 52%, over 2005 levels.

Clean Air Mercury Rule

On March 15, 2005, EPA issued the Clean Air Mercury Rule to permanently cap and reduce mercury emissions from coal-fired power plants for the first time ever.

On February 8, 2008, the D.C. Circuit Court vacated the Clean Air Mercury Rule (New Jersey vs. EPA). The plaintiffs maintained that cap-and-trade contributed to "hot spots" for mercury.

EPA intends to propose air toxics standards for coal- and oil-fired electric generating units by March 15, 2011 and finalize a rule by November 16, 2011.