ATMOSPHERIC AEROSOLS: THEIR INFLUENCES ON CLIMATE AND WHY IT IS ESSENTIAL THAT WE UNDERSTAND THEM

Stephen E. Schwartz

Chemical Sciences Roundtable
Washington DC
February 2, 2010
www.ecd.bnl.gov/steve
OVERVIEW
“You have a short course... not a 20 min talk.” – BJF-P

Earth’s energy balance and perturbations

Climate sensitivity – definition, importance, past and current estimates

Expected increase in global mean surface temperature and the *warming discrepancy*

Aerosol forcing and implications

Allowable future CO₂ emissions

The path forward

Concluding remarks – Importance
GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

\[ \frac{1}{4} S_0 (1 - \alpha) = \sigma T^4 \]

Stefan-Boltzmann radiation law

\[ 69\% = 1 - \alpha \]

\[ 237 \approx 254K \]

\[ \alpha = 31\% \]

106

Rayleigh 27

Aerosol 4

H\(_2\)O, CO\(_2\), CH\(_4\)...

390 \approx 288K

31

Latent heat
Sensible heat

Schwartz, 1996, modified from Ramanathan, 1987
RADIATIVE FORCING

A change in a radiative flux term in Earth’s radiation budget, $\Delta F$, W m$^{-2}$.

Working hypothesis:

On a global basis radiative forcings are additive and fungible.

- This hypothesis is fundamental to the radiative forcing concept.
- This hypothesis underlies much of the assessment of climate change over the industrial period.
Global carbon dioxide concentration and infrared radiative forcing over the last thousand years.

ATMOSPHERIC CARBON DIOXIDE IS INCREASING

Polar ice cores
- Law Dome
- Adelie Land
- Siple
- South Pole

Mauna Loa Hawaii

Inset: Year vs. CO₂ concentration (ppm) from 1960 to 2000.
GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

\[ \frac{1}{4} S_0 \approx 254K \]

\[ \frac{1}{4} S_0 (1 - \alpha) = \sigma T^4 \]

\[ \Delta F = +2.6 \text{ W m}^{-2} \]

\( \alpha = 31\% \)

\( 69\% = 1 - \alpha \)

Schwartz, 1996, modified from Ramanathan, 1987
CLIMATE RESPONSE

The change in global and annual mean temperature, $\Delta T$, K, resulting from a given radiative forcing.

Working hypothesis:

The change in global mean temperature is proportional to the forcing, but independent of its nature and spatial distribution.

$$\Delta T = S \Delta F$$
CLIMATE SENSITIVITY

The change in global and annual mean temperature per unit forcing, $S$, K/(W m⁻²),

$$S = \Delta T/\Delta F.$$ 

Climate sensitivity is not known and is the objective of much current research on climate change.

Climate sensitivity is often expressed as the temperature for doubled CO₂ concentration $\Delta T_{2\times}$.

$$\Delta T_{2\times} = S\Delta F_{2\times}$$

$$\Delta F_{2\times} \approx 3.7 \text{ W m}^{-2}$$
Estimates of central value and uncertainty range from major national and international assessments.

Despite extensive research, climate sensitivity remains highly uncertain.
EXPECTED INCREASE IN GLOBAL TEMPERATURE
Long-lived GHGs only – Dependence on climate sensitivity

Equilibrium Climate Sensitivity, K/(W m⁻²)

Increase in GMST ΔT, K

CO₂ Doubling Temperature ΔT₂x, K

"Likely" range ~1 σ
IPCC AR4
Best estimate
LLGHG, Equilibrium

Warming discrepancy

Observed

This discrepancy holds throughout the IPCC AR4 “likely” range for climate sensitivity.
Radiative Forcing by Tropospheric Aerosol
AEROSOL EFFECTS ON CLOUDS AND RADIATION

GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

\[ \frac{1}{4} S_0 (1 - \alpha) = \sigma T^4 \]

\[ \alpha = 31\% \]

\[ \Delta F \approx 0.5 \]

\[ \Delta F \approx 0.7 \]

\[ \frac{1}{4} S_0 = 343 \]

\[ 69\% = 1 - \alpha \]

\[ 237 \approx 254K \]

\[ 106 \]

\[ 68 \]

\[ 390 \approx 288K \]

\[ 27 \]

\[ 48 \]

\[ 27 \]

\[ 169 \]

\[ 296 \]

\[ 31 \]

\[ 90 \]

\[ 16 \]

\[ H_2O, CO_2, CH_4 \ldots \]

\[ Latent heat \]

\[ Sensible heat \]

Schwartz, 1996, modified from Ramanathan, 1987
Total forcing includes other anthropogenic and natural (solar) forcings. Forcing by tropospheric ozone, $\sim 0.35 \text{ W m}^{-2}$, is the greatest of these. Uncertainty in aerosol forcing dominates uncertainty in total forcing.
The warming discrepancy is certainly resolved by countervailing aerosol forcing (within the IPCC range) for virtually any value of sensitivity.
Effect of uncertainty in forcing

\[ F_{\text{eff}} = F - H \]

\[ \Delta T = S F_{\text{eff}} \]

\[ F_{\text{eff}} = \Delta T S^{-1} \]

Uncertainty in aerosol forcing allows climate models with widely differing sensitivities to reproduce temperature increase over industrial period.
ALLOWABLE FUTURE CO₂ EMISSIONS

Dependence on climate sensitivity and acceptable increase in temperature relative to preindustrial

For $\Delta T_{\text{max}} = 2$ K . . .
- If sensitivity $\Delta T_{2\times}$ is 3 K, no more emissions.
- If sensitivity $\Delta T_{2\times}$ is 2 K, ~30 more years of emissions at present rate.
- If sensitivity $\Delta T_{2\times}$ is 4.5 K, threshold is exceeded by ~30 years.
THE PATH FORWARD

Determine aerosol forcing with high accuracy.

Multiple approaches are required:

- **Laboratory studies** of aerosol processes.

- **Field measurements** of aerosol processes and properties: emissions, new particle formation, evolution, size distributed composition, optical properties, CCN properties, removal processes . . .

Represent aerosol processes in *chemical transport models*.

Evaluate models by *comparison with observations*.

*Satellite measurements* for spatial coverage.

Calculate forcings in *chemical transport models and GCMs*. 
AEROSOL PROCESSES THAT MUST BE UNDERSTOOD AND REPRESENTED IN MODELS

- condensation
- evaporation
- surface chemistry
- coagulation
- light scattering and absorption $f(RH)$
- oxidation
- precursor emissions
- water uptake
- new particle formation
- aqueous chemistry
- autoconversion
- diffusion
- scavenging
- subcloud scavenging
- radiation transfer in clouds
- evaporation
- dry deposition
- primary emissions
- activation

Isomorphism of processes to computer code

Modeling aerosol processes requires understanding these processes, developing and testing their numerical representations, and incorporating these representations in global scale models.
AEROSOL OPTICAL DEPTH IN 17 MODELS (AEROCOM)

Comparison also with surface and satellite observations

Surface measurements: AERONET network.
Satellite measurements: composite from multiple instruments/platforms.
Are the models getting the “right” answer for the wrong reason?
Are the models getting the “right” answer because the answer is known?
Are the satellites getting the “right” answer because the answer is known?
ORGANIC CONTRIBUTIONS TO TROPOSPHERIC AEROSOL

Mass-spec determination of primary vs secondary organics

New analytical techniques permit identification of formation mechanisms.

Evolution of Organic Aerosols in the Atmosphere
Recent review of aerosol influences on climate

www.climatescience.gov/Library/sap/sap2-3
IMPORTANCE OF KNOWLEDGE OF CLIMATE TO INFORMED DECISION MAKING

• The lifetime of incremental atmospheric CO₂ is about 100 years.

• The expected life of a new coal-fired power plant is 50 to 75 years.

Actions taken today will have long-lasting effects.

Early knowledge of climate sensitivity can result in huge averted costs.