KOREAN ATMOSPHERIC SCIENTISTS AT BROOKHAVEN

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Yonsei University

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OVERVIEW

Earth’s energy budget

Perturbations

Carbon dioxide

Temperature change

Climate sensitivity

Climate forcing by anthropogenic aerosols

Understanding Earth’s climate sensitivity

Future directions

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

Schwartz, 1996, modified from Ramanathan, 1987
ATMOSPHERIC RADIATION

Energy per area per time

Power per area

Unit: Watt per square meter
W m\(^{-2}\)
ATMOSPHERIC CARBON DIOXIDE IS INCREASING

Global carbon dioxide concentration and infrared radiative forcing over the last thousand years.
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.
Prior to 1910 CO₂ emissions from land use changes were dominant.

Subsequently fossil fuel CO₂ has been dominant and rapidly increasing!
CO₂ from land use emissions – \textit{not fossil fuel combustion} – was the dominant contribution to atmospheric CO₂ and forcing over the 20\textsuperscript{th} century.
CHANCE IN GLOBAL MEAN SURFACE TEMPERATURE 1855-2004

Climate Research Unit, University of East Anglia, UK
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$^{-2}$),

$$S = \frac{\Delta T}{\Delta F}.$$  

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 CO$_2$ concentration $\Delta T_{2\times}$.

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

$$\Delta F_{2\times} \approx 3.7 \text{ W m}^{-2}$$
CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

Estimates of central value and uncertainty range from major national and international assessments.

Despite extensive research, climate sensitivity remains highly uncertain.
Equilibrium sensitivity to doubled CO₂ $\Delta T_{2x}$, K

Sensitivity varies by more than a factor of 2.
CLOUDS

THE ACHILLES HEEL OF CLIMATE MODELS
CLOUD FEEDBACK STRENGTH AND CLIMATE SENSITIVITY IN 9 GCMS

\[ S = S_{SB} \frac{1}{1 - \Phi} \]

\( S \) = Climate sensitivity

\( S_{SB} \) = Stefan-Boltzmann sensitivity

\( \Phi \) = feedback strength

\( \Phi = \sum \Phi_i \)

sum over all feedbacks

Variation in climate model sensitivity is dominated by variation in cloud feedback strength.

Adapted from Webb et al., Clim. Dyn., 2006
ZONAL MONTHLY MEAN ALBEDO

20 GCMs – Difference vs. ERBE Satellite

Modified from Bender et al., Tellus, 2006
CLIMATE FORCING BY ANTHROPOGENIC AEROSOLS
GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

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

\[ 343 \]

\[ 1/4 S_0 \times (1 - \alpha) = \sigma T^4 \]

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

\[ 237 \approx 254K \]

\[ \alpha = 31\% \]

\[ 106 \]

\[ Rayleigh 27 \]

\[ Aerosol 4 \]

\[ 48 \]

\[ H_2O, CO_2, CH_4... \]

\[ 390 \approx 288K \]

\[ 296 \]

\[ Latent heat \]

\[ Sensible heat \]

\[ 68 \]

\[ Atmosphere \]

\[ 31 \]

\[ 27 \]

\[ 169 \]

\[ Schwartz, 1996, modified from Ramanathan, 1987 \]
Radiative Forcing by Tropospheric Aerosol

Partial Reflection and Absorption of Incoming Solar Radiation

Aerosol Haze

Clouds

Organics

Dust

SO₂

Soot

Sea salt

Organics

Industrial Emissions

Biomass Burning

Land Use Changes

Ocean

DMS
AEROSOLS AS SEEN FROM SPACE

Fire plumes from southern Mexico transported north into Gulf of Mexico.
Aerosols from ship emissions enhance reflectivity of marine stratus.
Global average sulfate optical thickness is 0.03: $1 \text{ W m}^{-2}$ cooling.

In continental U. S. typical aerosol optical thickness is 0.1: $3 \text{ W m}^{-2}$ cooling.
AEROSOL OPTICAL DEPTH
Determined by sunphotometry
North central Oklahoma - Daily average at 500 nm
MONTHLY AVERAGE AEROSOL JUNE 1997
Polder radiometer on Adeos satellite

Optical Thickness $\tau$

$\lambda = 865$ nm

Ångström Exponent $\alpha$

$\alpha = -d \ln \tau / d \ln \lambda$

Small particles are from gas-to-particle conversion.
Cloud albedo and forcing calculated from measured effective radius and liquid water path
North Central Oklahoma

Effective radius determined from slope of Optical depth vs. Liquid water path

Cloud albedo is calculated for observed data and for average effective radius for each day.
Forcing is calculated for indicated conditions relative to October 26.

<table>
<thead>
<tr>
<th>Date, 2000</th>
<th>Effective radius ( r_e ), ( \mu \text{m} )</th>
<th>Optical Depth</th>
<th>Net flux at TOA, ( \text{W m}^{-2} )</th>
<th>Forcing relative to 10/26, ( \text{W m}^{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/26</td>
<td>10.2</td>
<td>15.1</td>
<td>293</td>
<td>—</td>
</tr>
<tr>
<td>10/21</td>
<td>7.8</td>
<td>20.8</td>
<td>266</td>
<td>27</td>
</tr>
<tr>
<td>02/18</td>
<td>5.8</td>
<td>28.3</td>
<td>240</td>
<td>53</td>
</tr>
</tbody>
</table>

Kim, Schwartz, Miller, and Min, JGR, 2003
AEROSOL PROCESSES THAT MUST BE UNDERSTOOD AND REPRESENTED IN CLIMATE MODELS
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
- Activation
- Autoconversion
- Diffusion
- Scavenging
- Subcloud scavenging
- Dry deposition
- New particle formation
- Aqueous chemistry
- Evaporation
- Primary emissions

APPROACH TO DETERMINE AEROSOL FORCING

Numerical simulation of physical processes

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 FORCING

WHAT’S NEW?

Organics
Organic aerosol is major or dominant species throughout the anthropogenically influenced Northern Hemisphere.
OOA fraction increases with increasing distance from urban sources.
AEROSOL IN MEXICO CITY BASIN
Mexico City is a wonderful place to study aerosol properties and evolution.
SECONDARY AEROSOL PRODUCTION
Eight aircraft flights above and downwind of Mexico City, March 2006

Parcel photochemical age measured using $-\log(\text{NO}_x/\text{NO}_y)$ as clock. Aerosol normalized to CO above background to account for dilution.

*Fivefold increase* in organic aerosol.

Measured increase in organic aerosol exceeds modeled based on laboratory experiments and measured volatile organic carbon *tenfold.*
Following the growth of particles formed from nucleation at Tecamac, Mexico.

Sulfate accounts for only ~10% of particulate mass. Growth rate exceeds that from sulfuric acid by order of magnitude.

Smith, McMurry et al., GRL, 2008
Particle formation rates and particle concentrations depend strongly on NPF mechanism.
AEROSOL PARTICLE NUMBER CONCENTRATION

Average particle number concentrations North America, July 2004

Aitken mode particles ($D \leq 100$ nm)

Accumulation mode particles ($D \geq 100$ nm)

Strong dependence on new particle formation mechanism

Strong dependence on size of primary emissions

Accurate representation of number concentrations and aerosol indirect effects requires improved knowledge of \textit{new particle formation rate} and \textit{size distributed emissions}.

L.-S. Chang et al., JGR, in review
GLOBAL-MEAN RADIATIVE FORCINGS (RF)
Pre-industrial to present (Intergovernmental Panel on Climate Change, 2007)

<table>
<thead>
<tr>
<th>RF Terms</th>
<th>RF values (W m⁻²)</th>
<th>Spatial scale</th>
<th>LOSU</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Long-lived greenhouse gases</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>1.66 [1.49 to 1.83]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.48 [0.43 to 0.53]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.16 [0.14 to 0.18]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Halocarbons</td>
<td>0.34 [0.31 to 0.37]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td><strong>Ozone</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stratospheric</td>
<td>-0.05 [-0.15 to 0.05]</td>
<td>Continental to global</td>
<td>Med</td>
</tr>
<tr>
<td>Tropospheric</td>
<td>0.35 [0.25 to 0.65]</td>
<td>Continental to global</td>
<td>Med</td>
</tr>
<tr>
<td><strong>Stratospheric water vapour from CH₄</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land use</td>
<td>0.07 [0.02 to 0.12]</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Surface albedo</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black carbon on snow</td>
<td>-0.2 [-0.4 to 0.0]</td>
<td>Local to continental</td>
<td>Med - Low</td>
</tr>
<tr>
<td></td>
<td>0.1 [0.0 to 0.2]</td>
<td>Local to continental</td>
<td>Med - Low</td>
</tr>
<tr>
<td><strong>Total Aerosol</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct effect</td>
<td>-0.5 [-0.9 to -0.1]</td>
<td>Continental to global</td>
<td>Med - Low</td>
</tr>
<tr>
<td>Cloud-albedo effect</td>
<td>-0.7 [-1.8 to -0.3]</td>
<td>Continental to global</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Linear contrails</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.01 [0.003 to 0.03]</td>
<td>Continental</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Natural</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar irradiance</td>
<td>0.12 [0.06 to 0.30]</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Total net anthropogenic</strong></td>
<td>1.6 [0.6 to 2.4]</td>
<td>Global</td>
<td>Low</td>
</tr>
</tbody>
</table>

Losu denotes level of scientific understanding.
Uncertainty range: 5 - 95%.

Factor of 4 limits empirical inferences and model evaluation.
Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a consistent explanation of the observed temperature record.

These simulations used models with different climate sensitivities, rates of ocean heat uptake and magnitudes and types of forcings.
The models did not span the full range of the uncertainty and/or . . . The forcings used in the model runs were anticorrelated with the sensitivities of the models.
CORRELATION OF AEROSOL FORCING, TOTAL FORCING, AND SENSITIVITY IN CLIMATE MODELS

Eleven models used in 2007 IPCC analysis

Climate models with higher sensitivity have lower total forcing.  
Total forcing decreases with increasing (negative) aerosol forcing.

Modified from Kiehl, GRL, 2007
IMPLICATIONS OF UNCERTAINTY IN CLIMATE SENSITIVITY

Uncertainty in climate sensitivity translates directly into . . .

• Uncertainty in the amount of incremental atmospheric CO₂ that would result in a given increase in global mean surface temperature.

• Uncertainty in the amount of fossil fuel carbon that can be combusted consonant with a given climate effect.

At present this uncertainty is at least a factor of 2.
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.
CARBON EMISSIONS PATHWAYS TO STABILIZE GLOBAL MEAN TEMPERATURE

Emissions for $\Delta T$ not to exceed 2 K above preindustrial

Dependence on climate sensitivity

Climate sensitivity expressed as equilibrium increase in GMST for doubled atmospheric CO$_2$ mixing ratio $\Delta T_{2\times}$. 

Edmonds and Smith, 2006
IMPROVING CLIMATE MODELS RAPIDLY
A new approach to climate modeling

Run climate models in real-time forecast mode, initialized by observations. Compare forecasts with global meteorological observations. Compare with detailed observations at multiple highly instrumented sites. Identify needed improvements in parameterizations, revise, test.
CONCLUDING OBSERVATIONS

• Earth’s climate sensitivity is **uncertain to at least a factor of 2.**

• This uncertainty has **decreased little in 30 years.**

• This uncertainty greatly **limits effective and efficient energy planning.**

• The range in climate model sensitivity arises largely from **differing cloud feedbacks.**

• **Uncertainty in climate forcing by aerosols** greatly limits the ability to constrain climate sensitivity and to evaluate climate models.

• Substantially decreasing uncertainty in Earth’s climate sensitivity will require **bold new approaches.**