CLIMATE CHANGE
CERTAINTIES AND UNCERTAINTIES

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http://www.ecd.bnl.gov/steve
KOREAN ATMOSPHERIC SCIENTISTS AT BROOKHAVEN

O-Ung Kwon
1996-1998
Korea Meteorological Administration

Byung-Gon Kim
2002-2003 +
Kangnung University

Lim-Seok Chang
2005-2007
Global Environment Research Center

Seong Soo Yum
2007-2008
Yonsei University
OVERVIEW

Earth’s energy balance and perturbations
Contributions to the increase in atmospheric CO₂
Changes in global mean surface temperature
Climate sensitivity – definition, importance, past and current estimates
Climate sensitivity from climate models
Aerosol forcing – uncertainties and implications
Total forcing – uncertainties and implications
Climate sensitivity – uncertainties and implications
Looking to the future
Concluding remarks
GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

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.
ATMOSPHERIC CARBON DIOXIDE IS INCREASING

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

Subsequently fossil fuel CO₂ has been dominant and rapidly increasing!
CO\textsubscript{2} from land use emissions – \textit{not fossil fuel combustion} – was the dominant contribution to atmospheric CO\textsubscript{2} and forcing over the 20\textsuperscript{th} century.
GREENHOUSE GAS FORCING AND CHANGE IN GLOBAL MEAN SURFACE TEMPERATURE 1855-2004

IPCC, 2001; Climate Research Unit, University of East Anglia, UK
GREENHOUSE GASES AND TEMPERATURE OVER 450,000 YEARS

Vostok core, Antarctica

Modified from Petit et al., Nature, 1999
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 $\Delta T_{2\times}$.

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

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

Despite extensive research, climate sensitivity remains highly uncertain.
Sensitivity varies by more than a factor of 2.
CLOUD FEEDBACK STRENGTH AND CLIMATE SENSITIVITY IN 9 GCMS

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

\( S = \) Climate sensitivity

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

\( \mathcal{F} = \) feedback strength

\( \mathcal{F} = \sum \mathcal{F}_i \)

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
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.
GLOBAL-MEAN RADIATIVE FORCINGS (RF)
Pre-industrial to present (Intergovernmental Panel on Climate Change, 2007)

LOSU denotes level of scientific understanding.
Radiative Forcing by Tropospheric Aerosol

Partial Reflection and Absorption of Incoming Solar Radiation

Aerosol Haze

Clouds

Organics
Dust
SO₂
Soot
Sea salt
Organics
DMS

Land Use Changes
Industrial Emissions
Biomass Burning
Ocean
Upward scattering of light by aerosol exerts a cooling effect on climate.
Fire plumes from southern Mexico transported north into Gulf of Mexico.
CLOUD BRIGHTENING BY SHIP TRACKS

Satellite photo off California coast

Aerosols from ship emissions enhance reflectivity of marine stratus.
GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

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

\[ \alpha = 31\% \]

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

\[ 237 \approx 254K \]

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

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

\[ 106 \]

\[ 27 \]

\[ 48 \]

\[ \text{Rayleigh}, 27 \]

\[ \text{Aerosol}, 4 \]

\[ \text{H}_2\text{O}, \text{CO}_2, \text{CH}_4 \ldots \]

\[ 390 \approx 288K \]

\[ 90 \]

\[ 16 \]

\[ \text{Latent heat}, \text{Sensible heat} \]

\[ 296 \]

\[ 31 \]

\[ 68 \]

\[ 27 \]

\[ 169 \]

\[ \text{Atmosphere} \]

Schwartz, 1996, modified from Ramanathan, 1987
Global average sulfate optical thickness is 0.03: **1 W m⁻² cooling**.

In continental U. S. typical aerosol optical thickness is 0.1: **3 W m⁻² cooling**.
AEROSOL OPTICAL DEPTH

Determined by sunphotometry

North central Oklahoma - Daily average at 500 nm

J. Michalsky et al., JGR, 2001
MONTHLY AVERAGE AEROSOL JUNE 1997
Polder radiometer on Adeos satellite

Optical Thickness $\tau$
$\lambda = 865$ nm

Ångström Exponent $\alpha$
$\alpha = -\frac{d \ln \tau}{d \ln \lambda}$

Small particles are from gas-to-particle conversion.
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

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

L.-S. Chang et al., JGR, in review
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 $r_e$, $\mu$m</th>
<th>Optical Depth</th>
<th>Net flux at TOA, W m$^{-2}$</th>
<th>Forcing relative to 10/26, 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
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></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropospheric</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.05 [-0.15 to 0.05]</td>
<td>Continental to global</td>
<td>Med</td>
<td></td>
</tr>
<tr>
<td>0.35 [0.25 to 0.65]</td>
<td>Continental to global</td>
<td>Med</td>
<td></td>
</tr>
<tr>
<td><strong>Stratospheric water vapour from CH₄</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></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>Land use</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></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cloud albedo effect</td>
<td>-0.5 [-0.9 to -0.1]</td>
<td>Continental to global</td>
<td>Med/Low</td>
</tr>
<tr>
<td></td>
<td>-0.7 [-1.8 to -0.3]</td>
<td>Continental to global</td>
<td>Low</td>
</tr>
<tr>
<td>Linear contrails</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>
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<tr>
<td><strong>Solar irradiance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></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></td>
<td></td>
<td></td>
</tr>
<tr>
<td></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.

Factor of 4 limits empirical inferences and model evaluation.
TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models

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.

Schwartz, Charlson & Rodhe, Nature Reports – Climate Change, 2007
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.*
RECAPITULATION

Present estimates of Earth’s climate sensitivity range over at least a factor of 2.

The range of sensitivity in climate models results largely from differing treatment of clouds, resulting in differing cloud feedbacks.

Evaluation of climate models is limited mainly because of uncertainty in aerosol forcing over the industrial period.
IMPLICATIONS OF UNCERTAINTY IN CLIMATE SENSITIVITY

Uncertainty in climate sensitivity translates directly into . . .

• Uncertainty in the amount of incremental atmospheric CO$_2$ 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.
Looking to the Future . . .
Prediction is difficult, especially about the future.

– Niels Bohr
PROJECTIONS OF FUTURE CO2 EMISSIONS
PROJECTIONS OF FUTURE TEMPERATURE CHANGE
PROJECTIONS OF FUTURE SEA LEVEL RISE

Thermosteric (density change) only
EFFECT OF SEA LEVEL RISE
Population density, current coastline

Weiss and Overpeck, University of Arizona
EFFECT OF SEA LEVEL RISE

Population density, 1 meter sea level rise

Weiss and Overpeck, University of Arizona
MELTING OF GREENLAND ICE CAP
Satellite determination of extent of glacial melt 1992 vs 2002

Complete melt of the Greenland ice sheet would raise the level of the global ocean 7 meters.
EFFECT OF SEA LEVEL RISE

Population density, 1 meter sea level rise

Weiss and Overpeck, University of Arizona
EFFECT OF SEA LEVEL RISE

Population density, 6 meter sea level rise

Weiss and Overpeck, University of Arizona
EFFECT OF SEA LEVEL RISE

Population density, current coastline

Weiss and Overpeck, University of Arizona
EFFECT OF SEA LEVEL RISE

Population density, 6 meter sea level rise

Weiss and Overpeck, University of Arizona
CONCLUDING REMARKS

Atmospheric carbon dioxide will continue to increase absent major changes in the world’s energy economy.

The consequences of this increase are not well known but they range from serious to severe to catastrophic.

Present scientific understanding is sufficient to permit “no regrets” decision making.

Research is urgently needed to refine “what if” projections. Especially important is reducing uncertainty in climate sensitivity.

Actions taken (or not taken) today will inevitably affect future generations.