Radiative Forcing by Greenhouse Gases and its Representation in Global Models

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SORCE Meeting
20-22 Sept. 2006
Outline

• Observational evidence for radiative effects of GHGs*
• Current estimates of radiative effects since 18th C.
• Simulation of the climatic effects of GHGs
• Representation of radiative forcing in climate models
• Large range of radiative forcing in climate models
• New methods to improve accuracy of radiative transfer

*GHGs = (Long-Lived) Green House Gases
Effects of GHG Increases from 1970 to 1997:
Lower Mid-Infrared Emission to Space

Harries et al, 2001
Effects of GHG Increases from 1995 to 2002:
Higher Longwave Emission to the Surface (Alpine Stations)

Philipona et al., 2004

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Radiative Effects of GHGs from 18th C to 2005
Current State of the Art

• Changes in GHG concentrations are known to a few percent.
• Models and limited observations agree to within 10 to 15%.
• Line-by-line calculations from multiple models typically agree to within 1%.
• All-sky global estimates agree to within ~10% for the range of background atmospheric analyses.
• Recent updates in GHG spectroscopy have had minimal effects on broadband forcing estimates.
• Best-guess formulae relating GHGs to radiative forcing have not changed since the IPCC TAR (2001).

Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.
Role of Simulation in Climate-Change Assessment

Emissions Scenarios

Climate Change Simulations

Climate Assessment

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Representation of the Climate System in Coupled Models

Emissions → Chemistry + BGC + Physics + Ecosystems → Concentrations → Forcing → Climate Response

Feedbacks

Chemical Reservoirs

CCSM3
- Atmosphere (CAM 3)
- Land (CLM 3)
- Coupler (CPL 6)
- Sea Ice (CSIM 4)
- Ocean (POP 1)

Collins et al, 2006a,b
Climate forcing and response are related by:

\[ \Delta Q = \lambda \Delta T_s + \Delta F \]

with

\[ \Delta Q = \text{radiative forcing from higher GHGs, etc.} \]
\[ \lambda = \text{climate sensitivity} \]
\[ \Delta T_s = \text{change in surface temperature} \]
\[ \Delta F = \text{change in climatic heat storage} \]

Are \( \Delta Q \) estimated with climate models accurate?

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Figure 1. Change in net forcing (Wm\(^{-2}\)) at the model top versus change in surface temperature (°C) from the T42 CAM3 slab ocean model simulation for doubled CO\(_2\). Each data point is the annual mean value from the first 20 years of the simulation.

Kiehl et al, 2006
Link between Changing Rainfall and Temperature

- Uncertainties in forcing affect not only temperature but also the hydrological cycle.

Figure 9.18: Equilibrium climate and hydrological sensitivities from AGCMs coupled to mixed-layer ocean components; blue diamonds from the SAR, red triangles from models in current use (LeTreut and McAvaney, 2000 and Table 9.1).

IPCC TAR, 2001
Goals of the Radiative Transfer Model Intercomparison Project (RTMIP)

• Compare forcing by well-mixed GHGs from:
  - GCMs participating in the IPCC AR4
  - Line-by-line (LBL) codes: benchmarks

• Determine accuracy of GCM codes under idealized conditions.

• Types of forcing considered:
  - Present-day – preindustrial changes in WMGHGs
  - $2\times CO_2 - 1\times CO_2$ and $4\times CO_2 - 1\times CO_2$
  - Combinations of increased CH$_4$, N$_2$O, and CFCs
  - Feedbacks from increased H$_2$O
Design of the Intercomparison

• **Comparison of instantaneous forcing (not flux):**
  - Stratospheric adjustment is not included.
  - Instantaneous forcings are included in WGCM protocol for IPCC simulations.

• **Calculations are for clear-sky conditions.**
  - We use a climatological mid-latitude summer profile.
  - Including clouds would complicate the intercomparisons.

• **Radiative effects of constituents:**
  - Absorption by H$_2$O, O$_3$, and WMGHGs
  - Rayleigh scattering
  - Self and foreign line broadening
Participating AOGCM and LBL groups

AOGCM Groups

<table>
<thead>
<tr>
<th>Originating group</th>
<th>Country</th>
<th>Model</th>
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</thead>
<tbody>
<tr>
<td>BCCR</td>
<td>Norway</td>
<td>BCCR-BCM2.0</td>
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<td>CCCma</td>
<td>Canada</td>
<td>CGCM3.1(T47/T63)</td>
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<td>CCSR/NIES/FRCGC</td>
<td>Japan</td>
<td>MIROC3.2(medres/hires)</td>
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<td>GISS</td>
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<td>GISS-EH/ER</td>
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<tr>
<td>INM</td>
<td>Russia</td>
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<td>IPSL</td>
<td>France</td>
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<tr>
<td>LASG/IAP</td>
<td>China</td>
<td>FGOALS-g1.0</td>
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<td>MIUB/METRI/KMA</td>
<td>Germany/Korea</td>
<td>ECHO-G</td>
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<tr>
<td>MPIfM</td>
<td>Germany</td>
<td>ECHAM5/MPI-OM</td>
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<td>MRI</td>
<td>Japan</td>
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<td>NCAR</td>
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<td>NCAR</td>
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<td>PCM</td>
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<td>HadCM3</td>
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<td>UKMO</td>
<td>UK</td>
<td>HadGEM1</td>
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LBL Modelers

<table>
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<th>Model</th>
<th>Reference</th>
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<td>GFDL LBL</td>
<td><em>Schwarzkopf and Fels [1985]</em></td>
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<td>UK</td>
<td>GENLN2</td>
<td><em>Edwards [1992]; Zhong et al. [2001]</em></td>
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<td>LaRC</td>
<td>USA</td>
<td>MRTA</td>
<td><em>Kratz and Rose [1999]</em></td>
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<tr>
<td>UR</td>
<td>UK</td>
<td>RFM</td>
<td><em>Dudhia [1997]; Stamnes et al. [1988]</em></td>
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- There are 16 groups submitting simulations from 23 AOGCMs to the IPCC AR4.
- RTMIP includes 14 of these groups and 20 of the AOGCMs.
Forcing by historical increase in $CO_2$

**Longwave**

Relative difference is 8% at 200hPa and 33% at surface.

**Shortwave**

Large range in surface forcing: RMS / mean = 0.94

*Collins et al, 2006*
Forcing by historical increase in GHGs

**Longwave**

None of the differences are statistically significant.

**Shortwave**

All of the differences are statistically significant.

Collins et al, 2006
Forcing by methane and nitrous oxide

Longwave: The overestimation of surface forcing is statistically significant.
Shortwave: None of the codes treat the effects of CH4 and N2O.

Collins et al, 2006
Forcing by water vapor feedback

**Longwave**

Longwave: None of the differences are statistically significant.

**Shortwave**

Shortwave: Underestimation of surface forcing magnitude is significant.

*Collins et al., 2006*
Change in heating rates by $H_2O$

**Longwave**

Calculation of cooling by $H_2O$ is generally accurate.

**Shortwave**

Some models produce tropospheric cooling, an error in sign.

Collins et al, 2006
Conclusions of RTMIP

• No sign errors in the ensemble-mean forcings from AOGCMs!
  - Out of 228 individual forcing calculations, there is only sign error for one model.
• Forcing by historical changes in WMGHGs:
  - Mean LW forcings agree to within ±0.12 Wm⁻².
  - Individual LW forcings range from 1.5 to 2.7 Wm⁻² at TOM.
  - This adversely affects separation of forcing from response.
  - Mean SW forcings differ by up to 0.37 Wm⁻² (43% error).
  - Large SW errors are related to omission of CH₄ and N₂O.
• Largest forcing biases occur at the surface level:
  - Majority of the differences in mean forcings are significant.
  - AOGCM RT codes have been designed to produce reasonable forcings at the tropopause.
  - Developers also should insure accuracy of forcing at the surface.
## Range of CO2 Forcing from AGCM Simulations

<table>
<thead>
<tr>
<th>Group</th>
<th>Model</th>
<th>Total (W m⁻²)</th>
</tr>
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<tbody>
<tr>
<td>CCCma</td>
<td>CGCM 3.1 (T47/T63)</td>
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<td>CSIRO-Mk3.0</td>
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<td>MIROC 3.2-hires</td>
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<tr>
<td>CCSR/NIES/FRCGC</td>
<td>MIROC 3.2-medres</td>
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<td>ECHAM5/MPI-OM</td>
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<td>UKMO-HadGEM1</td>
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<tr>
<td><strong>Mean±std. deviation</strong></td>
<td><strong>3.67±0.28</strong></td>
<td></td>
</tr>
</tbody>
</table>

- The forcing values are for $2\times$CO2 - $1\times$CO2.
- The 5 to 95% confidence interval is 3.2 to 4.1 W m⁻².
- This corresponds to a 25% uncertainty in forcing.
Longwave: The 5 to 95 percentile range of at 2100 is ~50% of the mean.
Shortwave: The models do not agree on sign or magnitude of forcing.
Principle Cause of Errors: Errors in Atmospheric Transmission

Upwelling and downwelling longwave fluxes are

\[ \begin{align*}
F^\uparrow_\lambda & \approx B_\lambda(T_{SRF}) T_\lambda + B_\lambda(T_{TRO}) \left[ 1 - T_\lambda \right] \\
F^\downarrow_\lambda & \approx B_\lambda(T_{TOA}) T'_\lambda + B_\lambda(T_{STR}) \left[ 1 - T_\lambda \right]
\end{align*} \]

where

\[ B_\lambda(T) = \text{Planck function} \]

\[ T = \text{Temperature} \]

\[ T_\lambda = \text{Transmission} \]

Forcing is the change in flux for a change in \( T_\lambda \):

\[ \begin{align*}
\Delta F^\uparrow_\lambda & \approx B_\lambda(T_{SRF}) \Delta T_\lambda + B_\lambda(T_{TRO}) \left[ 1 - \Delta T_\lambda \right] + \cdots \\
\Delta F^\downarrow_\lambda & \approx B_\lambda(T_{TOA}) \Delta T'_\lambda + B_\lambda(T_{STR}) \left[ 1 - \Delta T_\lambda \right] + \cdots
\end{align*} \]

Errors in \( \Delta T_\lambda \) are the main cause of errors in \( \Delta F \).
A major challenge of radiative parameterization

The solar and infrared spectra exhibit variations in extinction, optical depth, and heating rates of $\geq 12$ orders of magnitude.

Collins et al., 2006
k-distribution Band Models

In the k-distribution band model, the absorption coefficients are sorted by magnitude.

The transmission integral should be much easier to approximate in this sorted form.

Yet classical approximation methods may not be suitable.

Are there physically and mathematically optimal methods for approximation?
Methods for representing transmission in AOGCMs

Existing Methods:
- Classical numerical quadrature
- Empirical parameter estimation
- Exponential Sum Fitting of Transmission (ESFT)
- More exotic methods from signal-processing theory

These methods lack:
- Practical error estimates
- Guaranteed accuracy for all paths
- Link between order & accuracy
- Guarantee of global optimality
- Continuous approximations over a range of atmospheric conditions

Our new method provides:
- Formal error estimates
- Absolute accuracy for all paths
- Theory for order and accuracy
- Globally optimal solutions
- Mathematical continuity
  \rightarrow \text{New insights into radiative processes}
Error bounds on transmission approximation

Let

\[ \varepsilon = \text{chosen limit on error in transmission} \]
\[ u = \text{path length through atmospheric medium} \]
\[ T(u) = \text{exact transmission} \]
\[ \hat{T}(u) = \text{approximation to transmission} \]

The error in the approximation is

\[ E(u) = |T(u) - \hat{T}(u)| \]

The basic requirement is:

\[ E(u) \leq \varepsilon \quad \text{for all path lengths } u \]
Error bounds on weak and strong transmission

Divide the k-distribution integral into intervals:

\[ T(u) = \sum_{i=1}^{N} T_i(u) \delta g_i \]

\[ \delta g_1 \quad \cdots \quad \delta g_N \]

\[ \hat{T}(u) = \sum_{i=1}^{N} \hat{T}_i(u) \delta g_i \]

\[ \delta g_1 \quad \cdots \quad \delta g_N \]

The error in the approximation for each interval is:

\[ E_i(u) = \left| T_i(u) - \hat{T}_i(u) \right| \]

Assume that the error in each interval obeys:

\[ E_i(u) \leq \epsilon \quad \text{for all path lengths } u \]

Then we satisfy our global requirement since

\[ E(u) \leq \sum_{i=1}^{N} E_i(u) \delta g_i = \epsilon \]
Variation of transmission with path length

The exact and approximate transmissions are:

\[ T_i(u) = \exp[-\kappa_i(u)u] \]
\[ \hat{T}_i(u) = \exp[-\hat{\kappa}_i u] \]

where

\( \kappa_i(u) \) = effective extinction coefficient
\( \hat{\kappa}_i \) = approximate extinction coefficient

One can prove for each interval that:

- \( \kappa_i(u) \) is a decreasing function of \( u \)
- For \( u = 0 \), \( \kappa_i(0) \) is the average extinction
- For \( u \to \infty \), \( \kappa_i(\infty) \) is the minimum extinction

Optimal choices for \( \hat{\kappa}_i \) follow from these properties.
Relationship of specific extinction and error

Low. $\hat{\kappa}_i < \kappa_i(\infty)$
   Reject: Errors > Errors for Middle option

Medium. $\kappa_i(\infty) \leq \hat{\kappa}_i \leq \kappa_i(0)$
   Accept

High. $\hat{\kappa}_i > \kappa_i(0)$
   Reject: Errors > Errors for Middle option
Variation of error with path length

For extinctions in the middle range:

- The errors vanish for 3 paths:
  - \( u = 0 \)
  - \( u = u_0 \) for some \( u_0 > 0 \)
  - \( u = \infty \)
- The errors are maximized for 2 paths:
  - \( u = u_< \) for some \( u_< < u_0 \)
  - \( u = u_> \) for some \( u_> > u_0 \)
Basic equations for extinction and interval width

Suppose we require the maximal errors obey:

\[ E_i(u_\prec) = \varepsilon \]
\[ E_i(u_\succ) = \varepsilon \]

This gives two equations in two unknowns:

\[ E_i(u_\prec) = \varepsilon \]
\[ E_i(u_\succ) = \varepsilon \]
\[ \Rightarrow \begin{bmatrix} \delta g_i \\ \hat{\kappa}_i \end{bmatrix} \]
Approximation for Near-IR H$_2$O Transmission
Implications for anomalous shortwave absorption

AOGCMs tend to systematically overestimate the surface insolation.

Wild et al., 1995
Anomalous absorption in atmospheric “windows”

- The constructive method yields underestimates absorption for path lengths below a threshold value.
- This underestimation is characteristic of other methods as well.
- The threshold path lengths increases with decreasing extinction.
- This implies that models systemically underestimate absorption in atmospheric “windows” where extinction is low.

![Graphs showing path lengths and specific extinctions](image)
Conclusions regarding the constructive method

• **Advantages of the constructive method:**
  - Mathematical foundation
  - Strict error bounds on transmission
  - New insights into radiative transfer: atmospheric “windows”

• **Future work:**
  - Applications in the stratosphere
  - Development of new parameterizations for AOGCMs
  - Application to future climate assessments
Change in energy balance in 10 years of CCSM Development
Total Greenhouse Effect in IPCC Simulations

**Greenhouse Effect**

**Precipitable Water**
Change in heating rates by $CO_2$

Longwave: Most models agree in magnitude and sign of the additional heating.
Shortwave: Average model agrees in magnitude and sign of the additional heating.

Collins et al, 2006
Change in heating rates by WMGHGs

Longwave: Some models show evidence of numerical artifacts.
Shortwave: Some models produce tropospheric cooling, an error in sign.

Collins et al, 2006
Change in heating rates by $\text{CH}_4$ and $\text{N}_2\text{O}$

Longwave: Some models have upper tropospheric cooling, an error in sign.
Shortwave: None of the models treat the shortwave heating by $\text{CH}_4$ and $\text{N}_2\text{O}$.

*Collins et al., 2006*
Longwave radiative forcing at 200 mb

Largest forcings are at wavelengths outside the centers of absorption bands.

Collins et al, 2006
Largest forcings are at wavelengths outside the centers of absorption bands.

*Collins et al., 2006*