Modeling the Combined Effects of $CH_4$, $CO_2$, and Climate

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Future Projections

Based on ISAM

Major Uncertainties

- Socioeconomic (Future Emissions SRES Scenarios)
- Carbon Cycle (Resulting CO₂ Concentration) and
- Climate Sensitivity (°C for 2×CO₂)
Modeled Terrestrial Fluxes of Anthropogenic CO₂ (1900-2100)

(McGuire et al., 2001)

- The terrestrial biosphere has historically been a source of carbon to the atmosphere - it is currently a net sink.
- The current terrestrial carbon sink is caused by land management practices, higher carbon dioxide, nitrogen deposition and possibly recent changes in climate.
- This uptake by the terrestrial biosphere will not continue indefinitely. The question is when will this slow down, stop or even become a source?
Modeled Ocean Fluxes of Anthropogenic CO\textsubscript{2} (1900-2000) (Orr et al., 2000)

- Modeled results do not include natural variability and therefore appear smoother than in reality.
- Modeled estimates of anthropogenic tracers agree reasonably well with observations.
- Modeled Ocean uptake is constrained by observations of anthropogenic traces (Anthropogenic CO\textsubscript{2}, 14C, and CFCs).
Full carbon cycle–climate–biosphere–chemistry linkage further affects the impact of human activities on climate
Integrated Assessment Model

Tool to Study Feedbacks Throughout The Earth System

- **EMISSIONS**
  - PNNL MiniCam Model
  - GHG emissions from industrial & energy-related sources

- **CHEMICAL TRANSPORT**
  - 2D Atmospheric Chemical Transport Box Model
  - Concentrations of GHG, aerosols and other radiatively active species

- **BIOSPHERE**
  - Agricultural Land Use Model
  - CO2 fluxes from land use change & Biogenic emissions for non-CO2 gases

- **CARBON CYCLE**
  - 2D Coupled Atmosphere-Ocean-Biosphere Model
  - Carbon dioxide concentrations

- **CLIMATE MODEL**
  - 2D Radiative Transfer Model
  - 2D Atmosphere-Ocean-Land Moisture & Energy Balance Model
  - Changes in global temperature, precipitation and sea level

**IMPACT ASSESSMENT STUDIES**
Terrestrial Carbon Cycle
ISAM Terrestrial Carbon Cycle Model

Effects of land cover changes and various ecosystem processes simultaneously considered
Land Cover Change Activities

Land use emissions estimates are based on two sets of data with the following land clearing activities:

- Natural ecosystems → croplands
- Natural ecosystems → pastures

McGuire et al. (2001)
- Natural ecosystems → croplands
Area of Cropland Based on Houghton & Ramankutty’s Data

Houghton

Ramankutty

1765

1765-1990

1765-1990
ISAM Estimated Terrestrial Biospheric Emissions
(Clearing of Forests for Croplands only)

Land Use Emissions

Net Biospheric Emissions

McGuire et al. (2001)
ISAM Estimated Zonal Distribution of Biospheric Emissions for the 1980s

*Clearing of Forests for Croplands only

Land Use Emissions

Net Biospheric Emissions

McGuire et al. (2001)
## Comparison of ISAM Estimated Global Biospheric Emissions for 1980s with IPCC (GtC/yr)

<table>
<thead>
<tr>
<th>Land Cover Change Activities</th>
<th>ISAM</th>
<th>IPCC (2001)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Croplands</td>
<td>Croplands+Pasturelands</td>
</tr>
<tr>
<td></td>
<td>H*</td>
<td>M*</td>
</tr>
<tr>
<td>Land Use Emission</td>
<td>1.21</td>
<td>0.36</td>
</tr>
<tr>
<td>Carbon Sink*</td>
<td>−1.26</td>
<td>−1.22</td>
</tr>
<tr>
<td>Net Flux</td>
<td>−0.05</td>
<td>−0.86</td>
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</tbody>
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The ISAM model estimated land use emissions due to croplands for 1980s ranges between 0.36 - 1.21 GtC/yr

- Estimates based on Houghton (2003) were higher than McGuire et al. particularly after 1960

- Based on ISAM results for croplands, the terrestrial biosphere has historically been a source of carbon to the atmosphere - it is a net sink for 1980s

- magnitude of net flux based on Houghton’s data was much smaller than based on McGuire et al.

- Based on ISAM results for croplands, the terrestrial was sink of carbon for 1980s, but source for croplands and pasturelands
Ocean Climate-Carbon Cycle
The Global Carbon Cycle Is Sensitive to Climate Change

Climate change will affect the uptake of anthropogenic carbon dioxide by the oceans.

Present carbon uptake by the oceans (Moles CO$_2$/square meter/year)

Major Carbon Sink Regions in Oceans
Important Climate- Ocean Carbon Cycle Feedbacks

- Increase air and sea surface temperature (SST)
  - reduces CO2 solubility and decreases carbon uptake
- Increase high latitude freshwater input through enhanced hydrological cycle, sea ice melting, and river runoff weakens the ocean thermohaline circulation (THC)
  - reduces surface-to-deep ocean carbon transport and decreases carbon uptake
ISAM has the ability to resolve major ocean basins and continents.
ISAM-simulated influence of climate warming on the Ocean Carbon Cycle (WRE1000)
The Simulated Influence of Climate Warming on the Oceanic Carbon Cycle: Conclusions

- Both SST feedback and the ocean circulation feedback decrease oceanic uptake.
  - Before 2050: SST-solubility is stronger
  - After 2050: Circulation feedback becomes important as climate change increases

- Climate change feedbacks result in lower predicted allowable emissions for the CO$_2$ stabilization pathways, relative to no-climate-feedback scenarios.
  - For period 1990-2100, the difference in cumulative emissions is 9% (25 GtC) for WRE1000 CO$_2$ pathway.
THE END
Non-CO$_2$ Gas Cycles
Climate-Chemistry-Climate Interactions: The Example of CH₄
Modeling Methane Concentrations
Future Scenario Analysis

◆ CH4 is the second most important GHG produced by human activities
◆ Changes in future atmospheric CH4 concentrations will depend on:
  ➢ CH₄ emissions
    ◆ Economic and policy-driven changes in anthropogenic sources (fossil fuels, agriculture, waste, biomass burning)
    ◆ Human and climate-driven changes in natural sources (wetlands, forest fires, hydrates)
  ➢ Atmospheric OH concentrations, affected by CO, NOx and NMHC emissions and water vapor concentrations
    ◆ Economic, social and policy-driven changes in emissions from transport, other fossil fuel use, manufacturing, agricultural cultivation & fertilization, and biomass burning
    ◆ Climate-driven changes in natural sources (oceans, vegetation, wildfires, soils) and atmospheric water vapor concentrations
Multi-Dimensional Atmospheric Chemistry Transport Model

- Background-dependent chemistry resolved in 3 environments: urban, continental, and marine
- Temperature and water vapor profiles interactively determined by climate model output
- Seasonal & regional surface fluxes resolved for important greenhouse gases and pollutants
- Temperature-dependent reaction pathways & photolysis rates calculated for 67 chemicals
CH₄-Chemical Interactions for IPCC Reference Scenario IS92a

Assumed constant NOₓ, & CO emissions

Emissions (CH₄)↑ ⇒ [CH₄]↑
Emissions (CO)↑ ⇒ [CH₄]↑
Emissions (NOₓ)↑ ⇒ [CH₄]↓

Kheshgi, Jain, et.al.(1999)
Hayhoe, Jain, Kotamarthi (2001)
Future Avenues of Research …

- Fully interactive exploration of chemistry-carbon cycle-climate feedbacks including surface albedo, clouds, water vapor, etc.
- Analysis of the direct and indirect effects of sulfate and carbonaceous aerosols
- The influence of urban chemistry on global climate
- Further applications in carbon sequestration studies
- Analysis of the net impact of radiative forcing, carbon cycle and climate-related feedbacks on the future scenarios
Climate change will affect the uptake of anthropogenic carbon dioxide by the oceans.

Present carbon uptake by the oceans (Moles CO$_2$/square meter/year)
Evaluation of the Climate Change Feedbacks for Stabilization Scenarios

**Atmospheric CO$_2$ Concentrations:**
- Period 1765-1990: Observed record.
- After 1990: WRE550 and WRE1000 ppm.

**Climate Simulations:**
- Baseline Simulations: $\Delta T_{2x} = 0.0^\circ\text{C}$.
- Climate Feedback Simulations: $\Delta T_{2x} = 3.7^\circ\text{C}$.

**Climate Change and Carbon Cycle Feedbacks:**
- Solubility: Sea Surface Temperature (SST) & CO$_2$ Solubility Feedback
- Ocean Circulation: Salinity-Ocean Circulation Feedback
ISAM Terrestrial Carbon Reservoirs for Each Land Cover Classification


Rate Coefficients Chosen to Match Observed NPP, Biomass and Soil Carbon for Each Land Cover Classification
Land Cover Classifications (1765)
Simulated Net Primary Productivity in 1765 and 1980s (kg cm^{-2} yr^{-1})

(Clearing of Forests for Croplands only)
Steady-State Comparison for CH₄ Concentrations (Lifetime ~ 12 yrs)

2D CTM (36x57)

MBCM (3x6x4)
Steady-State Comparison for CO Concentrations (Lifetime $\sim 2-3$ mths)

2D CTM (36x57)

MBCM (3x6x4)
Steady-State Comparison for OH Concentrations (Lifetime ~ 1-2 s)

2D CTM (36x57)  

MBCM (3x6x4)
Integrated Science Assessment Model (ISAM) as a *Tool for Scientific and Policy Analysis*

- **Represent** all key Climate System Components and Feedbacks at appropriate level of detail;

- Account for **sub-grid climate processes** by using empirical relationships to approximate net effects;

- Approximate the effects of various **physical and chemical processes** based on AOGCM and CTM results;

- **Fully interactive** during calculations;

- **Evaluate** chemical and climate **feedback effects** on climate and policy development;

- **Treat uncertainty** as an essential feature;

- **Global in scope, but resolve** regional distribution.
Integrated Assessment Modeling as a Tool for Scientific and Policy Analysis

To Study Feedbacks Throughout The Earth System
Comparison of ISAM-simulated anthropogenic CO$_2$ uptake with OGCM results

Global Anthropogenic CO$_2$ uptake GtC/yr

(1980-1989)

Regional Anthropogenic CO$_2$ uptake in 1990 GtC/yr

OGCM results are from OCMIP (Orr. et al. 2001)
Time-dependent land cover changes for each grid point are calculated based on Houghton’s (2003) and McGuire et al. (2001) total regional land cover changes (ha/yr).
Global Emission Estimates for Biogenic VOC Emissions

1992 Global (upper) and regional (lower) distributions of isoprene emissions

1 – North America
2 – Latin America
3 – Europe
4 – North Africa and Middle East
5 – Tropical Africa
6 – EUSSR
7 – China
8 – S & SE Asia
9 – Pacific Developed Region
Overall Conclusions

- The climatic impact of GHGs and aerosols depends strongly on interactions between various components of the Earth’s system.
- Due to these interactions, a comprehensive Earth System approach is required to study GHGs and aerosols.
- This approach is crucial to determining accurate emission pathways that ensure the desired impact on climate.