POTENTIAL ENVIRONMENTAL IMPACTS OF HYDROGEN-BASED TRANSPORTATION & POWER SYSTEMS

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Potomac Hudson Engineering, Inc.

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Overview

- Timeline
  - Start: Sept 2007
  - Finish: Sept 2009
  - 70 % Complete
- Budget
  - Total project funding: $573K
  - Funding received in FY07: $265K
  - Funding for FY08: $167K
  - Funding for FY09: $141K
- Barriers Addressed
  - Contribute consistent set of data and assumption/scenario definitions and assessment tools to support program decisions
  - Contribution to environmental studies that are necessary to assess technology readiness
- Partners
  - Tetra Tech, Inc.
  - Stanford University, Mark Z. Jacobson
  - Potomac-Hudson Engineering

Objectives

- Compare emissions of hydrogen, the six criteria pollutants (CO, SO_x, NO_2, PM, ozone, and lead) and GHGs from near and long-term methods of generating hydrogen for vehicles and stationary power systems

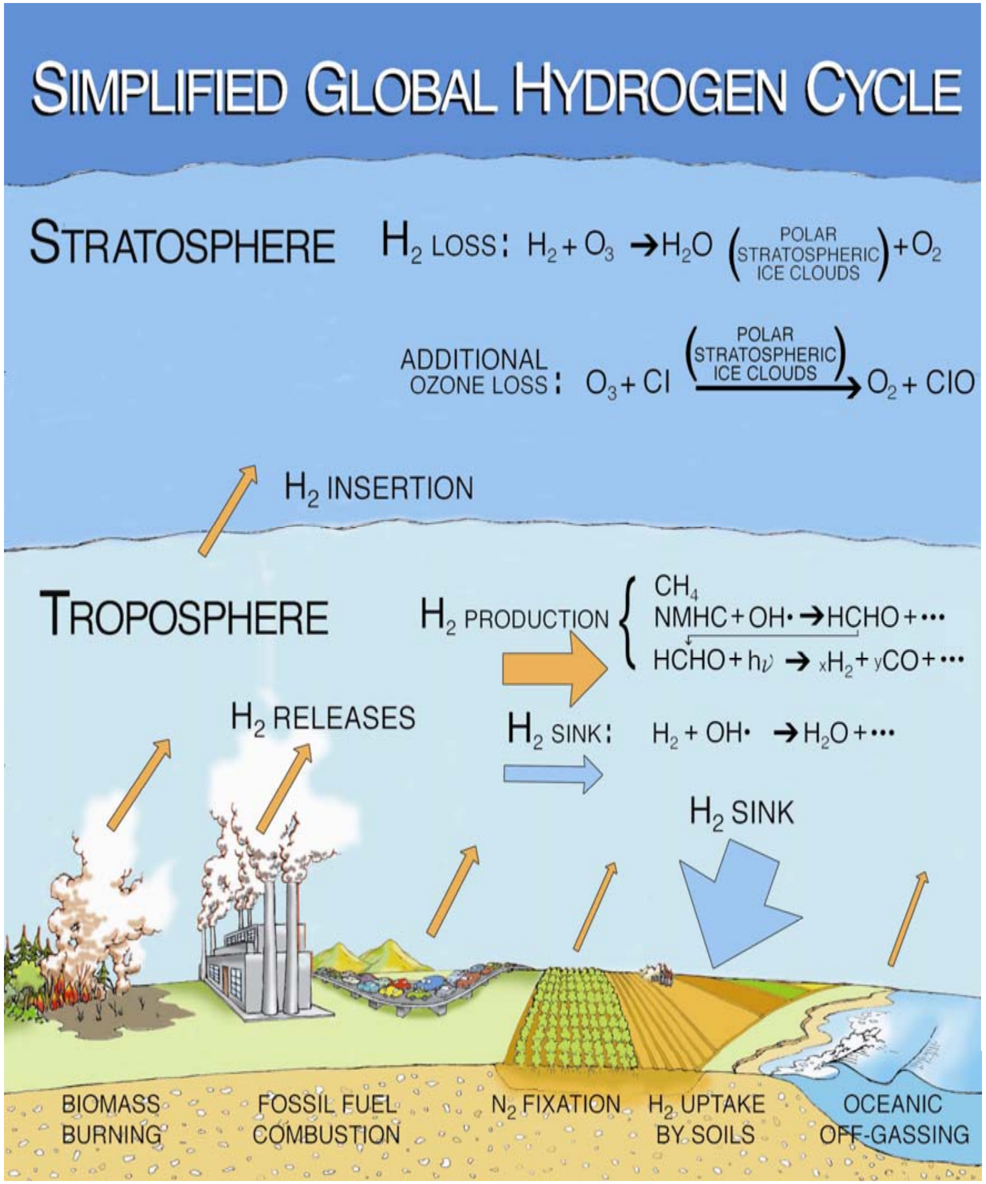
- Evaluate effects of emissions on climate, human health, ecosystem and structures

Milestones

Milestones	Month/Year
Project Kick-off Meeting	December 2007
Technical Brief on Vehicle Penetration & Stationary Source Scenarios & Emission Profiles	July 2008
Draft Report Potential Effects of Shifting to a Hydrogen-based Economy	October 2008
Revised Draft Report on Impact Assessment Model with Preliminary Results	June 2009
Final Report on Inputs, Methodologies, and Outputs	July 2009
Final Report on Impact Assessment Model	August 2009
Final Conclusions of Comprehensive Impact Assessment	September 2009

Technical Approach

- Problem Definition (100 % Complete)
  - Develop market penetration scenarios for vehicles
  - Develop market penetration scenarios for electricity generation
  - Develop emission-profile databases
- Environmental Simulations (50 % Complete)
  - Develop soil uptake model
  - Predict changes in hydrogen and other atmospheric gases and aerosols in troposphere and stratosphere
- Environmental Assessment (40 % Complete)
  - Quantify effects due to implementation of two market penetration scenarios


SIMPLIFIED GLOBAL HYDROGEN CYCLE
STRATOSPHERE
H2 LOSS: H2 + O3 → H2O (POLAR STRATOSPHERIC ICE CLOUDS) + O2
ADDITIONAL OZONE LOSS: O3 + Cl (POLAR STRATOSPHERIC ICE CLOUDS) → O2 + ClO
H2 INSERTION
TROPOSPHERE
H2 PRODUCTION
CH4
NMHC + OH· → HCHO + ···
HCHO + hν → xH2 + yCO + ···
H2 RELEASES
H2 SINK: H2 + OH· → H2O + ···
H2 SINK
BIOMASS BURNING
FOSSIL FUEL COMBUSTION
N2 FIXATION
H2 UPTAKE BY SOILS
OCEANIC OFF-GASSING

2008 Project Activities

- Emission Analyses Using GREET Model (1.8b)
- Development of soil uptake model
- Simulation of atmospheric chemistry effects of hydrogen economy using Gas, Aerosol, Transport, Radiation General Circulation, Mesoscale, Ocean Model (GATOR-GCMOM)
  - Model processes
  - Calibration
  - Simulations
    - Conversion of fossil-fuel vehicles to hydrogen fuel cell vehicles (HFCV), H2 produced by wind-powered electrolysis
    - 2050 A1B emissions replaced with HFCV, H2 produced by steam reforming of natural gas

GATOR-GCMOM Model

- Model is a global-through-urban Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, and Ocean Model.

- Model uses 4° S-N x 5° W-E global domain and 42 layers up to 55 km; 25 layers in troposphere (5 in bottom 1km) and 16 in stratosphere.

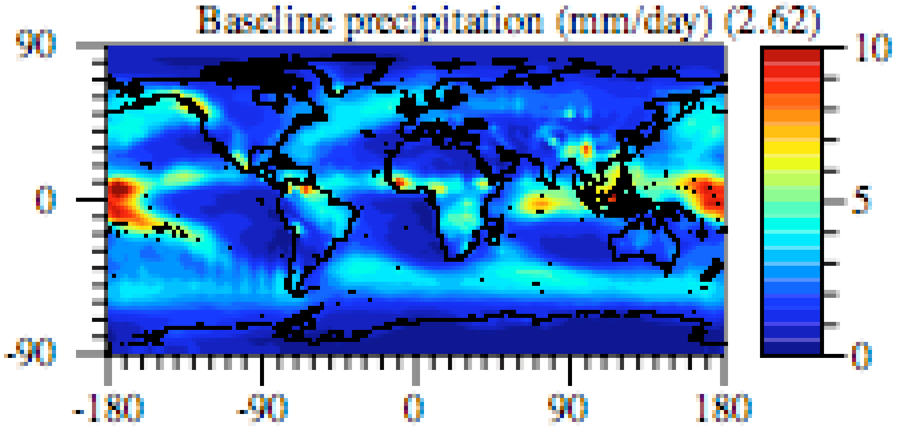
- Model solves atmospheric gas photochemistry for 128 gases using 282 kinetic reactions and 52 photolysis reactions.

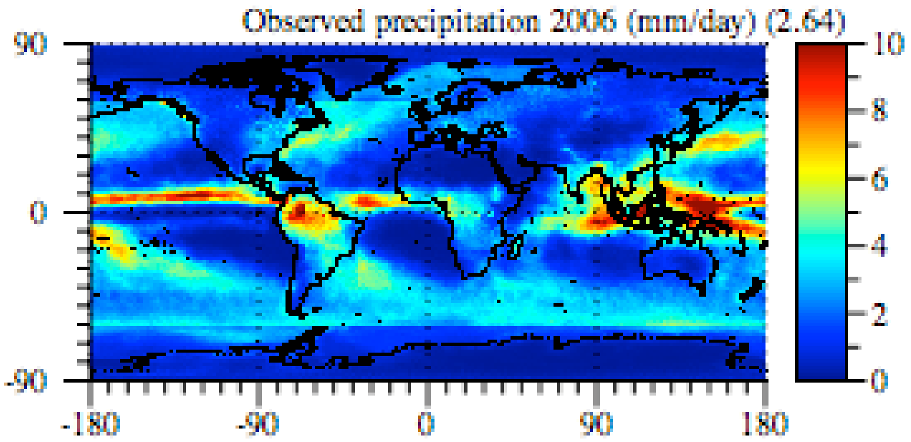
- Uses global emissions of GHGs, speciated organic gases, BC, POC, and PM on 1° x 1° resolution.

GATOR-GCMOM Processes

- Gas processes
  - Emission
  - Photochemistry
  - Gas-to-particle conversion
  - Cloud removal
- Aerosol processes
  - Emission
  - Nucleation/condensation
  - Gas dissolution
  - Aqueous chemistry
  - Crystallization
  - Aerosol-aerosol coagulation
  - Aerosol-cloud coagulation
  - Dry deposition
  - Sedimentation
  - Rainout/washout
- Meteorological processes
  - Pressure, winds, temp., TKE
- Cloud processes
  - Subgrid clouds, size-resolved physics
  - Liquid/ice growth on aerosol particles
  - Liquid drop freezing/breakup
  - Hydrometeor-hydrometeor coagulation
  - Hydrometeor-aerosol coagulation
  - Precipitation, aer./gas rainout/washout
  - Below-cloud evaporation/melting
  - Lightning from collision bounce-offs
- Radiative transfer
  - UV/visible/near-IR/thermal-IR
  - Gas/aerosol/cloud scat./absorption
  - Predicted snow, ice, water albedos
- Surface processes
  - Soil, water, snow, sea ice, vegetation, road, roof temperatures/moisture
  - Ocean 2-D dynam., 3-D diffus/chem.
  - Ocean-atmosphere exchange

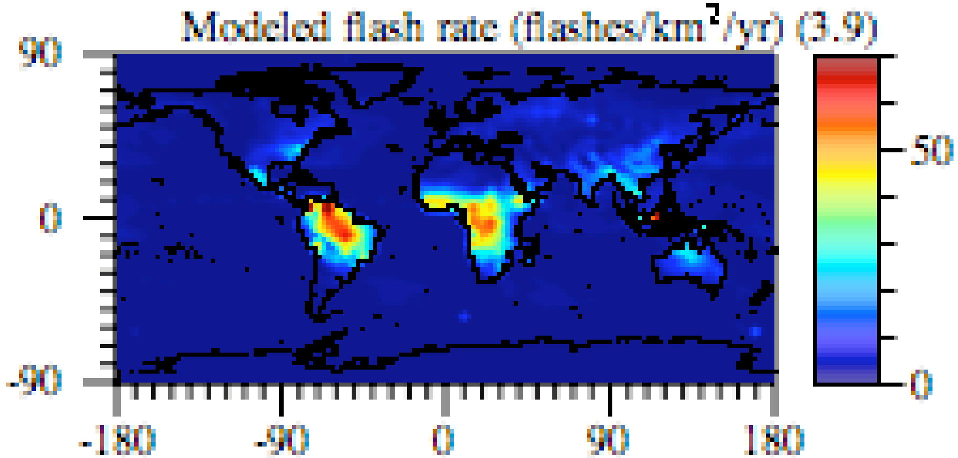
Modeled vs. Measured Annual Precipitation

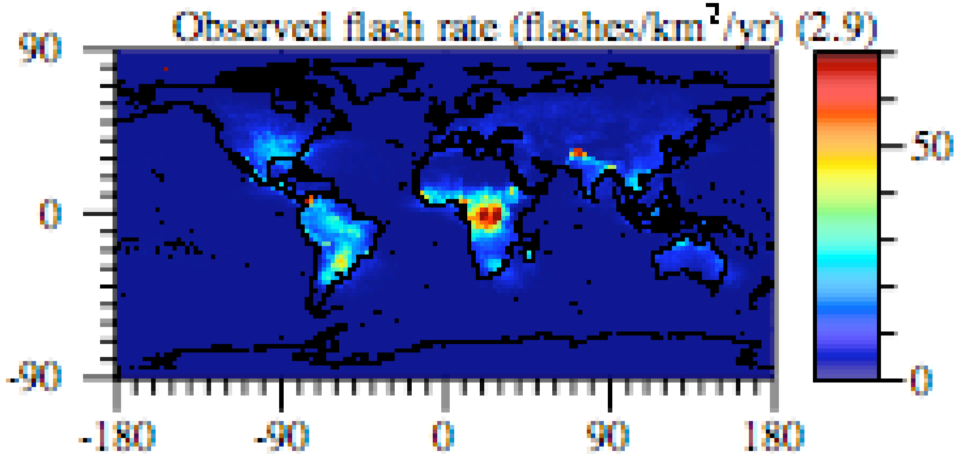




Observations from Huffman et al. Values in () are global averages.

Modeled vs. Measured Annual Lightning Flash Rate

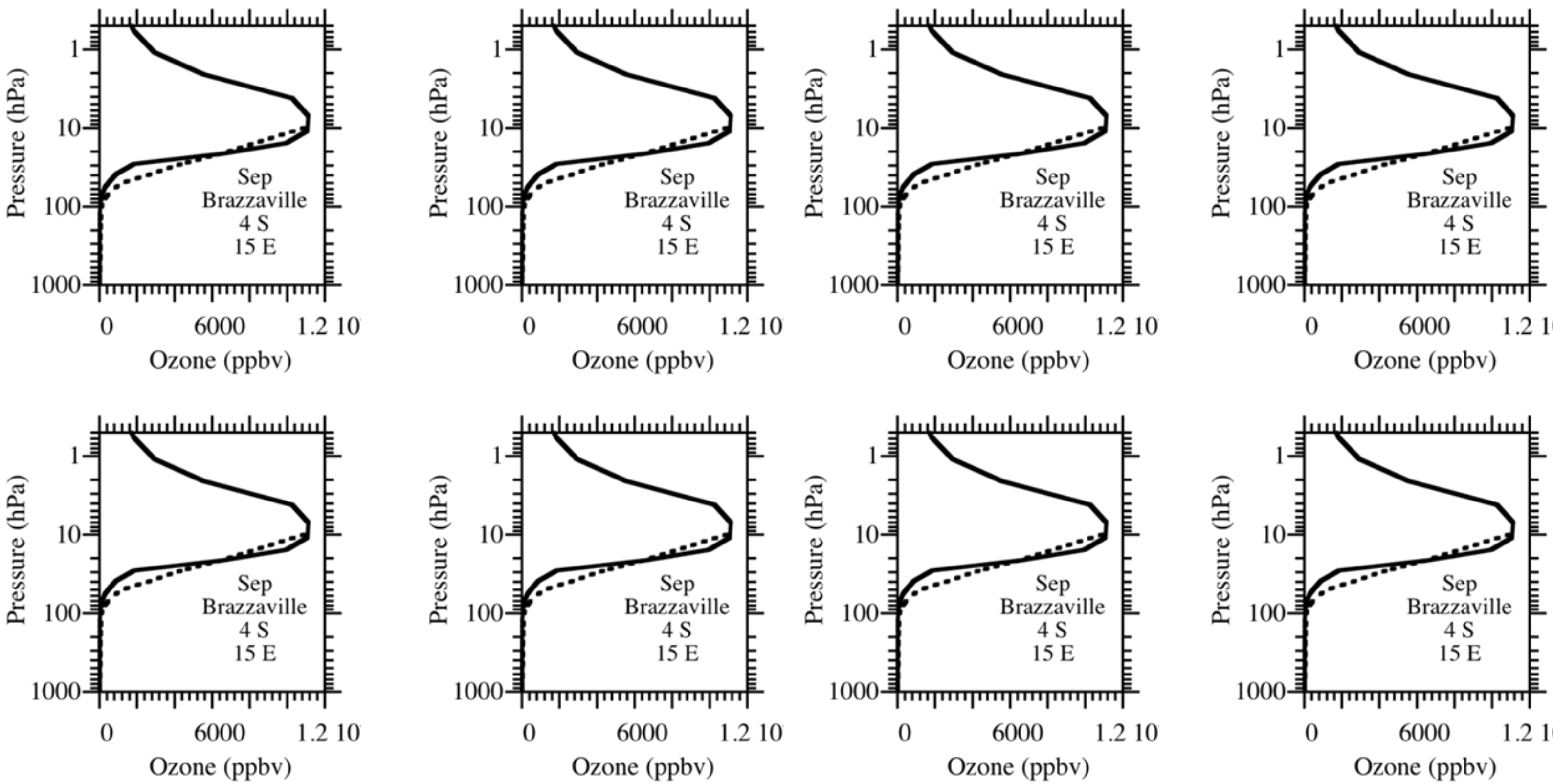




Observations from NASA
LIS/OTD Science Team

Values in () are global averages.

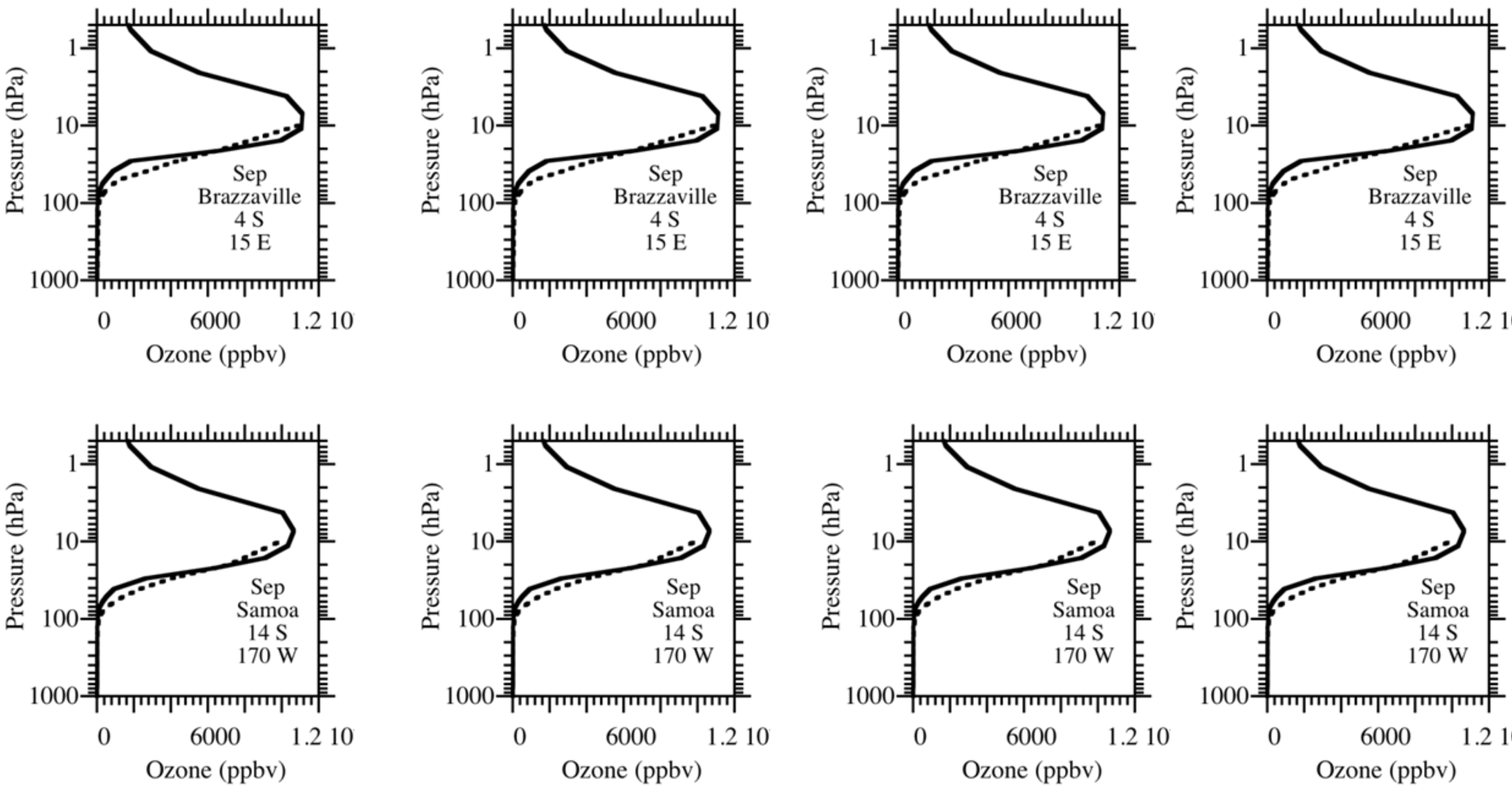
Modeled vs. Measured Monthly T and T_d: Eight Locations



T = Temperature
T_d = Dew point temperature

Data from FSL (2008)

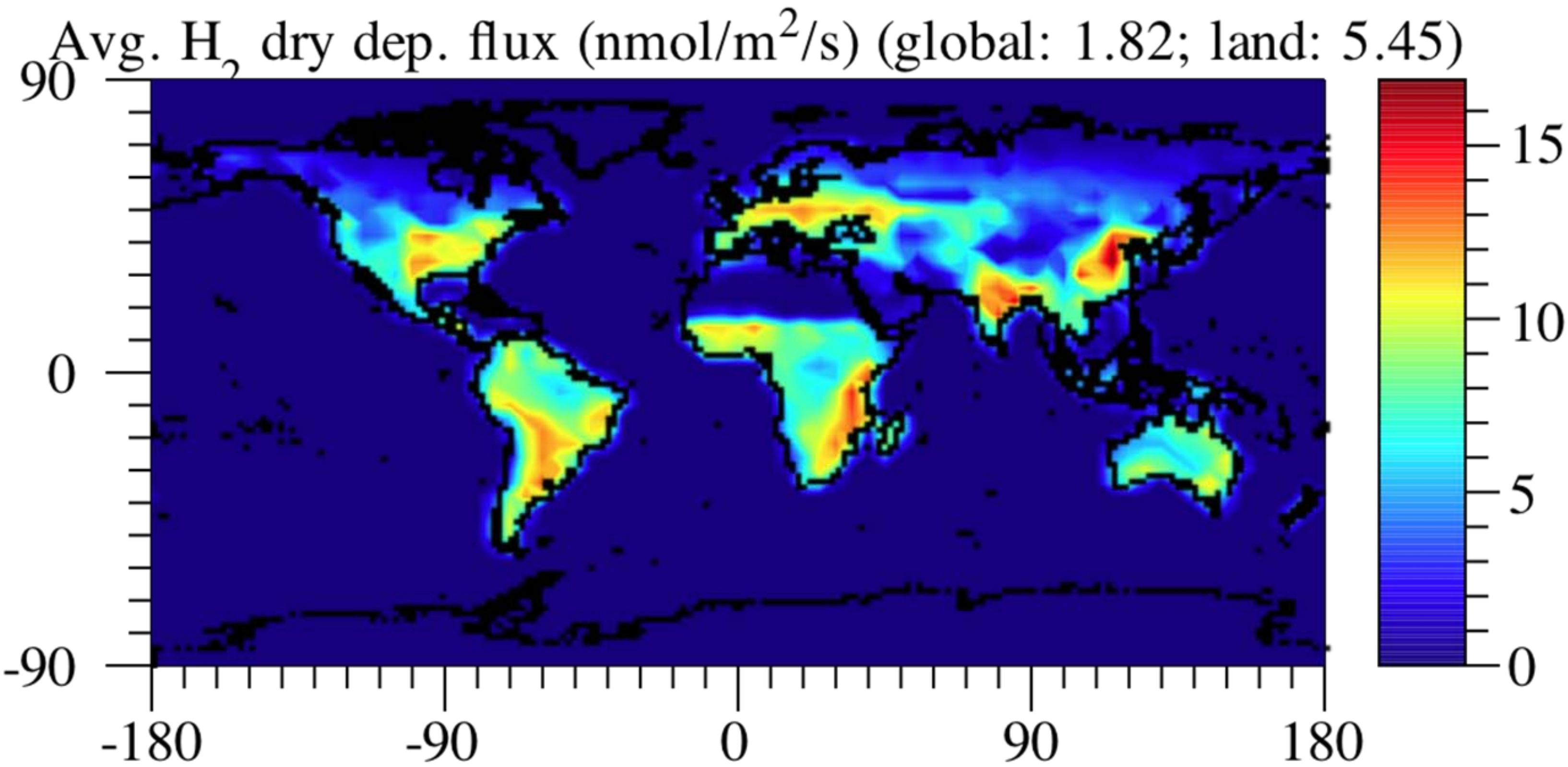
Modeled vs. Measured Monthly Climatological Ozone



Data from Logan et al. (1999)

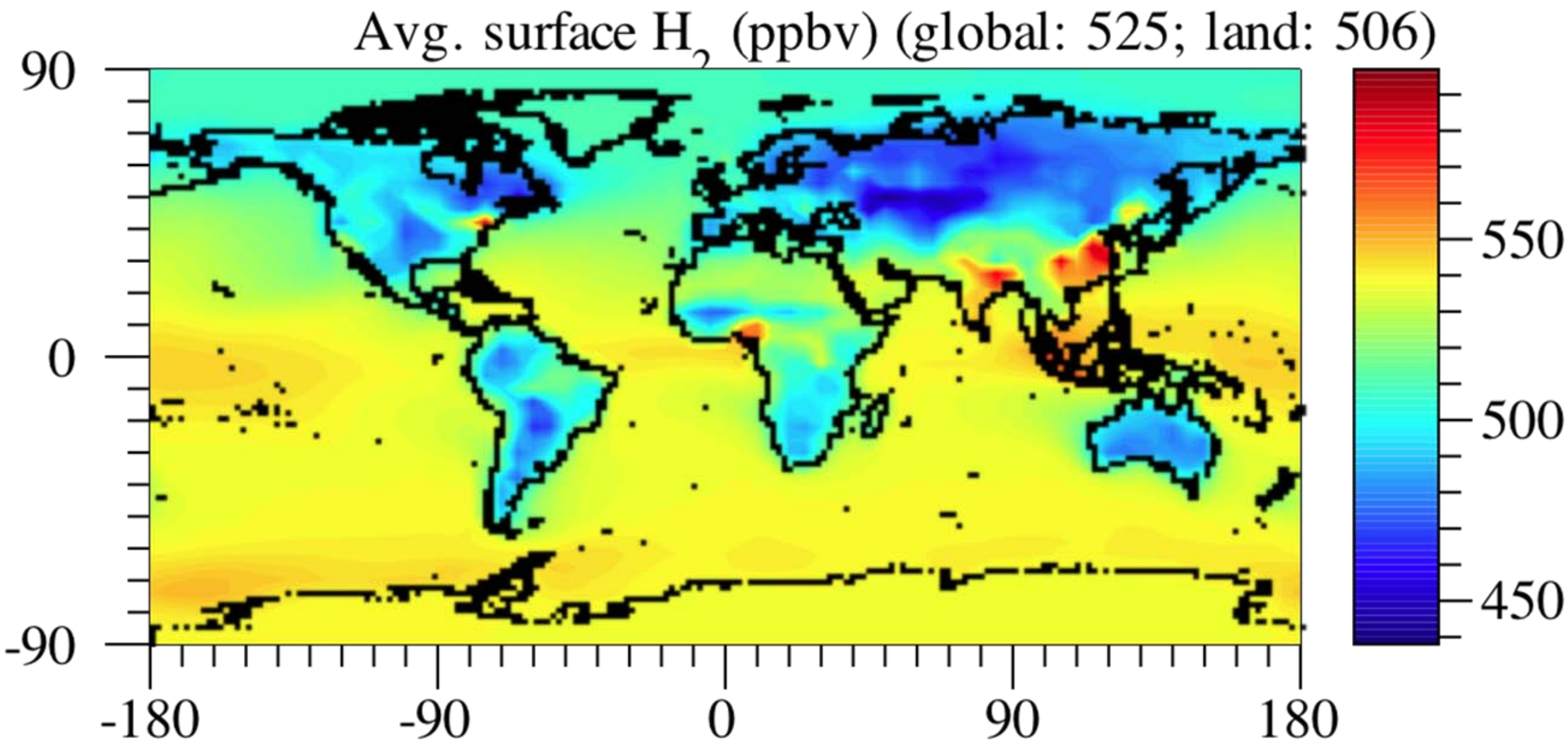
measured data
simulation

Modeled H_2 Deposition Flux



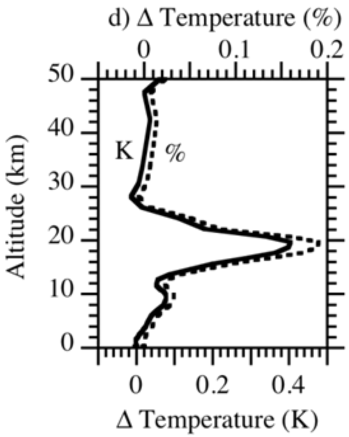
New model algorithms were added to predict hydrogen uptake by soil bacteria.

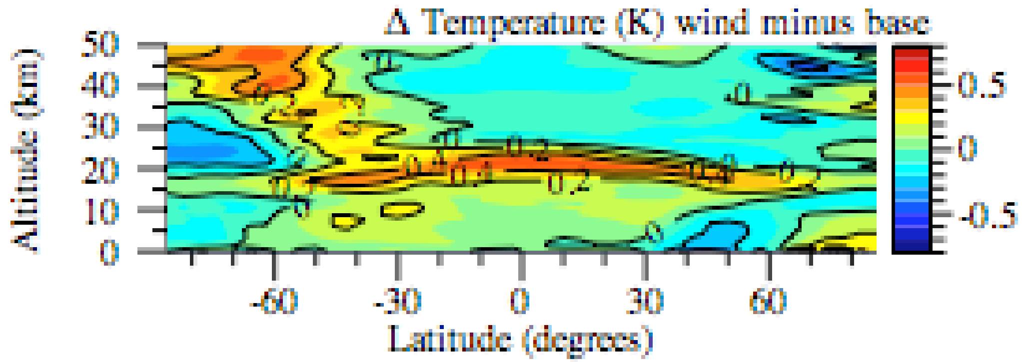
Modeled H_2 Surface Concentration



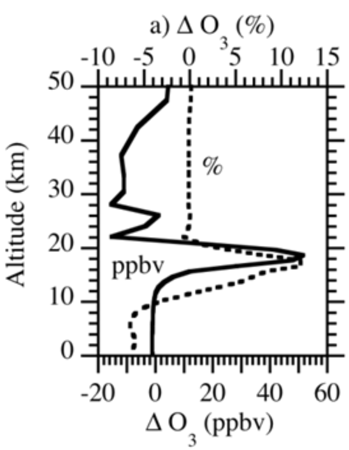
Predicted atmospheric hydrogen using new hydrogen uptake module.

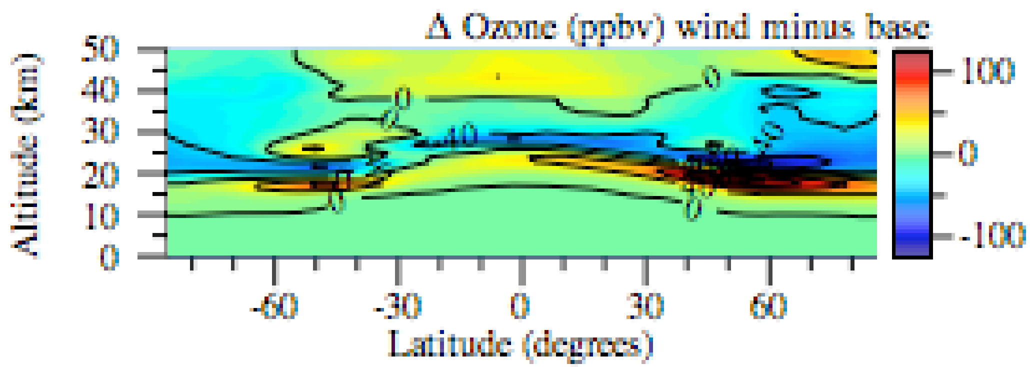
Effects of wind-HFCV on Global Climate and the Ozone Layer





Net surface cooling, stratospheric warming





Increase in column ozone by ~0.4%

GATOR-GCMOM Modeling Scenarios

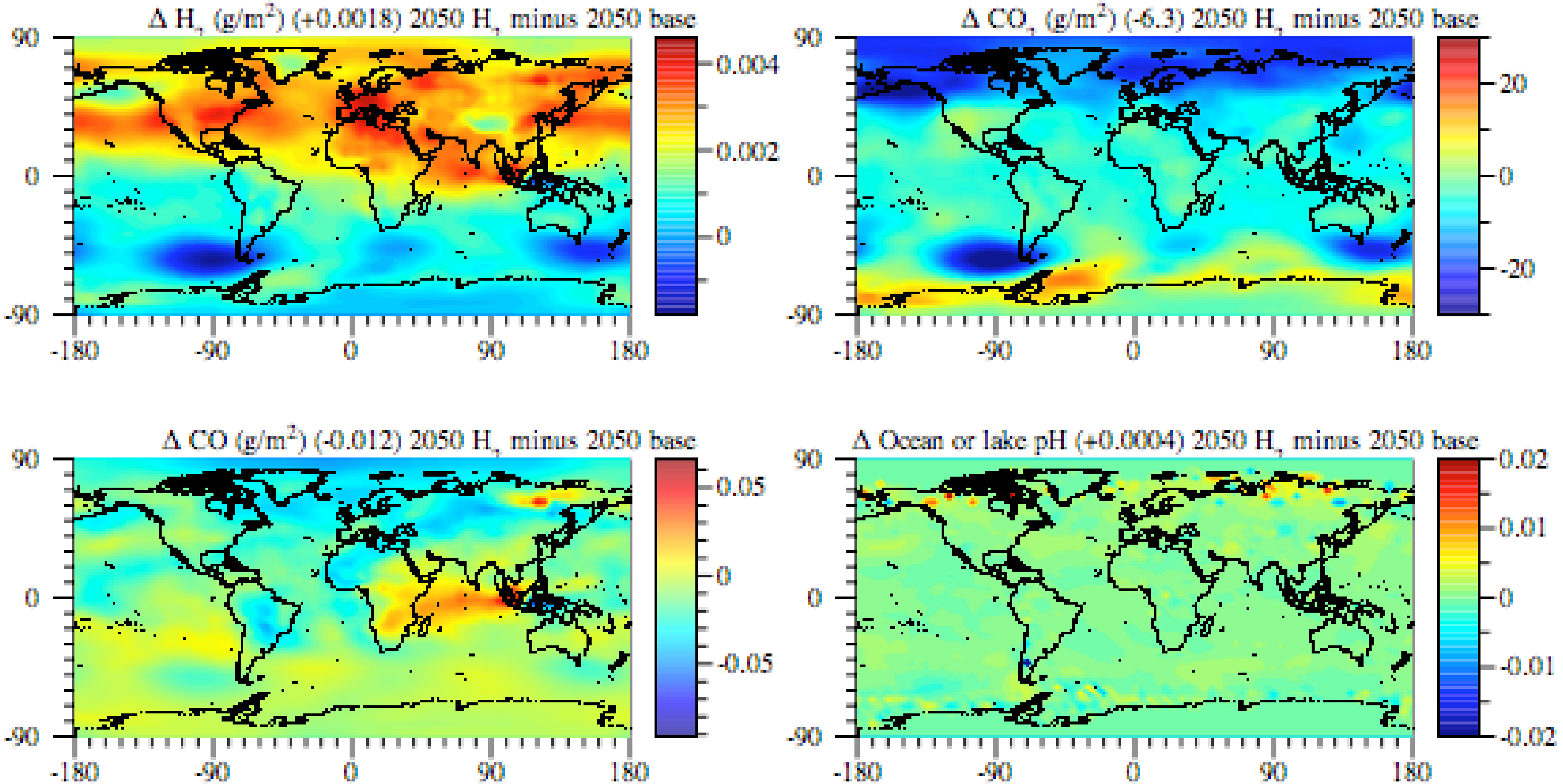
- Baseline ~2000
- IPCC Scenario 2050 A1B
- 2050 A1B with 90% HFCV penetration in developed countries and 45% HFCV penetration in other countries and where the H_2 is produced by steam-reforming of natural gas.
- Emission factors for the two 2050 scenarios for each of 17 world regions, 27 gas and particle chemicals, and 8 emission sectors were developed by D.G. Streets (Argonne National Laboratory).

Fossil-fuel Emissions (Tg/yr)

	2000	2050 A1B	2050 A1B+HFCV
H_2	8.4	14.6	17.2
NO	48	153	149
NO_2	8.2	26.1	25.4
N_2O	11.1	9.7	9.6
CO	294	514	484
CO_2	25,560	95,900	93,200
Methane	284	357	356
Methanol	4.5	13.0	13.8
Ethene	4.4	12.6	13.4
Toluene	4.4	8.1	8.8
SO_2	129	212.5	213
FF-BC	3.8	6.7	5.1
FF-POM	5.5	6.0	7.6
BF-BC	4.1	1.5	1.5
BF-POM	38	14.6	14.6

Emission factors from D. Streets, Argonne National Laboratory

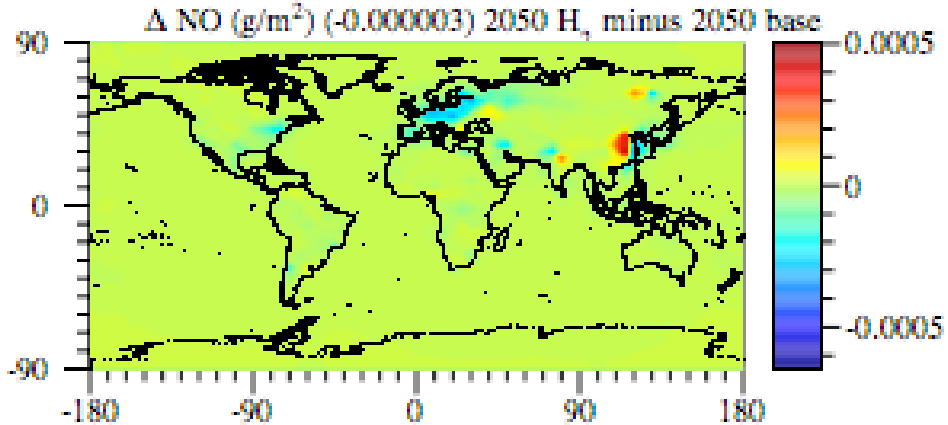
Preliminary* 2050 H_2 Minus 2050 Base

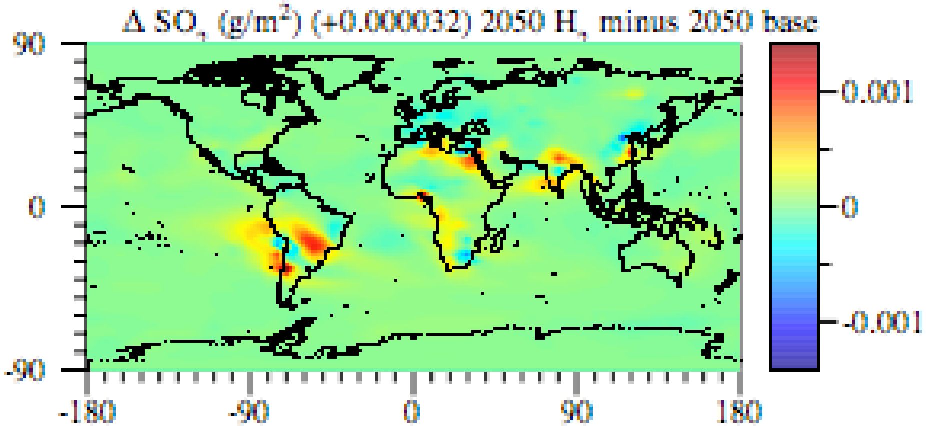


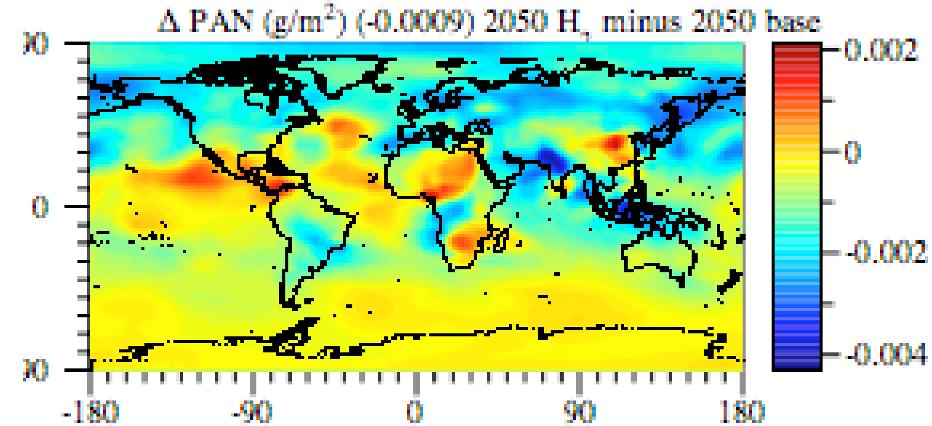
Natural gas-HFCV increased H_2, decreased CO, CO_2, increased ocean pH; Values shown in parentheses are global average changes.

*1.5 year run-up

Preliminary* 2050 H_2 Minus 2050 Base



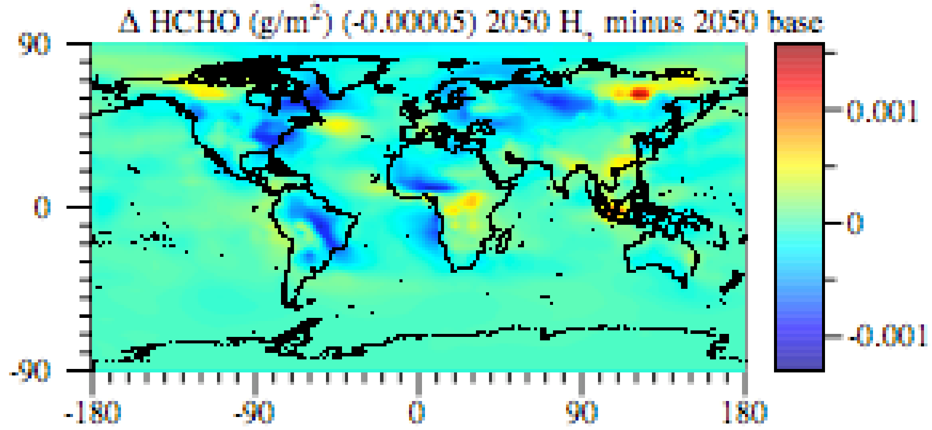


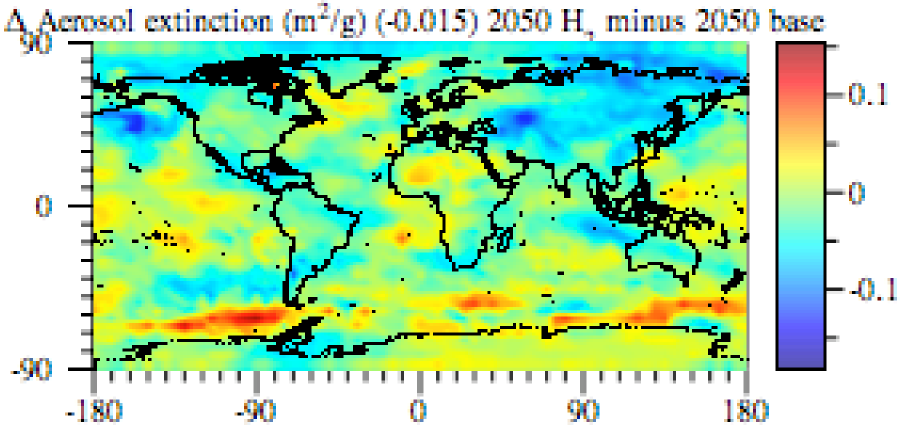


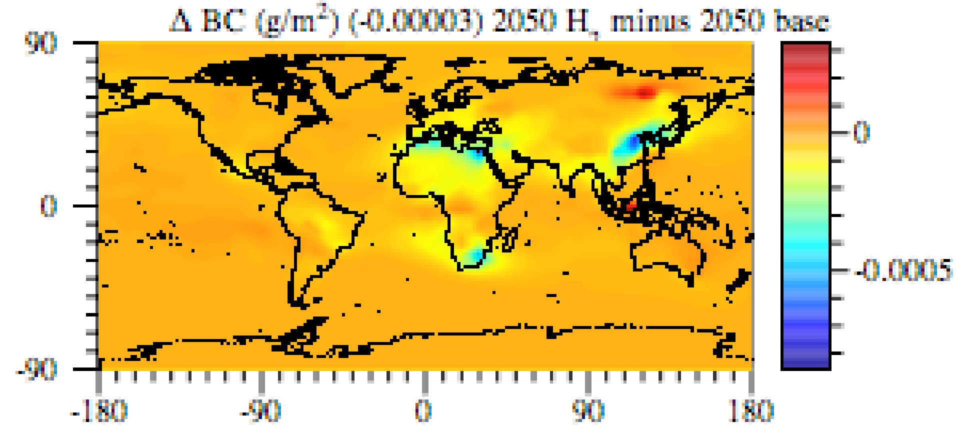
Natural gas-HFCV decreased NO, PAN, increased SO_2 slightly.

*1.5 year run-up

Preliminary* 2050 H_2 Minus 2050



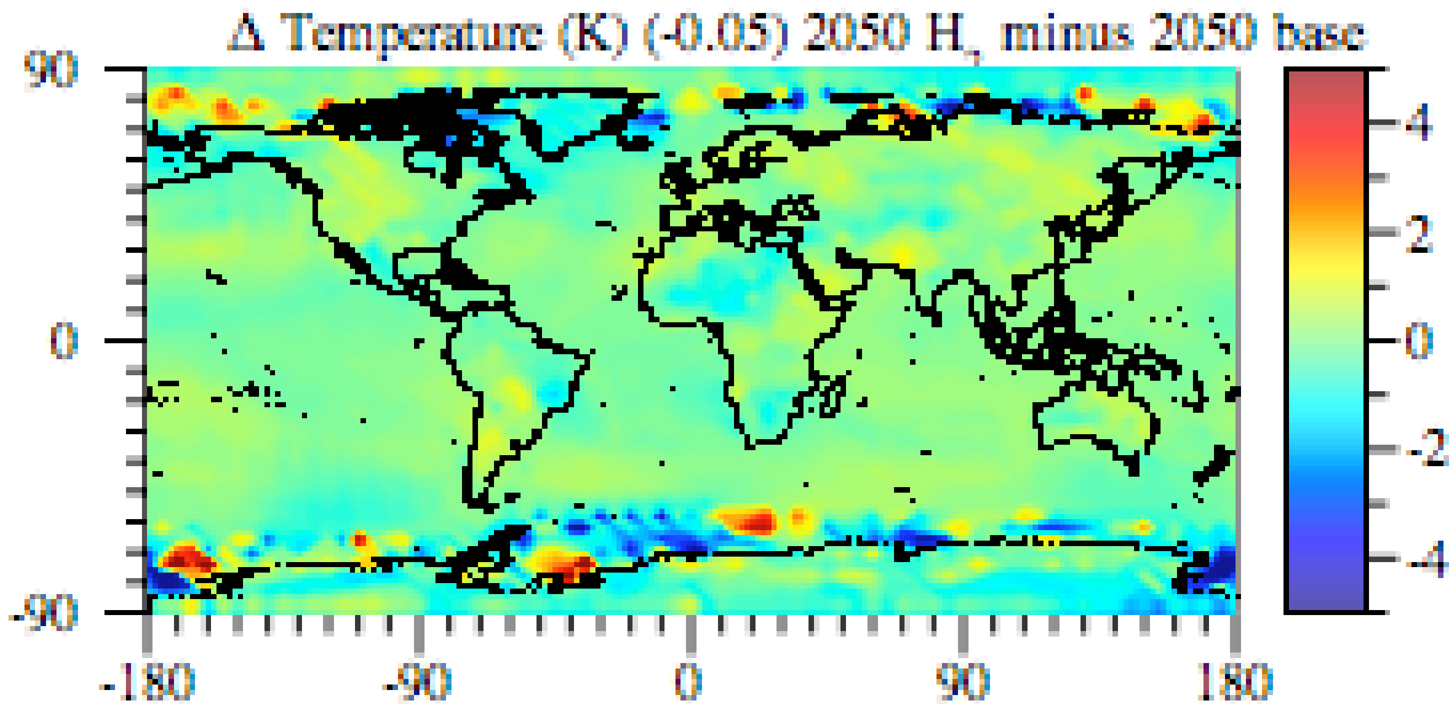




Natural gas-HFCV decreased formaldehyde (HCHO), black carbon, aerosol extinction.

*1.5 year run-up

Preliminary* 2050 H_2 Minus 2050 Base



Natural gas-HFCV decreased surface temperatures, but simulations must be run longer to more accurately quantify the magnitude.

*1.5 year run-up

Summary: Wind-generated HFCV Case

- Converting the world's fossil-fuel onroad vehicles (FFOV) to hydrogen fuel cell vehicles (HFCV), where the H2 is produced by wind-powered electrolysis, is estimated to reduce current global emissions by:
  - CO_2 by ~13.4%,
  - NO_x ~23.0%
  - nonmethane organic gases ~18.9%,
  - black carbon ~8%
  - H_2 ~3.2% (at 3% leakage),
  - and H_2O ~0.2%.
- Over 10 years, such reductions were calculated to reduce tropospheric concentrations by:
  - CO ~5%,
  - NO_x ~5-13%,
  - most organic gases ~3-15%,
  - OH ~4%, ozone ~6%, and
  - PAN ~13%,
  - but to increase tropospheric CH4 ~0.25% due to the lower OH.
- Lower OH also increased upper tropospheric/lower stratospheric ozone, increasing its global column by ~0.41%. WHFCV cooled the surface and warmed the stratosphere.

www.stanford.edu/group/efmh/jacobson/fuelcellhybrid.html
GRL (2008) 35, L19803

Summary: 2050 A1B Case with HFCV

- Preliminary results (after 1.5 years of simulation)
  - Conversion will cool global surface temperatures, on average.
  - Conversion will also reduce emissions:
    - CO_2
    - CO
    - NO_x
    - aldehydes
    - and black carbon.
  - Conversion will slightly increase H_2 and SO_2.
- Longer simulations underway will clarify net effects on O_3 and other secondary pollutants in the atmosphere.

Future Work: Modeling

- Complete GATOR-GCMOM Model simulations to predict changes in atmospheric concentrations of hydrogen and other constituents and effect on ozone in troposphere and stratosphere
  - Output on global scale with more detail for the US
  - Output includes: atmospheric concentrations of H_2, GHGs and PM, oxidative capacity of the atmosphere, stability of the ozone layer, and microbial ecosystems involved in hydrogen uptake
- Quantify H_2 and criteria pollutants released from each technology used to generate hydrogen (fuel cells & electricity) for two market penetration scenarios and complete sensitivity analyses for vehicle and electricity fuel sources

Future Work: Effects

- Quantify Effects of Implementing Market Penetration
  - Climate: air temperature, cloud production, ozone levels, photochemical smog
  - Human health: six criteria pollutants, lead, GHG compared to health-effect levels and national ambient air quality standards
  - Ecosystems: use effects levels for criteria pollutants and GHGs to evaluate impacts on aquatic and terrestrial biota
  - Structures: effects of acids, ozone, PM, and GHGs on materials, buildings, structures, historical sites, roadways
  - Other environmental effects: e.g. mining and processing of trace metals used as catalysts or in PV cells

Project Summary

Objective:

- Quantify near and long-term air quality, human health, ecosystem, and structure effects associated with shift to hydrogen-based economy

Approach:

- Develop emission profiles for viable market penetration scenarios
- Simulate changes in hydrogen and other atmospheric gases
- Assess effects using model projections

Technical Accomplishments and Progress:

- Synthesis of emissions associated with broadly accepted market penetration scenarios and quantified emissions for future scenarios
- Advancement and testing of soil uptake model
- GATOR-GCMOM simulations underway; have 1-2 years output

Next Steps:

- Complete model simulations
- Evaluate impacts to air quality and ozone
- Evaluate impacts of changes in criteria pollutants and GHGs on human health, structures, and environment
- Development of environmental information to support assessment of technology readiness

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