Hydrogen Effects on Climate, Stratospheric Ozone, and Air Pollution

Investigators
Mark Z. Jacobson, Associate Professor, Civil & Environmental Engineering
David M. Golden, Consulting Professor, Mechanical Engineering
Whitney Colella, Former Postdoctoral Student Researcher
Cristina Archer, Postdoctoral Student Researcher
Gerard Ketefian, Graduate Student Researcher

Introduction

The purpose of this project is to study the potential effects on air pollution, climate, and stratospheric ozone, of replacing fossil-fuel motor vehicles and electric power plants with hydrogen fuel cell vehicles and power plants, respectively, where the hydrogen is produced either from steam reforming of natural gas, coal gasification, or wind energy. The effects are being estimated with a three-dimensional numerical model of the atmosphere and ocean that is driven by emissions and treats gases, aerosol particles, meteorology, clouds, radiation, oceans, soils, and other surfaces. During the first stage of the project, U.S. emission scenarios were developed and nested global-U.S. simulations were run to examine the short-term effects on air pollution and health of replacing gasoline and diesel in all onroad U.S. vehicles with hydrogen generated from wind, natural gas, or coal. In the second stage of the project, a global emission scenario was developed and global simulations are being run to examine the long-term effect of hydrogen from wind on global climate, stratospheric ozone, and tropospheric pollution. Final results for the first stage and preliminary results for the second stage of this project are discussed.

Background

During the last two years, some papers have been published examining the effects of a hydrogen economy on the atmosphere. Tromp et al.[1] modeled the potential impact of increasing atmospheric hydrogen on stratospheric ozone. They suggested that the addition of hydrogen would increase stratospheric water vapor and cool the stratosphere, a process that would delay recovery of the ozone layer. The paper did not look at the effect of simultaneously reducing fossil-fuel emission nor calculate the climate response of hydrogen itself, which is examined here.

Schultz et al.[2] examined the effects of a hydrogen economy on tropospheric air chemistry and direct radiative forcing of gases. Their scenarios assumed that a reduction in anthropogenic emission would accompany an increase in hydrogen use. They calculated that NO_x, CO, and OH would decrease and methane would increase in the global troposphere upon switching to hydrogen. Warwick et al.[3] similarly examined the effect of hydrogen leakage plus reduction in NO_x, CO, CH_4, and NMHC on tropospheric chemistry. Neither study (1) treated the effects of hydrogen on climate response (e.g., feedbacks to meteorology); (2) examined the effects of switching to hydrogen on local or regional pollution (they looked at large-scale effects); (4) treated aerosols or effects of a hydrogen economy on them; (5) treated specific emission scenarios, or (5) treated emissions resolved to the county level. These processes are treated here.

In addition, a few recent studies have examined the economic benefits and drawbacks of different methods of producing hydrogen[4,5] and the economic feasibility of a hydrogen economy[6,7,8,9]

Results

To date, six papers relating to this project have been published. Two of the papers examined the effects on air pollution and health of converting all U.S. onroad vehicles to hydrogen fuel cell vehicles. Three papers discussed model improvements, and one examined wind resources, which are relevant to one of the hydrogen scenarios. Abstracts of two of the papers (Publications 1 and 2) are as follows:

Switching to a U.S. Hydrogen Fuel Cell Vehicle Fleet: The Resultant Change in Emissions, Energy Use, and Greenhouse Gases
W.G. Colella, M.Z. Jacobson, and D.M. Golden
Journal of Power Sources, 150, 150-181, 2005

This study examines the potential change in emissions and energy use from replacing the current U.S. fleet of fossil-fuel on-road vehicles (FFOV) with hybrid electric fossil fuel vehicles or hydrogen fuel cell vehicles (HFCV). Emissions and energy usage are analyzed for three different HFCV scenarios, with hydrogen produced from 1) steam reforming of natural gas, 2) electrolysis powered by wind energy, and 3) coal gasification. With the US EPA's National Emission Inventory as the baseline, other emission inventories are created using a life cycle assessment (LCA) of alternative fuel supply chains. For a range of reasonable HFCV efficiencies and methods of producing hydrogen, we find that the replacement of FFOV with HFCV significantly reduces emissions associated with air pollution, compared even with a switch to hybrids. All HFCV scenarios decrease net air pollution emissions, including nitrogen oxides, volatile organic compounds, particulate matter, ammonia, and carbon monoxide. These reductions are achieved with hydrogen production from either a fossil fuel source such as natural gas or a renewable source such as wind. Furthermore, replacing FFOV with hybrids or HFCV with their fuel derived from natural gas, wind, or coal may reduce the global warming impact of greenhouse gases and particles (measured in carbon dioxide equivalent emission) by 6%, 14%, 23%, and 1%, respectively. Finally, even if HFCV are fueled by a fossil fuel such as natural gas, if no carbon is sequestered during hydrogen production, and 1% of methane in the feedstock gas is leaked to the environment, natural gas HFCV still may achieve a significant reduction in greenhouse gas and air pollution emission over FFOV.

Cleaning the Air and Improving Health With Hydrogen Fuel Cell Vehicles
M.Z.Jacobson, W.G. Colella, and D.M. Golden
Science, 308, 1901-1905, 2005

Converting all U.S. onroad vehicles to hydrogen fuel-cell vehicles (HFCV) may improve air quality, health, and climate significantly, whether the hydrogen is produced by steam-reforming of natural gas, wind-electrolysis, or coal gasification.

> Most benefits would result from eliminating current vehicle exhaust. Wind- and natural-gas-HFCV offer the greatest potential health benefits and could save 3700-6400 U.S. lives annually. Wind-HFCV should benefit climate most. An all-HFCV fleet would hardly affect tropospheric water vapor concentrations. Conversion to coal-HFCV may improve health but would damage climate more than fossil/electric hybrids. The real cost of hydrogen from wind-electrolysis may be below that of U.S. gasoline.

Publications 3-5 describe GATOR-GCMOM model improvements during the project period. The improvements were (a) a new method of solving nonequilibrium gas-aerosol transfer of acids and bases, (b) a new method of calculating absorption coefficients among multiple gases simultaneously, and (c) a new method of solving ocean-atmosphere exchange and ocean chemistry. Paper 6 discusses quantification of global wind resources from data.

Much of the work during the past year has focused on the second phase of the project, which is to examine the effect of a hydrogen economy on global climate, stratospheric ozone, and tropospheric air quality. Due to the large computational requirement for this portion of the project, it was decided that one scenario, that of converting all vehicles worldwide to hydrogen vehicles, where the hydrogen originates from wind-electrolysis, would be run. Because wind-electrolysis provides lesser overall emissions than does coal gasification or steam-reforming of natural gas (as determined from the first phase of the project), differences between results from the wind-hydrogen simulation and the global baseline simulation (also run) should bracket results from all other scenarios (as was found from Phase I).

For the global baseline simulations, hourly U.S. gas and particle emissions were obtained from the 2002 U.S. National Emission Inventory[10]. The inventory accounts for over 370,000 stack and fugitive sources, 250,000 area sources, and 1700 source classification code (SCC) categories of on- and nonroad mobile sources. Emitted gases include NO_x, SO_2, NH_3, CO, CH_4, and speciated reactive organic gases (ROGs), including paraffins, ethane, other olefins, formaldehyde, higher aldehydes, toluene, and xylene. Emitted particle components included BC, organic carbon (OC), sulfate, nitrate, and "other". Global emissions (monthly or yearly) of the same parameters were obtained from several inventories[11-14] at 1°x1° resolution. Emissions of additional species were accounted for in the model through physical processes (e.g., in the case of emissions from sea-spray, soil-dust, lightning, phytoplankton, vegetation).

For the wind-hydrogen scenario, U.S. and global emissions (including water vapor) from fuel combustion in onroad motor vehicles were reduced, hydrogen emissions from leakage (assumed at 3%) and water vapor emissions from hydrogen reaction in vehicles were increased. Sulfur dioxide and other power-plant emissions were also slightly increased to account for increased electric power due to compression of hydrogen. These assumption (except the choice of 3% leakage here) and assumptions about hydrogen and fossil vehicle efficiencies are the same or similar to those in Publications 1 and 2. In those publications, a 10% leakage, recognized as being high in order to ensure conservative results, was used. Here, a more realistic 3% leakage rate is used.

One pair of global simulations has been run for seven years. Results are shown below. For this simulation, the effects of switching to hydrogen on climate and atmospheric chemistry were simulated in the absence of chlorine chemistry. A second set of simulations has been started, in which chlorine chemistry is included.

Figure 1(a) shows the seven-year time- and zonally-averaged differences in the latitude-altitude profile of carbon dioxide when wind-hydrolysis replaces fossil-fuel onroad vehicles worldwide. The greatest reductions after seven years (4 ppmv) occurred over northern latitudes near the surface; reductions in the stratosphere were on the order of 1.5 ppmv.

The impact, primarily of the carbon dioxide change, on global temperatures is seen in Figure 1(b). The figure shows that reducing carbon dioxide cooled air near the surface and warmed it in the stratosphere, as expected from theory. Greenhouse gases warm air near the surface by trapping thermal-infrared radiation emitted by the surface of the earth. By absorbing this radiation, they prevent a portion of it from reaching the stratosphere, where it would otherwise be absorbed by background greenhouse gases, including carbon dioxide and ozone, thereby cooling the stratosphere. As such, when carbon dioxide mixing ratios decrease, near-surface temperatures should decrease and stratospheric temperatures should increase, as seen in Figure 1(b).

Figure 1(c) shows that hydrogen increased by 20 ppbv in the stratosphere and 40 ppbv in the troposphere after 7 years of leakage. Figure 1(d) shows that water vapor decreased in the troposphere and stratosphere. Although hydrogen reaction added water vapor to the stratosphere, cooler surface temperatures (Figure 1(b)) reduced surface water evaporation in the troposphere and stratosphere.

Figure 1(e) shows that a hydrogen economy increased zonally-averaged stratospheric ozone by up to 50 ppbv in some locations and decreased it near the surface by less than a ppbv after 7 years in the absence of chlorine chemistry. Stratospheric ozone increased in part because of the reduction in the stratosphere of oxides of nitrogen and oxides of hydrogen, which otherwise destroy ozone. Figures 1(f-h), for example, show that a hydrogen vehicle economy reduced stratospheric nitric oxide (NO), nitrogen dioxide (NO_2), and nitric acid (HNO_3). Near-surface ozone decreased because of the reduction there in oxides of nitrogen and organic gases, which, in combination, otherwise increase ozone in the troposphere. Few organic gases, aside from methane, reach the stratosphere, so stratospheric ozone was not affected much by the reduction in organics.

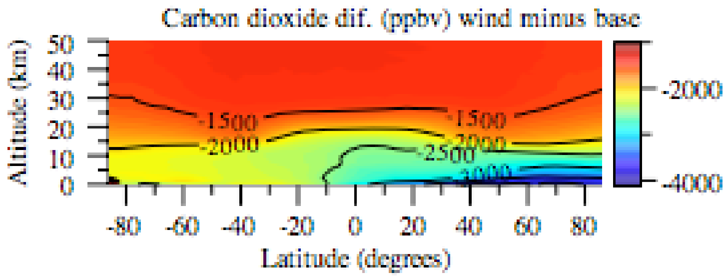
Tromp et al.[1] previously suggested that the addition of hydrogen to the stratosphere would increase stratospheric water vapor and cool the stratosphere, a process that would delay recovery of the ozone layer. However, that paper did not examine the simultaneous reduction in carbon dioxide and other pollutants that a hydrogen economy would replace. As seen in the previous figures, a hydrogen economy would increase hydrogen in the stratosphere (consistent with Tromp et al.), but decrease water vapor, warm the stratosphere, and increase stratospheric ozone, a conclusion opposite to that of Tromp et al. The addition of chlorine to the simulations is expected to enhance stratospheric ozone further because warmer stratospheric temperatures due to a hydrogen economy will melt ice clouds, on which reactions that otherwise form ozone-destroying chlorine compounds occur.

Figure 1(i) shows that a hydrogen vehicle economy decrease carbon monoxide (CO), emitted from fossil-fuel vehicles, in the troposphere and stratosphere. The reduction in CO and many other organics reduced mixing ratios of the hydroxyl radical (OH), (Figure 1(j)), which otherwise destroys carbon monoxide. Although methane (CH_4) mixing ratios decreased (Figure 1(k)) near the surface in northern latitudes due to reduced emissions from fossil-fuel vehicles there, methane increased in much of the troposphere and stratosphere due to the reduction there in OH, the primary destroyer of methane. The overall increase in methane and decrease in CO, OH, and NO_x found here is qualitatively consistent with results from Schultz et al.[2], who examined the effect on tropospheric gas-phase chemistry of replacing fossil emissions with hydrogen.

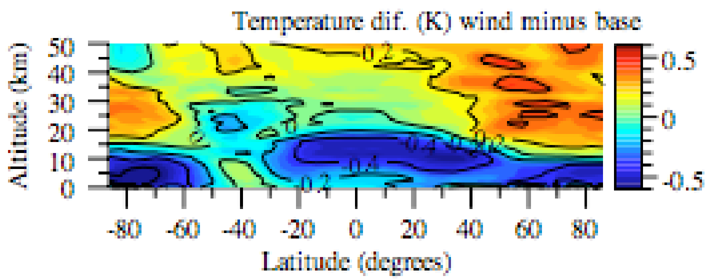
Figure 1(l) shows that a hydrogen economy reduced peroxyacetyl nitrate (PAN), a potent eye irritant formed from aldehyde products, and nitrogen dioxide. A hydrogen economy also reduced toluene (Figure 1(m)), primarily near the surface in the Northern Hemisphere. Toluene breaks down chemically relatively quickly, so toluene changes were not expected to be significant in the stratosphere.

Figures 1(n) and 1(o) show that externally- and internally-mixed particle black carbon (BC) decreased. Decreases in externally-mixed BC were over a smaller region than were decreases in internally-mixed BC since externally-mixed BC became internally-mixed as it aged, so it was present primarily near source regions. Since most BC was removed by rainout before it reached the stratosphere, a hydrogen road vehicle economy had little effect on stratospheric BC. Figures 1(p) and 1(q) show that internally-mixed primary organic matter (POM) and secondary organic matter (SOM) decreased overall, with decreases in SOM over a larger region than decreases in POM, as expected since SOM is formed by gas-to-particle conversion whereas POM is formed by direct emission. POM increased slightly in high northern latitudes due to a slight reduction in its rainout rate there. Similarly, internally-mixed sulfate decreased in most locations but slightly increased at high latitudes. Although sulfur dioxide emission rates from power plants increased, sulfur dioxide and primary-particle sulfate emissions from vehicles decreased in the hydrogen scenario, resulting in a mixed effect of hydrogen on particle sulfate.

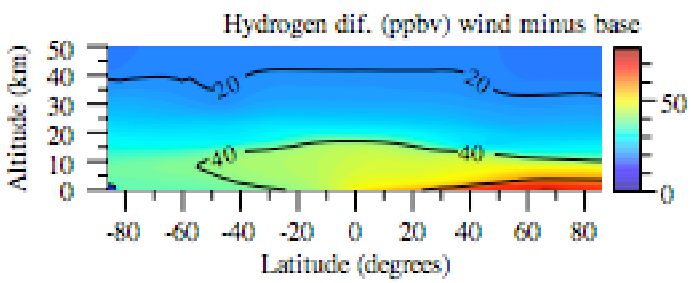
Figure 1: Seven-year time- and zonally (over all longitudes) -averaged differences in the latitude-altitude profiles between the wind-hydrogen and the baseline case for several parameters.


Carbon dioxide dif. (ppbv) wind minus base
Altitude (km)
Latitude (degrees)
-1500
-2000
-2500
-3000
-4000

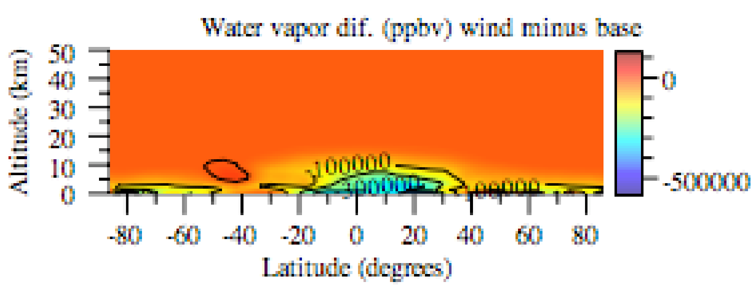
(a)


Temperature dif. (K) wind minus base
Altitude (km)
Latitude (degrees)
0.5
0
-0.5

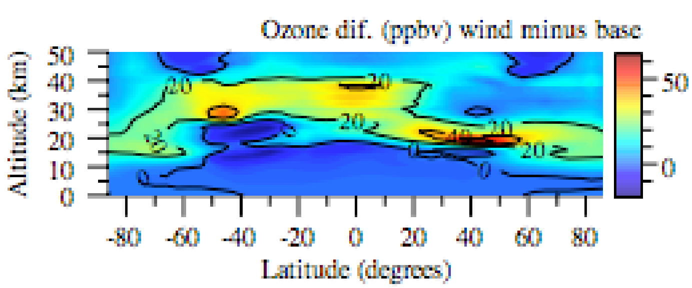
(b)


Hydrogen dif. (ppbv) wind minus base
Altitude (km)
Latitude (degrees)
20
40
50
0

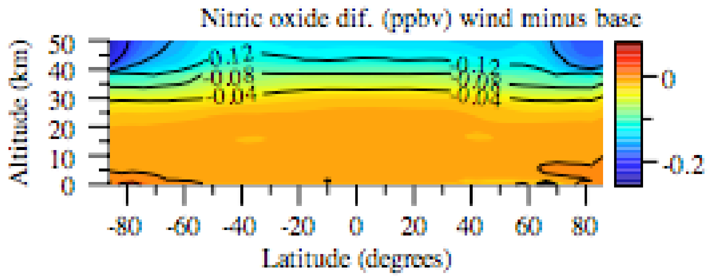
(c)


Water vapor dif. (ppbv) wind minus base
Altitude (km)
Latitude (degrees)
0
-500000

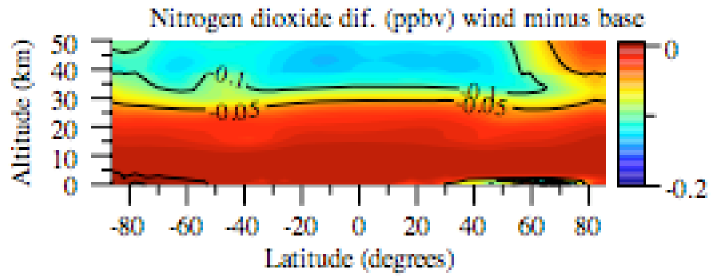
(d)


Ozone dif. (ppbv) wind minus base
Altitude (km)
Latitude (degrees)
20
40
50
0

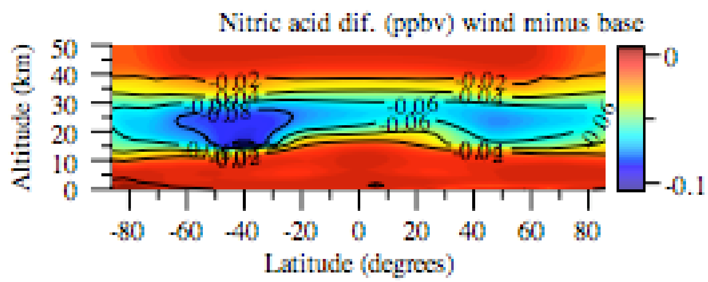
(e)


Nitric oxide dif. (ppbv) wind minus base
Altitude (km)
50 40 30 20 10 0
-80 -60 -40 -20 0 20 40 60 80
Latitude (degrees)
0
-0.2

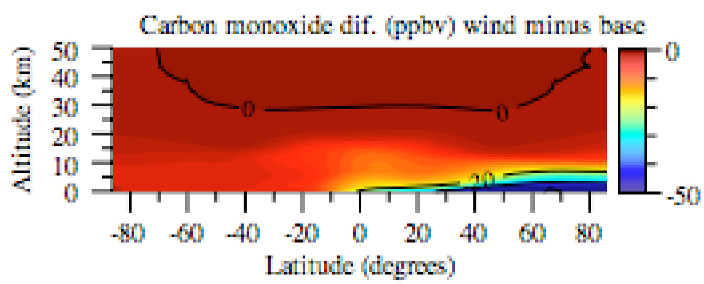
(f)


Nitrogen dioxide dif. (ppbv) wind minus base
Altitude (km)
50 40 30 20 10 0
-80 -60 -40 -20 0 20 40 60 80
Latitude (degrees)
0
-0.2

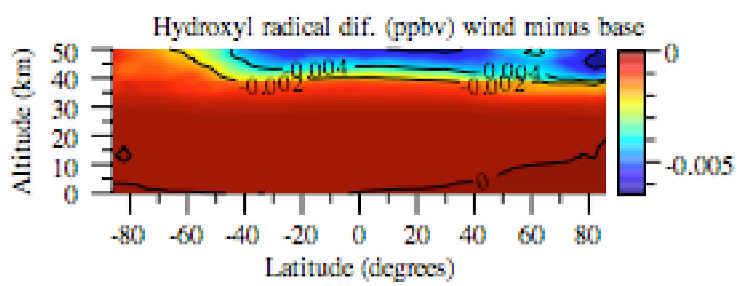
(g)


Nitric acid dif. (ppbv) wind minus base
Altitude (km)
50 40 30 20 10 0
-80 -60 -40 -20 0 20 40 60 80
Latitude (degrees)
0
-0.1

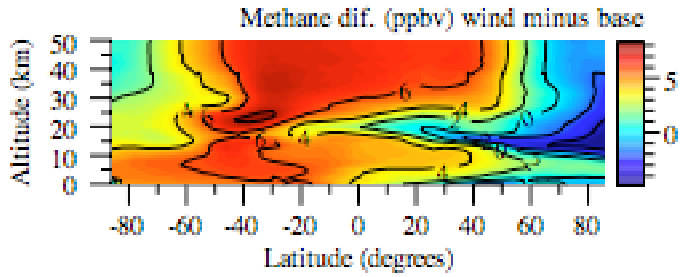
(h)


Carbon monoxide dif. (ppbv) wind minus base
Altitude (km)
50 40 30 20 10 0
-80 -60 -40 -20 0 20 40 60 80
Latitude (degrees)
0
-50

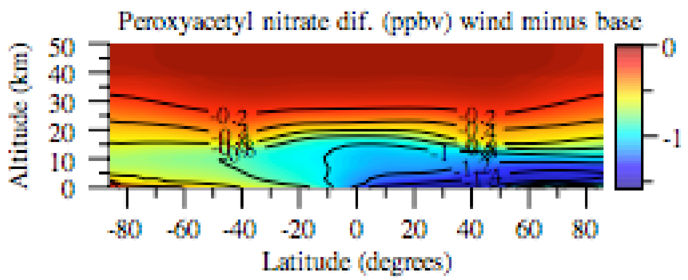
(i)


Hydroxyl radical dif. (ppbv) wind minus base
Altitude (km)
50 40 30 20 10 0
-80 -60 -40 -20 0 20 40 60 80
Latitude (degrees)
0
-0.005

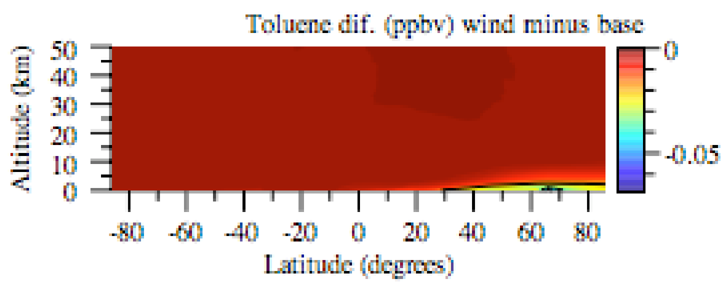
(j)


Methane dif. (ppbv) wind minus base
Altitude (km)
Latitude (degrees)

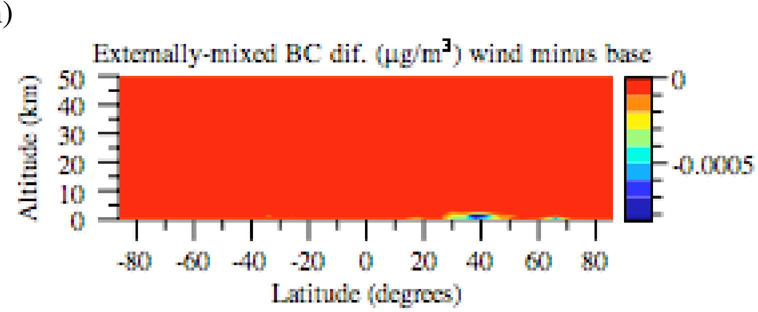
(k)


Peroxyacetyl nitrate dif. (ppbv) wind minus base
Altitude (km)
Latitude (degrees)

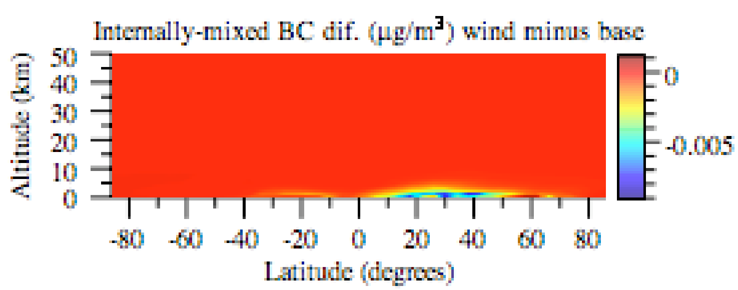
(l)


Toluene dif. (ppbv) wind minus base
Altitude (km)
Latitude (degrees)

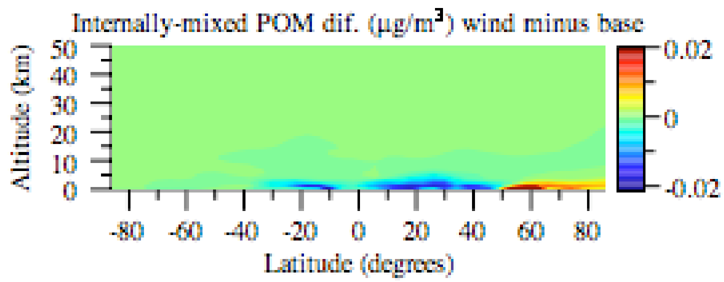
(m)


Externally-mixed BC dif. (μg/m³) wind minus base
Altitude (km)
Latitude (degrees)

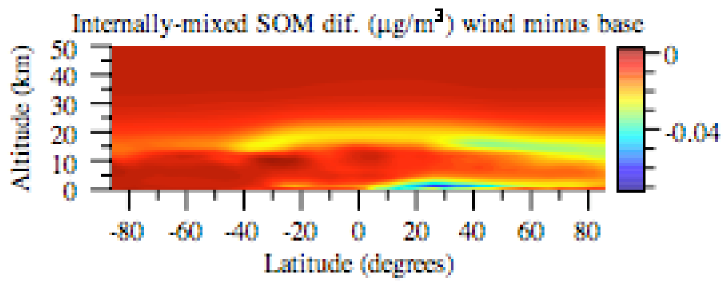
(n)


Internally-mixed BC dif. (μg/m³) wind minus base
Altitude (km)
Latitude (degrees)

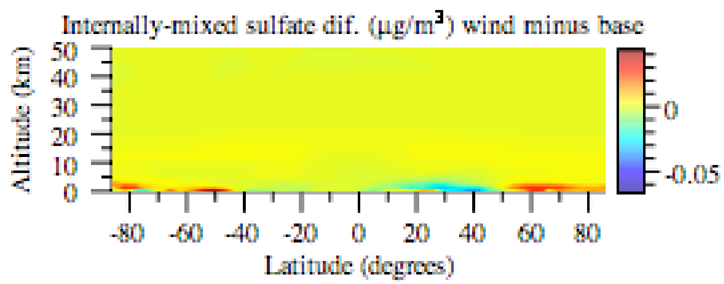
(o)



(p)



(q)



(r)

Progress

The main progress to date toward determining technologies that would reduce greenhouse gases and air pollutants is described in Publications 1 and 2 and in the new results above. The publications laid out scenarios examining the effects on air pollution, health, and climate of converting all U.S. vehicles to hydrogen fuel cell vehicles when the hydrogen is generated in one of three ways. The papers also examined the effects of converting to gasoline-electric hybrid vehicles. Primary conclusions from the two published papers (first phase of this project) are as follows:

1) Switching from the 1999 fossil-fuel onroad vehicle (FFOV) fleet to a hydrogen fuel cell vehicle (HFCV) or hybrid fleet may reduce air pollution, health, and climate problems and costs.
2) Although all three HFCV cases studied (wind, natural gas, coal) reduced health costs (since most air quality improvements resulted from eliminating FFOV exhaust), wind- and natural gas-HFCV reduced such costs the most and reduced ozone by up to 20 ppbv.
3) Wind-HFCV reduced climate costs the most, making it the most environmentally beneficial energy technology scenario.

4) Natural gas-HFCV increased CH_4 but reduced CO_2, making it the second-most-beneficial technology after wind-HFCV.
5) Hybrids reduced climate costs but increased health costs relative to coal-HFCV, suggesting a rough tie for third.
6) Hybrids and coal-HFCV reduced health and climate costs relative to FFOV.
7) HFCV had little impact on water vapor emission, either in terms of magnitude or location of the emission.

The main conclusions of the second phase of this project are as follows:

1) A wind-hydrogen economy is estimated to cool near-surface global temperatures and warm stratospheric temperatures, thereby slowing the effects of global warming.
2) A wind-hydrogen economy is estimated to reduce stratospheric and tropospheric mixing ratios of oxides of nitrogen and oxides of hydrogen.
3) Warmer stratospheric temperatures combined with lower NO_x and HO_x is estimated to increase stratospheric ozone.
4) Reduced NO_x and organic gases in the troposphere is estimated to reduce tropospheric ozone.
5) A hydrogen economy is estimated to reduce Northern-Hemisphere near-surface methane but increase tropospheric and stratospheric methane in many regions. Methane decreases are due to reduced emissions; methane increases, to reduced OH mixing ratios.
6) A hydrogen economy is expected to reduce particulate concentrations overall although some local increases may occur due to changes in precipitation patterns.

Future Plans

The final stage of the project is to complete the current global simulations, which do not include chlorine, and an additional pair of simulations, which include chlorine chemistry. Results will be written up for peer-reviewed journal publication.

Publications

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Contacts

Mark Z. Jacobson: jacobson@stanford.edu
David M. Golden: david.golden@stanford.edu