Impact of a hydrogen economy on the stratosphere and troposphere studied in a 2D model

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Abstract.

A switch from a fossil fuel to a hydrogen-based energy system should cause significant changes in the magnitude and composition of anthropogenic emissions. Model simulations suggest the most significant impact of these emission changes would occur in the troposphere and is dependent upon the magnitude and nature of trade-offs in changing fossil use (e.g. decline in methane leaks). In contrast, the expected increase in molecular hydrogen emissions via leaks occuring during production, transport and storage is very unlikely to have a substantial impact on stratospheric ozone, certainly much smaller than the ozone changes observed in the last two decades.

1. Introduction

Changing to molecular hydrogen as the principle currency of energy is seen as environmentally beneficial both in global and local terms [*Prather*, 2003]. Hydrogen could replace conventional fossil fuels at the point of use (e.g. in transport vehicles), thus reducing urban pollution. Hydrogen technology is well established in some industries and wider use in transport vehicles and fuel cells is expected within the next few years. The small hydrogen molecule is notoriously difficult to contain and leakage is likely to occur during production, transport and storage, and use as a fuel [*Zittel and Altmann*, 1996; *Schultz et al.*, 2003]. The projected magnitude of leakage is presently very difficult to quantify as it will depend both upon the leakage rate into the atmosphere (which may be cut by engineering improvements) and on the extent to which hydrogen replaces fossil fuels. However, a simple estimate of the magnitude of H_2 emissions resulting from a switch to a hydrogen economy can, of course, be made. Our calculations assuming: (1) lower and upper leakage rates of 1% and 12%; (2) that 2.6 Pg H_2 will deliver sufficient energy for a global hydrogen economy; and (3) that hydrogen will supply between one third to all of the present-day energy consumption, imply an increase in tropospheric H_2 mixing ratios of between 10% and 330% (provided there is no substantial change in the sinks of H_2). Today's reported losses of gaseous and liquid hydrogen are below 1% and 10% respectively [*Zittel and Altmann*, 1996], suggesting

that any future increase in H_2 mixing ratios would be in the lower half of the above range. In addition, the high end-use efficiency of H_2 (not accounted for in our assumptions above) will influence the total amount of hydrogen required to provide a global energy service, thus lowering the predicted increases in H_2 emissions (by perhaps a factor of 2) [*Lovins*, 2003]. If better engineering containment and hence smaller leakage rates were to be achieved, or if other sources of hydrogen were reduced, then future global anthropogenic H_2 emissions in a hydrogen economy could potentially be less than today.

A preliminary assessment of the potential impact of a hydrogen economy on atmospheric chemistry was performed by *Tromp et al.* [2003]. This study (hereafter refered to as TR2003) calculated the expected increases in stratospheric water vapour resulting from increased concentrations of atmospheric hydrogen and speculated on the possible implications of these changes on stratospheric temperature and ozone. A fuller assessment of the impact of a hydrogen economy on atmospheric composition needs, at least, (a) to account for the expected trade-offs associated with the switch to a hydrogen economy, (e.g. the concurrent reductions in carbon monoxide, methane and nitrogen oxides emissions from the fossil fuel industry, see the recent study of the tropospheric impact of this shift by *Schultz et al.* [2003]) and (b) to explicitly calculate the coupling between temperature changes and changes in all the radiatively active gases, not only H_2O, but also CH_4 and O_3. In this study, we use an interactive global 2-dimensional model of the atmosphere to assess the effect on the atmospheric composition of moving from a fossil fuel-based energy industry to a hydrogen-based industry.

2. Model Description

The 2D model in this study has been used previously for a variety of atmospheric studies and its basic formulation is described elsewhere [*Harwood and Pyle*, 1975; *Law and Pyle*, 1993a, b]. The model contains detailed representations of atmospheric chemistry (including heterogeneous reactions on sulphuric acid aerosols), transport and emissions of CH_4, CO, NO_x, and NMHCs. Atmospheric circulation is calculated from forcing terms which include solar heating by O_2 and O_3 and longwave cooling by CO_2, H_2O, O_3, CH_4 and N_2O [*Haigh*, 1984; *Bekki et al*, 1996]. Tropospheric radiative heating rates and surface temperatures are specified.

To investigate the potential impact of switching to a hydrogen economy on atmospheric chemistry, the model is run for a base-line emission scenario (representing today's emissions from the energy industry) and six possible illustrative hydrogen economy scenarios. These scenarios are designed to assess the influence of various trade-offs in fossil fuel and hydrogen emissions on atmospheric composition and are described in Table 1. In the first hydrogen scenario, H_2 mixing

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ratios at the surface level of the model are increased from 0.55 ppmv to 2.3ppmv, as in the TR2003 study. This quadrupling of H_2 mixing ratios is the expected effect of highly enhanced H_2 emissions resulting from a hydrogen energy economy equivalent to today's total fossil fuel energy and assuming a relatively high H_2 leakage rate (e.g. ∼12%). It should be noted that so high a leakage rate is unlikely to occur on a large scale, because it is both unsafe and, tellingly, expensive [*Schultz et al.*, 2003]. There would be powerful pressure for development of better containment. However, it is useful to consider extreme assumptions for an H_2 economy and it aids comparison of our model results with the TR2003 study. The absence of trade-offs in this experiment (fossil fuel emissions remain unchanged) makes it unreasonable to consider it as a plausible worst-case scenario because the rationale for the development of a global hydrogen economy includes potential reductions in fossil fuel consumption. The results of Experiment 1 therefore correspond to an extreme scenario. We view them as the maximum possible impact of switching to an hydrogen economy.

In Experiments 2 and 3, hydrogen mixing ratios at the surface are raised to 2.3 ppmv and 1.4 ppmv (based on a smaller leakage rate of 5%) respectively, and emissions of methane are reduced by 85Tg/yr (or 16%). This decrease in methane emissions represents the maximum emission trade-off expected from the complete removal of the fossil fuel industry, especially the gas industry. Again, we regard this scenario as an extreme end-member of possible scenarios as production of hydrogen (which is a currency or energy carrier) is likely, at least in part, to be from fossil fuels, although nuclear or renewable power represent viable alternatives. Experiments 4, 5 and 6 are as Experiment 2, but include additional reductions in the emissions of CO, NO_x and non-methane hydrocarbons (NMHCs) from the fossil fuel industry.

3. Results and Discussion

The results from these model experiments are summarised in Table 2. It shows the change in concentrations of H_2, CH_4, H_2O, O_3 and NO_2 for each of the model experiments, averaged over both the troposphere and stratosphere. The modelled hydrogen distribution for the base-line emission scenario, together with the percentage change for Experiment 1 is presented in Figure 1. Raising surface hydrogen mixing ratios by 1.75 ppmv from 0.55 to 2.3 ppmv, increases stratospheric mixing ratios by ∼214%. In this scenario, stratospheric H_2O increases by up to 12% with maximum enhancements in the upper stratosphere at high latitudes. This percentage increase is at least a factor two lower than was found by TR2003, who reported increases of water vapour of up to 35% in the same region based on a similar experiment performed using the Caltech/JPL 2D model. The 35% increase over a background concentration of about 6 ppmv in the upper stratosphere (representing an H_2O increase of at least 2 ppmv) is hard to reconcile with the magnitude of the 1.75 ppmv H_2 increment, especially since not all the H_2 is oxidised to water vapour.

Methane also contributes to stratospheric water. When reductions in emissions of methane from the fossil fuel industry are included, the model-calculated maximum H_2O increase in the upper stratosphere is reduced to 7% or 0.4ppmv (see Figure 2). The averaged stratospheric increase is 2.4% with even smaller increases in the lower stratosphere. These changes are much more modest than those reported from

balloon and satellite observations which suggest increases in H_2O of about 10-20% for the past couple of decades [*Nedoluha et al*, 1998; *Oltmans and Hofmann*, 1995; *Oltmans et al.*, 2000; *Rosenlof et al.*, 2001]. It is already acknowledged that even these possible very large changes in H_2O are a minor factor in the ozone depletion problem compared to the chlorine loading issue [*Chipperfield and Pyle*, 1998]. Chemistry-transport model simulations suggest a low sensitivity (less than 2%) of Arctic ozone loss to an increase of 1 ppmv of H_2O in the lower stratosphere (which is still larger than our calculated H_2O increases). If it is assumed that engineering quality is adequate to restrict the hydrogen leakage rate to 5% (Experiment 3), then the modelled average increase in stratospheric water vapour is restricted to 0.5% with a maximum of 1% in the upper stratosphere.

The atmospheric impact of strong reductions in CO and NO_x emissions resulting from the complete removal of the fossil fuel industry source (Experiments 4 and 5) is most apparent in the troposphere. In Experiment 5, the model calculates global mean tropospheric decreases in OH and O_3 (-12.3 and -12.2% respectively) relative to the base-line emission scenario. These results are consistent with OH and O_3 decreases calculated in a recent study focusing on the tropospheric impact of a hydrogen economy [*Schultz et al.*, 2003]. The global mean changes of tropospheric O_3 and OH in our model are the averaged result of local decreases in O_3 and OH throughout much of the Southern and Northern Hemispheres and some model-calculated increases in both OH and O_3 in latitudes north of 40°N, the result of strong NO_x reductions in the polluted model chemical regime. (Note that the model's coarse resolution and the zonal averaging limit its ability to reproduce more local changes in the chemical regime.) Removing the fossil fuel emissions of NMHCs (Experiment 6) in the model did not have a significant additional effect on the atmospheric concentrations of the species considered in Table 2.

In all model experiments, the changes in stratospheric ozone resulting from the recorded changes in emissions are small (less than 1%) and not significant compared to the magnitude of the ozone changes observed in the last two decades. Changes in global average stratospheric temperatures are also small and range from -0.03K to -0.13K in the six model scenarios. Below 40km, the changes in temperature are negligible and the greatest cooling (-0.8K in Experiment 1) occurs at 60km. The changes in temperature are found to be marginal in the lower stratosphere because the changes in H_2O are very small in this region which is critical for the radiative balance of the atmosphere compared to the upper stratosphere. These changes are also much smaller than the stratospheric H_2O changes assumed by TR2003 (-0.5°C) to derive enhancements in polar ozone depletions resulting from a fourfold increase of H_2.

4. Conclusions

The model predictions outlined above suggest that a move from a fossil fuel-based energy industry to a hydrogen-based industry would most plausibly have little effect on the concentrations of stratospheric ozone. Leakage rates from a global H_2 energy industry as high as 12% result in a small decrease in stratospheric O_3 of ∼0.2% and an average stratospheric cooling of -0.13K (with the largest temperature change at the top of the stratosphere). However, we find that switching to a hydrogen economy could significantly influence the chemical composition and oxidation capacity of the troposphere, depending on the magnitude of the trade-offs. This highlights the need for further investigation in this area.

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Figure 1. Simulated H_2 mixing ratios in January resulting from the base-line emission scenario (given by contours in units of ppmv) and the percentage increase in H_2 mixing ratios resulting from a fourfold increase of H_2 in the surface model level (given by colour in % change).

Figure 2. Simulated stratospheric H_2O mixing ratios in January in the base-line emission experiment (given by contours in units of ppmv) and the percentage increase in H_2O mixing ratios resulting from a fourfold increase of H_2 in the surface model level and a 16% reduction in surface methane emissions (given by colour in % change).

Table 1. Surface emission variables in the base-line emission scenario and the six hydrogen emission scenarios.

Table 2. Percentage changes in global annual mean hydrogen, methane, water vapour, hydroxyl radical and ozone in the troposphere (T) and stratosphere (S) for each of the six hydrogen emission scenarios relative to the base-line emission scenario.
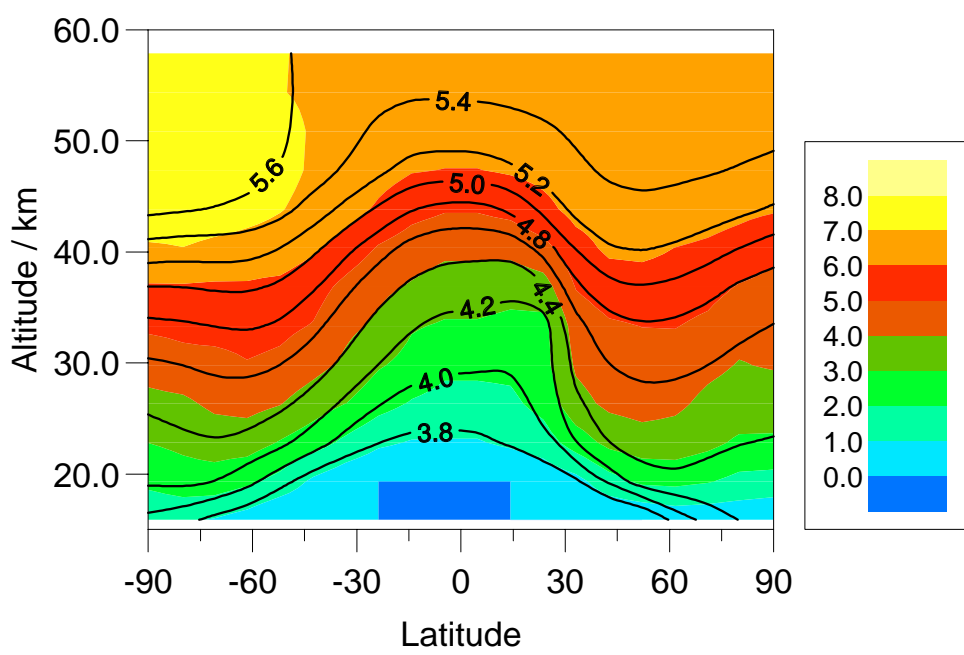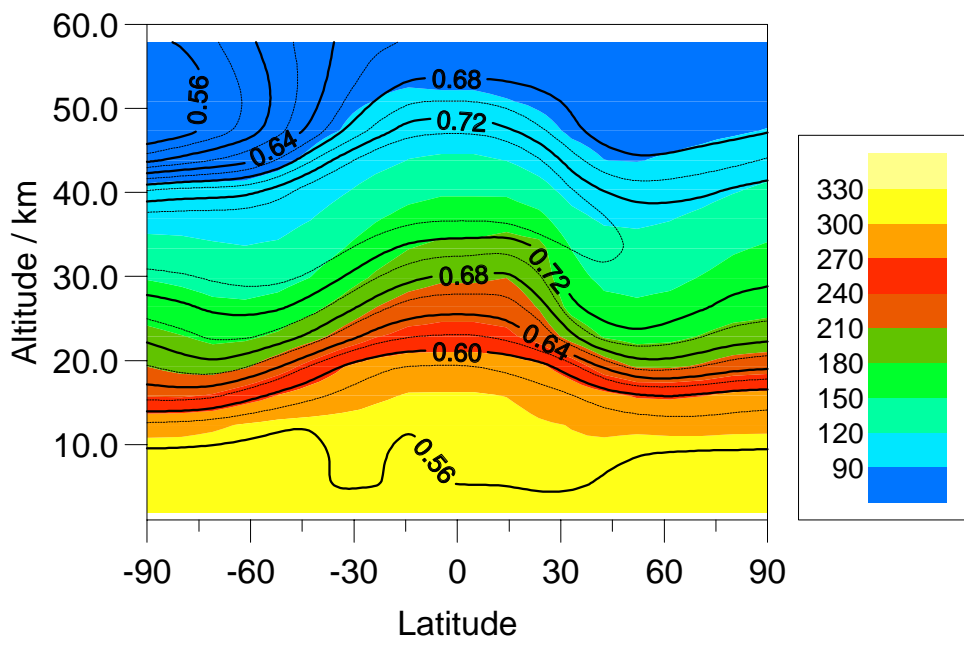
Model Experiment	H_2/ppmv (set in surface level)	CH_4/Tgyr^{-1}	CO/Tgyr^{-1}	NO_x/TgNyr^{-1}	NMHCs/Tgyr^{-1}
Base-line emissions	0.55	525	680	51.4	Hough [1991]
1	2.3	525	680	51.4	Hough [1991]
2	2.3	440	680	51.4	Hough [1991]
3	1.4	440	680	51.4	Hough [1991]
4	2.3	440	380	51.4	Hough [1991]
5	2.3	440	380	18.4	Hough [1991]
6	2.3	440	380	18.4	Hough [1991] (fossil fuel source removed)

Model Experiment	% Changes in H_2		% Changes in CH_4		% Changes in H_2O		% Changes in OH		% Changes in O_3	
	T	S	T	S	T	S	T	S	T	S
1	313	214	7.9	7.3	0	4.0	-10.4	8.0	-8.2	-0.2
2	313	210	-10.6	-10.3	0	2.4	-6.5	5.3	-11.7	-0.7
3	155	103	-14.1	-13.4	0	0.5	-1.2	1.4	-13.9	-0.9
4	313	209	-15.1	-14.5	0	2.1	-0.6	4.8	-16.2	-0.9
5	313	211	-4.3	-4.5	0	2.9	-12.3	6.7	-12.2	-0.4
6	313	211	-4.3	-4.5	0	2.9	-12.2	6.7	-12.3	-0.4