

Potential Environmental Impact of a Hydrogen Economy on the Stratosphere

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The widespread use of hydrogen fuel cells could have hitherto unknown environmental impacts due to unintended emissions of molecular hydrogen, including an increase in the abundance of water vapor in the stratosphere (plausibly by as much as ~1 part per million by volume). This would cause stratospheric cooling, enhancement of the heterogeneous chemistry that destroys ozone, an increase in noctilucent clouds, and changes in tropospheric chemistry and atmosphere-biosphere interactions.

Hydrogen fuel cells, which produce energy from the controlled oxidation of molecular hydrogen (H_2), are a proposed alternative to conventional fossil fuels (1). Their use would likely result in substantial reductions in urban pollution from soot, nitrogen oxide gases, and sulfate, but they could also have hitherto unknown environmental impacts due to emissions of H_2 . H_2 is an important trace constituent [~ 0.5 part per million by volume (ppmv)] of the atmosphere (2, 3) and participates in atmospheric chemical cycles of H_2O and various pollutants and greenhouse gases (4, 5). Its modern budget is influenced by anthropogenic emissions (such as car exhaust) but is dominated by photochemical reactions in the atmosphere and uptake in the soil (3, 6, 7). It is difficult to foresee the magnitude of H_2 emissions associated with a hydrogen fuel cell economy, both because the current budget of H_2 is poorly known and because the technical details and scope of the future fuel cell industry can only be guessed at. In principle, a perfectly efficient system of hydrogen production, transport, and oxidation would involve no H_2 emissions (it would all be oxidized to H_2O). In that case, the evolution from fossil fuel combustion to hydrogen fuel cells would actually result in a reduction of anthropogenic H_2 emissions, because fossil fuel combustion is a source of H_2 .

However, on the basis of experience with technologies associated with the transportation of natural gas and other volatiles, it seems likely that systems of H_2 production, storage, and transport will involve losses to the atmosphere. The magnitude of these losses will naturally depend on the amount of effort expended to contain them but have been reasonably projected to be on the order

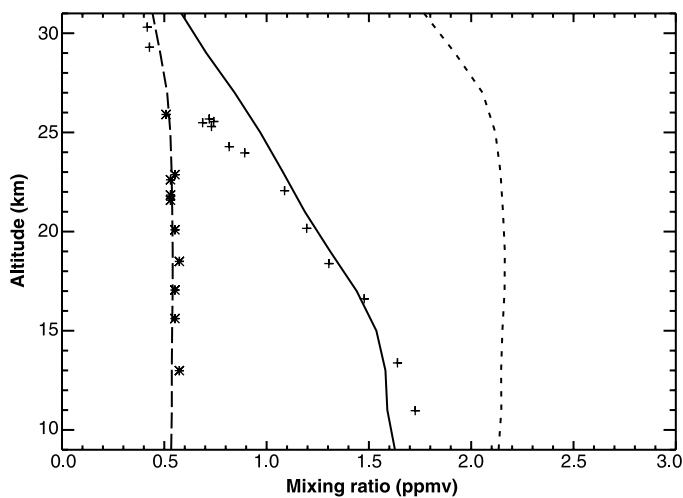
of 10% (8). Losses during current commercial transport of H_2 are substantially greater than this (9), suggesting to us that a range of 10 to 20% should be expected. If so, and if all current technologies based on oil or gasoline combustion were replaced by hydrogen fuel cells, then anthropogenic emissions of H_2 would be on the order of 60 to 120 Tg/year, or roughly four to eight times estimates of current anthropogenic H_2 emissions (15 ± 10 Tg/year). In that case, contributions from human activity would dominate the budget and result in approximate doubling or tripling of the annual production of H_2 from all sources combined. More or less dramatic scenarios are equally imaginable, but clearly the potential impact on the H_2 cycle is great.

H_2 added to the troposphere freely moves up and mixes with stratospheric air, and the oxidation of H_2 is a source of stratospheric H_2O (10). Therefore, increasing the source of H_2 to the atmosphere, unless compensated by an equally vigorous increase in rates of processes that destroy hydrogen, should moisten the stratosphere. This would result in cooling of the lower stratosphere (11) and the distur-

bance of ozone chemistry, which depends on heterogeneous reactions involving hydrochloric acid and chlorine nitrate on ices of H_2O (12).

Here, we report the results of models of atmospheric chemistry and transport that estimate the effects that an increase in H_2 emissions would have on stratospheric temperatures and on concentrations of stratospheric H_2O and ozone. We examine the atmospheric chemistry of H_2 using the Caltech/JPL 2-D model, which has been described elsewhere (13–15). This model solves the continuity equation for all important long-lived species and includes all the chemistry recommended by NASA for stratospheric modeling (16). To assess the potential impact of an increase of H_2 in the atmosphere, we ran our model for two cases: (a) concentrations of H_2 and CH_4 are assumed to equal their approximate current global annual means at Earth's surface; and (b), the same as (a), except that the concentration of H_2 at Earth's surface is raised to 2.3 ppmv (about four times the current global annual mean). Intermediate cases are discussed below. Figure 1 presents simulated vertical profiles in concentrations of H_2 and CH_4 in the stratosphere for these two cases and a comparison of case (a) with recent measurements. The results for case (a) show that the model correctly describes the relation between H_2 and CH_4 concentrations in the lower stratosphere, which reflects the balance of photo-oxidative reactions that are important for converting H_2 and CH_4 to H_2O . The model prediction for the vertical profile for H_2 for case (b) is the dashed line in Fig. 1. Figure 2 (contour lines) shows the concentration of water vapor (in ppmv) as a function of altitude and latitude in the stratosphere in January in the standard model, case (a). The model correctly simulates the increase in H_2O with altitude and latitude from the oxidation of H_2 and CH_4 . The low concentration in the tropical tropopause region is the result

Fig. 1. Mixing ratios of CH_4 (solid line) and H_2 (long-dashed line) simulated by our two-dimensional model for January at 60° to $70^\circ N$ for case (a). The H_2 mixing ratio for case (b) is given by the short-dashed line. The data (asterisks and crosses) are from the SOLVE balloon measurements (22). The model uses a pressure coordinate, with altitude $z = H \ln(p_0/p)$, where the scale height (H) = 6.95 km, p = pressure, and p_0 = surface pressure; z is approximately equal to the geometric altitude.



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of upwelling air that has been dehydrated by the tropical cold trap. The change in stratospheric water content, as computed by the difference between case (b) and case (a), is shown by the color contours in Fig. 2. As expected, the additional quantity of H₂O is highest (~30%) at high altitudes, where most of the H₂ becomes oxidized.

Based on our modeling results, the increase in stratospheric water content caused by a quadrupling of the H₂ mixing ratio at Earth's surface (Figs. 1 and 2) would result in a negligible (<1%) change in abundances of stratospheric ozone due to homogenous gas-phase reactions alone. However, this increase in stratospheric water vapor would have several indirect consequences, including lower stratospheric temperatures. Colder temperatures would create more polar stratospheric clouds, delay the breaking up of the polar vortex, and thereby make the ozone hole deeper, larger (in area), and more persistent (in spring). The direction and approximate magnitude of resulting changes in temperature and ozone concentration can be approximated as follows: An increase of 0.5 ppmv

in stratospheric H₂O will cool the lower stratosphere by 0.5°C (11). Based on the climatology of the National Centers for Environmental Prediction Reanalysis data (17), this will increase the area of the northern polar vortex by 7% and that of the southern polar vortex by 4%. Finally, empirical data suggest that the polar vortices last 5 to 8 days longer when there is a 0.5°C temperature drop (18). It is known that a colder vortex that lasts longer results in greater loss of ozone (19). Figure 3 depicts the percentage of ozone column density change. The O₃ depletion is about 5 to 8% in the boreal spring in the northern polar region, and about 3 to 7% in the austral spring in the southern polar region. The reason for the larger change in the north versus the south is that the Antarctic ozone hole is already "saturated," whereas the Arctic ozone hole is not and has the potential to become more like the Antarctic.

The model predictions outlined above suggest that anthropogenic emissions of H₂ could substantially delay the recovery of the ozone layer that is expected to result from the regulation of chlorofluorocarbons.

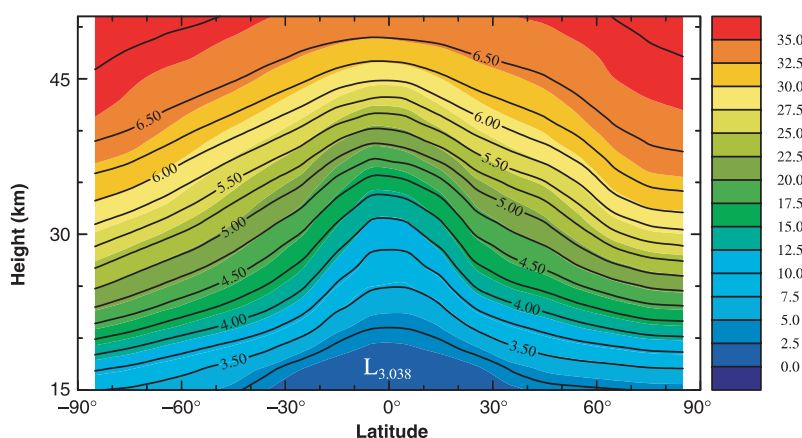


Fig. 2. The background H₂O mixing ratio (given by contours in units of ppmv) and the increase of stratospheric H₂O in January due to the assumed fourfold increase of H₂, computed using the Caltech/JPL 2-D model (given by color in % change). The altitude is defined as in Fig. 1.

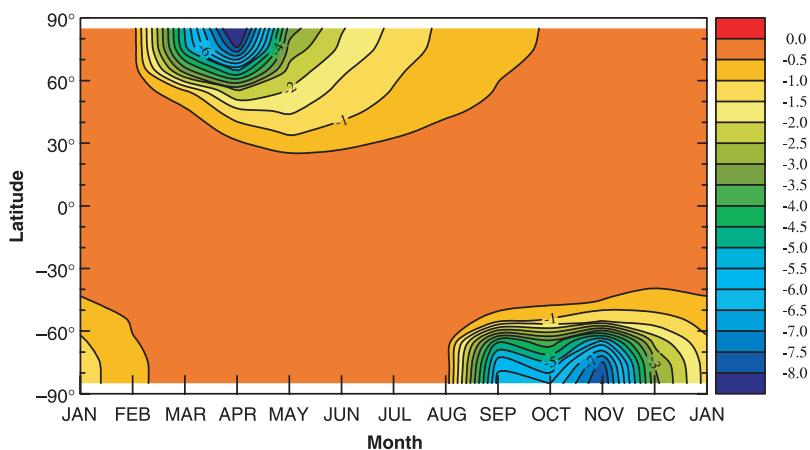


Fig. 3. Latitudinal and seasonal distribution of column ozone depletion (in %) due to an assumed fourfold increase of H₂, simulated by the Caltech/JPL 2-D model.

However, we also note that the lower levels of chlorofluorocarbons expected several decades in the future should lead to less destruction of stratospheric ozone for a given amount of stratospheric moistening and cooling (20). Thus, the real consequences of a hydrogen economy will depend, in part, on whether it develops within about 20 years, when chlorofluorocarbon levels remain high; or more than 50 years in the future, when chlorofluorocarbon levels have substantially decreased. Alternatively, we may devise a strategy that regulates the growth of the fuel cell industry, so that the impact on the ozone layer is minimized.

The model results presented in Figs. 1 to 3 suggest that a fourfold rise in surface H₂ concentrations, such as might occur because of large rises in anthropogenic emissions, will lead to substantial moistening and cooling of the lower stratosphere and substantial decreases in stratospheric O₃. Figure 4 shows the magnitude of these effects predicted by our model for smaller and larger changes in H₂O concentration in the lower stratosphere. Cases (a) and (b) correspond to one and four times the current H₂ concentration, respectively.

Predicting the rise in H₂ concentration at the surface in the future will require better knowledge of several factors. First and most clearly, we must have an understanding of the emissions that could be produced by technologies associated with a hydrogen economy. It is likely that such emissions could be limited or even made negligible, although at some cost against which potential environmental impacts must be balanced. Second, a large, possibly dominant, sink of H₂ from the atmosphere is uptake in soils (3, 7, 21). The mechanisms of this uptake and its variation with time and location are poorly understood, and it is unclear how the global rate of uptake would respond to an increased flux of H₂ to the atmosphere. It is possible that this process could entirely compensate for new anthropogenic emissions, although

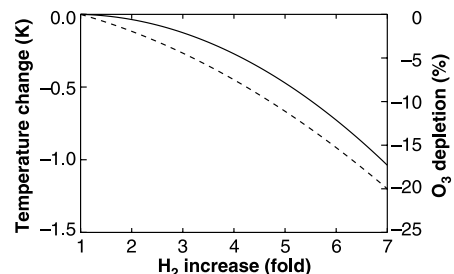


Fig. 4. The temperature changes at 74°N in the lower stratosphere (solid line) (11, 23) and the resulting maximum ozone depletion in the northern polar vortex (dashed line) caused by the increase of H₂O. Cases (a) and (b) in the text correspond to a one- and fourfold increase of H₂O, respectively.

study will be needed to determine whether this is the case.

Finally, there are at least three other potential impacts of a rise in anthropogenic H₂ emissions that are beyond the scope of this study but deserve further consideration: (i) Our model predicts that a rise in H₂ concentration at the surface will make the mean OH concentration in the troposphere decrease by about 7%, whereas that in the stratosphere will increase by 10%; these changes will affect the lifetimes of other trace gases that react with OH (such as CH₄ and CO). (ii) An increase in the mesosphere of H₂O derived from H₂ could lead to an increase in noctilucent clouds, with potential impact on Earth's albedo and mesospheric chemistry. (iii) H₂ is a microbial nutrient, and thus increased partial pressures of H₂ over natural soils might have unforeseen effects on microbial communities.

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Sex-Dependent Gene Expression and Evolution of the *Drosophila* Transcriptome

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Comparison of the gene-expression profiles between adults of *Drosophila melanogaster* and *Drosophila simulans* has uncovered the evolution of genes that exhibit sex-dependent regulation. Approximately half the genes showed differences in expression between the species, and among these, ~83% involved a gain, loss, increase, decrease, or reversal of sex-biased expression. Most of the interspecific differences in messenger RNA abundance affect male-biased genes. Genes that differ in expression between the species showed functional clustering only if they were sex-biased. Our results suggest that sex-dependent selection may drive changes in expression of many of the most rapidly evolving genes in the *Drosophila* transcriptome.

Sexual dimorphism is ubiquitous among higher eukaryotes. Differential selection pressure between the sexes has been postulated to explain the substantial between-sex differences observed in morphology, physiology, and behavior, indicating the existence of different optimal sex-dependent phenotypes (1). Studies of gene expression during the life cycle of *Drosophila melanogaster* have found that, for sexually mature males and females, a substantial fraction of the *Drosophila* transcriptome displays sex-dependent regulation (2-4). Increasing evidence suggests that molecular mechanisms associated with sex and reproduction change substantially faster between species than those more narrowly restricted to survival (5, 6). New data also suggest that some of the interspecific changes that are driven by differential selection between the sexes have a regulatory origin (7, 8). However, the evolutionary pattern of differences in gene expression between the sexes on a genomic scale is presently unknown.

We performed competitive hybridizations with cDNA microarrays (fig. S1) (9) to identify genome-wide regulatory differences in sex-biased genes between *D. melanogaster* and *D. simulans*. These morphologically nearly identical species belong to the *melanogaster* subgroup of the subgenus *Sophophora* and diverged ~2.5 million years ago (10, 11). Our results are based on the 30 hybridizations outlined in fig. S1, which were performed with either cDNA to assay differences in transcript abundance or else genomic DNA as controls (9). The microarrays contained 4776 coding sequences amplified from cDNA clones (9). The hybridizations with

genomic DNA were performed to detect coding sequences whose apparent transcript abundance might be affected by sequence divergence or by changes in gene-copy number. The species differ in an estimated 3.8% of nucleotides at the DNA sequence level (12) and in copy number of some transposable elements (13) and a few multicopy genes (14). Across the six interspecific DNA hybridizations, genomic DNA from *D. melanogaster* showed an average of 4.2% greater hybridization than genomic DNA from *D. simulans*, in good agreement with the estimated sequence divergence. The distribution of hybridization intensities across coding sequences was essentially gaussian (15) with only a few outliers identified, mostly as transposable elements such as the retrotransposon *springer* or multicopy genes such as *Stellate* (14, 16). Apart from these exceptional sequences, the differences in genomic hybridization are well within the limit of detection of significant differences in gene expression with our level of replication. Accordingly, no correction for sequence divergence between the species was required for the estimates of transcript abundance.

The cDNA hybridization data were analyzed by a Bayesian method (17) that yielded an estimated mean and 95% credible interval of the relative level of expression of each gene in each sex of each species (table S1). Genes were classified as differentially expressed between sexes within species or for the same sex between species if their 95% credible intervals failed to overlap (Fig. 1). The main categories into which the 4776 coding sequences were classified are shown in Table 1. Comparison with the reported pattern of expression in *D. melanogaster* was used to validate our classification (9). Random permutations of the data provided an estimated false-positive rate of 0.03%; hence, no adjustment was made for multiple tests.

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