D- AND E-REGION EFFECTS

Jeffrey M. Forbes

Space Data Analysis Laboratory, Boston College, Chestnut Hill, MA 02167

D 83

A time-dependent analytic formalism is utilized to examine the competing effects of transport, photodissociation, and frequency of injection on the steady-state global distribution of HLLV second-stage discharges of H_2O, and to estimate concomitant effects on the ion chemistries of the D- and E-regions. For details of the following presentation, see Forbes (1980).

The model assumes the 70-120 Km height range to be a slab, or closed system; in other words, diffusion of H_2O to above 120 Km or below 70 Km is prohibited. This simplifying assumption can be crudely justified by noting the slow vertical diffusion velocity near 70 Km and the short photochemical half-life of H_2O compared to the diffusive residence time near 120 Km (see Forbes (1980)). In slab model the equation governing the height-integrated number density of H_2O is

$$\frac{\partial n}{\partial t} + \bar{u}\frac{\partial n}{\partial x} + \bar{v}\frac{\partial n}{\partial y} - K_h\frac{\partial^2 n}{\partial x^2} - K_h\frac{\partial^2 n}{\partial y^2} = C_o\,\delta(x)\,\delta(y)\,f(t) - Jn \tag{1}$$

where $\bar{u}$ = an average E-W wind speed (30 deg long day^{-1})

$\bar{v}$ = an average N-S wind speed (.5 deg long day^{-1})

x = E-W coordinate

y = N-S coordinate

t = time

K_h = horizontal eddy diffusivity (10^{10} cm^2 sec^{-1})

J = rate of photolysis of H_2O (.5 day^{-1})

$C_o = N_o/(z_2 - z_1)$

N_o = total number of H_2O molecules injected between 70 and 120 Km per launch (7.0×10^{31})

z_2 = 120 Km

z_1 = 70 Km

If the time history of the water discharges is represented by equally-spaced delta functions with period T, $f(t) = \sum_{n=o}^{\infty} \delta(t-nT)$, then the solution to (1) is

$$n(x,y,t) = \sum_{m=o}^{M} \frac{C_o U(t_m)}{4\pi D t_m} \exp\left\{-\left(\frac{(x-\bar{u}t_m)^2 + (y-\bar{v}t_m)^2}{4D t_m} - Jt_m\right)\right\} \tag{2}$$

where $t_m = t-mT$, $M=t/T$, and $U(t-t_0)$ is the unit step function. This solution represents the superposition of M 3-dimensional Gaussian-shaped pulses moving away from the point of injection at $\bar{u}$ = 30 deg long day^{-1} and $\bar{v}$ = .5 deg long day^{-1}, the width of the pulses increasing as $\sqrt{t}$ due to diffusive expansion, and the peak amplitude decreasing as $t^{-1}e^{-Jt}$ due to diffusive expansion and photolysis of H_2O. Forbes (1980) describes how a water vapor volume mixing ratio (χ) representative of the 75-95 Km height region can be inferred from the height integrated number densities. Steady-state values of χ for T = .125, .25, 1.0, and 4.0 days at 1 hr and 6 hr after injection are plotted vs. longitude in Figure 1, illustrating that only for T $\geq$ 1 day to the pulses retain their longitudinal identity without diffusing into one another. This is because the 10% width of the pulses is $\sqrt{4~Dt~\log_e 10}$ or ~ 10 $\sqrt{t}$ deg (where t is in days), whereas the peak-to-peak spacing is $\bar{u}T$ in longitude. As shown in Figure 2, the pulses do not retain their identity with respect to latitude since 10 $\sqrt{t}$ >> $\bar{v}T$.

Note that χ is diminished to less than ambient values (~3 ppmv) long before being advected one circuit (360 deg) around the earth. The combined effects of advection by winds, the high mixing rates characteristic of the mesosphere and lower thermosphere, and the short photolytic lifetime of H_2O (~2 days), act to prevent significant global or even regional steady-state buildups of H_2O. As indicated by Forbes (1980), a baseline value for measurable environmental effects is χ = 100 ppmv between 80 and 90 Km, which is only exceeded within an area on the order of 20,000 Km^2 (.5 deg lat x 2 deg long) around the point of release.

In the lower ionosphere there exists a sharp transition somewhere between 75 and 85 Km where NO^+ and O_2^+ are the dominant positive ions above, and water clusters of the type $H^+(H_2O)_n$ (n=1-7) are dominant below. The major source of molecular ions in the 70 to 90 Km region is photoionization of NO by L_α(1216Å) radiation. Since the cross section of H_2O at L_α is about 1.4 x 10^{-17} cm^2, a H_2O column content of 10^{-17} molecules cm^{-2} yields about 75% attenuation of L_α. For χ > 100 ppmv, L_α radiation reaching the D region is thus reduced by at least 50%.

NO^+ and O_2^+ are precursor ions for reactions which lead to formation of $H^+(H_2O)_n$. It is estimated that values of χ exceeding 100 ppmv would lead to a near complete conversion of O_2^+ and NO^+ (with recombination coefficients α_1 ~ 7 x 10^{-7} cm^3 sec^{-1}) to hydrated ions (α_2 ~ 3 x 10^{-6} cm^3 sec^{-1}) between 70 and 100 Km. Assuming a square loss law ($L=\alpha[e]^2$) and steady-state conditions, the corresponding reduction in electron density would be no more than $(\alpha_1/\alpha_2)^{\frac{1}{2}} \simeq 0.5$. Combined with the L_α screening effects expected at χ = 100 ppmv, a nominal reduction of order 75% in ionization density between 70 and 100 Km can be expected over areas of order 20,000 Km^2.

One of the net effects of H_2O photolysis is to create OH and H. The nature of the formalism adopted here precludes any prediction of the diffusion and redistribution of H atoms in the thermosphere. However, it can be crudely estimated that at least 100 metric tons of H must be added to the natural abundance of 50 metric tons above 105 Km to globally increase the attenuation of L_α radiation reaching the daytime D-region from the normal 1.6% to 10%, and that

455

the additional H must be replenished at least once a week to be maintained. This may be compared to the nominal 200 tons of H atoms introduced by every second stage HLLV exhaust. Since injection frequency will probably exceed 1 week^{-1} and H atoms will not have time to redistribute themselves uniformly over the globe in their 1-week thermospheric lifetime, a nominal 10% attenuation of L_α may be assigned to this global effect as a lower limit until more quantitative estimates are available.
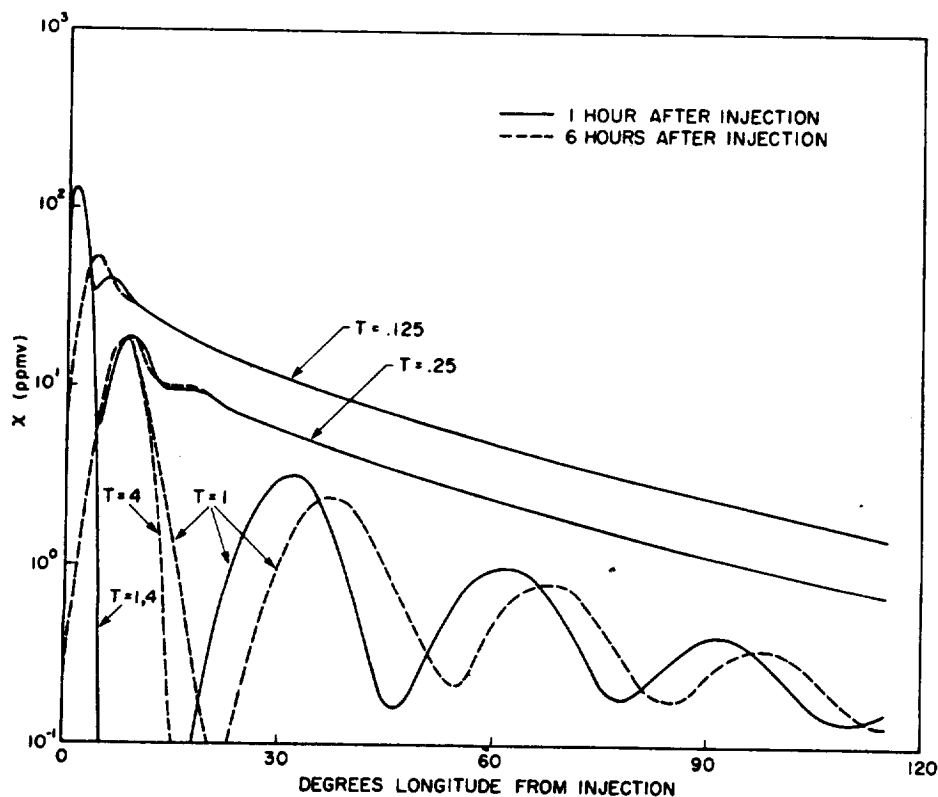

Figure 1. Steady-state longitudinal distribution of X at Δt = 1 hr and Δt = 6 hr after injection for T = .125, .25, 1.0, and 4.0 days. (The latitude varies along each curve and is given by $\bar{v}$ ($\lambda/\bar{u}$) in deg lat, where $\bar{v}$ = .5 deg lat day^{-1} and λ is deg long from injection.)

Furthermore, it is qualitatively expected that hydrogen released by photolysis of H_2O can increase the loss rate of ozone between 75 and 95 Km, can significantly increase OH concentrations and accompanying airglow emissions, and also can act to increase nighttime E-region ionization by geocoronally-scattering L_α and L_β radiations after diffusing into the upper thermosphere. These effects of hydrogen released by H_2O photolysis may indeed comprise the most important upper atmosphere environmental impacts of discharging water in the 70 and 120 Km height regime by SPS-type activities and should be investigated further.
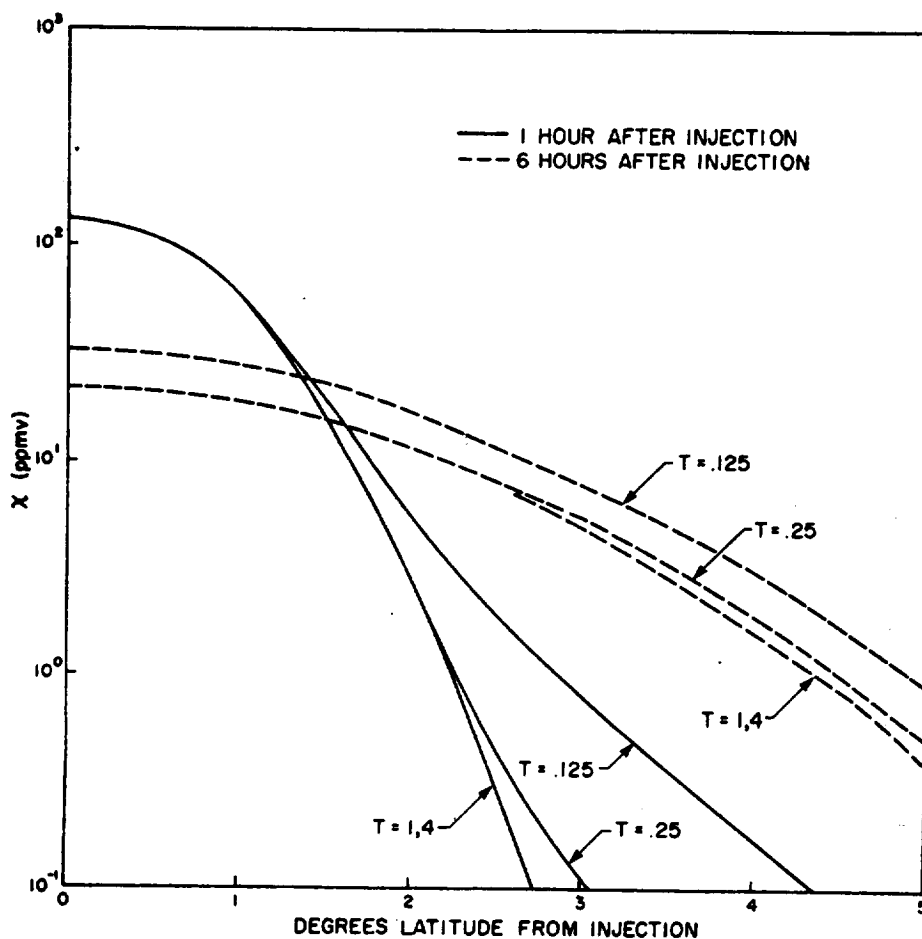

Figure 2. Steady-state latitudinal distribution of X at $\Delta t = 1$ hr and $\Delta t = 6$ hr after injection for $T = .25$, 1.0, and 4.0 days. (The longitudes corresponding to each curve are $\bar{u} \, \Delta t/24$ where $\bar{u} = 30$ deg long day^{-1} and Δt is in hours.)

REFERENCES

Forbes, J.M., "Upper Atmosphere Modifications Due to Chronic Discharges of Water Vapor from Space Launch Vehicle Exhausts", in Space Systems and Their Interactions with the Earth's Space Environment, edited by C. Pike and H. B. Garrett, to be published in 1980.

457