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REPLY

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In the accompanying comment Donahue (1986) finds unacceptable the suggestion by Frank et al. (1986) that a substantial amount of water is being deposited into the earth's upper atmosphere by small comets. The objection arises in part from the implied large water vapor concentrations as derived with a one-dimensional molecular diffusion and eddy transport model of the upper atmosphere (cf. Hunten and Donahue, 1976). Frank et al. (1986) identify this problem and suggest that three-dimensional advection and downward vertical transport of water vapor dominates over molecular diffusion and eddy transport. Donahue (1986) states that the required vertical transport speeds are too large.

The water concentrations in the upper atmosphere are a sensitive function of the altitude for penetration of the cometary water cloud. The diameter of this water cloud is estimated to be ~ 50 km and its initial speed of entry is ~ 20 km/sec. Frank et al. (1986) give a coarse estimate of direct cometary gas penetration as ~ 100 km altitude in order to demonstrate that the 100 tons of cometary water vapor would not traverse the tropopause or impact the earth's surface before its initial momentum is expended. For the current discussion an improved estimate of the altitude for direct comet penetration is required. Consider the simple model of the water cloud's deceleration in the upper atmosphere by the accumulation of all atmospheric gas in its path. The speeds of the cometary water vapor, along with the accumulated atmospheric gas, are 4 km/sec at ~ 120 km, 40 m/sec at ~ 85 km, and 40 cm/sec at ~ 55 km. The speed becomes subsonic at ~ 100 km. The cometary water vapor and atmospheric gas are turbulently mixed during the descent. Cometary water concentration in the accumulated atmospheric gas at 55 km is ~ 20 ppm, or typical of measured values. The dispersal of the water vapor can be expected also at somewhat higher altitudes by the turbulent flow of strong horizontal winds, ~ tens of m/s, past the injected cometary water mass. Thus the major fraction of the cometary water vapor can be dispersed in the mesosphere at concentrations in the range of a few tens of ppm or less. A more accurate assessment of the depth of penetration and the mixing ratio appears to require a numerical simulation with a kinetic model.

At higher altitudes the water vapor concentration is a sensitive function of the amount of water vapor deposited with the transit of the cometary cloud. At these higher altitudes near the mesopause, water concentrations should exhibit substantial temporal and spatial fluctuations. For example, Solomon et al. (1982) find water concentrations, within their error limits, to range from 0.08 to 20 ppm at altitudes 110 to 120 km. At 110 km Grossman et al. (1985) find 10 ppm. Donahue and his colleagues (1972) report the discovery of a thin ice particle layer at noctilucent cloud altitudes. This thin ice layer is found by Reid (1975) and Gadsden (1982) to indicate that the water concentration at these altitudes is considerably greater than that expected from upward transport of surface water. Indeed noctilucent clouds sporadically appear in the presence of the same temperature, a feature that indicates a temporal variability of the water concentration (cf. Gadsden, 1982). Thus there are evidences of a variable source of water.

Because the globally averaged water concentrations in the upper mesosphere and lower thermosphere due to the cometary influx are expected to be ~ few tens of ppm or less, the exospheric loss rate for H will be limited to ~ 10^8 to 10^9/cm^2-sec (Hunten and Donahue, 1976).

The cometary water vapor deposited in the mesosphere and lower thermosphere can be transported downward by atmospheric circulation, e.g., a Hadley cell. The vertical transport speeds required for accommodating various globally averaged water influxes are shown in Figure 1. The downward transport is assumed for one hemisphere. For example, for an average influx of 3 × 10^{11} H_2O molecules/cm^2-sec, the downward speed is ~ 5 m/sec at 90 km if the water concentration is 15 ppm and all of the cometary H_2O is deposited above 90 km. However only a fraction of the cometary H_2O is deposited above 90 km. If 1% of the cometary mass is injected above 90 km, a flux of 3 × 10^9/cm^2-sec, then the required transport speed is 5 cm/sec. In fact the transport speed does not have to exceed 5 cm/sec at any altitude

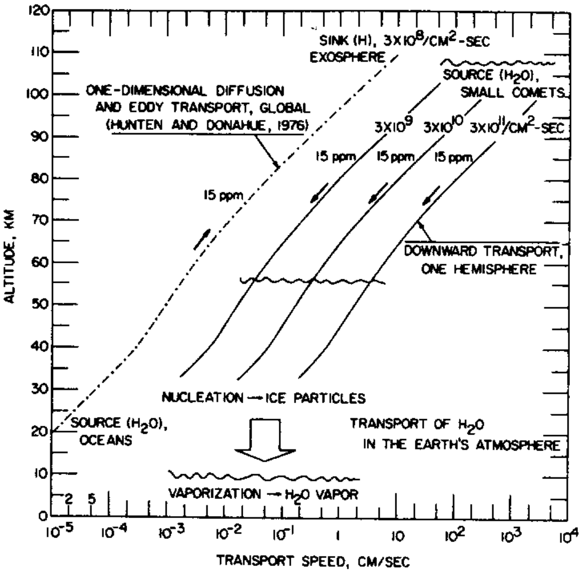

Fig. 1. Vertical transport speeds for H_2O as a function of altitude for two sources, oceans and small comets.

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> 55 km to accommodate an influx of $3 \times 10^{11}/cm^2$-sec. The deposition region is shown as ~ 55 to 105 km in Figure 1. For comparison the requirements of the one-dimensional diffusion and eddy transport model (Hunten and Donahue, 1976) are given also in Figure 1. The total hydrogen is assumed to be accounted for by water for simplicity. At 90 km, the equivalent upward vertical transport speed is 0.3 cm/sec at 15 ppm H_2O. Vertical transport speeds by atmospheric circulation are expected to be less than these values for this model.

As the cometary water vapor is transported downward into the lower stratosphere, ice particles are formed by nucleation at the frost point and precipitate into the troposphere. The yearly accumulation of cometary water at the earth's surface is 260 $\mu g/cm^2$, or 0.0001 inches of rainfall, for a cometary influx of 3×10^{11} H_2O molecules/cm^2-sec. The storage capacity of the mesosphere and upper stratosphere above 35 km is substantial. The times for accumulation of 15 ppm of H_2O are 5 days and 70 days for altitudes $\geq$ 55 km and $\geq$ 35 km, respectively. Thus fluctuations of the upper atmospheric circulation speeds or of the influx of small comets on time scales of several days do not result in large variations of the mesospheric water concentration.

The global mesospheric cloud predicted by Donahue (1986) for the present cometary influx does not exist because the water concentrations, tens of ppm, are insufficient to attain the frost point. However his comment is of substantial interest since an increase of comet influxes could produce such a global cloud cover, thereby effecting a rapid climactic change.

Donahue et al. (1982) propose that the water vapor in the Venus atmosphere is the signature of a previously existing ocean, ~ 0.3% of the earth's oceans. The presence of the small comets provides another source for the water vapor. The influx rate of such comets into the upper atmosphere of Venus is unknown but is expected to be considerably lesser than that at the earth due to increased vapor pressure in the dust-mantled comets nearer the sun. Lewis (1974) and Bauer (1983) previously suggest the cometary origin for water vapor in the Venus atmosphere. An average influx of ~ 3×10^8 H_2O molecules/cm^2-sec for 4×10^9 years and exospheric H loss can account for the present water content of the Venus atmosphere with a D/H abundance ratio of ~ 1.5×10^{-2}. Thus a current cometary influx is a viable alternative to an ancient ocean for the source of Venus atmospheric water.

The average global influx rate of water at Mars due to the small comets must be of the same order as, or greater than, that at the earth. The precipitable water column densities in the Mars atmosphere are in the range of ~ 0 to 10^{-2} gm/cm^2 (Jakosky and Barker, 1984). If the global average is 3×10^{-3} gm/cm^2 of H_2O then an influx of 3×10^{11} H_2O molecules/cm^2-sec replaces the water vapor in the Mars atmosphere in ~ 10 years. A global covering of water ice with depth 1 meter is acquired in ~ 4×10^5 years. Thus the climactic conditions on Mars are sensitive to the cometary influx on a short geological time scale. Because the range of center-of-mass energies for the impact of cometary H_2O molecules with Mars atmosphere CO_2 molecules brackets the dissociation energy for water, a large fraction of the H_2O is not likely to be dissociated in the transit of the Mars atmosphere. With the same momentum criterion as employed for the earth above, the piston of cometary gas is expected to directly penetrate to a Mars altitude of ~ 40 to 50 km. Subsequent vertical transport to the surface yields frost and polar cap water ice. The relatively small fractions of the cometary water deposited near the exobase can supply a correspondingly small exospheric loss of H and O. The rapid loading of water into the Mars atmosphere and of ice on the surface on short geological time scales may yield periodic warmings of the Mars atmosphere and enhanced exospheric outflow of water vapor. The flow of surface water during these geologically brief warming periods may be responsible for the recent surface erosion features on Mars (cf. Masursky et al., 1977).

Donahue (1986) discusses several important implications for an influx of small comets into the earth's atmosphere. However his major criticisms were considered prior to the publication of the interpretation of atmospheric holes by Frank et al. (1986) and do not alter the conclusions of these latter authors.

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