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The dry stratosphere: A limit on cometary water influx

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Abstract. The stratosphere accumulates the bulk of meteoric and cometary material that impacts the Earth and provides a measure of that flux. Recent models and measurements of the effective age of stratospheric air demonstrate our ability to simulate this buildup. Current observations of H_2O in the stratosphere and mesosphere are consistent with an extraterrestrial source of H_2O, but limit its influx to less than 2 Tg/yr. Such a flux is consistent with standard estimates but is 100 times less than the small-comet hypothesis.

1. Introduction

The original proposal that the Earth is being bombarded daily by large numbers of small icy comets was based on satellite observations of the far-ultraviolet dayglow [*Frank et al.*, 1986] and was not generally accepted by the community [*Dessler*, 1991; *Morgan and Shemansky*, 1991]. Such an hypothesis had large implications for the evolution of the Earth's volatiles-the oceans would be filled by comets over the age of the Earth-but independent corroborating scientific evidence for large numbers of impacting comets was lacking. This proposal was reasserted based on new pictures from the Visible Imaging System (VIS) on the POLAR spacecraft [*Frank and Sigwarth*, 1997]. Five new papers again question this hypothesis [*Boslough and Gladstone*, 1997; *Grier and McEwan*, 1997; *Parks et al.*, 1997; *Rizk and Dessler*, 1997; *Swindle and Kring*, 1997]. These papers point out five tracks of compelling evidence against interpreting the POLAR data as meaning that Earth is being bombarded annually by 200 Tg of cometary material, but they do not attack directly the thesis that large amounts of water are now being deposited in the upper atmosphere.

We present here a sixth piece of scientific evidence negating the basic consequence of the small-comet hypothesis: the observed dryness of the stratosphere limits the present-day flux of water from extraterrestrial sources. A stratospheric-mesospheric circulation model is developed, tested, and then used to simulate the stratospheric buildup of excess water vapor from the proposed small comets. Recent observations from the UARS satellite are found to be inconsistent with a large source of cometary water, requiring the influx to be at least 100 times smaller than proposed.

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2. Extraterrestrial Sources of H_2O

The bombardment of the Earth by meteors and meteorites is clearly observed. The ablation of this material sustains the sodium layer in the mesosphere [*Mégie and Blamont*, 1977; *Sze et al.*, 1982]. This flux, however, is sufficiently small such that speculation of its influence on stratospheric chemistry [*Turco et al.*, 1981; *Prather and Rodriguez*, 1988] is not clearly borne out by observations. Indeed, estimates of the total meteoric influx [*Wasson and Kyte*, 1987] would sustain only part per billion levels of the major chondritic elements in the upper mesosphere and part per trillion levels in the lower stratosphere. Wasson and Kyte argue that the meteoric/cometary source of H_2O for a typical chondrite/ice ratio of 0.2 would equal about 0.4 Tg/yr and be spread over a wide size-range of infalling objects. This flux might indeed have measurable impact on the upper mesosphere. If we scale the results of *Prather and Rodriguez*, we expect increases in H_2O above 60 km altitude and reaching lower altitudes in the winter poles just exceeding 0.1 ppmv.

The small-comet hypothesis predicts a massive influx of H_2O from large cometary objects [*Frank et al.*, 1986; *Frank and Sigwarth*, 1997]. The lower range of these values, 200 Tg(H_2O)/yr, is still a factor of 500 greater than our best estimate above. Simply scaling this flux to previous atmospheric simulations gives a global mean increase above 60 km of more than 50 ppmv H_2O, a patently absurd result. We critically examine this modeling result, validating the model circulation with recent measurements and deriving a limit on the flux of stratospheric water vapor from small comets.

3. Modeling the Cometary Influx

The cometary influx is simulated in a three-dimensional chemistry-transport model (CTM) using meteorological fields from the new Goddard Institute for Space Studies (GISS) general circulation middle-atmosphere model *II'* described in *Koch and Rind*, [1998; see also model *II'* documentation in *Rind and Lerner,* 1996]. The CTM uses the UC Irvine transport shell [*Prather et al.,* 1987; *Jacob et al.,* 1997] and has been applied to studies of stratospheric trace gases over the past decade, including the fate of meteoric metals [*Prather and Rodriguez,* 1988]. The earlier GISS meteorological fields from Model-II have been tested against observations and have demonstrated a very good simulation of tracer transport [*Hall and Prather,* 1995; *Avallone and Prather,* 1997]. The CTM using GISS Model-*II'* winds has resolution of 4°-latitude by 5°-longitude with 28 layers. The vertical grid of the parent GCM and the CTM is ideal for this problem: the resolution of 4 km in pressure altitude ($z^* = 16 \log_{10} [1000 / p \text{ (hPa)}]$ km) extends throughout the stratosphere and lower mesosphere up to 72 km; and the CTM combines the top 3 GCM layers into a single 72 - 90 km layer into which the cometary source is injected.

The new meteorological fields accurately simulate the turnover of the stratosphere. For example, we show in Figure 1 contours of the average age of stratospheric air from the model [e.g., *Hall and Waugh,* 1997] which can be compared with similar values derived from measurements of SF_6, CO_2, or HF. Each of these gases has a steadily increasing tropospheric source, and the time that the stratospheric concentration lags behind the tropospheric can be defined as the mean age of stratospheric (and mesospheric) air. Values derived from balloon profiles of SF_6 [*Harnisch et al.,* 1996] are shown in Figure 1 in square boxes; those from ER-2 measurements of SF_6 [*Elkins et al.,* 1996], in circles; and that from HF [*Russell et al.,* 1996], in an oval. The model has an excellent simulation of this "age" diagnostic and thus should likewise be able to represent a quasi-conserved downward moving tracer such as H_2O.

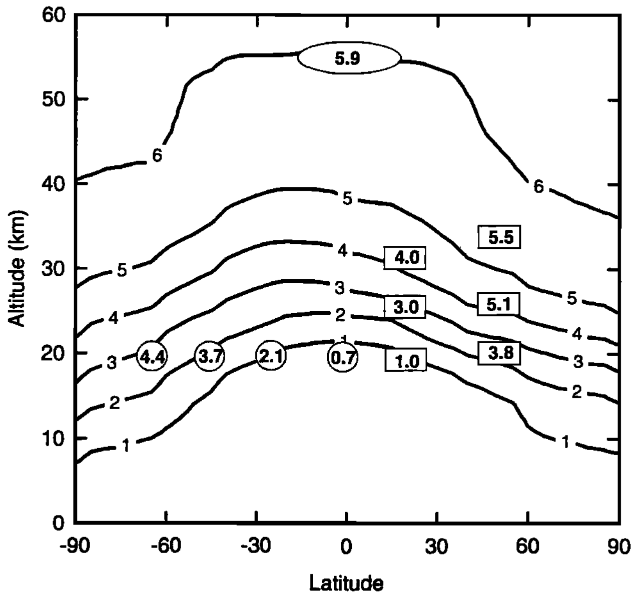

Figure 1. Annual mean-age of stratospheric air (yr, since contact with troposphere) from UCI 3-D chemistry-transport model (CTM) as a function of latitude and pressure-altitude. The CTM uses winds from the new middle atmosphere GISS Model-*II'*. Values inside squares and circles represent ages (yr) reported from SF_6 observations; and the value inside the oval, from HF observations (see text).

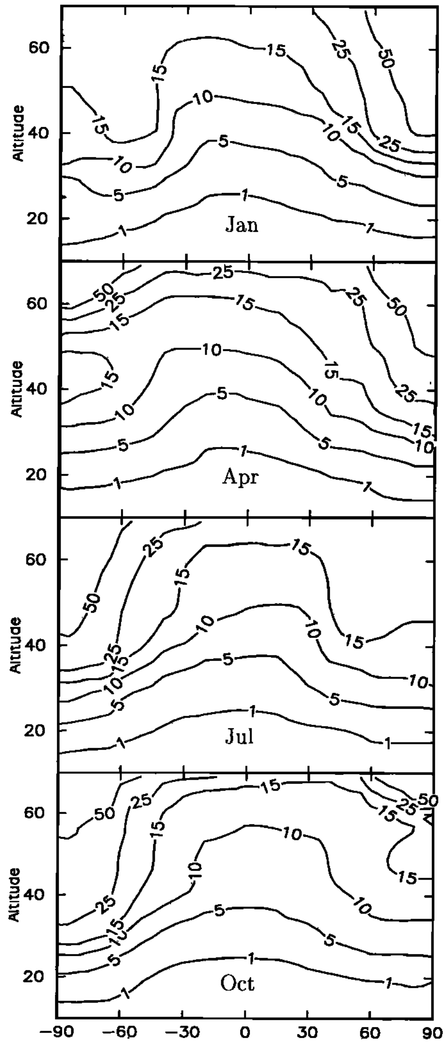

Figure 2. Excess H_2O (ppmv) as a function of latitude and pressure-altitude for a uniform extraterrestrial source of 200 $Tg(H_2O)/yr$. The 4 months (from top: Jan, Apr, Jul, Oct) are Year-11 of the UCI CTM simulation (see Figure 1). The large annual cycle of mesospheric winds produces descent of high excess H_2O over the winter poles.

The simulation of cometary water is shown in Figure 2. We have put in the hypothesized flux from small comets as a constant annual uniform source of 200 Tg of H_2O, distributed evenly over the globe with rapid removal in the troposphere. No chemistry has been included in these simulations; and thus our results, plotted as mixing ratio of H_2O, represent the increase over background for the sum of hydrogen species (H_2O + H_2 + 2 × CH_4). Results are not sensitive to the geographic location of the source or to the tropospheric removal as long as the cometary water flux is assumed to be rapidly taken up and dominated by the much larger hydrological cycle. For this extraterrestrial source the annual cycle of mesospheric air sloshing back and forth between poles is readily seen in Figure 2 as in in previous studies [*Prather and Rodriguez,* 1988]. The increase in H_2O is often 50 ppmv above 60 km altitude at mid- and high-latitudes. Between 20 and 30 km this source would more than double the background values of stratospheric water vapor. A consistent feature of the extraterrestrial flux is the gradient with much greater mixing ratios aloft.

4. Constraints from Observed H_2O

The stratospheric circulation was deduced by *Brewer* [1949] based on the distribution of water vapor. Tropospheric air enters the stratosphere through the tropical tropopause, is dried to a mixing ratio of about 3 ppmv, rises and spreads throughout the stratosphere, and then descends and re-enters the troposphere at mid- and high-latitudes. Brewer's description has been verified many times over by measurements and models of the stratospheric circulation and chemistry. The control of stratospheric H_2O by the tropical tropopause was recently re-affirmed [e.g., *Jackson et al.,* 1998; *Rosenlof et al.,* 1997; *Mote et al.,* 1996]. Generally, stratospheric H_2O is observed to increase with altitude away from the tropopause because oxidation of each CH_4 molecule produces two molecules of H_2O. The mixing ratio of $2 \times CH_4 + H_2O$ remains approximately constant at about 6 to 7 ppmv throughout the stratosphere [*Dessler et al.,* 1994; *Jones and Pyle,* 1984], except for the dehydration of the lower winter stratosphere over Antarctica. Stratospheric measurements of H_2 show a nearly uniform mixing ratio of 0.5 ppmv, and thus total hydrogen (i.e., $2 \times CH_4 + H_2O + H_2$) appears to be conserved [*Harries et al.,* 1996a] as expected in the absence of stratospheric precipitation or extraterrestrial sources.

The most restrictive limit on the extraterrestrial source of H_2O can be placed using the HALOE data for CH_4 and H_2O [*Harries et al.,* 1996b]. We focus on mid-latitude winters where mesospheric air descends into the stratosphere and brings large amounts of extraterrestrial H_2O (Figure 2). The small-comet source would produce a decrease of about 20 ppm from 55 km altitude to 24 km (0.3 - 30 hPa) in January at 45°N and in July at 45°S latitude. From this region's HALOE data over several years, we can detect no obvious gradient in stratospheric hydrogen that would point to an extraterrestrial source. We estimate an upper limit to the gradient of $2 \times CH_4 + H_2O$ over this altitude range to be less than 0.2 ppmv. Recent increases in CH_4 would produce a gradient in total hydrogen over this region that is smaller than 0.1 ppmv, not significantly affecting this limit. Scaling the 20 ppm gradient predicted for small comets constrains the extraterrestrial source to approximately 2 Tg(H_2O)/yr, a factor of 100 less than the small-comet hypothesis estimate. A source of greater than 5 Tg(H_2O)/yr would have been readily observed in the stratosphere. Above 60 km in the mesosphere, the CH_4 has been oxidized, and the H_2O mixing ratio falls off due to the more rapid formation of H_2 [*Harries et al.,* 1996a].

Along with the cometary H_2O flux there would also be an associated flux of other volatiles from the comet mantles. For instance, any carbon present in the mantles would be oxidized to CO_2 in the stratosphere. Using measurements of stratospheric CO_2 which generally show decreasing concentrations with height up to about 30 hPa (24 km) and constant CO_2 concentrations (to within ± 2 ppmv) above 30 hPa [*Schmidt and Khedim,* 1991], we calculate that the extraterrestrial carbon source must be less than 26 Tg(C)/yr, a factor of 4 less than the small-comet hypothesis estimate.

5. Conclusions

Observations of water vapor and other hydrogen species in the stratosphere place severe constraints on the flux of extraterrestrial H_2O from comets or any other source. Both the absolute amount of H_2O in the lower stratosphere and the vertical gradient of the major hydrogen species ($2 \times CH_4 + H_2O$) from the tropopause to 55 km show no clear evidence for an extraterrestrial source. We use these data with a calibrated model of stratospheric-mesospheric circulation to derive our best upper limit to the current influx of 2 Tg/yr. This upper limit is 5 times larger than, and hence consistent with, a previous estimate of meteoric influx [*Wasson and Kyte,* 1987]; but it is 100 times smaller than proposed in the small-comet hypothesis [*Frank and Sigwarth,* 1997]. Renewed efforts to find such cometary impacts on Earth should be pursued if they are sensitive enough to detect a much smaller influx that is consistent with the middle atmospheric water content.

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