**EARLY TRANSIENT VOLCANICALLY-INDUCED LUNAR ATMOSPHERES: THEIR LONGEVITY AND EFFECT ON VOLATILE DEPOSITION.** I. Aleinov[1,2], M. J. Way[2,3], J. W. Head[4], K. Tsigaridis[1,2], C. Harman[5], E. T. Wolf[6], G. Gronoff[7,8], and C. W. Hamilton[9], [1]Center for Climate Systems Research, Columbia University, New York, NY 10025, USA (igor.aleinov@columbia.edu), [2]NASA Goddard Institute for Space Studies, New York, NY, 10025, USA, [3]Theoretical Astrophysics, Department of Physics & Astronomy, Uppsala University, Uppsala SE-75120, Sweden, [4]Brown University, Providence, RI, USA, [5]Space Sciences Division, NASA Ames Research Center, Moffett Field, CA, USA, [6]University of Colorado, Boulder, USA, [7]Science Directorate, Chemistry and Dynamics Branch, NASA Langley Research Center, Hampton, VA, USA, [8]SSAI, Hampton, VA, USA, [9]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA.

**Introduction:** Since the discovery of lunar polar volatiles a few decades ago [1], their origin and distribution remain open questions. While one cannot completely discard the solar wind as a source of lunar volatiles, it is more likely that they were delivered by impactors or produced through volcanic outgassing [2]. In both such cases it is possible that delivered volatiles would form a transient tenuous atmosphere [3,4,5], so that the deposition of volatiles at the polar cold traps would be defined by the atmospheric transport rather than by ballistic hopping. Hence, knowing the properties of such a hypothetical atmosphere can help us to estimate the amount and the distribution of volatiles which were delivered by such processes to the polar cold traps or were buried under a protective layer of regolith.

We investigate the atmospheres which could have been produced by the volcanic outgassing during the peak of lunar volcanic activity at ~3.5 Ga. The thickness and composition of such atmospheres are not well constrained. Needham and Kring [4] suggested that their surface pressure could reach 10 mb if all outgassing happened during a short period of time. Preliminary investigation of such "thick" atmospheres was done in [6]. In a more recent research Head et al. [5] argued that due to large intervals between the eruptions such volcanically induced atmospheres are unlikely to accumulate to pressures higher than a few microbars. Here we study such atmospheres in a "thin" limit down to 1 microbar and investigate their stability and their ability to transport water. We have found that even 1 microbar atmospheres can efficiently deliver water to the polar regions where it can be preserved in polar cold traps.

**Methods:** For our research, we utilize the ROCKE-3D planetary General Circulation Model [7], which we have extended to handle atmospheres down to 1 microbar surface pressure. Since we are interested in the period after the Late Heavy Bombardment, we assume that the lunar surface has not significantly changed since then, so we use modern topography and albedo. We use radiation parameters corresponding to ~3.5 Ga (i.e. the solar constant 0.75 of the modern value and the corresponding solar spectrum). For orbital parameters we use a rotation period of 17.8 days and zero obliquity with respect to the Sun, but we also investigate the sensitivity of the atmospheric stability and its ability to transport volatiles to non-zero obliquities. Though we assume that the major outgassed component is CO [4], our preliminary research has shown [6] that for the conditions on the Moon ~3.5 Ga it was likely to convert to $CO_2$. For this reason we use a $CO_2$-dominated atmosphere in our experiments.

**Experiments:** We simulate $CO_2$-dominated volcanically-induced atmospheres for a range of surface pressures from 1 mb to 1 microbar. We look at their temperature and circulation patterns and investigate their stability with respect to $CO_2$ condensation in polar regions. We then conduct a major volcanic eruption experiment. For the transient atmosphere in equilibrium, we set up a typical volcanic eruption event [8] in the middle of Mare Imbrium and follow the fate of the water released during the volcanic eruption. We perform this experiment for a range of atmospheric pressures and for both a completely dry and a wet original atmosphere.

**Results:** In all our experiments we found that the atmosphere was stable, and, though the temperature in polar regions in some cases was approaching the $CO_2$ condensation point, a small departure from zero obliquity (a few degrees) was typically sufficient to keep the atmosphere stable.

In volcanic eruption simulations, the originally wet atmosphere was typically delivering a substantial amount of water (40–85% of the total outgassed amount) to the polar regions (north of 68° N or south of 68° S) in just 3 years after the onset of an eruption lasting 100-days. An originally completely dry planet (no water in either the atmosphere or soil) was less efficient in delivering the outgassed water to the poles. However, even in this case the delivery of water to the poles was substantial. Figure 1 shows the deposition of water 3 years after the onset of eruption for the case of the 0.01 mb originally dry atmosphere. Here, 19% of the outgassed water ended in the polar regions. Figure

2 shows a time series of the water deposition flux in polar regions for originally dry atmospheres from 1 mb to 1 microbar. One can see that in this case most of the water delivery happens during or shortly after the eruption (the length of eruption was 100 days). This is mainly the result of the fact that dry soil is trapping water and would not release it until it is saturated to the hygroscopic limit. Thinner atmospheres in our experiments were in general more efficient in transporting water, most likely due to the stronger circulation cell.

**Conclusions:** We investigate the tenuous (1 mb to 1 microbar) atmospheres which could have been produced by volcanic outgassing during the peak of the Moon's volcanic activity ~3.5 Ga. We find that for the parameter space we use such atmospheres are in general stable though in some cases require non-zero obliquity to prevent atmospheric collapse due to $CO_2$ condensation at the poles. In all our experiments the atmosphere could efficiently transport volatiles to the poles. In some cases thinner atmospheres were more efficient due to the stronger circulation cell.

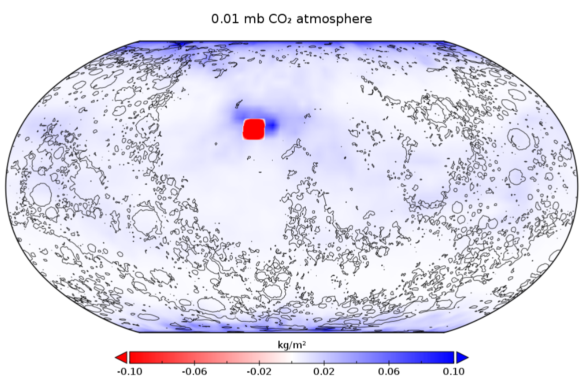


Figure 1. The amount of water (kg/m$^2$) deposited on the ground 3 years after the onset of the eruption: 0.01 mb dry $CO_2$ atmosphere case.

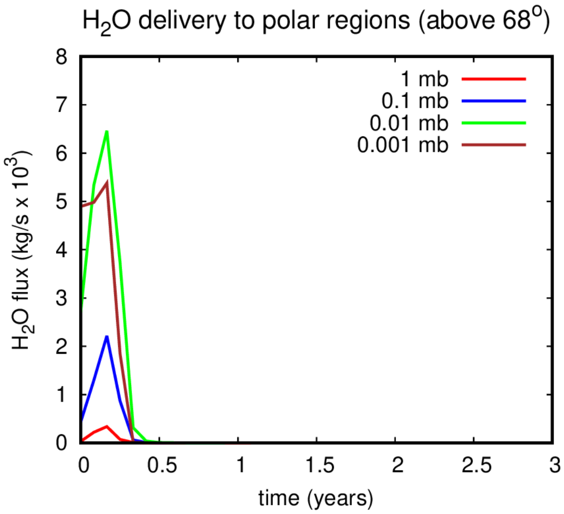


Figure 2. Water deposition flux in the polar regions as a function of time since the onset of the eruption: dry $CO_2$ atmosphere case.

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**References:** [1] Nozette, S. et al. (1996) Science, 274, 1495–1498. [2] Mandt K. E. et al. (2021) *AGU* 2021, Abstract #P53B-05. [3] Prem P. et al. (2015) *Icarus*, 255, 148–158. [4] Needham D. H. and Kring D. A. (2017) *Earth and Planetary Sci. Lett.,* 478, 175–178. [5] Head J. W. et al. (2020) *GRL*, 47, e2020GL089509. [6] Aleinov I. et al. (2019) *GRL*, 46, 5107–5116. [7] Way M.J. et al. (2017) *ApJS*, 231, 12. [8] Wilson L. and Head J. W. (2018) *GRL*, 45,5852–5859.