Was Venus the first habitable world of our solar system?

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Abstract Present-day Venus is an inhospitable place with surface temperatures approaching 750 K and an atmosphere 90 times as thick as Earth's. Billions of years ago the picture may have been very different. We have created a suite of 3-D climate simulations using topographic data from the Magellan mission, solar spectral irradiance estimates for 2.9 and 0.715 Gya, present-day Venus orbital parameters, an ocean volume consistent with current theory, and an atmospheric composition estimated for early Venus. Using these parameters we find that such a world could have had moderate temperatures if Venus had a prograde rotation period slower than ~16 Earth days, despite an incident solar flux 46–70% higher than Earth receives. At its current rotation period, Venus's climate could have remained habitable until at least 0.715 Gya. These results demonstrate the role rotation and topography play in understanding the climatic history of Venus-like exoplanets discovered in the present epoch.

1. Introduction

The habitability states of Earth and Mars have changed through the five billion year history of our solar system [*Sleep*, 1994; *Sleep and Zahnle*, 2001; *Sleep and Hessler*, 2006; *Sleep*, 2010; *DiAchille and Hynek*, 2010; *Ehlmann et al.*, 2011; *Arndt and Nisbet*, 2012]. Given the similarity of Venus's size and bulk density, and its proximity to Earth, it is plausible that Venus formed with a similar bulk composition and initial volatile inventory, although other scenarios have been proposed [e.g., *Chassefiere et al.*, 2012]. At the same time, Venus has a deuterium-to-hydrogen (D/H) ratio that is 150 ± 30 times that of terrestrial water [*Donahue et al.*, 1982, 1997] but is currently a parched world with atmospheric H_2O of 6×10^{15} kg, compared to Earth's surface inventory of 1.4×10^{21} kg [*Lecuyer et al.*, 2000]. The D/H ratio implies that Venus has lost substantial quantities of water over its history, but it is unclear when and at what rate [*Kasting and Pollack*, 1983; *Donahue*, 1999]. When continuing exogenous and endogenous sources are included, the primordial value is very poorly determined [*Grinspoon*, 1993]. However, modern formation models indicate a great deal of mixing among terrestrial planet protoplanets [e.g., *Morbidelli et al.*, 2012], strongly suggesting that Venus and Earth did not form with 5 orders of magnitude difference in water inventory.

A variety of estimates give paleo-Venus the equivalent of 4–525 m of liquid water if spread evenly across its surface [*Donahue and Russell*, 1997], while the idea of an ancient Venus with oceans is hardly new [e.g., *Kasting et al.*, 1984; *Kasting*, 1988; *Grinspoon and Bullock*, 2003]. At the same time, some planet formation scenarios for Venus-type objects close to their parent star indicate that most water may have been expelled in the first 100 Myr of their history [*Hamano et al.*, 2013]. Recent work demonstrates that Earth may have also lost much of its initial volatile inventory within the first 100 Myr of its history [*Finlay et al.*, 2016; *Pujol et al.*, 2013]. For Venus to obtain an ocean depth of hundreds of meters after such an initial loss, it would require substantial water delivery during the late veneer [e.g., *Chou*, 1978; *Drake and Richter*, 2002; *Frank et al.*, 2012].

One surprising observation is that Venus, while being smaller than the Earth, has more than twice as much nitrogen in its atmosphere as Earth: 1.1×10^{19} versus 3.9×10^{18} kg. These numbers were calculated from http://nssdc.gsfc.nasa.gov/planetary/factsheet/venusfact.html and the Cambridge Handbook of Earth Science Data. It is estimated that Venus may have similar abundant quantities of nitrogen beneath its surface [*Lecuyer et al.*, 2000]. At the same time Venus has far more CO_2 in its atmosphere than Earth contributing to its high surface temperatures by being a potent greenhouse gas. Venus's atmosphere contains 1.2×10^{20} kg of

Table 1. Paleo-Venus Experimental Setups and Results[a]

Simulation	Topography	Spectrum/Flux/S0X	Rotation Period	T (min)	T (max)	T (avg)	Time (avg)
A	Venus	2.900 Gya/2001/1.46	Modern Venus	−22°C	36°C	11°C	1/6 day
B	Venus	0.715 Gya/2357/1.70	Modern Venus	−17°C	35°C	15°C	1/6 day
C	Earth	2.900 Gya/2001/1.46	Modern Venus	−13°C	46°C	23°C	1/6 day
D	Venus	2.900 Gya/2001/1.46	16 × Earth	27°C	84°C	56°C	1/8 day

[a]The Spectrum/Flux/S0X is the solar spectrum used (Gya = 10^9 years ago), the incident solar flux the world receives in W/m^2, and the ratio, S0X, of the solar irradiance the world receives compared to that of present-day Earth. T indicates the minimum and maximum surface temperature values from individual grid cells in the time averages shown in Figure 2. T (avg) is the globally averaged surface air temperature. Time (avg) is the time period in solar days for each world over which the global temperatures are averaged as indicated in the temperature columns.

carbon, while all superficial Earth reservoirs (the largest being carbonate rock) combined contain 5.4×10^{19} kg carbon [*Lecuyer et al.*, 2000].

The history of Venus's orbital state is more uncertain. Currently Venus has a 116.75 Earth-day-length solar day. It orbits the Sun every 225 days and has a "retrograde" sidereal rotation period of 243 days. It had been thought that atmospheric tides in the thick Venusian atmosphere eventually led to the present rotation rate of Venus [*Dobrovolskis and Ingersoll*, 1980] and that this condition was not likely to be primordial. However, it has recently been shown that even a 1 bar atmosphere is sufficient to create the same tidal effect [*Leconte et al.*, 2015]. Other work has shown that approaching a tidally locked or nearly tidally locked state like that of modern Venus may be a natural consequence of planetary tidal-bulge/Sun interaction (R. Barnes, Tidal Locking of Habitable Exoplanets, submitted to *Celestial Mechanics and Dynamical Astronomy*, 2016), with important climate implications [*Yang et al.*, 2014]. New work by *Barnes et al.* [2016] has shown that if Venus started with its current obliquity near 180°, it is likely to have remained so throughout its existence. How it would have obtained its initial ~180° obliquity is still debated.

In this paper we use a three-dimensional general circulation model (GCM) to explore scenarios under which an ancient Venus with shallow oceans and an Earth-like atmosphere may have been habitable and to estimate the potential duration of such a habitable phase.

2. Methods

Several hypothetical Venus climates were simulated (see Table 1) via the Goddard Institute for Space Studies ROCKE-3D (Resolving Orbital and Climate Keys of Earth and Extraterrestrial Environments with Dynamics) GCM. ROCKE-3D is derived from the parent Earth climate GCM ModelE2-R [*Schmidt et al.*, 2014]. The simulations were run on a Cartesian grid point system at 4° × 5° latitude-longitude resolution, and 20 atmospheric layers with a top at 0.1 hPa. The atmosphere is coupled to a 13 layer fully dynamic ocean [*Russell et al.*, 1995]. Land albedo is initially set to 0.2 following *Yang et al.* [2014]. There is no land ice at model start, but snow is allowed to accumulate. Given the fact that Venus shows substantial N_2 in its atmosphere today and has few modern day sources or sinks (unlike Earth), we assume that an ancient Venus could have had a ~1 bar N_2 atmosphere (1012.6 mb) in its early history. A modern Earth amount of CO_2 and CH_4 is also included (400 ppm, 1 ppm), given otherwise poor constraints on these gas concentrations. A variety of ancient solar spectra were generated (Table 1, column 3) with a model by *Claire et al.* [2012] using a modern Sun reference spectrum: 0.5–2397.5 nm [*Thuillier et al.*, 2013], and 2397.5–99999.5 nm [*Lean*, 2000]. The faintest spectrum at 2.9 Gya is ~77% of the present-day luminosity of the Sun.

Venus was resurfaced by volcanic activity hundreds of millions of years ago [e.g., *McKinnon et al.*, 1997; *Kreslavsky et al.*, 2015], so its topography before that time is unknown. As an estimate with some observational basis, we use modern topographic data from the Venus Magellan mission via the PDS (Planetary Data System) archive (http://pds-geosciences.wustl.edu/mgn/mgn-v-rss-5-gravity-l2-v1/mg_5201) and fill the resurfaced lowlands with water. The ocean level was set to the mean radius of Venus from the same PDS data. This provides an ocean of 310 m depth if spread evenly across the surface, fortuitously within the range estimated in *Donahue and Russell* [1997]. The ocean volume is 1.4×10^{17} m^3, an order of magnitude smaller than that of modern Earth at 1.3×10^{18} m^3. If an equivalent depth Earth ocean were to exist on modern Venus, less than 10% of the surface would still be land [*Taylor*, 2016]. While Earth's ocean covers ~70% of
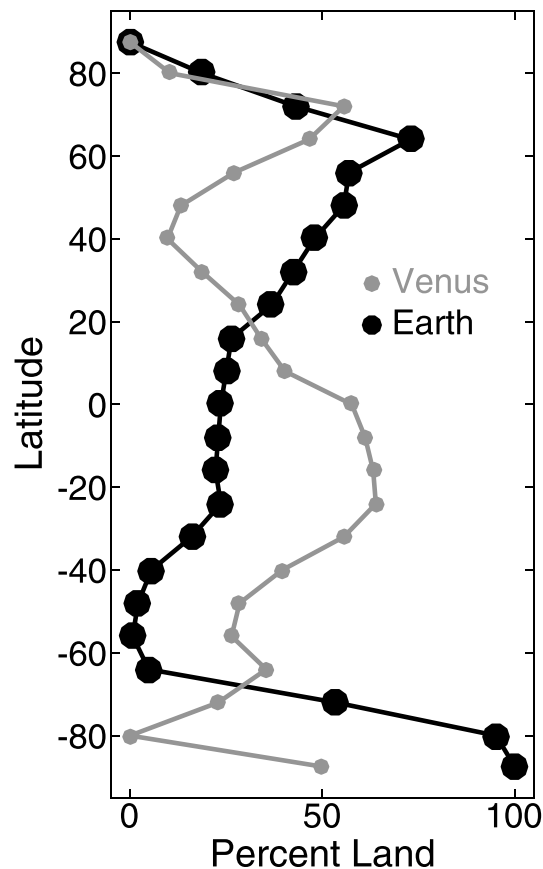
Figure 1. Land fraction as a function of latitude for modern Earth (Sim C) versus our paleo-Venus reconstruction (Sims A, B, and D). The paleo-Venus world has a global land/ocean fraction of ~40/60% while modern Earth's is ~30/70%.

its surface area, this paleo-Venus ocean covers only 60%, with a latitudinal distribution of land distinct from that of modern Earth (Figure 1). The impact on atmospheric dynamics and thermodynamics of the distribution of land by latitude and land/ocean fraction has seldom been explored [*Abe et al.*, 2011; *Charnay et al.*, 2013], and so we repeat our baseline simulation (Sim A) with identical forcing but with Earth's topography (Sim C). All simulations use Venus' radius, gravity, modern obliquity, and modern eccentricity.

To test the range of ages and rotations over which the climate of paleo-Venus might have been stable, paleo-Venus was also simulated using a solar spectrum estimated for 0.715 Gya (Sim B), equivalent to ~94% of modern day solar luminosity (Table 1 and Figure 2b) and a solar flux at Venus's orbit ~70% higher than that for modern Earth. The value of 0.715 Gya was chosen to represent the time slice around the time of the most recent resurfacing event on Venus. To test the possible effects of rotation, Sim D (Figure 2d) uses the same 2.9 Gya solar spectrum as in Sim A but changes the rotation period from the modern Venus value to 16 times that of modern Earth's sidereal day length.

3. Results

Sim A gives a global mean surface air temperature of 11°C (Table 1 and Figure 2a) and a maximum of 36°C in a single grid cell despite an incident solar flux at Venus's orbit ~46% higher than that received by modern Earth. The range of surface temperatures in Sim A is narrower than that of modern Earth (Figure 3), primarily because dynamical heat transports more efficiently reduce horizontal temperature gradients on slowly rotating planets and secondarily because Earth's lowest temperatures occur in its polar continental regions that Sim A lacks. Previous 1-D work by *Grinspoon and Bullock* [2007] has shown that an N_2 atmosphere with 6 mb of H_2O (at the surface) can generate a surface air temperature of 27°C if 100% cloud cover is assumed. Their 100% cloud cover assumption is nicely reflected in that of Sim A where the dayside of the planet is almost completely overcast (Figure 4a).

Comparing Sims A and B, where the solar flux increases from 77% to 94% of modern, one sees that the global mean surface air temperature increases only 4°C. However, the effect of rotation on temperature is much stronger when the world's rotation period is decreased to 16 times the present-day sidereal rotation rate of modern Earth, but the solar spectrum remains from 2.9 Gya (Sim D, Figure 2d). The faster rotation rate gives Sim D a mean surface air temperature 45°C warmer than that of Sim A. This should be unsurprising considering the similar results of *Yang et al.* [2014, their Figure 2c], who also find a pronounced surface air temperature difference between their 16 and 256 sidereal day length worlds.

The high-level cloudiness on the dayside of Sim A (Figure 4a) has values as high as 100% for a given grid cell. This is the result of this world's slow rotation which generates a strong circulation with rising motion (implied
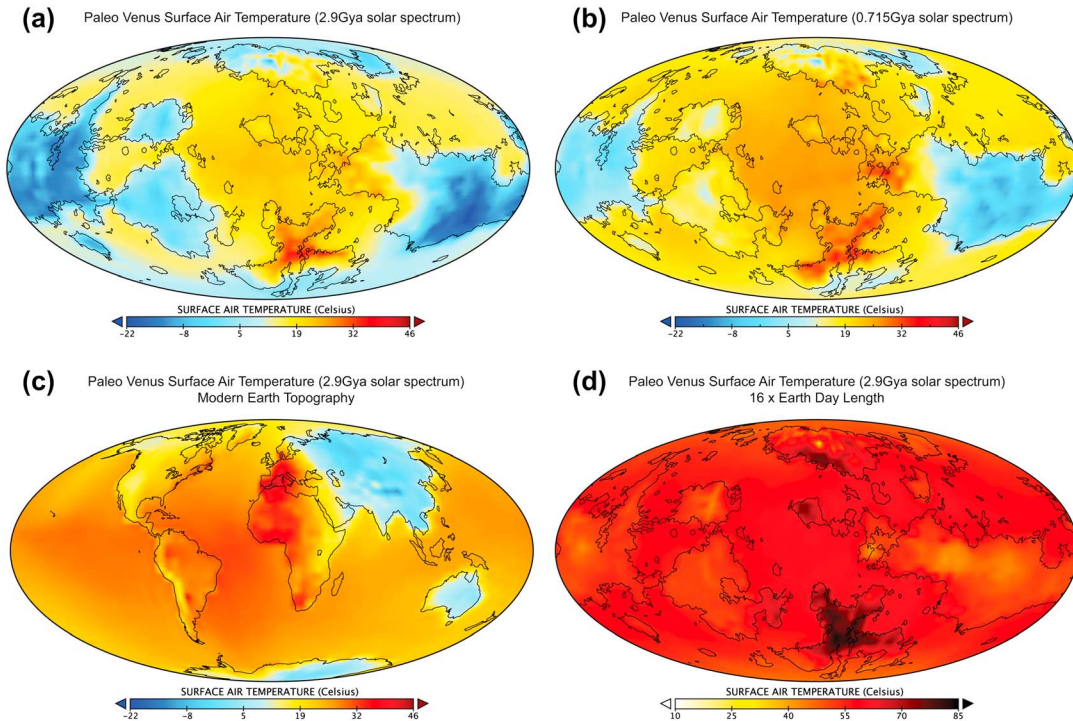
Figure 2. (a) A time average (over one sixth of a Venusian solar day) of the surface air temperature (SAT) for the paleo-Venus world with modern day rotation rate and a solar spectrum estimated for 2.9 Gya (Sim A). (b) The SAT for the same world in Figure 2a but using a 0.715 Gya solar spectrum (Sim B). (c) The same as Figure 2a but using a modern day Earth topography (Sim C). (d) This uses a 2.9 Gya solar spectrum but contrary to the other three simulations has a sidereal day 16 times that of modern Earth (Sim D). The snapshot shown in Figure 2d is an average over one eighth of a solar day on this world, again contrary to the other three simulations. Note that the color scale in Figure 2d has changed from that of Figures 2a–2c. The yellow color in Figure 2d has a similar value to the yellow in Figures 2a–2c (around 17–19°C). Sim D reaches the limit of the accuracy of the current ROCKE-3D radiation tables, which use a simple linear extrapolation above 77°C.
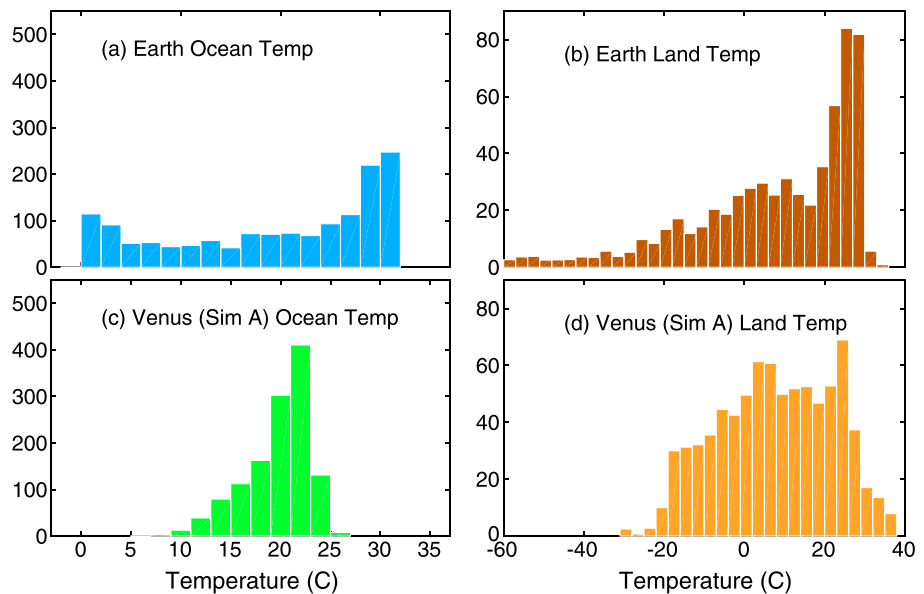

Figure 3. Left column shows equal area histograms of ocean surface temperatures for (a) modern Earth [*Schmidt et al.*, 2014] and (c) Sim A. Right column contains land temperatures for (b) modern Earth and (d) Sim A.
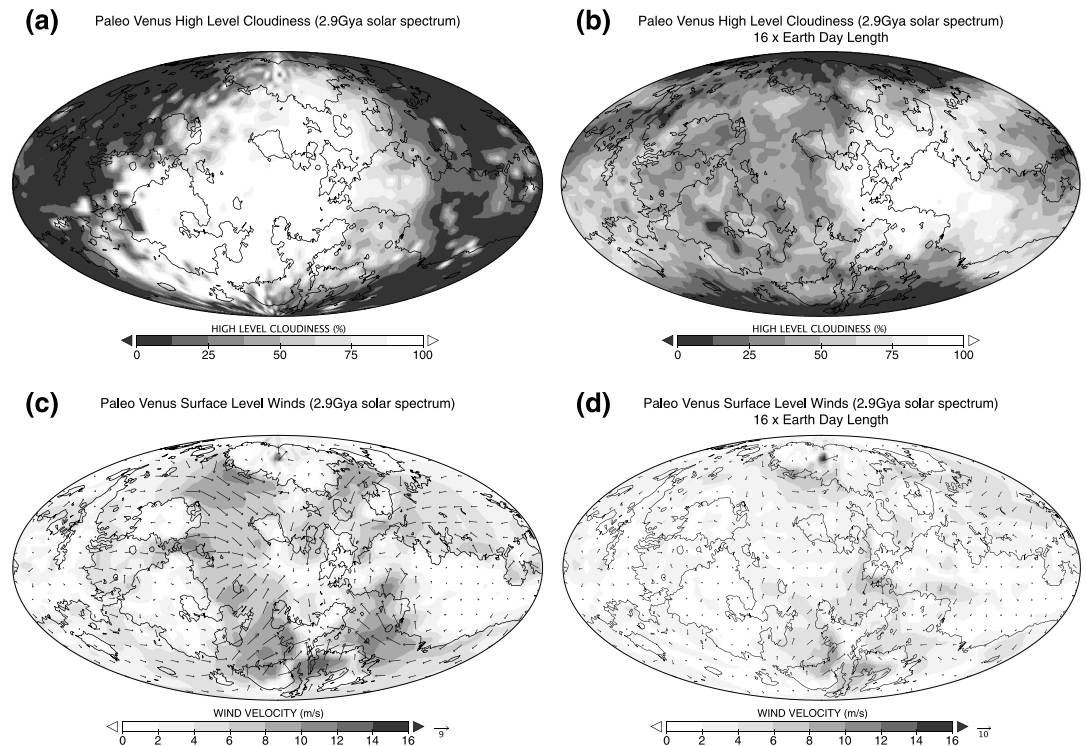
Figure 4. High-level clouds (white) for (a) Sim A and (b) Sim D, and surface level winds for (c) Sim A and (d) Sim D. Shading in Figures 4c and 4d is related to wind strength.

in the surface wind plot of Figure 4c) and accompanying high thick clouds on the dayside that reflect a substantial fraction of the incident sunlight, as also shown in experiments by *Yang et al.* [2014]. These highly reflective thick areally extensive clouds are formed from smaller scale parameterized convective clouds that carry water vapor and condensed water to high altitudes in buoyant updrafts. When these updrafts reach the stable middle/upper troposphere they lose buoyancy and the flow diverges and spreads, injecting water vapor and cloud particles that form a reflective shield of cirrus anvil clouds. This is similar to much of the cloudiness seen in the Intertropical Convergence Zone on Earth, except that the convection in our paleo-Venus worlds sits more or less in place for many days at a time since the rotation is so slow and can make a large area overcast for several months.

This circulation pattern is peculiar to the assumed Earth-like thickness of the paleo-Venus atmosphere, which allows it to cool significantly on the nightside by emitting thermal radiation [*Way et al.*, 2015] generating a strong day-night circulation (Figure 4c). The latter may be contrasted with the wind pattern in Figure 4d for the 16 days rotation period case (Sim D) where the surface level winds do not show a strong day-night flow. Modern Venus, which has a much thicker CO_2 atmosphere that takes centuries to cool radiatively, has only a weak day-night circulation and is dominated instead by a broad Hadley cell that stretches from the equator to high latitudes [*Rossow et al.*, 1990].

The simulation with Earth topography (Sim C) produces habitable surface temperatures but is 12°C warmer than the otherwise equivalent Sim A with Venus topography (Table 1 and Figure 2). This result can be explained by the finding by *Abe et al.* [2011] that "dry" planets with limited water reservoirs are less sensitive to increases in solar flux than all-water "aquaplanets." In particular, the large land fraction in the tropics in the Venus topography case relative to that for Earth topography (Figure 1) appears to limit surface evaporation (which is largest over the tropical oceans) and thus the buildup of atmospheric water vapor and its attendant greenhouse effect at low latitudes.

From Figure 2 it is clear that the nightside of the slowly rotating Sims A–C are cold enough for snow to accumulate. In most places this snow amounts to a few centimeters and completely melts by the time the Sun is overhead. We find no trend in this behavior over the length of the simulations that would lead to a

large cold trap. However, in Sims A and B the two highest altitude grid cells (over 5000 m) in Ishtar Terra (high northern latitude) have a permanent snow cover of about 5 m in depth which appears constant in time.

One might also believe that the land would get quite dry from repeated heating, yet the water in the first ground layer (10 cm) has a relatively zonal distribution and does not appear to be drying out due to the very long periods of solar heating in the slowly rotating cases. In fact, the ground appears to get wet during the day and stays mostly wet throughout the night.

The mean precipitation rate is at least 8 mm/d in the subsolar region, with tens of millimeters per day in some grid boxes for Sim A. This is as strong or stronger than anything seen on Earth, The potential for weathering and erosion on such a planet would exist, but only within ~20° of the equator (unlike on Earth). Hence, a future mission to Venus should explore Aphrodite Terra and Beta Regio, rather than Ishtar Terra, to search for such erosion. Visual signs of such water-related erosion and transport of sediment (e.g., stream downcutting through land forms, gravelly/braided stream deposits, mudslides, alluvial fans, or deltas) would indicate physical erosion mainly. Both of these are potentially detectable via remote sensing, just as they have been for Mars. Indications that chemical weathering had taken place would include the presence of certain clays, depending on the composition of the parent rock. However, rates of chemical weathering are difficult to constrain, given Venus' extreme long term climate variability.

If these hypothetical worlds were in or were approaching a moist greenhouse state then it could be possible to conclude something quantitative about the likelihood of water loss over the history of the planet. *Kasting* [1988] showed that this state would be attainable if the mixing ratio of H_2O in the upper atmosphere reached ~0.1%. The paleo-Venus Sim A world is well below that mixing ratio, and its stratosphere (100 mb level and higher) is as dry as modern Earth, nearly 2 orders of magnitude below the moist greenhouse limit. Sim B is 1 order of magnitude below, and Sim C is halfway between Sims A and B, while Sim D is 1 order of magnitude over the limit.

4. Discussion

Several caveats need to be discussed in the context of the ancient climates of Venus, Earth, and Mars. Early Earth and Mars would have been very cold worlds ~2.9 Gya without substantial greenhouse gases or other means to absorb and reradiate thermal radiation [*Goldblatt and Zahnle*, 2010; *Charnay et al.*, 2013; *Ramirez et al.*, 2014]. Another item seldom mentioned in studies of ancient Mars and the possibility of life is the issue of climate stability: a mechanism to keep the sinks and sources of greenhouse gases in balance for long enough periods of time to allow life to begin. The same holds true for Venus. Venus has substantial sources of N_2 and CO_2 as measured in its atmosphere today, but no substantial sinks have been measured thus far. Studies since the time of the Magellan mission have shown that subductive style plate tectonics do not presently exist on Venus to give it a substantial sink like that on Earth, even if there may be other types of tectonic activity allowing sinks of unquantified magnitude [e.g., *Elkins-Tanton et al.*, 2007]. So while this work demonstrates that it may have been possible to have a moderate climate on Venus on short time scales compared with Earth [*Sleep and Zahnle*, 2001; *Bertaux et al.*, 2007], we must wait until future data help us better constrain that planet's ancient geologic history to understand if it was capable of long-term stable habitable climates. Other anticipated spacecraft measurements will reduce current large uncertainties in the geologic and atmospheric history of Venus. High-resolution radar and global near-infrared mapping will help clarify both ancient and recent levels of geologic activity, informing comparisons with terrestrial tectonic style and history [*Smrekar et al.*, 2016]. In situ measurements of rare gases and their isotopes, currently highly uncertain, as well as precision measurements of D/H and other stable isotope ratios, will greatly refine current constraints on the atmospheric and climatic history of this nearby Earth-sized planet [*Glaze et al.*, 2016].

Since Venus is similar to Earth in size and adjacent to it in our solar system, it is of particular interest for the characterization of seemingly similar exoplanets that could have followed different evolutionary paths [*Kane et al.*, 2014]. It is not known with certainty whether Venus ever had an ocean. Venus could have formed with less water than Earth [*Raymond et al.*, 2006] or with considerable water that escaped during an extended early runaway greenhouse period during formation [*Hamano et al.*, 2013; *Luger and Barnes*, 2015]. Yet these results and others [*Yang et al.*, 2014] suggest that for warm rocky planets that retain significant water after formation, an extended period of habitability is possible well inside the traditionally defined inner edge of the habitable zone for cloud-free atmospheres [*Kopparapu et al.*, 2013] if they rotate slowly enough. Furthermore, while the

possibility of surface liquid water defines the traditional habitable zone, our results suggest that a planet with a modest amount of surface liquid water is more conducive to habitability over a wide range of stellar fluxes than a planet largely or completely covered by water. The inner edge should therefore be considered a transition region in which the probability of habitability gradually decreases inward rather than a strict boundary separating completely different regimes [*Barnes et al.*, 2015].

References

Abe, Y., A. Abe-Ouchi, N. Sleep, and K. Zahnle (2011), Habitable zone limits for dry planets, *Astrobiology*, *11*(5), 443–460, doi:10.1089/ast.2010.0545.

Arndt, N. T., and E. G. Nisbet (2012), Processes on the young Earth and the habitats of early life, *Annu. Rev. Earth Planet. Sci.*, *40*, 521–549.

Barnes, J. W., B. Quarles, J. J. Lissauer, J. Chambers, and M. M. Hedman (2016), Obliquity variability of a potentially habitable early Venus, *Astrobiology*, *16*(7), 487–499, doi:10.1089/ast.2015.1427.

Barnes, R., V. S. Meadows, and N. Evans (2015), Comparative habitability of transiting exoplanets, *Astrophys. J.*, *814*, 91.

Bertaux, J. L., M. Carr, D. J. Des Marais, and E. Gaidos (2007), Conversations on the habitability of worlds: The importance of volatiles, *Space Sci. Rev.*, *129*, 123–165.

Charnay, B., F. Forget, R. Wordsworth, J. Leconte, E. Millour, F. Codron, and A. Spiga (2013), Exploring the faint young Sun problem and the possible climates of the Archean Earth with a 3-D GCM, *J. Geophys. Res. Atmos.*, *118*, 10,414–10,431.

Chassefiere, E., R. Wieler, B. Marty, and F. Leblanc (2012), The evolution of Venus: Present state of knowledge and future exploration, *Planet. Space Sci.*, *63–64*, 15–23.

Chou, C. L. (1978), Fractionation of siderophile elements in the Earth's upper mantle, in *Proc. LPSC IX*, vol. 1, pp. 219–230, Lunar and Planetary Institute, Houston, Tex.

Claire, M. W., et al. (2012), The evolution of solar flux from 0.1 nm to 160 um: Quantitative estimates for planetary studies, *Astrophys. J.*, *757*, 1.

DiAchille, G., and B. Hynek (2010), Ancient ocean on Mars supported by global distribution of deltas and valleys, *Nat. Geosci.*, *3*, 459.

Dobrovolskis, A. R., and A. P. Ingersoll (1980), Atmospheric tides and the rotation of Venus, *Icarus*, *41*, 1.

Donahue, T. M. (1999), New analysis of hydrogen and deuterium escape from Venus, *Icarus*, *141*, 226–235.

Donahue, T. M., and C. T. Russell (1997), The Venus atmosphere and ionosphere and their interaction with the solar wind: An overview, in *Venus II Geology, Geophysics, Atmosphere, and Solar Wind Environment*, edited by S. W. Baugher, D. M. Hunten, and R. J. Phillips, pp. 3–31, Univ. of Ariz. Press, Tucson.

Donahue, T. M., J. J. Hoffman, R. R. Hodges Jr., and A. J. Watson (1982), Venus was wet: A measurement of the ratio of deuterium to hydrogen, *Science*, *216*, 630.

Donahue, T. M., D. H. Grinspoon, R. E. Hartle, and R. R. Hodges Jr. (1997), Ion/neutral escape of hydrogen and deuterium: evolution of water, in *Venus II Geology, Geophysics, Atmosphere and Solar Wind Environment*, edited by S. W. Bougher, D. M. Hunten, and R. J. Phillips, pp. 585–414, Univ. of Ariz. Press, Tucson.

Drake, M. J., and K. Richter (2002), Determining the composition of the Earth, *Nature*, *416*, 39.

Ehlmann, B. L., J. F. Mustard, S. L. Murchie, J.-P. Bibring, A. Meunier, A. A. Fraeman, and Y. Langevin (2011), Subsurface water and clay mineral formation during the early history of Mars, *Nature*, *479*, 53–60.

Elkins-Tanton, L. T., S. E. Smrekar, P. C. Hess, and E. M. Parmentier (2007), Volcanism and volatile recycling on a one-plate planet: Applications to Venus, *J. Geophys. Res.*, *112*, E04S06, doi:10.1029/2006JE002793.

Finlay, M. S., D. F. Mark, P. Gandanger, and P. McConville (2016), Earth-atmosphere evolution based on new determination of Devonian atmosphere Ar isotopic composition, *Earth Planet. Sci. Lett.*, *446*, 21–26, doi:10.1016/j.epsl.2016.04.012.

Frank, E. A., W. D. Maier, and S. J. Mojzsis (2012), The 'Late Veneer' on Earth: Evidence from Eoarchean ultramafic schists (metakomatiites) Lunar Planet. Sci. Conf. 43rd, LPI Contribution No. 1659, id. 2890, Woodlands, Tex., 19–23 March.

Glaze, L. S., et al. (2016), DAVINCI: Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging Abstract for Lunar Planet. Sci. Conf. 47th.

Goldblatt, C., and K. J. Zahnle (2010), Clouds and the faint young Sun paradox, *Clim. Past Discuss.*, *6*(3), 1163–1207.

Grinspoon, D. H. (1993), Implications of the high D/H ratio for the sources of water in Venus' atmosphere, *Nature*, *363*, 428.

Grinspoon, D. H., and M. A. Bullock (2003), Did Venus experience one great transition or two? *Bull. Am. Astron. Soc.*, *35*, 44–03.

Grinspoon, D. H., and M. A. Bullock (2007), Astrobiology and Venus exploration, in *Exploring Venus as a Terrestrial Planet*, edited by L. W. Esposito, E. R. Stofan, and T. E. Cravens, pp. 191–206, AGU, Washington, D. C.

Hamano, K., Y. Abe, and H. Genda (2013), Emergence of two types of terrestrial planet on solidification of magma ocean, *Nature*, *497*, 607.

Kane, S. R., R. K. Kopparapu, and S. D. Domagal-Goldman (2014), On the frequency of potential Venus analogs from Kepler data, *Astrophys. J. Lett.*, *794*, L5.

Kasting, J. F. (1988), Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus, *Icarus*, *74*, 472–494.

Kasting, J. F., and J. B. Pollack (1983), Loss of water from Venus. I. Hydrodynamic escape of hydrogen, *Icarus*, *53*, 479.

Kasting, J. F., J. B. Pollack, and T. P. Ackerman (1984), Response of Earth's atmosphere to increases in solar flux and implications for loss of water from Venus, *Icarus*, *57*, 335–355.

Kopparapu, R. K., et al. (2013), Habitable zones around main sequence stars: New estimates, *Astrophys. J.*, *765*, 131.

Kreslavsky, M., A. Ivanov, and J. W. Head (2015), The resurfacing history of Venus: Constraints from buffered crater densities, *Icarus*, *250*, 438.

Lean, J. (2000), Evolution of the Sun's spectral irradiance since the Maunder minimum, *Geophys. Res. Lett.*, *27*(16), 2425–2428, doi:10.1029/2000GL000043.

Leconte, J., H. Wu, K. Menou, and K. N. Murray (2015), Exoplanet dynamics. Asynchronous rotation of Earth-mass planets in the habitable zone of lower-mass stars, *Science*, *347*(6222), 632–635, doi:10.1126/science.125868.

Lecuyer, C., L. Simon, and F. Guyot (2000), Comparison of carbon, nitrogen, and water budgets on Venus and the Earth, *Earth Planet. Sci. Lett.*, *181*, 33.

Luger, R., and R. Barnes (2015), Extreme water loss and abiotic O_2 buildup on planets throughout the habitable zones of M dwarfs, *Astrobiology*, *15*, 119–143.

McKinnon, W. B., K. J. Zahnle, B. A. Ivanov, and H. J. Melosh (1997), Cratering on Venus: Modeling and observations, in *Venus II Geology, Geophysics, Atmosphere and Solar Wind Environment*, edited by S. W. Bougher, D. M. Hunten, and R. J. Phillips, pp. 585–414, Univ. of Ariz. Press, Tucson.

Morbidelli, A., J. I. Lunine, D. P. O'Brien, S. N. Raymond, and K. J. Walsh (2012), Building terrestrial planets, *Annu. Rev. Earth Planet. Sci.*, *40*, 251–275, doi:10.1146/annurev-earth-042711-105319.

Pujol, M., B. Marty, R. Burgess, G. Turner, P. Philippot (2013), Argon isotopic composition of Archaean atmosphere probes early Earth geodynamics, *Nature*, *498*, 87–90, doi:10.1038/nature12152.

Ramirez, R. M., R. Kopparapu, M. E. Zugger, T. D. Robinson, R. Freedman, and J. F. Kasting (2014), Warming early Mars with CO_2 and H_2, *Nat. Geosci.*, *7*(1), 59–63.

Raymond, S. N., T. Quinn, and J. I. Lunine (2006), High-resolution simulations of the final assembly of Earth-like planets. I. Terrestrial accretion and dynamics, *Icarus*, *183*, 265–282.

Rossow, W. B., A. D. Del Genio, and T. P. Eichler (1990), Cloud-tracked winds from Pioneer Venus OCPP images, *J. Atmos. Sci.*, *47*, 2053–2084.

Russell, G. L., J. R. Miller, and D. H. Rind (1995), A coupled atmosphere-ocean model for transient climate change studies, *Atmos.-Ocean*, *33*, 683.

Schmidt, G. A., et al. (2014), Configuration and assessment of the GISS ModelE2 contributions to the CMIP5 archive, *J. Adv. Model. Earth Syst.*, *6*(1), 141–184, doi:10.1002/2013MS000265.

Sleep, N. H. (1994), Martian plate tectonics, *J. Geophys. Res.*, *99*(E3), 5639–5655, doi:10.1029/94JE00216.

Sleep, N. H. (2010), The Hadean-Archaean environment, in *Cold Spring Harbor Perspectives in Biology*, edited by S. Deamer and J. W. Szostak, pp. 1–14, Cold Spring Harbor Laboratory Press, Harbor, N. Y.

Sleep, N. H., and A. M. Hessler (2006), Weathering of quartz as an Archean climatic indicator, *Earth Planet. Sci. Lett.*, *241*, 594.

Sleep, N. H., and K. Zahnle (2001), Carbon dioxide cycling and implications for climate on ancient Earth, *J. Geophys. Res.*, *106*(E1), 1373–1399, doi:10.1029/2000JE001247.

Smrekar, S. E., S. Hensley, M. D. Dyar, J. Helbert, and the VERITAS Science Team (2016), VERITAS (Venus Emissivity, Radio Science, Insar, Topography And Spectroscopy): A proposed discovery mission Abstract for Lunar Planet. Sci. Conf. 47th.

Taylor, F. W. (2016), *The Scientific Exploration of Venus* chap. 4, pp. 51, Cambridge Univ. Press, New York.

Thuillier, G., L. Floyd, T. N. Woods, R. Cebula, E. Hilsenrath, M. Hersel, and D. Labs (2013), Solar Irradiance Reference Spectra, in *Solar Variability and its Effects on Climate*, *Geophys. Monogr.*, vol. 141, pp. 171–194, AGU, Washington, D. C., doi:10.1029/141GM13.

Way, M. J., A. D. Del Genio, M. Kelley, I. Aleinov, and T. Clune (2015), Exploring the inner edge of the habitable zone with coupled oceans arXiv:1511.07283.

Yang, J., B. Gweanel, D. C. Fabrycky, and D. S. Abbot (2014), Strong dependence of the inner edge of the habitable zone on planetary rotation rate, *Astrophys. J.*, *787*, 2.